APPENDIX A

From: "Middleton, Wesley (WAMI)" <WAMI@chevron.com> Save Address - Block Sender
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Subject: Oil for EMD
Date: Fri, 13 Jul 2001 09:52:21 -0500

Reply Reply All Forward Delete Previous Next Close

Harry; Per our telcon here is a letter box view of railroad products.

Railroad lubricants have evolved quite drastically in the past 15 years.........in the earily 1990s all products were SAE 40 medium viscosity index (75VI) and all contained around 2000ppm of chlorine from a chlorinated paraffin......this was added specifically to impart some extra EP for the EMD silver insert bearing.........then in the mid 1990s the chlorinated hydrocarbons were declared carcinogenic and the used oil reclaimers started testing for chlorine in the waste oil they were picking up and if it contained more than 1000 ppm chlorine they would not pick up........even though the chlorniated paraffin is not considered a carcinogen there was no way to prove the source of the chlorine in the waste oil..........as a result the additives companies responded by reformulating their products chlorine free (usually less than 100ppm some residual cl from other additive processes)..........no easy task taking out the cl...........in order to get emd approval for a product you have to pass the 2 holer silver bering engine test as well as field test in 6 locomotives for one year.......today all the major additive compaines have a cl free additive Ethyl (Amoco), Shell, Mobil, Lyondel.......only Lubrizol doesn't but they haven't been in the RR market in the US but are now actively working on one...........todays RR lubricants are multigrade 20W-40 high viscosity index (100 130VI) chlorine free known as generation 5 lubricants.........with the exception of one RR in Canada all North American RRs are running generation 5 multigrade.

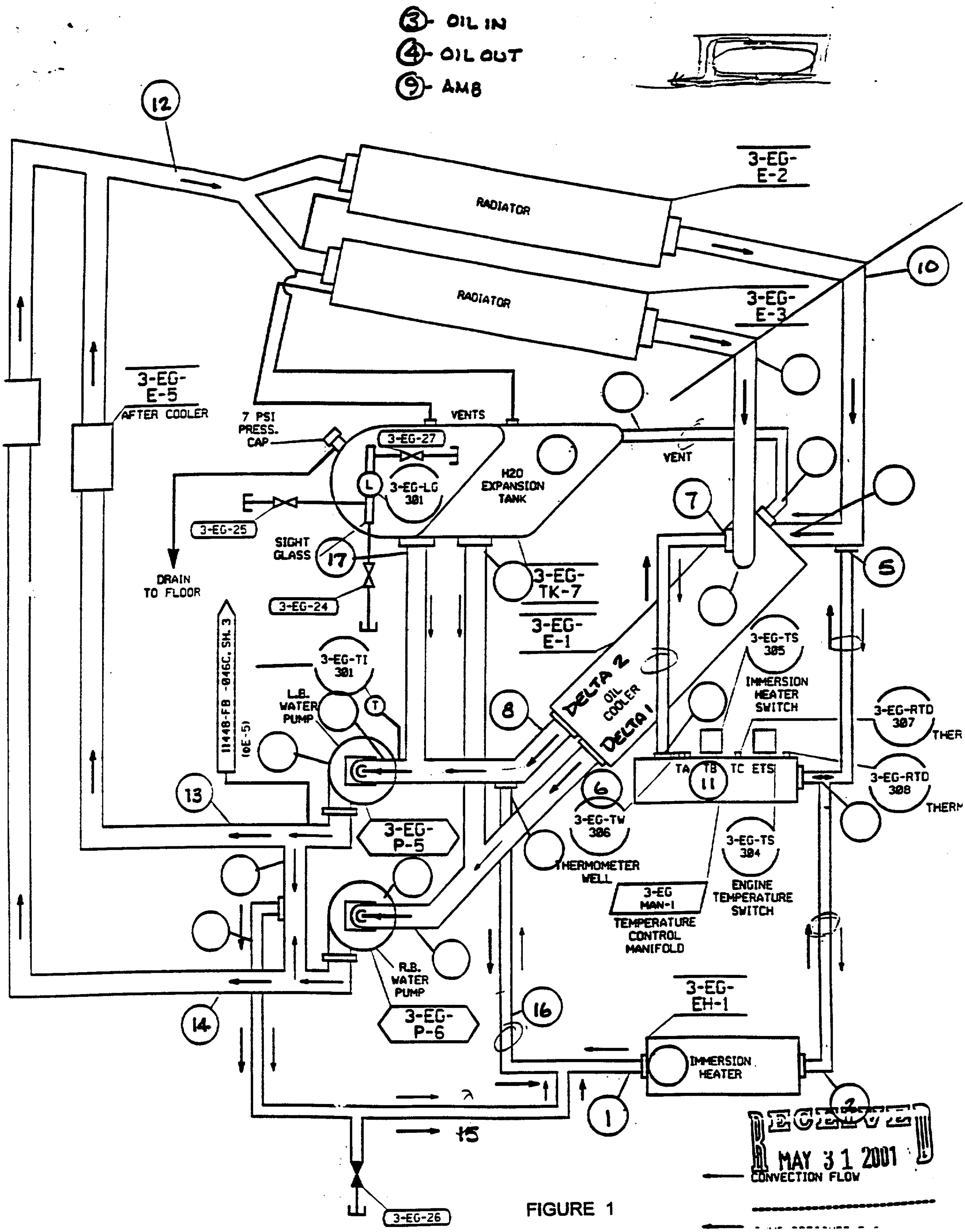
The previous product that was used at Surry, Amoco Super 13 would have been formulated as an SAE 40 using Amoco 6555D......this is an older generation product probably a gen 3........in addition this product would have about 1200 to 2000 ppm of chlorine........then Surry switched to Chevron DELO 6170 CFO (OLOA 2000) a generation 5 chlorine free technology.......while the chlorine free prducts provide adiquate protection for the silver bearing in these engines the extreemly severe operating conditions at Surry have tested the limits of the cl free product.........the silver bearings are the first to fail......my concern would now be the con-rod and main bearings........if surry continues to operate under 0-80% load in 10 sec. look for lead and copper to increase

I have attached a document that I put together a while back to help support the use of our additive package globally if you have any questions give me a call or drop me an email......hope this helps
<<OL2000credentialsglobal..doc>>

Regards
Wes

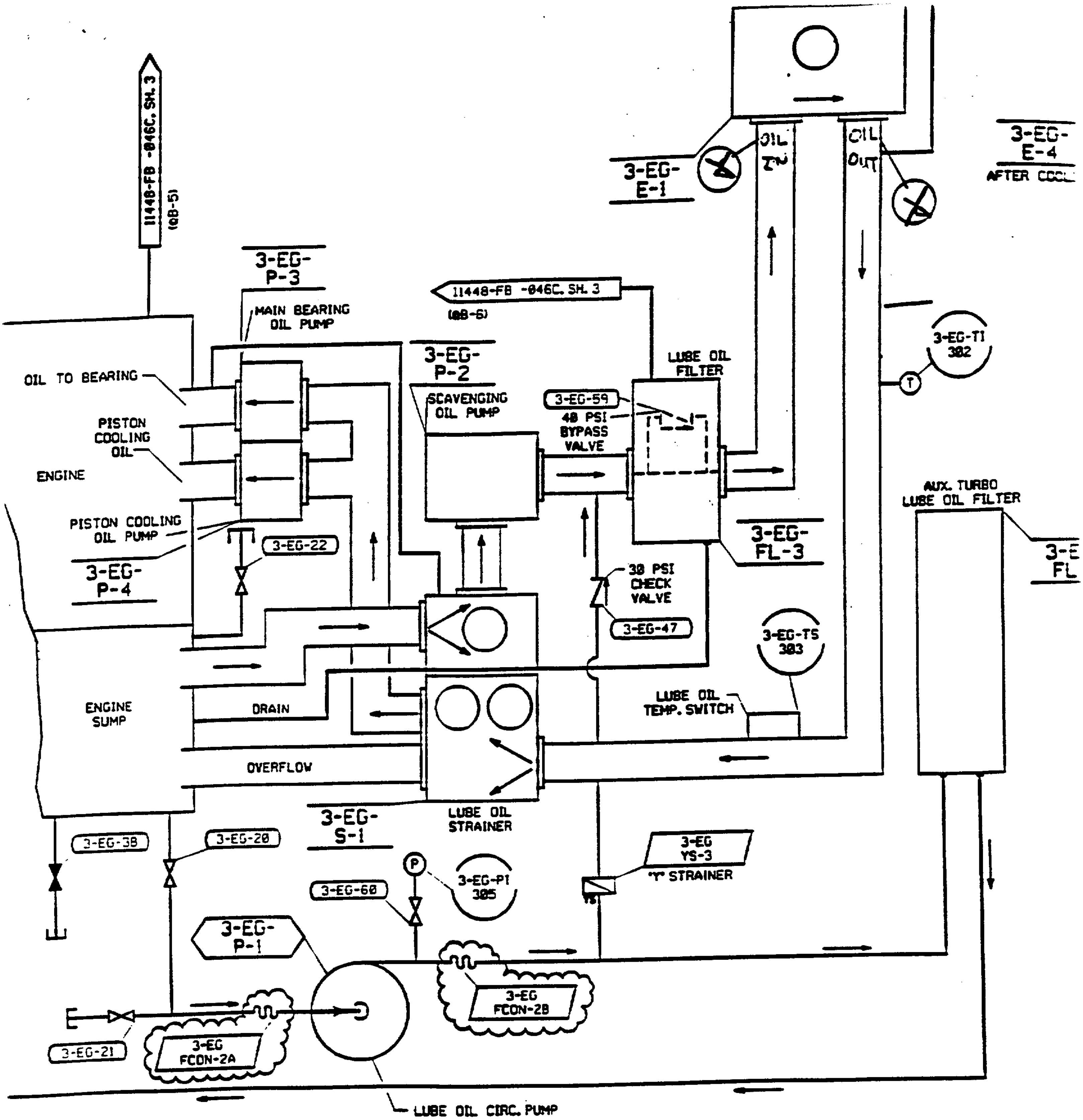
Attachment: OL2000credentialsglobal..doc (207k) -- View Attachment

APPENDIX B



3 - OIL IN
4 - OIL OUT
9 - AMB
12
RADIATOR
RADIATOR
3-EG-E-2
3-EG-E-3
10
3-EG-E-5
AFTER COOLER
7 PSI PRESS. CAP
VENTS
3-EG-27
3-EG-LG 301
L
H2O EXPANSION TANK
VENT
7
3-EG-25
SIGHT GLASS
17
DRAIN TO FLOOR
3-EG-24
3-EG-TK-7
5
3-EG-E-1
11448-FB -046C, SH. 3 (oE-5)
3-EG-TI 301
T
L.B. WATER PUMP
8
DELTA 2
OIL COOLER
DELTA 1
3-EG-TS 305
IMMERSION HEATER SWITCH
3-EG-RTD 307
THER
3-EG-RTD 308
THERM
13
3-EG-P-5
TA TB TC ETS
11
6
3-EG-TW 306
THERMOMETER WELL
3-EG MAN-1
TEMPERATURE CONTROL MANIFOLD
3-EG-TS 304
ENGINE TEMPERATURE SWITCH
R.B. WATER PUMP
3-EG-P-6
14
16
3-EG-EH-1
IMMERSION HEATER
1
2
15
3-EG-26
RECEIVED
MAY 31 2001
CONVECTION FLOW

FIGURE 1



LUBE OIL SYSTEM DIAGRAM

RECEIVED
MAY 31 2001

FIGURE 2

EDG TEMPERATURE DATA COMPARISON

Pos	EDG 2			EDG 3			EDG 1		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
1	108	108	101	77	76	77	NA	NA	NA
2	147	137	141	75	101	75	NA	NA	NA
3	95	95	96	75	96	74	NA	NA	NA
4	116	116	116	75	140	114	NA	NA	NA
5	139	135	132	120	73	122	NA	NA	NA
6	114	112	112	75	75	109	123	118	118
7	129	125	122	75	76	119	146	138	131
8	114	112	112	75	83	109	120	118	118
9	70	70	71	75	74	73	77	77	77
10	136	131	136	75	75	138	149	145	145
11	156	152	149	129	143	128	157	151	142
12	77	77	79	76	75	82	86	86	86
13	88	88	88	77	99	94	101	100	100
14	87	87	88	75	97	90	98	98	98
15	86	86	87	74	90	85	90	90	90
16	108	108	104	NA	NA	NA	NA	NA	NA
17	112	112	112	NA	NA	NA	NA	NA	NA

Table 1

Engine Life Predictions for EDG3 at Surry Nuclear Power Station for Dominion Virginia Power

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Project: H0829
Archive: D01-1740
Date: 15 Nov 2001
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Engine Life Predictions for EDG3 at Surry Nuclear Power Station for Dominion Virginia Power

EXECUTIVE SUMMARY

Ricardo has undertaken an examination of components, reports and laboratory data from Surry Station following the failure of the wrist pin bearings on two EMD 645 engines. The engines were found to have severely or partially degraded wrist pin bearings. Ricardo were engaged to review the failure mode and determine if it were possible to predict when the EDG3 engine entered a degraded condition such that it could not operate for a period of 24 hours supplying emergency power.

The substantial damage to the wrist pin bearing on EDG 3 cylinder #15 had allowed piston pin to bearing shell contact that would be considered in Ricardo's opinion to render the engine at risk in any further operation. Although other OE indicates it is unlikely the engine would have seized, the risk of a crankcase explosion increases with further damage. No evidence of foreign material contamination could be found in either the wrist pin bearings or the piston thrust washer. The material that was found in the thrust washer was ferrous in nature with traces of silver suggesting the material originated from the failure of the wrist in bearing.

The failure mode of the wrist pins is consistent with a lubrication starvation derived failure. Wiping of the softer material is primarily categorized with insufficient pre-lubrication or a lubricant with insufficient film strength and retention between starts. The failure is initiated with repeated starts relocating the silver and lead bearing material into the oil grooves of the wrist pin bearing. The engine will operate satisfactorily in this condition once started. However once the oil grooves become blocked through successive starts, the failure will progress once the engine is running by limiting or preventing lubricant flow across the full surface of the wrist pin bearings.

The date at which the damage to the bearing was sufficient that the wrist pin of EDG3 was committed to failure was after the October 3rd 2000 date postulated by the NRC. Until damage was sufficient that portions of the wrist pin bearing were being starved of oil, the failure would not have perpetuated itself after the engine was running. There were 13 starts in the period from Oct 3rd 2000 through April 23rd 2001. It is however pure speculation as to the date of the transition point that the condition of the wrist pin committed it to failure, but this date is later than Oct 3rd.

Information received from Orinite – Chevron and Dana indicate the change to non-chlorinated oils resulted in the removal of an EP additive. This chlorinated paraffin wax was removed from the formulation to avoid the disposal issues associated with chlorinated oil. The wax was present as an extreme pressure lubricant with the function of promoting lubrication under marginal conditions and is the most likely cause for the wrist pin failures. No references to the use of Chevron oil being qualified for use in nuclear stand-by duty could be found.

The DR ferrography results were inconclusive in determining a point in time or operating hour when bearing failure commenced.

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TABLE OF FIGURES

1. INTRODUCTION

Ricardo was contacted by Dominion Virginia Power (Mr. Gary Thompson) (of Surry Power Station – SPS), in October 2001 with a request to participate in a serviceable life and operability investigation on two EMD 645 E4 Emergency Diesel Generator (EDG) units at SPS in Virginia. Mr. Clive Wotton and Mr. Bill Brogdon from Ricardo Inc visited Surry station on October 25, 2001. This work was conducted under SPS PO# 70014234.

Due to the Sept 11, 2001 terrorist attacks, plant security was heightened and so the EDG's were not visited. Materials were provided to Ricardo outside the protected area. The investigation focused on a brief examination of some of the damaged and degraded components, namely wrist pin bearings and piston pins from several cylinders. In addition, Ricardo was furnished with a wealth of reports and data. These included all the reference material detailed at the end of the report.

The NRC issued a Special Inspection Report (50-280/01-06 and 50-281/01-06) indicating that Surry station had failed to react appropriately in monitoring the condition of the EDG's and, using the Significance Determination Process, rated the finding as "Yellow" on the Green-White-Yellow-Red rating scale. The report indicated that the NRC considered Surry to have violated terms on the license on two counts:

a) The first apparent violation was the failure to ensure that a condition adverse to quality involving the #3 EDG was promptly identified and corrected as required by 10CFR 50 Appendix B, Criterion XVI

b) The second apparent violation involved EDG3 being inoperable for a period of time greater than allowed by Technical Specification 3.16.B 1.a.3.

The NRC determined that, by its calculation procedure, EDG3 would have been inoperable for a period of 201 days using one of three methods of calculation for this figure. Surry Plant engaged the services of Ricardo to review the data to determine whether it was possible to more closely define the date of actual engine failure since the last Preventative Maintenance period and inspection. In addition, the opportunity was taken to evaluate the reports produced for Surry pertaining to EDG1 and EDG3 bearing conditions from the Dominion Materials Laboratory and ESI (Engine Systems Inc.), the primary vendor and provider of support for the EMD EDG's.

2. BACKGROUND

SPS had a good record of operating the three EDG's which undertake stand-by duties for the two nuclear reactors at Surry Station. Surry had noticed an increasing trend in silver in the lubrication oil (LO). The silver level had increased from 0.1 to 2.6 ppm over a period from 3/2000 through 4/2001 for EDG3. The two bearings in the engine that feature a silver overlay, are the piston wrist pin bearings and the turbocharger bearing. Consequently, the increasing presence of silver in the LO is an indicator of wear in either of these two bearings. EMD had established two criteria for the silver level in the LO. Maintenance Instruction (MI) 1760 specifies silver concentrations of 0 to 1ppm as "Normal –No action required". Samples in the range 1-2 ppm are deemed to be "Borderline - Take extra samples" and in the 2 and above ppm concentration range, the recommendation is "High - Correct Condition". The advice from the manufacturer includes instructions to "check for broken piston cooling tubes, inefficient oil cooler, improper temperature control and to check if the oil contains zinc."

Usually the figures quoted by manufactures have some significant degree of tolerance attached to the condition to allow time for preventative maintenance to be performed prior to catastrophic failure. Therefore, it was somewhat of a surprise to SPS that, upon dismantling the EDG3 engine in mid April 2001, severe damage was noted on seven of the twenty wrist pins and piston carrier bearing surfaces. The damage "included displacement of the silver bearing material such that some of the lubricant dispersal channels were blocked."

The fully or partially blocked oil channels would have prevented normal oil flow across the bearing surface resulting in increased bearing temperatures and further wiping of the bearing material into the oil grooves – see photograph below, from ESI Reports (Refs 8.1 and 8.2).

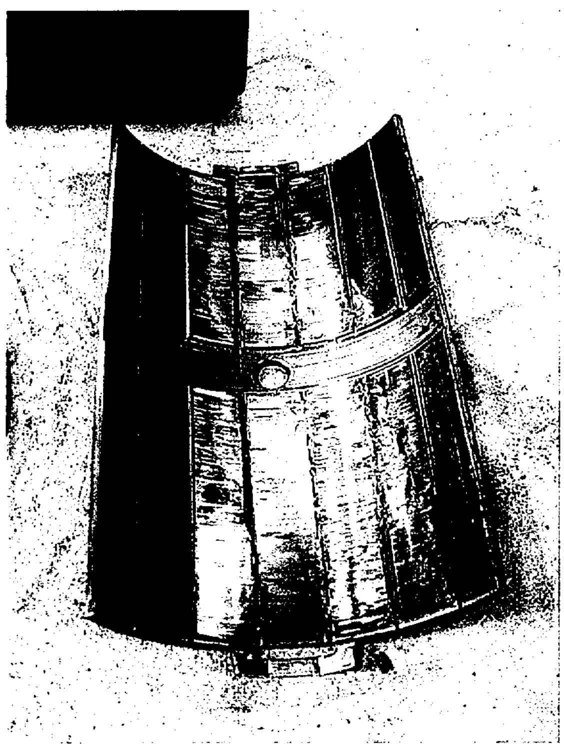


Figure 1 – Damaged Wrist Pin Bearing

EDG1 had seen an increase in silver concentrations in the oil, however EDG1 barely exceeded 1ppm concentration of silver in the LO. In July 2001, Surry removed 20 power packs and dispatched them to ESI for examination. One cylinder was reported to have a severely damaged wrist pin and bearing and seven further bearings demonstrated the early signs of failure. This was concerning as EDG1 had not reached the 2ppm "Take Action" level as advised by EMD.

A further complication was that the silver level was being recorded in the SPS oil analysis program but the alarm level had been incorrectly set in the computer to 10 ppm rather than 2 ppm. Silver bearings are sensitive to the presence of zinc, which can attack the integrity of the silver overlay, and so zinc concentration is measured during the regular oil analysis. Zinc generally remained in the 0 to 4 ppm over the past 4 years with one excursion to 6ppm. The EMD specified limit for zinc is 10 ppm.

In addition, the change of oil from an AMOCO Super Diesel 13 product to the Chevron DELO 6170 caused concern for SPS as the increasing silver levels in the oil correlated with the change to the Chevron product– See Figure 1. EDG2 did not adhere to the trends shown by EDG1 and EGD3 and remained almost consistent in Silver levels in the oil. The one high data point for EDG2 was erroneous data and subsequently determined to be a mislabeled sample from EDG3– see below.

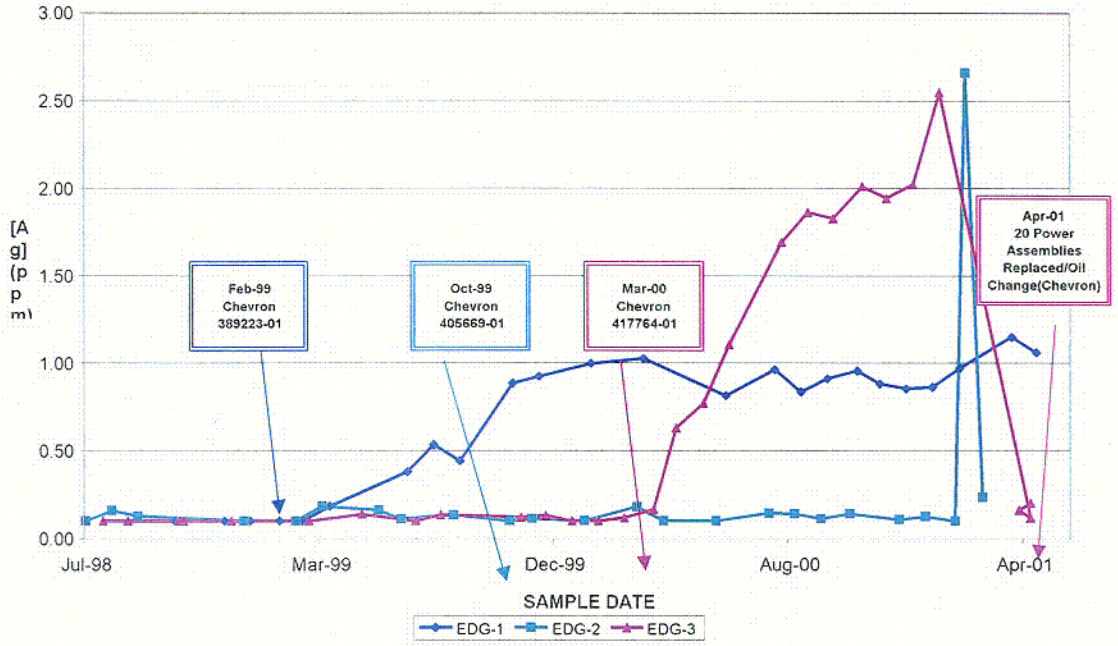


Figure 2 – Emergency Diesel Generator Lube Oil Results

3. OBJECTIVES

The objectives of the program for Ricardo are:

1) To review the reports provided to Surry by the NRC, ESI, NES and Trident in order to provide Ricardo's opinion on the failure mechanism.

2) To provide an opinion as to the probability that EDG3 could have run for 24 hours in the state it was found to be in upon disassembly.

C01

3) To evaluate the material to determine if it was possible to estimate the time or date at which the engine reached a degraded condition such that it would not be able to undertake 24 hours of continuous operation.

4. OBSERVATIONS AND ANLYSIS

4.1. Review of ESI, NES, Trident and Surry Station Reports

SPS provided Ricardo with the references detailed in the reference section. Four of these reports are considered to be original works, the NRC Special Inspection Report and the SPS report "#3 EDG – Category 2 Root Cause Investigation" were considered as secondary reports based off the materials generated in the first four reports. The SPS report, however, did have some fresh detail included by way of Operational Experience (OE), maintenance procedures and details of oil change dates.

Ricardo examined the bearings visually and with the aid of optical and Scanning Electron Microscopes. In addition, two premium manufacturers of bearings were consulted to provide an opinion on the failure mechanism of the bearings. The results of the analysis, microscopy and materials analysis and the opinions of DANA (Glacier-Vandervell) and Federal Mogul are described elsewhere in this report.

Generally, Ricardo would agree with the findings of the reports. Examination of the partially failed bearings usually provides far more detail than examination of bearings that had failed totally with only the steel backing remaining for inspection. Ricardo and the other experts consulted could find no evidence of oil contamination of the oil by foreign material such that it precipitated failure of the wrist pin bearings. Some foreign material was found using SEM, but this appeared to be secondary material that was generated during the failure and had become lodged in the piston thrust washer. This is described more fully in Section 4.2 below. Examination of the photographs in the ESI reports (Refs 8.1 and 8.2) from EDG3 show greater degradation of the bearings than the set that Ricardo examined in the SPS warehouse, but the trend was identical. The bearings appear to fail by initiating a "wiping" mechanism that entails relocation of the lead overlay and then the silver into the bearing oil distribution grooves. This progressively blocks the grooves, preventing oil supply to areas of the bearing surface which in turn generates frictional heat. The space between the piston carrier and the piston will contain oil and so some lubrication may be available from the outer edges of the bearing. This mechanism progresses to cause further wiping, causing failure in the bearing. Some of the photographs could be placed into series to show a very good case study of a "lack-of-lubricant" progressive failure. The reference materials on bearing failure attribute these characteristics to either inadequate lubrication on start-up or inadequate lubrication during service. The oil grooves on the most severely damaged bearings had been eliminated and the two pins that had suffered catastrophic failure showed steel-to-steel contact of the bearing backing to the wrist pin once silver had been removed in that area.

On EDG #3 cylinder 15 piston carrier, where steel-to-steel contact had been made, steel shavings that were severely discolored and oxidized could be seen adhering to the pin carrier, indicating that substantial temperatures had been achieved, although these were below the melting point of the steel. It could not be ascertained whether any of the shavings from the wrist pin had fallen into the crankcase during the time of failure. These hot particles could have acted as a catalyst for a crankcase explosion.

There were several small inaccuracies in the Trident report (Ref 8.3) with respect to the mechanism of the oil feed to the wrist pin. The EMD features a design of a piston commonly referred to as a "cocktail shaker" design. Oil is intermittently fed to a void beneath the piston crown with open drains. The void never becomes full and the inertial reciprocating motion of the piston distributes the oil so as to come into contact with the underside of the crown and fall into the cup on the upper side of the piston carrier. There is no pressure feed of oil from the engine oil supply directly to the wrist pin. Oil lubricates the wrist pin by virtue of gravity feed and inertial forces during the primary motion of the piston.

This mechanism is somewhat different to most highly-rated four stroke engines that feature a direct pressure feed to the wrist pin via a drilling running the length of the connecting rod. Four stroke engines also have the advantage that the wrist pin experiences inertial relief in normal operation when the piston slows at the top of exhaust stroke and commences the induction stroke. This allows some replacement of the oil in the pin bearing and reestablishment of the oil film.

The EMD and other two stroke engines have the disadvantage that the wrist pin never sees inertial relief and so lubrication of the wrist pin is less certain. However it still functions satisfactorily – see OE described in Section 5.2. EMD subsequently revised the design of the wrist pin to a "rocking pin" design which is described in reference 8.6

4.2. Bearing Examination and Failure

Ricardo examined both the bearings and thrust washers employing the use of a back scatter imaging scanning electron microscope. With the help of Climax Research Services, Inc it was determined that there was no significant presence of foreign material. However, there was material found on the copper thrust washer that was of significance.

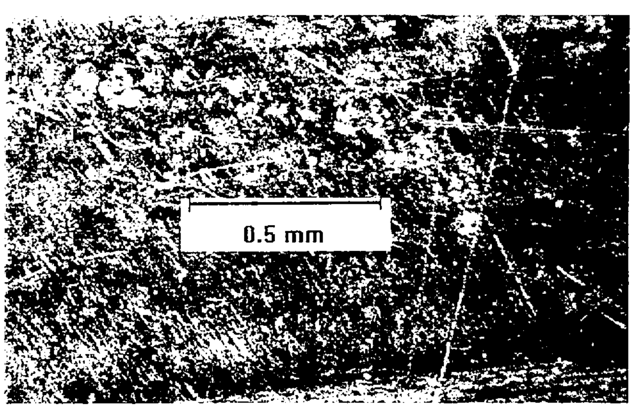


Figure 3 – Worm Track Under a Stereo Microscope

Upon visual inspection by Ricardo and ESI (report 87360-FA pg. 6), small "worm" tracks were seen in the thrust washer (Figure 3) of a failed piston. As ESI stated these where either "oil channeling or scratches from foreign material." The "worm" tracks were evident on both washers inspected, however the failed washer had many more "worm" tracks evident, while the un-failed washer showed only two smaller "worm" tracks. Figure 3 is from the thrust washer of a piston which did not suffer a wrist pin failure, and is an example of one of the smaller "worm" tracks found it is barely visible with out visual aide. The washer from the failed piston exhibited a higher density of "worm" tracks than a washer from a wrist pin that remained in-tact.

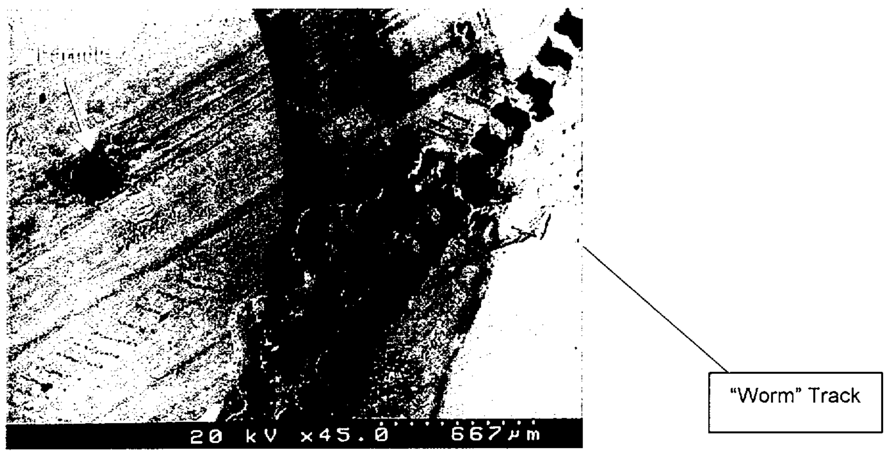


Figure 4 – "Worm Track With Embedded Particle

Upon SEM investigation of the thrust washer, particles where found embedded near the worm tracks. As seen in Figure 4 the size and shape of the particle are approximately the same. The worm track also follows a distinct pattern of repetition.

The particle was examined elementally and was found to consist mostly of iron with trace amounts of silver and copper. The full spectrograph is shown in Figure 4. The copper found was most likely the surrounding material. The iron and silver found is in line with the construction of the wrist pin bearing. The bearing did not have any lead left on it only steel with slight amounts of silver this correlates with the particle found on the washer, which would give evidence that the particles and "worm" tracks result from entrapment of the material from a failed bearing

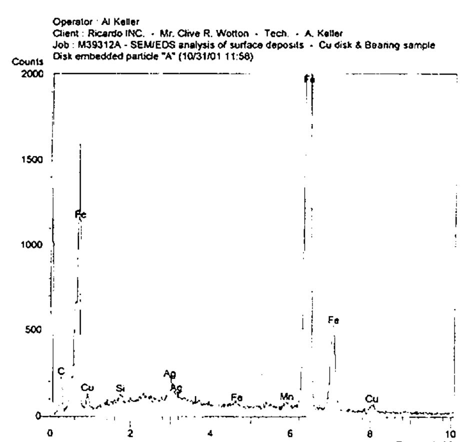


Figure 5 – Elemental Make-Up of Particle A

The type of marking as seen in Figure 4 was apparent without visual aid and was widely dispersed on the failed parts. There were also a significant number of particles elsewhere on the thrust washer. Upon further SEM investigation they were determined to be of the same material, iron with trace amounts of silver and copper. There was also many more "worm" tracks seen and they continued to exhibit the pattern and distinct shape made from one particle being repeatedly stamped on the thrust washer.

A second thrust washer was visually inspected and found to have only two noticeable "worm" tracks. The washer was then viewed under a stereo microscope and there was no noticeable embedded particles. The washer was then sectioned and viewed by a SEM.

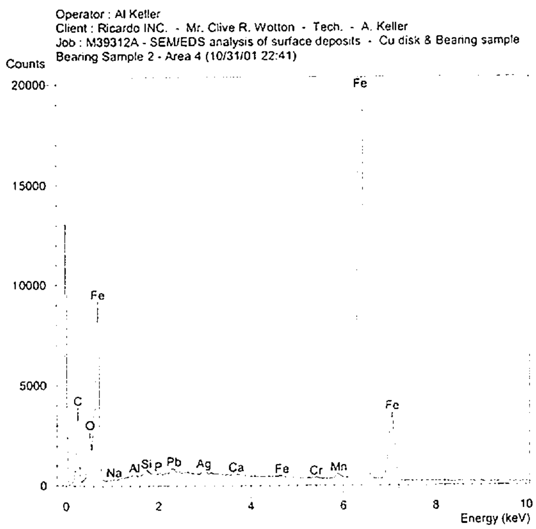
Under inspection with the SEM it was found that there were many particles of lead embedded or adhered to the surface of the washer. Two samples of these may be seen in figures 6 and 7.

Figure 7 – Embedded Lead

Figure 6 – Lead Particle

Figure 6 shows lead embedded on the surface of the thrust washer, while figure 7 magnified 1000x shows a lead particle adhered to the surface of the thrust washer with two scratches in the surface. The lead on the surface of the thrust washer is an early indicator of failure. The failure as discussed above would eventually lead to large iron particles scoring the surface of the thrust washer causing the "worm" tracks as seen. The finding of lead is consistent with the loss of lead overlay from the bearing as seen and discussed below. There was very little iron found in any of the particles on this thrust washer. That would be consistent with the condition of the bearing being in the initial phases of failure. The bearing was in good condition with only some lead missing and had not been wiped down to the steel.

Figure 8 – Iron Sample



EDG #3 cylinder 15 bearing showing signs of "heavy distress" was also examined with the SEM. It was viewed at four positions on the sectioned bearing. The bearing was severely wiped with all oil channels blocked and no visible lead overlay, there appeared to be silver in one area while the rest seemed to have "wiped" to the steel. After being examined in the SEM and undergoing elemental analysis the piece exhibited, as expected, three areas that were almost completely steel and one sample that was mostly silver. It should be noted that extremely low levels of lead were detected in only one of the samples, while the other three did not have any lead. The material found on the failed bearing surface was consistent with the particles found on the failed thrust washer as steel and silver particles were predominantly found on the surface of the washer. The elemental analysis of the silver section, iron-lead section and iron-silver section are shown in figures 8, 9 and 10.

Figure 9 – Iron-Silver Sample

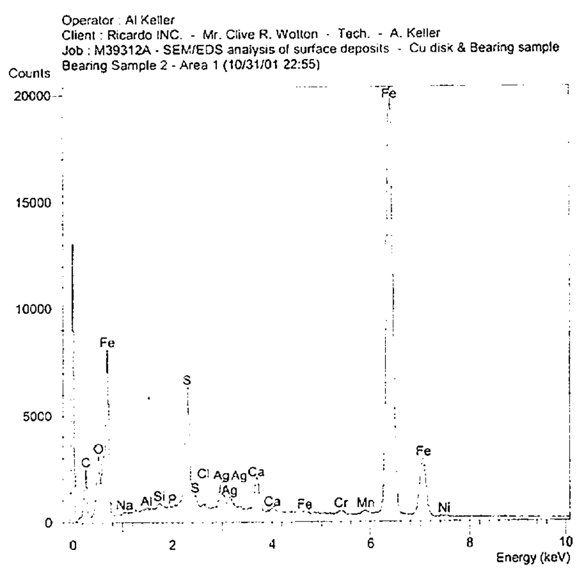


Figure 10 – Silver Sample

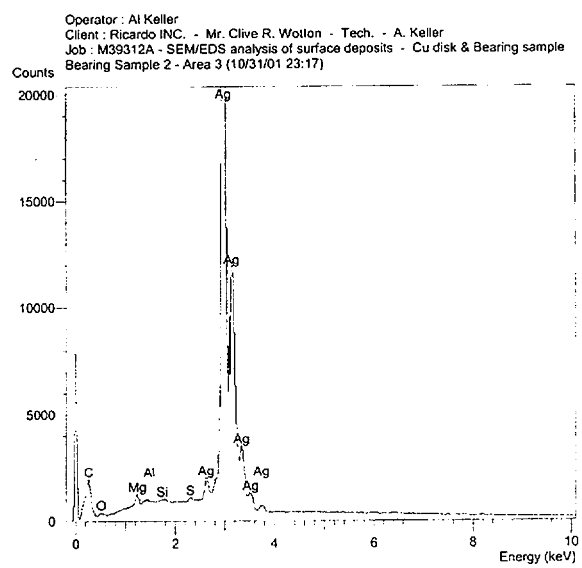
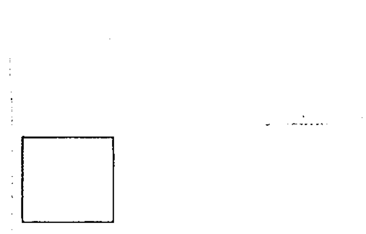


Figure 11- Bearing Section



A "good" bearing from EDG1 was visually examined and found to be discolored in a regular pattern beginning at the outermost parts of the bearing moving in towards the oil feed hole, see highlighted section of figure 11. The bearing was then analyzed using the SEM and the results showed a pattern of lead "islands" surrounded by silver see figure 12 and figures 13 and 14 for elemental analysis. This was again in line with findings of the un-failed bearing, which had only small lead and low silver content particles.

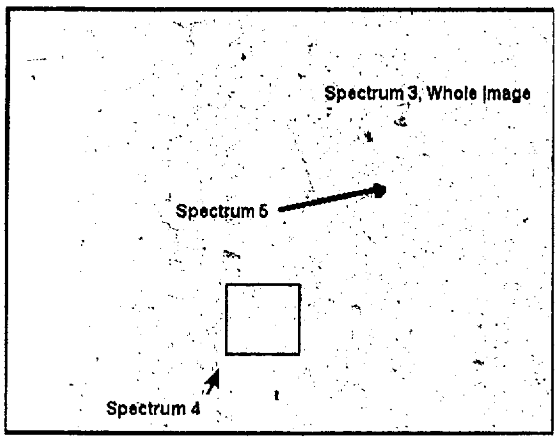


Figure 12 – Baring Surface

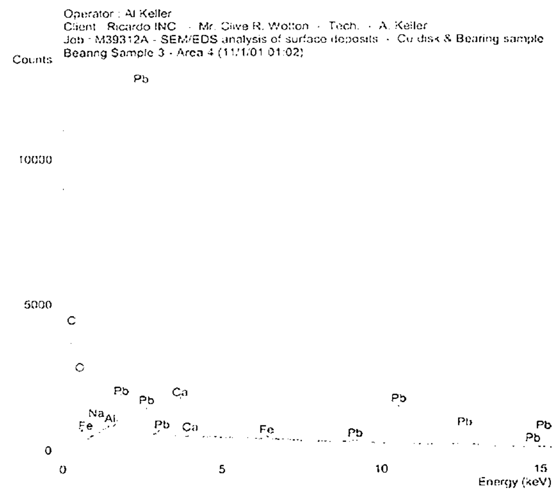


Figure 13 – Spectrum 4

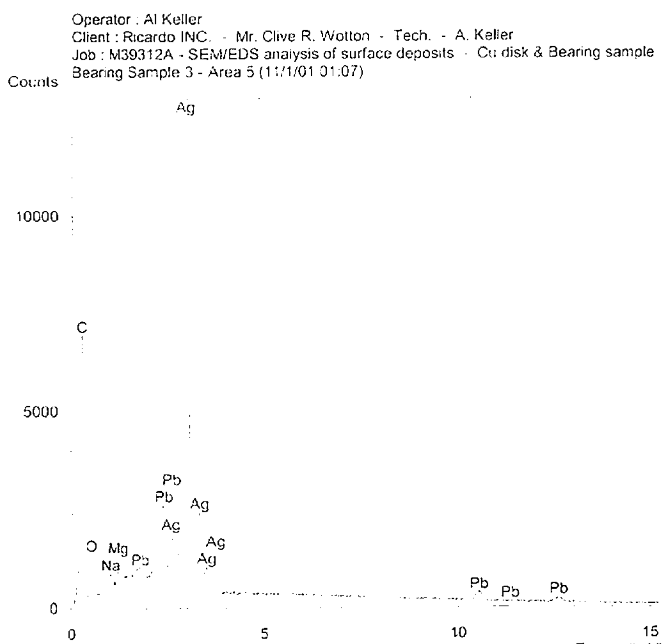


Figure 14 – Spectrum 5

In verbal discussions with Dana and Federal Mogul it has been corroborated that the failures occurred were due to insufficient lubrication of the surfaces not foreign materials. This is expanded in section 5.1

4.3. Ferrography and Spectrographic Analysis.

SPS had applied ferrography to the oil analysis samples. The readings supplied came from a Direct Reading (DR) Ferrograph. The ferrograph works by separating particles and categorizing them according to size, typically smaller than 5 microns and larger than 5 microns. Using the obscuration of light, the ferrograph gives density readings for the density of large particles - Dl - and Density of small particles – Ds. These two ratios can be used to calculate the density of wear particles – wpc (Dl+Ds=wpc). Generally the production of small particles is counted as normal wear. The production of large particles and changes in the wpc trend are used to indicate abnormal wear. A further trend is usually calculated and plotted – the percentage of large particles (%LP) using the following formula; %LP= ((Dl-Ds)/wpc)X100. Significant upward trends in %LP are usually taken as signs that abnormal wear is occurring.

SPS had been trending the ferrography results for several years. Although this gives a long term view of trends, it also includes oil changes and oil replenishments that affect the dilution of particles and result in a noisy data set. It is difficult to extract the trends related to the Chevron oil from this data set – See below.

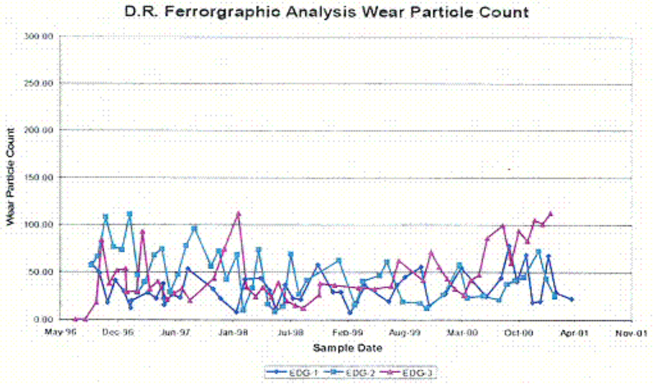


Figure 15 – Wear Particle Count

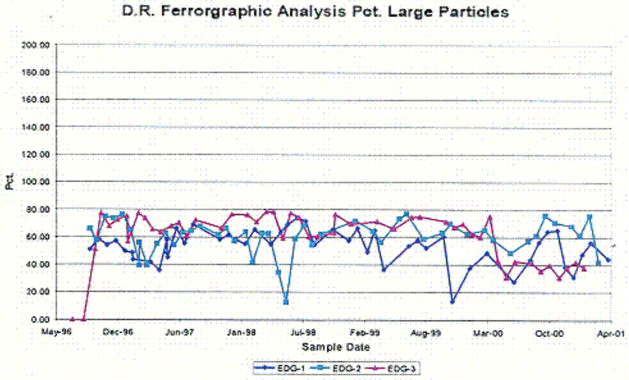


Figure 16 - % Large Particles

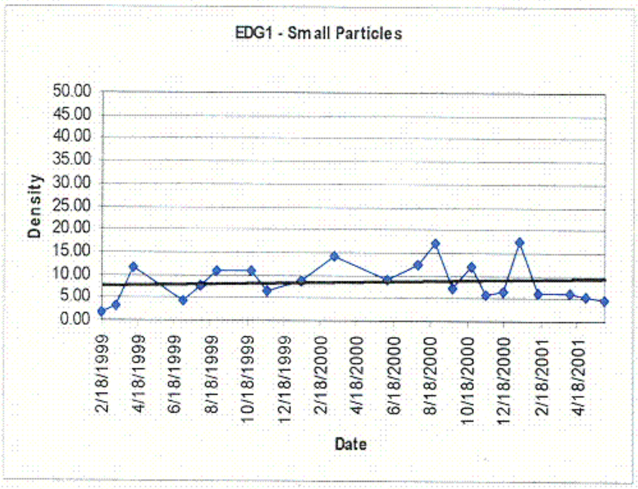
Ricardo have extracted the data from EDG1,2 and 3 running purely on the Chevron DELO 6170 oil during the period of concern. Because the silver results did not conclusively show when the engine actually failed, the ferrography results were examined since these were taken on a monthly basis and may have contained the data necessary to determine when the wrist pins could be considered to have essentially failed. These data are contained on the next 4 pages together with the tabular data from which the plots were derived.

C02

Client Name: Dominion Virginia Power
Project No.: H0829
Archive: D01-1740
Client Confidential

RICARDO

EMERGENCY DIESEL GENERATIOR LUBE OIL RESULTS					
D.R. FERROGRAPHIC ANALYSIS: D.R. SMALL					
DATE	EDG-1	DATE	EDG-2	DATE	EDG-3
Feb-99	1.90				
Mar-99	3.20				
Apr-99	11.60				
Jul-99	4.40				
Aug-99	7.70				
Aug-99	10.80				
Oct-99	11.00				
Nov-99	6.40	Nov-99	1.80		
Jan-00	8.70	Jan-00	5.00		
Mar-00	14.20	Mar-00	10.10		
Jun-00	9.00	Apr-00	4.90		
Jul-00	12.40	May-00	6.50	Mar-00	3.60
Aug-00	17.00	Jul-00	4.50	Apr-00	11.70
Sep-00	7.20	Aug-00	7.30	May-00	16.40
Oct-00	11.90	Sep-00	5.00	Jun-00	24.80
Nov-00	5.70	Oct-00	6.60	Aug-00	29.20
Dec-00	6.70	Dec-00	11.60	Sep-00	19.30
Jan-01	17.70	Jan-01	8.30	Sep-00	28.20
Feb-01	6.30	Feb-01	3.00	Oct-00	28.80
Apr-01	6.20	Mar-01	2.60	Nov-00	32.60
May-01	5.30	Apr-01	3.50	Dec-00	29.20
Jun-01	4.80	Jun-01	7.90	Jan-01	35.00
Jul-01	8.70	Jul-01	3.00	Feb-01	44.80
Jul-01	5.80	Aug-01	5.50	Apr-01	9.50
Jul-01	13.90	Sep-01	11.70	Apr-01	2.60
Jul-01	17.80	Oct-01	3.10	Apr-01	15.50
Jul-01	8.60			May-01	9.80
Aug-01	9.30			Jun-01	13.30
Sep-01	4.70			Jul-01	8.30
Sep-01	3.20			Aug-01	4.60
				Sep-01	2.90
				Sep-01	3.40



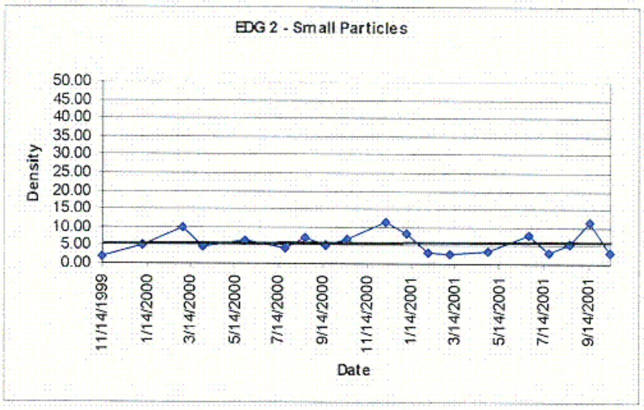
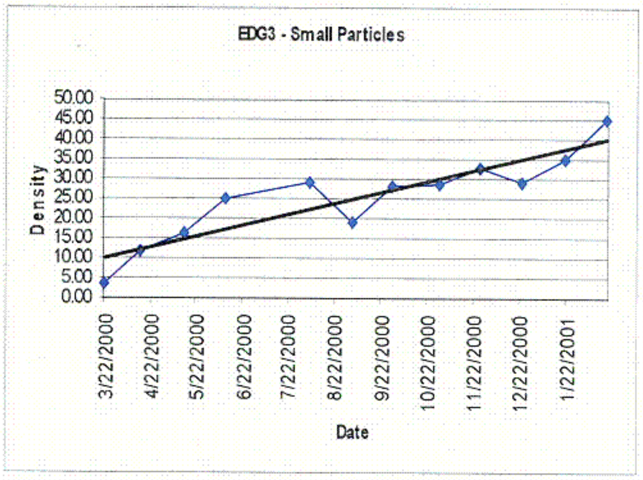
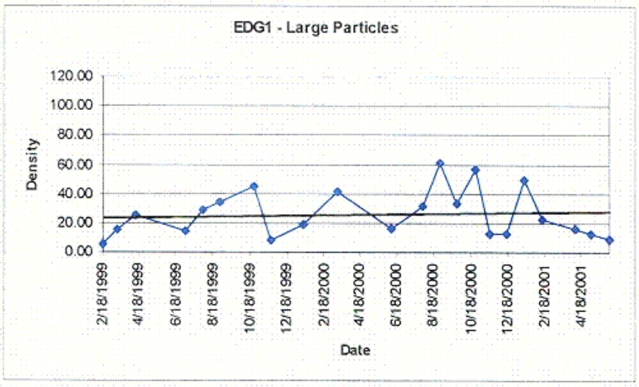


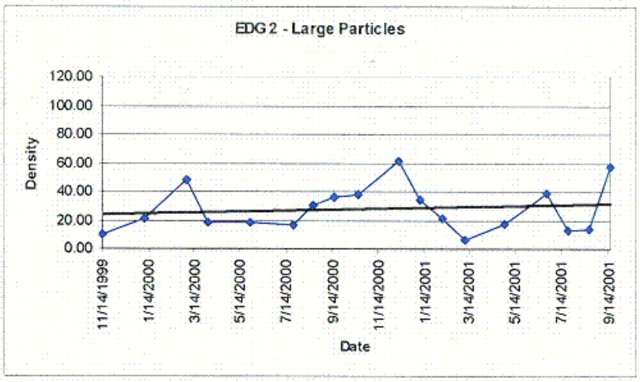
Figure 17 – DR Ferrographic Analysis of Small Particles



C03

EMERGENCY DIESEL GENERATIOR LUBE OIL RESULTS					
D.R. FERROGRAPHIC ANALYSIS: D.R. LARGE					
DATE	EDG-1	DATE	EDG-2	DATE	EDG-3
Feb-99	5.60				
Mar-99	15.10				
Apr-99	25.00				
Jul-99	14.70				
Aug-99	28.80				
Aug-99	34.40				
Oct-99	44.70				
Nov-99	8.40	Nov-99	10.10		
Jan-00	19.10	Jan-00	21.60		
Mar-00	41.20	Mar-00	48.30		
Jun-00	15.90	Apr-00	18.60		
Jul-00	31.70	May-00	18.90	Mar-00	22.60
Aug-00	61.10	Jul-00	16.60	Apr-00	29.90
Sep-00	33.10	Aug-00	30.60	May-00	31.20
Oct-00	56.50	Sep-00	36.60	Jun-00	61.80
Nov-00	12.90	Oct-00	38.60	Aug-00	70.50
Dec-00	12.80	Dec-00	61.30	Sep-00	40.70
Jan-01	50.00	Jan-01	34.70	Sep-00	65.70
Feb-01	22.50	Feb-01	21.80	Oct-00	54.60
Apr-01	16.10	Mar-01	6.40	Nov-00	72.70
May-01	12.20	Apr-01	17.30	Dec-00	72.00
Jun-01	9.10	Jun-01	39.10	Jan-01	77.80
Jul-01	38.40	Jul-01	13.20	Feb-01	110.60
Jul-01	28.00	Aug-01	13.50	Apr-01	30.60
Jul-01	43.20	Sep-01	57.80	Apr-01	12.80
Jul-01	74.00	Oct-01	21.10	Apr-01	52.60
Jul-01	20.50			May-01	33.40
Aug-01	58.30			Jun-01	30.70
Sep-01	10.90			Jul-01	37.70
Sep-01	7.80			Aug-01	10.90
				Sep-01	23.90
				Sep-01	21.30





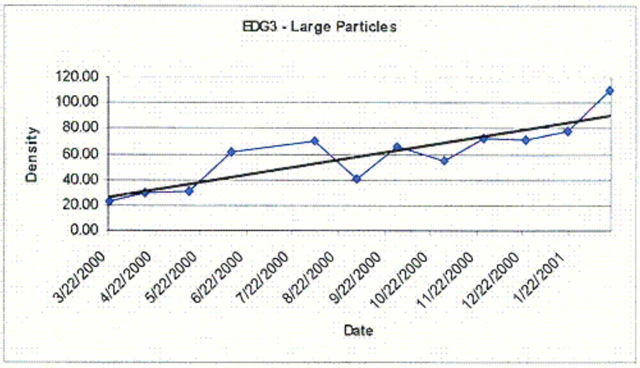
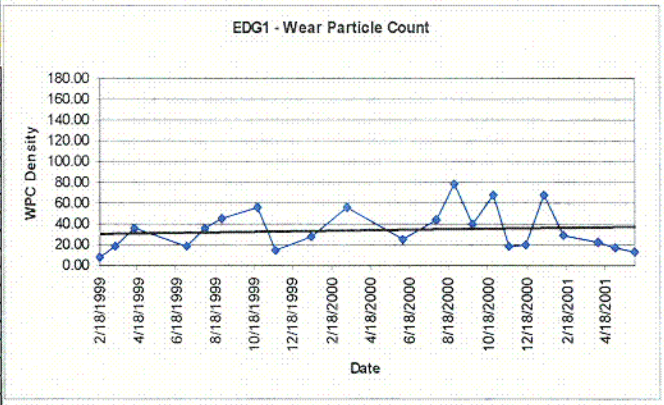


Figure 18 – DR Ferrographic Analysis of Large Particles

C04

Client Name: Dominion Virginia Power
Project No.: H0829
Archive: D01-1740
Client Confidential

EMERGENCY DIESEL GENERATIOR LUBE OIL RESULTS					
D.R. FERROGRAPHIC ANALYSIS: WEAR PARTICLE COUNT					
DATE	EDG-1	DATE	EDG-2	DATE	EDG-3
Feb-99	7.50				
Mar-99	18.30				
Apr-99	36.60				
Jul-99	19.10				
Aug-99	36.50				
Aug-99	45.20				
Oct-99	55.70				
Nov-99	14.80	Nov-99	11.90		
Jan-00	27.80	Jan-00	26.60		
Mar-00	55.40	Mar-00	58.40		
Jun-00	24.90	Apr-00	23.50		
Jul-00	44.10	May-00	25.40	Mar-00	26.20
Aug-00	78.10	Jul-00	21.10	Apr-00	41.60
Sep-00	40.30	Aug-00	37.90	May-00	47.60
Oct-00	68.40	Sep-00	41.60	Jun-00	86.60
Nov-00	18.60	Oct-00	45.20	Aug-00	99.70
Dec-00	19.50	Dec-00	72.90	Sep-00	60.00
Jan-01	67.70	Jan-01	43.00	Sep-00	93.90
Feb-01	28.80	Feb-01	24.80	Oct-00	83.40
Apr-01	22.30	Mar-01	9.00	Nov-00	105.30
May-01	17.50	Apr-01	20.80	Dec-00	101.20
Jun-01	13.90	Jun-01	47.00	Jan-01	112.80
Jul-01	47.10	Jul-01	16.20	Feb-01	155.40
Jul-01	33.80	Aug-01	19.00	Apr-01	40.10
Jul-01	57.10	Sep-01	69.50	Apr-01	15.40
Jul-01	91.80	Oct-01	24.2	Apr-01	68.10
Jul-01	29.10			May-01	43.20
Aug-01	67.60			Jun-01	44.00
Sep-01	15.60			Jul-01	46.00
Sep-01	11.00			Aug-01	15.50
				Sep-01	26.80
				Sep-01	24.70



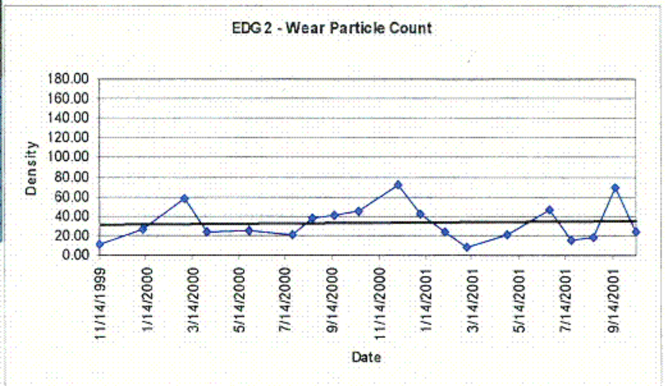
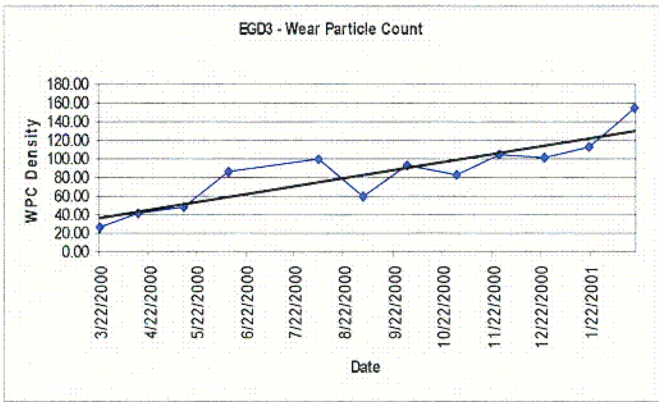
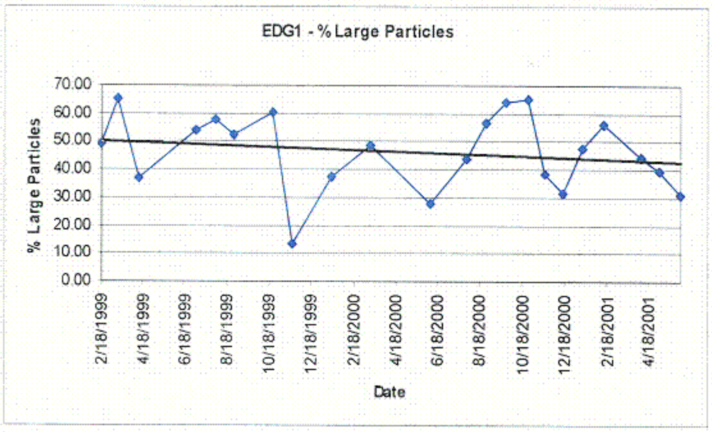


Figure 19 – DR Ferrographic Analysis – Wear Particle Count (WPC)



C05

EMERGENCY DIESEL GENERATIOR LUBE OIL RESULTS					
D.R. FERROGRAPHIC ANALYSIS: PCT. LARGE PARTICLES					
DATE	EDG-1	DATE	EDG-2	DATE	EDG-3
Feb-99	49.33				
Mar-99	65.03				
Apr-99	36.61				
Jul-99	53.93				
Aug-99	57.81				
Aug-99	52.21				
Oct-99	60.50				
Nov-99	13.51	Nov-99	69.75		
Jan-00	37.41	Jan-00	62.41		
Mar-00	48.74	Mar-00	65.41		
Jun-00	27.71	Apr-00	58.30		
Jul-00	43.76	May-00	48.82	Mar-00	75.52
Aug-00	56.47	Jul-00	57.35	Apr-00	43.75
Sep-00	64.27	Aug-00	61.48	May-00	31.09
Oct-00	65.20	Sep-00	75.96	Jun-00	42.73
Nov-00	38.71	Oct-00	70.80	Aug-00	41.42
Dec-00	31.28	Dec-00	68.18	Sep-00	35.67
Jan-01	47.71	Jan-01	61.40	Sep-00	39.94
Feb-01	56.25	Feb-01	75.81	Oct-00	30.94
Apr-01	44.39	Mar-01	42.34	Nov-00	38.08
May-01	39.43	Apr-01	66.35	Dec-00	42.29
Jun-01	30.94	Jun-01	66.38	Jan-01	37.94
Jul-01	63.06	Jul-01	62.96	Feb-01	42.34
Jul-01	65.68	Aug-01	42.11	Apr-01	52.62
Jul-01	51.31	Sep-01	66.33	Apr-01	66.23
Jul-01	61.22	Oct-01	74.38	Apr-01	54.48
Jul-01	40.89			May-01	54.63
Aug-01	72.49			Jun-01	39.55
Sep-01	39.74			Jul-01	63.91
Sep-01	41.82			Aug-01	40.65
				Sep-01	78.36
				Sep-01	72.47



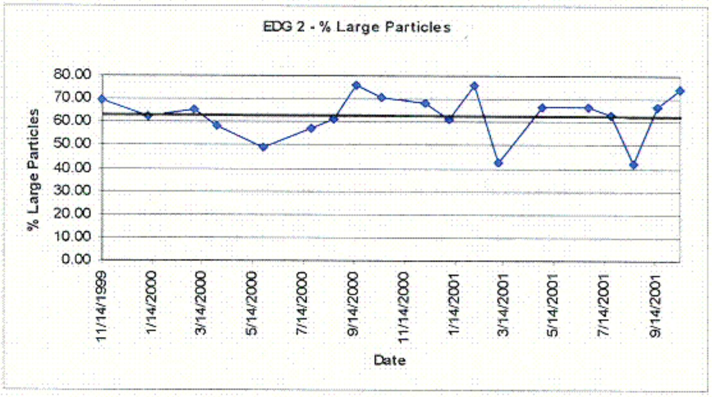
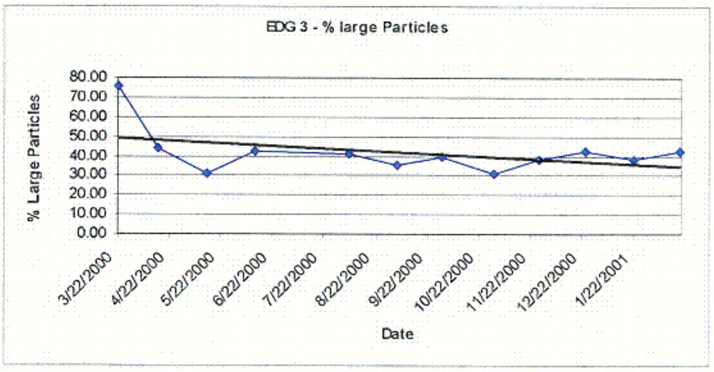


Figure 20 – DR Ferrographic Analysis - % Large Particles



Examination of Figures above which contain the ferrography results extracted for just the Chevron oil and excludes data from oil changes, reveals some apparently contradictory trends. The graphs are all plotted on similar scales with a linear trend-line put through the data set. EDG3 clearly shows a trend in increasing large and small particle counts resulting in the increase in wpc. Conventional ferrographic trending data states that a growth in Lp density is a sign of abnormal wear. However, the %LP is very consistent, around 40% for the 4 months up to Feb 2001 (the last oil sample taken from the engine) and, indeed, has hovered around that reading since May 2000. Thus the DR ferrography results give no clear indication of when a bearing started to fail catastrophically but the increase in small and large particle densities indicate wear was occurring, probably since the oil was changed to Chevron. A similar trend could not be detected for EDG1 and EDG2. The percentage of large particles seen for EDG2 is generally higher than for EDG3 and EDG1, however the silver concentration in the oil did not correlate with the apparent high concentration of large particles, but for the reasons discussed below, the ferrography may not be detecting all issues associated with the failure mechanism.

The oil silver and lead content data does not appear to correlate well, which is surprising as they are in contact on the surface of the bearing. Increasing silver was seen on EDG1 and 3 following the change to Chevron oil. However, the lead content of the oil samples fell for all three EDG's during the time that the Chevron oil was used. As the bearings are comprised of a 0.002" lead overlay over the silver, the lead must be worn off first before the silver can be worn off. Another reason for the oil analysis not picking up the lead and silver accurately could be due to the density of the materials and the method in which the material is removed from the bearings. Microscopy showed that relatively large chunks of the bearing materials were plucked out of the surface of the bearing. Sizes ranging from 0.2mm up through 1mm were observed. These particles are up to 100 times larger than the particles that are typically examined through DR ferrography. The microscopic pits left in the silver surface also displayed the classic signs of shallow sides reflecting adhesive wear. The dense single particles would probably have had a tendency to settle out of the oil in stagnant areas of the LO system where little flow and turbulence kept the large particles in suspension. If oil samples were taken from the crankcase in the middle of the sump oil, it is probable that the settled particles of dense material would not have been collected. For reference, the density of lead is 11.3g/cm^3 and silver is 10.5g/cm^3. The density of a typical lubricating oil is c.0.91 g/cm^3, approximately a tenth that of the silver and lead.

An alternate style of ferrography known as analytical ferrography is discussed in Section 5.4. Ricardo contacted SPS to determine if samples of oil from each of the months' operation prior to the failures have been kept. Unfortunately, it is not SOP to keep an oil sample for reference purposes. If oil samples were available, these could have been analyzed using analytical ferrography

The tables of spectrographic data supplied by SPS were examined for trends. The spectrographic analysis sorts the particles into four categories of sizes to allow comparison of particle numbers sorted by size EDG 3 apparently shows some trending of the oil sample taken in February 2001 being higher in particle count than the other samples taken with the Chevron oil being used. However, when the data from this time period is compared with the whole spectrum of readings taken across the Amoco, Mobil and Chevron oil usage, the increases in count and the rapidity with which they happen is not unusual compared to the entire data set and the engine wrist pins have not failed previously.

5. DISCUSSION

5.1. Oil chemistry

Ricardo used a number of employees and consultants from the lubricant and from the additive manufacturers to comment upon the oil chemistry and the suitability of Chevron NC oil in the nuclear standby application. From the information received by Ricardo and highlighted in Ref 8.3, the change to non-chlorinated oils does seem implicated in the failure. Feedback from a number of additive formulation experts confirmed the chlorinated element was a paraffin wax. The wax was present as an Extreme Pressure (EP) lubricant with the function of promoting lubrication under marginal conditions – such as those seen on a start after a period of standing. Chlorinated hydrocarbons were deemed to be carcinogenic and so special measures were required for the disposal of such lubricants. In order to avoid this complication, the locomotive industry moved to non-chlorinated oils for their ease of disposal without licensing arrangements.

The move to NC oil in the marine and loco applications has been well documented and is contained in test results and other supporting literature that is readily available. However, no references to the use of Chevron in Nuclear stand-by duty could be found. SPS indicated that the EMD Owners Group recommended the use of Mobilguard 450 NC. Feedback from the oil industry experience stated that the NC formulations would have been qualified on the rocking pin bearing design and the regular silver bearing in locomotive and marine applications. Some of the qualification tests for the silver bearings were simply bench type tests. The requirements of the oils in these service arenas is different to the nuclear stand-by application. Marine and locomotive operations are more interested in detergency, dispercency and high TBN. The nuclear stand by duty requires good film strength, and film retention upon standing, and low corrosive behavior. The use of highly refined low sulfur distillate fuel also calls for a different TBN requirement. The key difference is the apparent confirmation that the specific element that has been removed from the oil, the chlorinated wax, was the key EP additive. Orinite confirmed that Unichlor 40, an EP additive had been removed from the oil to meet the <1000ppm chlorine level required for disposal of the used oil. The chlorinated wax was reported to be particularly effective at activating the surface of the bearing to protect it under marginal lubrication conditions. The presence of zinc in the oil resulting in a chemical attack on the silver bearings was always a possibility. The spectrographs taken from the damaged an undamaged sections of the bearing do not show any traces of zinc, thus supporting the data from the SPS reports that zinc contamination had not occurred during the life of the engine

5.2. Operation Experience from Alternative Industries

Ricardo has undertaken a number of projects for utility companies, marine and railroad operators who use EMD engines in service. The staff involved with these projects and the reports produced from these projects were examined for experience of wrist pin failures. In addition, marine and railroad operators were contacted in the USA for current recent experience of the operation of EMD engines on chlorinated and non-chlorinated oils.

Ricardo experience and industry OE has found wrist pin failures in only two instances in the USA, both in Nuclear Plant EDG applications. The experiences from marine investigations centered upon engine failures caused through faulty oil systems that allowed air to enter the low pressure side of the lubricating system. This caused failure to the crank and main bearings which rely on a constant pressurized feed rather than intermittent splash fed lubrication like the wrist pin bearing.

Several locomotive operators and service yards were contacted with regard to current experience. The locomotive service supervisors, with a combined EMD experience of 23 years, reported that no wrist pin failures at all could be recalled. The EMD 645 and the smaller 567 variants of the engine, both having silver wrist pin bearings, had proved to be very reliable in the marine and locomotive applications. Ricardo questioned the maintenance supervisors for experience of seizure of the engines and in light of the answers given above, no experience of seizures could be given pertaining to the wrist pins.

Orinite-Chevron confirmed that used wrist pins and bearings went through an attempted re-qualification exercise on CP rail. The engines were rebuilt using previously used components. The engines returned to the service yard "a couple of days later" and the oil analysis confirmed 3 to 5 ppm silver in the oil. The engines were stripped and were found to have several failed wrist pin bearings. Although the oil analysis was above the 2ppm limit, the source at Orinite confirmed the debris was found as large particles in the bottom of the sump. Again, none of the wrist pins had seized and the engines apparently ran sufficiently well to get back to the service yard.

In August and September 2000, Ricardo was involved in the RCE (Root Cause Examination) of the EMD645 failure at Point Beach Nuclear Power Station. This engine had failed wrist pin bearings and the failure was traced to poor maintenance and FME practices that had allowed gross oil contamination to occur. Concrete and building debris were found in the lubricating oil and specifically in the upper end of the engine which had precipitated the failure of the wrist pin bearing. Characteristic "worm tracks" could be seen on the piston thrust washer between the aluminum piston and the piston carrier.

From the OE collected above and the inspections of the piston carriers, it appears that the EMD engine design is fairly forgiving of severe wrist pin damage. In 1986, ANO experienced a crankcase explosion following the failure of four wrist pins resulting in severe bearing shell to pin contact. Ricardo contacted a contributor to that investigation (MPR Associates) for first-hand feedback. MPR confirmed that none of the wrist pins had seized despite the substantial damage that had occurred. The experience at ANO suggested that damage could be tolerated up to 4 of the wrist pins for a crank case explosion to occur. However it should be noted this is only circumstantial evidence and should not be taken as a definitive guideline. The bearing would have continued to have been lubricated and cooled by the lubricant exiting from the piston cooling gallery and probably would have run for some time further in this condition. Discussions with SPS indicated that, if the engine were called upon to provide power for the loads on the emergency bus, the load drawn from the engine could be substantially less than the 2750kW rating and could be in the 1300 kW range. Reducing load on an engine has a very significant effect on component temperatures. Bearing loads are reduced, piston loads are reduced, oil coming from the piston-cooling gallery would be cooler and all these conditions would contribute to lengthening the service time that the engine could operate with failed bearings.

In September of 2001, TVA contacted Ricardo with respect to a failure of an EMD 645 engine at Sequoyah. At the time of preparation of this report, this investigation is still on-going, however the majority of possible failure mechanisms have been eliminated and the remaining probable root cause is the LO performance in stand-by duty. It is pertinent to note that one wrist pin on one engine and 3 pins on another engine had failed and there was contact between the steel bearing shell and the wrist pin. Sequoyah had not experienced a crankcase explosion, nor had any of the wrist pins seized. The LO was Shell Caprinus.

5.3. Failure Mechanism

The mechanism of the wiping wear also needs to be taken into account in the failure mode. Wiping of the soft layer of bearing is most commonly associated with lack of lubrication. This is detailed in several of the industry standard texts relating to bearing failure modes. The references produced by Glacier-Vandevell (Dana) are even more specific and state the primary cause of wiping to be inadequate pre-lubrication at engine startup. This would correlate closely with the service operation seen by the EMD 645's in Nuclear Standby Service and would also explain the contrast with the OE seen in the marine, stationary power generation and the railroad applications of the engines. Several of the railroads utilizing the 645 engines in switching duties were contacted. Their use also involved multiple starts and stops during the day, so the severe wrist pin wear appeared not to correlate with simply the number of stops and starts. The difference in the railroad experience was that very few engines were left at rest for periods longer than 48 hours. Those that were rested for more than 48 hours underwent a pre-lube and gentle start.

The mechanism for wiping-wear entails bearing material relocation into the oil grooves. The design of the EMD wrist pin bearing is unique in that it is not continuous and it features a number of oil distribution grooves. Generally, the conventional style of a small-end bushing is cylindrical and is pushed into place in the piston. Wiping occurs in the center of the bearing and spreads outward. The design of the EMD bearing is such that, as wiping occurs, the bearing material is pushed into the grooves, which can accommodate a substantial amount of material. If, during the wiping process, material is being accommodated in the grooves (as per the micrographs in the NES report (Ref 8.4), it may be that significant failure is occurring, but the adhesive qualities of the lead and the silver are such that material is relocated on each start-up. Rather than causing large increases in debris in the oil, material is actually accumulating in the wrist pin bearing grooves and could only be detected by visual inspection of the component. Some of the bearings in the early stages of failure appear to demonstrate this phenomenon (see Ref 8.1 and 8.2 ESI Reports).

There may be other contributory factors that caused the bearings to fail such as the drain and refill process itself. It is always possible that an airlock was created that inflicted some damage or caused a longer delay in the 30 to 90 s time lag that EMD have quoted for the time it takes to pump the piston cooling gallery to full pressure. In addition the oil exchange process also offers an opportunity for contamination to occur. Other factors such as oil temperature, bearing clearances, condition of the bearings may all have created conditions for EDG2 that made the engine further from the point of failure than EDG3 and EDG 1. The feedback from the oil and additive industry suggested the function of the chlorinated wax could be a contributor to avoiding wiping in marginal lubrication conditions.

5.4. Analytical Ferrography

It appears from the spectrographic and ferrographic analysis that these tools have not picked up the trend with the particular failure mode of the bearings. Ferrography is undoubtedly useful in many situations including wear of certain parts of the EMD engines. However with the combination of materials that are being abraded or re-positioned, the nature of the oil sampling technique, the sample preparation and the DR ferrography, the silver and lead debris from the bearing is not being accurately captured.

An alternative style of ferrography is available called Analytical Ferrography. Analytical ferrography employs microscopic and photographic evaluation of wear particles. The benefit of the test is that a trained analyst is used to provide in-depth analysis of particle makeup (e.g., steel, copper, bronze) and type of wear (e.g., corrosion, metal-to-metal contact). The lab technicians prepare a ferrogram slide by placing the oil sample on a transparent glass plate in the presence of a strong magnetic field. In this procedure, particles are stratified along the plate according to size. Both magnetic and non-magnetic particles are captured as non-magnetic particles are made to appear magnetic by virtue of having a fine coating of ferrous material.
Lubricant from the sample is then removed with a special solvent, leaving the particles clean, aligned with the magnetic field by size and composition, and fixed to the plate. The trained analyst then examines the ferrogram to determine the composition and sources of the particles, plus the types of wear present. Wear can be sorted into the following broad categories:

- Normal Rubbing Wear
- Bearing Platelet Wear
- Gear Wear
- Cutting Wear
- Severe Sliding Wear
- Spheres
- Sand and Dirt

By determining the morphology, size and composition of the debris, an analyst can accurately determine location of the origin of the wear and the extent of the wear. The analysis of the particles to find the bearing platelet wear would have been extremely useful in this instance.

In addition to the application of the technique of Analytical Ferrography, a revision to the oil sample technique may have been useful. Due to the density of the silver and lead and the size of the particles, it is probably appropriate to take special samples from the bottom of the sump or other areas where upon disassembly the debris from the bearing was found to have accumulated. If substantial debris was found in an oil sample an additional test such as a washed filter or patch test could be used to determine origin of the particles.

5.5. Engine Life Predictions

Ricardo have examined all the data, reports, tables and data plotted to determine trends to explore all avenues that may have allowed the point in time or date to be determined that EDG3 should be deemed to be inoperable. This included the silver content in the oil, the lead content, the ferrography and SOAP analysis. None of these data showed any distinct change in trend that could be assigned to the point at which a bearing entered a catastrophic failure mode. The progressive failure mechanism of the bearings involving successive wiping and blockage of the oil channels was an incremental failure without a distinct initiation point other than the adoption of the NC oil. The lack of clear trend data in the ferrography results, which is one of the clearest and most regularly taken pieces of data during the period of time covering the suspected degradation period of the engines prevents any data from being signified as the operable/inoperable transition date.

If the wiping initially occurred on start-up, with no further bearing degradation occurring once the engine was operable, an argument could be made that once started the engine would have run successfully. This is probably the case in the early stages of the failure mode when some relocation of material was just commencing. The engine would start with some wiping occurring and then would most probably have operated satisfactorily for any 24 hour period it was called upon to provide backup power for. Unfortunately once the failure progressed to the point of blocking some of the oil channels such that excessive temperatures and further wiping were occurring during operation the engine was on a path to failure. From all the measurements taken and data provided it is not possible to discern that transition point. It would take extensive lab testing to simulate the repeated dry-wiping to look at the number of starts required to relocate sufficient material to render the bearing sufficiently damaged that it would fail in operation. Such testing is beyond the scope of this project.

The most serious problem is not the probability of wrist pin seizure (which usually results in broken pistons and/or connecting rods), but the possibility of a crankcase explosion occurring. It is primarily because of this risk that Ricardo would agree with the NRC that at the time of disassembly the EDG would have to be considered inoperable.

The only point in time at which it is possible to back-calculate when the engine had 24 hours service life is to calculate the 24 operating-hour period back from the time in April 2001 when the engine was deemed inoperable through the severe wrist pin damage. Using the data from the NRC report, the engine performed 24h of duty service during the monthly runs between October 3rd 2000 and April 23rd 2001. Therefore the engine was deemed to be fully capable of fulfilling its safety requirement of 24 hours operation up to 3rd October. Examination of the operators log for EDG 3 in the time from October 3rd through April 23rd showed the engine to have undergone 13 starts, one of which was a fast start. In addition there were seven periods of approximately one month that the engine was at rest. The starts under these conditions would have been the major causal factors in the failure when combined with the NC lubricating oil implicated as being a contributor to this failure mode.

Undoubtedly at some time after the 3rd Oct.2000, the damage from start-ups would have transitioned from a state of operating satisfactorily once running to a state of continuing to accumulate damage once operating. It is at this transition that the engine would have failed to meet its operability demands. Unfortunately there is no data available from the instrumentation or lab reports that can pinpoint this transition date. It would be pure speculation to postulate after 6 of the 13 starts or approximately half way in time as being the point at which wrist pin failure was certain. Ricardo suggests however that the date at which the engine could not be guaranteed to run for a 24 hour period is later than October 3rd 2000.

Several guidelines or "Rules of Thumb" are quoted to calculate potential engine life. Ricardo has done studies on engine life against duty cycles and this has correlated against anecdotal evidence from other large engine manufacturer data that a fast start is worth 10 hours of regular operation. If a cautious approach is taken that a slow start is worth 1 to 2 hours operation, the one fast start and 12 slow starts sum to give 22 hours operation that can be accredited to the starts alone. This would put the date at which the engine could not be guaranteed to perform for 24 hours at the time of the fast start after October the 3rd. It must be stressed this is experience based guidelines rather than quantifiable data.

6. CONCLUSIONS

1) The substantial damage to the EDG3 wrist pin bearings had allowed piston pin to bearing shell contact and would be considered by Ricardo to have rendered the engine inoperable. Although the engine was unlikely to seize, there would have been an increasing risk of a crankcase explosion. Despite the mitigating evidence that no EMD engines with seized wrist pins were found during investigations, the reports from ANO indicating a crank case explosion is entirely possible with this type of engine, it is prudent to declare the engine inoperable for this reason.

2) No evidence of foreign material contamination could be found in either the wrist pin bearings or the piston thrust washer. The material that was found in the thrust washer was ferrous in nature with tell-tale traces of silver. This suggests the material that had been impressed into the surface of the thrust washer was secondary debris from the failure of the wrist pin bearing.

3) The failure mode of the wrist pins is consistent with a lubrication-derived failure. Wiping of the softer material is primarily associated with insufficient pre-lubrication or a lubricant with insufficient film strength and retention between starts (possibly aggravated by oil chemistry). Nuclear stand by duty certainly exacerbates this failure mode with the c. 30 day waits between starts. Another contributory factor may include oil starvation following an oil change.

4) The failure is initiated by repeated starts under marginal lubrication conditions. The mechanism involves relocating the silver and lead bearing material into the oil grooves of the wrist pin bearing, and then progresses once the engine is running by limiting or preventing lubricant flow across the full surface of the wrist pin bearings. The bearing goes into catastrophic failure mode when the groves are substantially blocked, causing the silver surface temperature to become significantly elevated, leading to further relocation, extrusion and removal of the bearing material. Finally when sufficient silver has been removed that the steel wrist pin contacts the steel bearing shell, a significant temperature increase occurs resulting in further softening and removal of the silver.

5) The date at which the damage to the bearing was sufficient that the wrist pin of EDG3 was committed to failure was probably after the October 3rd 2000 date postulated by the NRC. This is based on the failure mechanism being cumulative from repeated starts but also requiring a certain degree of accumulated damage before the bearing would continue to accumulate damage when operating in a lubricated condition. When the damage was such that portions of the wrist pin bearing were being starved of oil, the failure would progress when the engine was running. There were 13 starts in the period from Oct 3rd 2000 through April 23rd 2001. It is however pure speculation as to the date of the transition point that the condition of the wrist pin committed it to failure, but the date that the engine could not have been guaranteed to operate for 24 hours is after October 3rd.

6) From the information received by Ricardo, the change to non-chlorinated oils is the root cause. Feedback from a number of additive formulation experts from within the oil industry and bearing manufacturers confirm the chlorinated element was a paraffin wax and was present as an extreme pressure lubricant with the function of promoting lubrication under marginal conditions – such as those seen on a start after a period of standing.

7) No references to the use of Chevron being qualified for use in Nuclear stand-by duty could be found. Feedback from the oil industry experience stated that the NC formulations would have been qualified on the rocking pin or regular silver bearing design and for use in locomotive and marine applications. The requirement of the oils in these service arenas is different to the nuclear stand-by application. Marine and locomotive operations are more interested in detergency, dispercency and high TBN. The nuclear stand by duty requires good film strength, and film retention upon standing, and low corrosive behavior. The use of highly refined low sulfur distillate fuel also calls for a different TBN requirement.

8) The DR ferrography results were inconclusive in determining a point in time or operating hour when bearing failure commenced. DI, Ds, wpc and %LP from the pre- and post-Chevron oil change do not show a clear and convincing trend. It could be argued that some increase in wear particles is seen following the change to Chevron oil but the density counts are no different in ultimate levels than in the many years of successful operation prior to the addition of the Chevron oil.

7. RECOMMENDATIONS

Ricardo would make the following recommendations in light of the study completed:

1) The 2ppm silver limit in the oil for action to be taken is not a safe limit based on nuclear stand-by duty. This limit should be reduced to 1ppm. Over 0.5ppm should require frequent analysis and visual inspections (piston pin feel check, measurement of piston to head clearance, inspection of sump for wear metal).
2) SPS should contact Mobil with regard to specific oil formulations for nuclear stand by duty. Long term tugboat and locomotive tests should not be taken as qualification for stand by duty

3) SPS should also consult Mobil regarding the high TBN of the oil compared to the fuel sulfur level. The oil is formulated to tolerate high sulfur distillate fuels of up to 1.5% S, SPS are currently operating with 0.03% S fuel. In other applications this mismatch between fuel sulfur and TBN has caused bore polish and ring sticking issues
4) A brief investigation of alternative sampling points for oil and attempts to collect debris from the bottom of the sump or where the debris from the previous failure was encountered should be made. Examination of the filters and EDAX analysis of particles should be undertaken once 0.5ppm silver in the oil is obtained to avoid the ferrographic analysis missing important data.
5) Ensure the piston cooling galleries are primed after a drain and re-fill to minimize running time with no pressure in the gallery.

8. REFERENCES

8.1 ESI Report Re EDG 1 Report # 90342-FA
8.2 ESI Report Re EDG 3 Report # 87360-FA
8.3 Trident Engineering Associates Contract # PR-CU0012-000 Trident Contract # 918-007
8.4 NES Materials Engineering Laboratory Report # NESML-Q-465
8.5 NRC Special Inspection Report 50-280/01-06 and 50-281/01-06
8.6 Kotlin and Malina, Lube Oil and Engine Design Compatibility – A requirement for Achieving High Levels of Performance Reliability SAE 700891