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Ranking lubricating oil consumption of different power assemblies on an EMD 16-645-E locomotive diesel engine

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Abstract: Real-Time Oil Consumption (RTOC-III) measurements were made on a 1,500 kW EMD 16-645-E switcher locomotive diesel engine to evaluate commercially available power assemblies (head, piston, cylinder liner, and piston rings) that hold the potential to reduce lubricating oil consumption and hence reduce exhaust particulate matter emissions. Traditional volumetric oil consumption measurement techniques are not practical for measuring oil consumption of individual power assemblies.

The RTOC-III technique uses exhaust sulfur dioxide (SO_2) as a tracer for oil consumption by using ultra-low sulfur diesel fuel (lt 15 ppm) and commercially available mineral-based lubricating oil. The sulfur level in the oil and the instantaneous SO_2 concentration in the exhaust can be used with the air and fuel flow rates to calculate the real-time lubricating oil consumption rate on a second-to-second basis.

In this program, seven commercially available power assemblies were ranked according to lubrication oil consumption for steady-state operating conditions typical of North American freight locomotive operation. From highest to lowest, there was about a 40 percent reduction in oil consumption. The commercially available power assembly with the lowest oil consumption was selected for use in future engine tests to assess the practicality of applying diesel exhaust particulate filters (DPF).

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INTRODUCTION

This paper describes part of a larger program to reduce diesel locomotive exhaust particulate matter (PM) emissions from switcher locomotives operating in California. It is envisioned that existing diesel locomotives would be retrofitted with particulate filters similar in function to those currently being installed on on-highway trucks, transit buses, and various types of mobile non-road equipment. On-road small-volume diesel particulate filter (DPF) technology, in terms of both PM removal efficiency and system durability, is progressing rapidly, such that wide-scale implementation plans for retrofitting existing diesel engines is planned. Due to the fact that the average life of a locomotive engine is typically on the order of 30 years, it is important to consider emissions from the existing fleet that includes a number of switcher locomotives. Retrofitting DPF on these existing switcher locomotives could be a very effective means of reducing particulate matter emissions.

When considering DPF for locomotive applications, several technical challenges exist, including lubricating oil consumption, which can affect filter performance in several ways:

1. Oil-derived particulates contribute a significant portion to the total PM mass emissions from the engine.

2. Oil-derived particulates represent a means to poison the catalyst activity, needed to maintain a reasonably clean DFP. It also represents combustible hydrocarbons for catalyzed DPF, and too much can be detrimental to DPF durability.

3. Sulfur compounds, originating from the lubricant base stock and from the additive package, form sulfate emissions that are included in total PM mass emissions. These sulfate emissions can increase dramatically with certain exhaust temperatures and using catalyzed DPF.

4. Ash from the lubricating oil will increase the pressure differential across a PM filter, which ultimately dictates the time between maintenance or replacement intervals, or until the PM filter is "plugged."

Therefore, the objective of this portion of the program was to apply the RTOC-III measurement technique to quantify lubricating oil consumption from a locomotive engine, and then to use the technique to identify commercially available power assemblies (cylinder head, pistons, rings and cylinder liners) that demonstrate low lubricating oil consumption.

TECHNICAL APPROACH

<u>Engine Description and Operation</u>

The engine used in this study was manufactured by the Electro-Motive Division of General Motors Corporation (EMD). This engine is available in both naturally aspirated and turbocharged configurations, and in V-8, V-12, V-16, and V-20 configurations. It is popular for locomotive applications in North America, as well as in marine, industrial and power generation applications. For this program, the EMD 16-645-E engine was chosen because it is commonly found in switcher and road-switcher locomotive applications in North America, in power ranges from 750 kW to 1,500 kW. Roughly 3,000 of these switcher locomotives are in operation in North America. Figure 1 shows an EMD GP38-2 road-switcher locomotive, which is equipped with an engine like the one tested in this program.

Figure 1 - EMD GP38-2 road-switcher locomotive

Specifications for the EMD 16-645-E engine are given in Table 1. The EMD 645-E engine is a uniflow-scavenged, two-stroke, direct-injected diesel. Figure 2 shows a power assembly from the EMD 645-E engine. Figure 3 shows that the piston has four compression rings on the piston crown and two oil control rings at the piston skirt.

Prior to RTOC-III testing at SwRI, the engine was rebuilt, and equipped with a set of commercially available power assemblies, and broken in for 100 hours of operation.

Table 1 - EMD 16-645-E engine specifications

Engine Model	EMD 16-645-E
Cylinders	V-16
Bore	230 mm
Stroke	254 mm
Displacement/cylinder	10.6 L
Compression Ratio	16:1
Power	1,500 kW
BMEP	5.9 bar @ 900 rpm
BSFC @ rated power	254 g/kW-hr
Air Charging	Gear driven roots blower
Fuel Injection	Cam driven unit injectors
Crankcase Ventilation	Crankcase fumes are returned into the blower
Engine Condition	About 100 hours break-in upon complete engine overhaul
Emission Certification	EPA Tier 0 - switcher cycle

Figure 2 - EMD 645-E power assembly

Figure 3 - EMD 645-E pistons

During RTOC-III testing, the engine was operated at Low Idle (LI), at Notches 3, 5, and 8 (N3, N5, and N8), which are specific speed and load conditions. Table 2 shows the engine speed, the brake power, the fuel and air flow, as well as the air-fuel ratio. Air flow scales roughly with the engine speed because the engine is roots-blown and not turbocharged. The air-fuel ratio varied from about 350:1 at Low Idle to 36:1 at Notch 8.

Table 2 – Engine operating parameters

	Speed rpm	Power kW	Fuel Flow kg/hr	Air Flow kg/hr	A/F Ratio kg/kg
LI	252	~1	10.6	3,729	~350
HI	315	~1	14.2	4,924	~346
DB4	571	~2	32.3	8,633	267
N1	315	57	31.5	4,905	156
N2	383	283	55.9	5,767	103
N3	503	515	111.2	7,636	69
N4	572	689	148.1	8,634	58
N5	667	927	203.5	9,978	49
N6	736	1,028	245.2	10,818	44
N7	837	1,409	322.3	12,530	39
N8	904	1,567	377.1	13,382	36

Real Time Oil Consumption Measurements

Oil consumption was measured by the SwRI-developed SO_2-tracer technique, deemed the Real-Time Oil Consumption (RTOC-III), shown in Figure 4. SwRI has applied this technique successfully on numerous engine types over the last 14 years. The most recent published works can be found in references by *Froelund et al.* [1-6].

Figure 4 - SwRI RTOC-III™ system

The working principle of the RTOC-III technique is to use exhaust sulfur dioxide (SO_2) as a tracer for oil consumption by using ultra-low sulfur diesel fuel (<15 ppm) and commercially available mineral-based lubricating oil. Knowing the sulfur level in the oil, the SO_2 concentration in the exhaust from each power assembly can be used with the air and fuel flow rates to calculate the real-time lubricating oil consumption rate on a second-to-second basis. The engine parameters that need to be measured for RTOC-III measurements are:

- Air flow
- Fuel flow
- SO_2-concentration in exhaust gas
- Air sulfur concentration
- Fuel sulfur concentration
- Oil sulfur concentration

Typically, the first three quantities are measured simultaneously, which in turn allows time resolved oil consumption measurements for steady-state as well as transient testing. The sulfur concentration in air is generally assumed to be zero. The sulfur concentration in fuel was determined from taking fuel samples from the day tank for analysis by the ASTM D-5185 method. The fuel used for this work had less than 2 ppm sulfur by weight. The sulfur concentration in the lubricating oil was determined from drawing an oil sample from the oil sump for analysis by the ASTM D-5185 method. In this program, the lubricating oil sulfur concentration was about 4,700 ppm by weight. Appendix A contains additional properties of the oil used in this program.

The engine-out oil consumption rate is calculated algebraically as follows:

$$m_{OC} = \frac{m_{fuel}\left([S]_{exh} - [S]_{fuel}\right) + m_{air} \cdot \left([S]_{exh} - [S]_{air}\right)}{\left([S]_{oil} - [S]_{exh}\right)}$$

Where the quantities are defined as follows:

m_{OC}	Oil consumption rate, g/hr
m_{air}	Air mass flow rate, g/hr
m_{fuel}	Fuel mass flow rate, g/hr
$[S]_{air}$	Air sulfur concentration, wt. %
$[S]_{fuel}$	Fuel sulfur concentration, wt. %
$[S]_{oil}$	Oil sulfur concentration, wt. %
$[S]_{exh}$	Exhaust sulfur concentration, wt. %

As described in a previous publication by *Froelund et al.* [6] on this same EMD 16-645-E engine, this work assumed that air flow and fuel flow were constant across the individual cylinders. Using this assumption, individual cylinder, or power assembly lubricating oil consumption results can be compared directly in terms of SO_2-concentration. If the air and fuel flow distribution throughout the engine also are assumed consistent between engine builds, then the relative distribution of SO_2-concentration should be proportional to the relative distribution of cylinder oil consumption.

Note that the SO_2-concentration measurements in this paper reflect total oil consumption. No attempt has been made to determine the oil consumption contributors, such as from blowby (*Fritz et al.* [7]), valve stems, or piston rings and liners.

The detector in the RTOC-III instrument is a patented UV-light excited fluorescent detector with sensitivity to less than 50 parts per billion (less than 0.050 ppm). It has been used down to SO_2 concentrations of 5 ppb for other industrial applications. The detector is linear over several decades of concentration range. The high-resolution detector enables real-time (second-to-second) data. The RTOC-III response time is chiefly governed by the transport time of the exhaust sample to the detector, and it is typically about 5 seconds. For this application, using a 24-meter sampling line, the characteristic response time was about 25 seconds.

Applications of RTOC-III measurements require careful attention to conditioning the exhaust gas sample. Conditioning steps are as follows:

1. The exhaust gas sample enters a furnace section, where it is oxidized in an oxygen-rich environment, under very high temperature. Any unburned sulfur-containing fuel or lubricating oil species are converted into sulfur-dioxide, water, and carbon dioxide.

2. Water vapor in the sample is removed in a membrane drier system.

3. The engine emits NO_X emissions primarily as NO, for which specie the fluorescent detector exhibits a strong cross sensitivity to SO_2. To eliminate this interference, the sample is passed through a patented ozone chamber, which oxidizes NO to NO_2, prior to reaching the detector.

The RTOC-III system calibration was verified several times throughout a working day using an online SO_2 calibration gas of known concentration.

Baseline Oil Consumption Test

Figure 5 shows the 16-cylinder engine and the layout of the build configuration for the "baseline" oil consumption test. "Reference" (R) power assemblies were referred to as reference, only because they were the components supplied with the engine as delivered to SwRI after engine overhaul by a major U.S. railroad. During the overhaul, the engine was assembled with requalified cylinder heads and pistons, and new piston ring sets and cylinder liners. The cylinder liners were in the general category of "plain gray iron liners," as opposed to various hardened liner options available in the market. Oil consumption results for the bulk engine exhaust from the engine in this configuration is reported in a previous ASME paper by *Froelund et al.* [6].

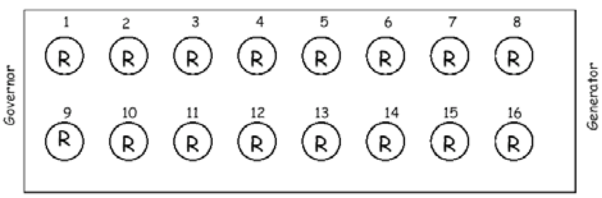

Figure 5 – Reference power assembly layout

The next step was to assess the cylinder-to-cylinder variability in SO_2-concentration for one selected operating condition, Notch 6. The individual cylinder exhaust manifolds of the EMD 16-645-E engine join two opposing cylinders of exhaust within the block, exiting on top of the engine. Therefore, there are eight exhaust outlet locations feeding the exhaust manifold. Given this exhaust arrangement, emission sample probes were installed in each of the eight exhaust outlet locations, as shown in Appendix B. Each sample probe obtained an average between opposing left and right bank cylinders. In this way the average oil consumption was measured for cylinder pairs 1-9, 2-10, 3-11, 4-12, 5-13, 6-14, 7-15, and 8-16, as shown in the photos in Appendix B.

Figure 6 shows the measured baseline SO_2-concentrations for pairs of "reference" power assemblies during Notch 6 operation. The SO_2-concentrations ranged from 0.70 to 0.85 ppm by weight. Considering the average cylinder SO_2-concentration was about 0.77 ppm, the oil consumption varied within +/-10 percent. This relatively low cylinder-to-cylinder variation in SO_2-concentration provided confidence to design an experimental test matrix to equip the engine with several candidate power assemblies simultaneously, using the RTOC-III technique to rank the oil consumption of candidate power assemblies under identical break-in and operating conditions.

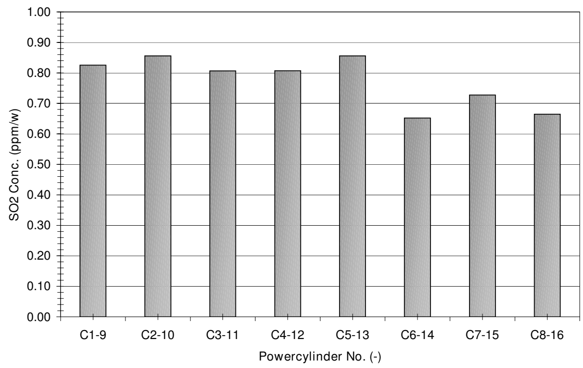

Figure 6 - Reference SO_2-concentration for power assembly pairs at notch 6

Design of Experiment

The purpose of this study was to identify the lowest oil consuming power assembly for subsequent particulate filter testing. The resulting oil consumption of seven different power assemblies were compared and ranked. Reference (R) power assemblies were those used prior to initiating this experiment, and their position was randomly chosen. Table 3 lists the power assemblies evaluated. Generally, the variable of interest was the cylinder liner. A common set of cylinder heads and pistons were used for all power assemblies, except for power assembly "C1", which consisted of a specific liner, head, and piston configuration from one supplier.

Table 3 – Power assemblies tested

Component	R	C1	C2	C3	C4	C5	C6
Liner Supplier	A	B	C	D	C	E	E
Liner Description	Plain gray Iron	HUB + plateau hone	HUB	Plain gray Iron	HUB + plateau hone	HUB	HUB
Ring Set	A	A	B	A	B	A	A with high-tension oil ring
Piston	A	B	A	A	A	A	A
Head	A	B	A	A	A	A	A

All seven power assembly types were tested (including the reference) using two engine builds. Had the volumetric method for oil consumption measurement been used, it would have involved seven complete engine builds with all 16 cylinders. This approach would have required long run times, which would have been very time consuming and prohibitively expensive. With the RTOC-III technique, cylinder pair oil consumption was measured, allowing a design of experiment that significantly accelerated the evaluation of oil consumption associated with each of the seven candidate power assemblies within just two engine builds. The third build was used to independently cross-check data.

Figures 7 through 9 show the power assembly configuration for the design of experiment (DOE). The "Round 1" configuration is illustrated in Figure 7 and consisted of:

- R: Two pairs of reference (R) power assemblies that remained in locations 1-9 and 5-13.
- C1: Two pairs of "C1" power assemblies were installed in locations 2-10 and 6-14.
- C2: Two pairs of "C2" power assemblies were installed in locations 3-11 and 8-16.
- C3: Two pairs of "C3" power assemblies were installed in locations 4-12 and 7-15.

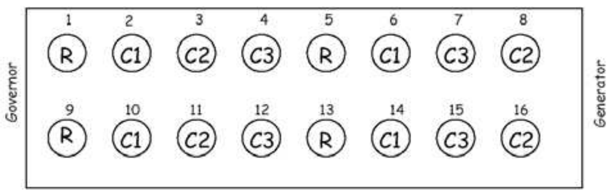

Figure 7 - Round 1 power assembly layout

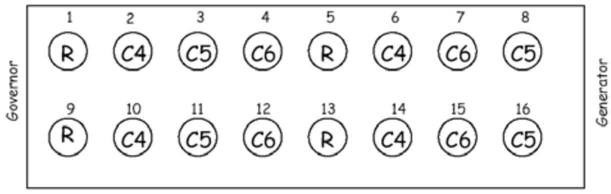

Figure 8 – Round 2 power assembly layout

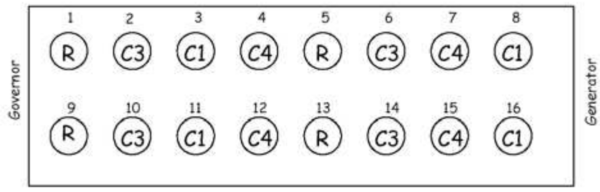

Figure 9 – Round 3 power assembly layout

In this way, the oil consumption of three candidate power assemblies was evaluated against the reference power assemblies in one engine build.

Data for the two pairs of reference power assemblies yielded a way to normalize the data for the two pairs of C1, C2, and C3 power assemblies. Before RTOC-III testing for each of the first two engine builds, Round 1 and Round 2, the engine was "broken in" over a 100-hour test. For Round 3 testing, a break-in was not required because the engine was assembled with power assemblies that were already broken in.

The engine build for Round 2 testing followed a similar power assembly placement approach, with the configuration given in Figure 8. Round 3 testing was added as a cross-check of the data obtained for Round 1 and Round 2.

Note that the four R power assemblies remained in the same locations for all tests, and were "undisturbed" during each engine buildup while the rest of the engine was reconfigured with candidate (C) power assemblies.

Round 1 and Round 3 tests consisted of duplicate test runs over two days, while triplicate test runs were performed during Round 2 over three days.

<u>Data Analysis</u>

To compare the SO_2 generated from the candidate "CX" power assemblies to the reference "R" power assemblies, the ratio of the average SO_2 from C to the average SO_2 from R was computed (CX/R) at each notch setting. The SO_2 ratios were computed within each test day and within each test round. For example, for the first day of Round 1, the ratio for C2 at Notch 8 was computed by dividing the average C2 SO_2 value at cylinder locations 2-10 and 6-14 by the average R SO_2 value at cylinder locations 1-9 and 5-13. Thus, each C cylinder pair average SO_2 was divided by the average R SO_2 within each day and each test round, and at each test point. This resulted in a daily CX/R SO_2 ratio for each cylinder pair at each notch.

SO_2 ratios greater than 1.0 meant that the oil consumption for that power assembly type and at that notch condition was higher than R. Likewise, an SO_2 ratio lower than 1.0 meant that the oil consumption of C was lower than R. This daily normalization minimized any impact of slight SO_2 changes in fuel sulfur concentration, in the bulk engine oil sulfur levels, and ambient air temperature and barometric pressure effects on exhaust flow rates, and allowed direct comparison between engine builds.

After the SO_2 ratios were computed, an analysis of variance (ANOVA) was used to compare the average SO_2 ratios against one another. If the ANOVA indicated that the mean ratio for the normalized power assembly types were significantly different, then Fisher's "least significant difference" (LSD) for multiple comparison was used to determine which means were significantly different from one another.

The mean of the SO_2 ratios, or the average, were also compared against the value 1.0 (i.e., compared the average candidate power assembly to the average reference power assembly). This was done by computing the 95 percent LSD intervals about the average SO_2 ratio and observing if the interval contained the value 1.0. If the average ratio was significantly different from 1.0, then the candidate power assembly average SO_2 ratio was considered different from the reference power assembly. Each notch was analyzed independently. All statistical tests were made at the five percent level of significance.

Figures 10 through 13 show the mean SO_2 ratios, that is the average CX SO_2 concentration normalized to the average R SO_2 concentration, for four operating conditions. All oil consumption data were obtained using multigrade SAE 20W40 lubricating oil (Appendix A), and ultra-low sulfur diesel fuel (2 ppm).

Figure 10 shows the following for Notch 8:

1. The lowest oil consumption was obtained with power assembly C3. By comparing the oil consumption of power assemblies C3 (lowest) to C2 (highest), the reduction in oil consumption is about 40 percent.
2. Comparing C2 with C4, the plateau-honed HUB power assembly, C4 demonstrated a statistically significant decrease in oil consumption compared to the C2 standard HUB liner, both of which were from the same supplier.
3. Comparing C5 to C6, C6 used a high-tension oil control ring, whereas C5 used a standard oil control. The high-tension oil control ring did not provide a statistically significant change in oil consumption.
4. Comparing R and C3 to the rest, it is clear that the lowest oil consuming power assemblies were found among the plain gray iron liners.

Comparing Figures 10 through 13, the following is observed:

1. The variability in the data was lowest for high-power modes of operation. This makes sense, because high-power modes of operation normally increase oil consumption and thus the SO_2-concentration in the exhaust, enabling a more accurate determination of oil consumption.
2. The average oil consumption ranking of the candidate power assemblies were similar across the operating conditions. This was an important finding, because it can be used for accelerating future testing so that power assembly oil consumption can be screened simply at one operating condition, Notch 8.
3. For low-idle operation (Figure 13), the oil consumption variability in the data made it difficult statistically to rank power assemblies.

Table 4 completes the ranking by sorting (from low to high) the power cylinder assemblies according to the mean normalized SO_2-concentration. C3 consistently demonstrated the lowest oil consumption at both Notch 8 and Notch 5, and essentially tied with C5 for the lowest oil consumption at Notch 3.

Table 4 – Ranking of power assemblies by normalized oil consumption at each notch

Notch	Power Assembly	Normalized SO_2 Concentration
8	C3	0.89
	R	1.00
	C5	1.03
	C6	1.08
	C1	1.10
	C4	1.17
	C2	1.45
5	C3	0.75
	C5	0.85
	C4	0.87
	R	1.00
	C6	1.02
	C1	1.03
	C2	1.17
3	C5	0.79
	C3	0.82
	C6	0.91
	C4	0.99
	R	1.00
	C2	1.12
	C1	1.34
Low Idle	C3	0.80
	R	1.00
	C2	1.17
	C4	1.23
	C6	1.58
	C1	1.67
	C5	2.10

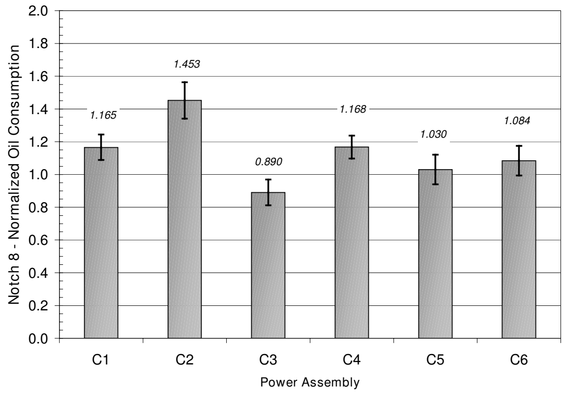

Figure 10 - Notch 8 normalized oil consumption

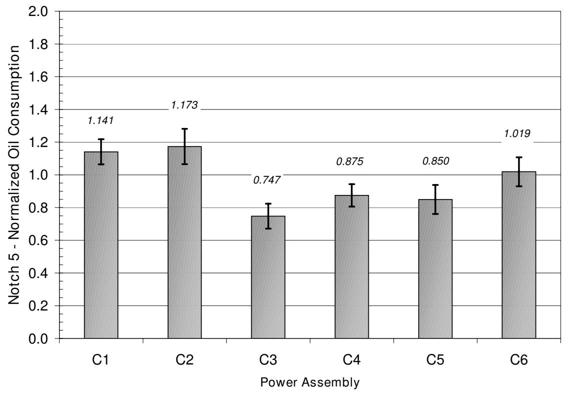

Figure 11 - Notch 5 normalized oil consumption

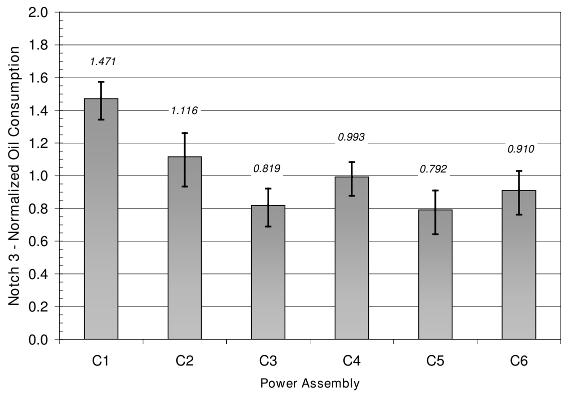

Figure 12 – Notch 3 normalized oil consumption

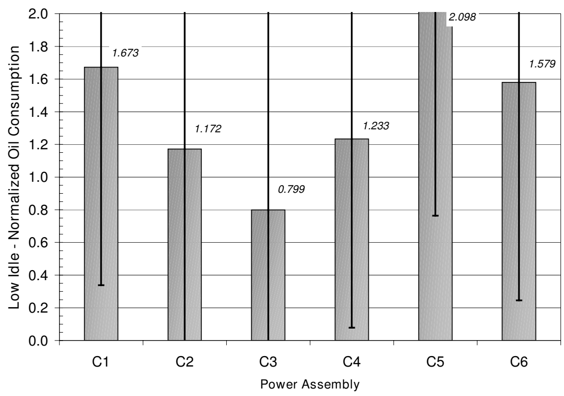

Figure 13 – Low idle normalized oil consumption

CONCLUSIONS

SwRI successfully applied the RTOC-III technique for real-time oil consumption measurement to the EMD 16-645-E locomotive diesel engine. Major findings include:

1. Power assembly C3 was identified as having the lowest oil consumption. As a result, this power assembly was chosen for use with a diesel particulate filter. C3 reduced oil consumption at Notch 8 (rated power) by about 40% compared to C2, and 11% compared to R.

2. Plain gray iron liners (R and C3) yielded lower oil consumption than hardened upper bore (HUB) liners (C1, C2, C4, C5, and C6). This interpretation is contingent upon that no attempt was made to assess long-term durability or trends on oil consumption.

3. High-tension oil control rings (C6) yielded no statistically significant change in oil consumption, as compared to a standard ring-pack in the same liner type (C5).

4. The ranking of oil consumption versus power assembly type was generally consistent across operating conditions. This strengthens the hypothesis that power assemblies can be screened for oil consumption at a single operating condition, Notch 8, reducing test time and cost.

5. The RTOC-III technique is a novel cost-effective oil consumption research and development tool for the locomotive engine design and application.

ACKNOWLEDGEMENTS

Special recognition should be extended to SwRI Staff Technician Marty McIntosh and Technician Matthew Dash for their excellent contribution to this work, along with Principal Analyst Mrs. Janet Buckingham for performing the statistical analysis. The project was funded by the Burlington Northern Santa Fe Railway and the Union Pacific Railroad through AAR.

NOMENCLATURE

A/F	Air-to-Fuel Ratio, kg/kg
ANOVA	Analysis of Variance
BMEP	Brake Mean Effective Pressure, bar
BSFC	Brake Specific Fuel Consumption, g/kW-hr
C	Candidate Power Assembly
DB	Dynamic Brake
DPF	Diesel Particulate Filter
HI	High Idle
LI	Low Idle
LSD	Least Significant Difference
PM	Particulate Matter
ppm/w	Parts per million by weight
N	Notch
R	Reference Power Assembly
RTOC-III	Real-Time Oil Consumption measurement
SO_2	Sulfur Dioxide
SwRI®	Southwest Research Institute®
TTCI	Transportation Technology Center, Inc.

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APPENDIX A: LUBRICANT SPECIFICATIONS

Property	Method		SAE 20W40
Viscosity Index	ASTM D2270	-	115
Kinematic Viscosity	ASTM D445	@ 40°C	115.7
		@100°C	13.6 cSt
Noack Volatility	ASTM D5800	@ 250°C, 1 hr	9.0 % w/w
Distillation	ASTM 86	IBP	175°C
		5%	298
		10%	316
		20%	339
		30%	345
		40%	348
		50%	351
		60%	353
		70%	355
		80%	357*
		90%	359*
		95%	360*
		FBP	361*
Elemental Analysis	D5185	Al	4 ppm w/w
		Sb	<1
		Ba	<1
		B	5
		Ca	5898
		Cr	<1
		Cu	1
		Fe	5
		Pb	<1
		Mg	20
		Mn	<1
		Mo	113
		Ni	<1
		P	<1
		Si	5
		Ag	<1
		Na	<5
		Sn	1
		Zn	<1
		K	<5
		Sr	2
		V	<1
		Ti	<1
		Cd	<1
		S	4710

APPENDIX B: PICTURES OF SO_2 SAMPLE LINE SETUP

FIGURE B-1 - Side view of sampling line setup

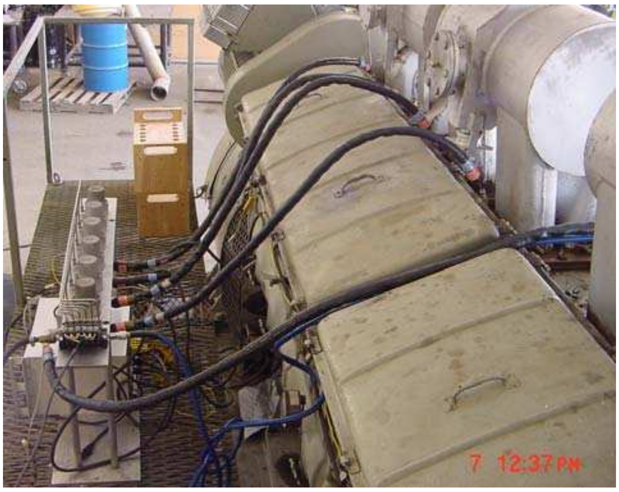

FIGURE B-2 - Top view of sampling line setup

FIGURE B-3 - Sampling probe