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Introduction

- Vale is trialling a passive regeneration-type diesel particulate filter (DPF) manufactured by Mammoth equipment on a Caterpillar AD30 haulage truck #231.
- CanmetMINING was contracted to provide an independent assessment of the in-use performance of the DPF.
  - Phase 1 - Surface workshop test – ECOM gas analyzer and smoke dot test.
  - Phase 2 - Underground in-use test – SEMTECH PEMS gas analyzer.
  - Phase 3 – Laboratory assessment of emissions including VOC/PAH

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Vehicle and DPF System

- Test vehicle: Caterpillar AD30 Unit #231
- DPF: Mammoth DPF System #78183

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Phase 1: Workshop Steady-State Tests

- CanmetMINING performed a series of steady-state emissions tests using an ECOM EN portable gas analyzer.
- These tests are similar to Vale's internal test program.

VALE #231 AD30
MAMMOTH DPF @ CCM

				VALE PASS FAIL CRITERIA				500		700		50		750	
				Smoke Dot Test		T.GAS TEMP (°F)		CO (ppm)		NO (ppm)		NO2 (ppm)		NOx (ppm)	
DESCRIPTION	DATE	UNIT HRS.	DPF HRS.	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
OEM	7-Apr	12,100				884	793	197	27	511	529	16	21	527	550
MAMMOTH DPF INSTALLED	8-Apr	12,166				878	781	161	44	535	578	18	11	553	589
FIRST BI-WEEKLY TEST	27-Apr	12,220	54			851	799	221	65	540	608	14	9	554	617
TEST 3	20-May	12,308	142			864	550	209	20	464	496	13	8	477	504
TEST 4	31-May	12,401	235			787	630	258	22	408	446	29	9	437	455
TEST 5	11-Jun	12,404	238			849	736	193	24	247	312	11	11	258	323
TEST 6	22-Jun	12,473	307			858	739	285	30	509	527	9	5	518	532
TEST 7 - Faulty #8 Injector	6-Jul	12,585	419			808	655	283	20	383	[illegible]	14	18	397	[illegible]
TEST 8	9-Jul	12,599	433.3			852	709	409	35	457	503	32	5	489	508
TEST 9	15-Jul	12,636	405			929	749	307	131	360	305	4	0	364	305
TEST 10	13-Sep	12,711	545			973	813	353	41	532	445	10	6	542	451
TEST 11	19-Oct	12,823	657			832	672	275	24	482	504	29	11	511	515
TEST 12	7-Nov	12,973	806.5			907	723	332	24	447	476	20	7	467	483
AVERAGE						865.67	713.00	273.83	40.00	447.00	501.58	16.92	8.33	463.92	509.32

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Steady-State Test Results

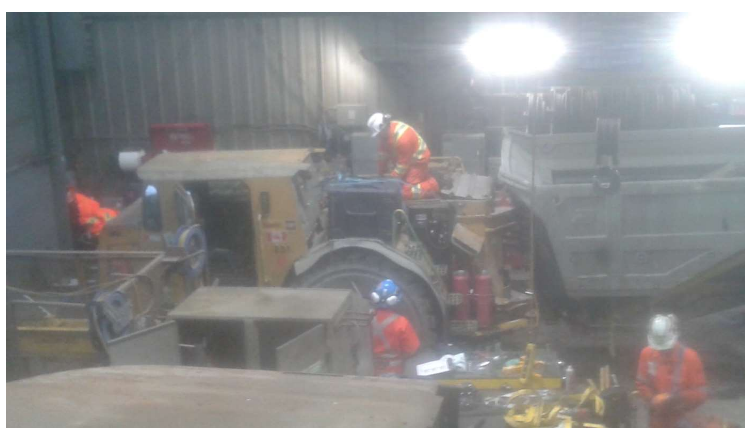
- Gases and Smoke

Pre-DPF (engine out) and post-DPF (tailpipe) smoke, CO, NO, and NO_2 concentrations are very close to the average values measured by Vale's program. There is a discrepancy in the post-DPF NO_2 concentrations. NO_2 is very sensitive to water so it is suggested that the Vale ECOM be checked for adequate water removal.

ECOM Emissions Test Data						
	Stall		Low Idle		High Idle	
Gas	Before DPF	After DPF	Before DPF	After DPF	Before DPF	After DPF
CO	235	27	65	38	243	96
NO	471	476	272	310	401	434
NO_2	21	27	37	10	61	19
NOx	492	503	309	320	462	453
Smoke	9	3				

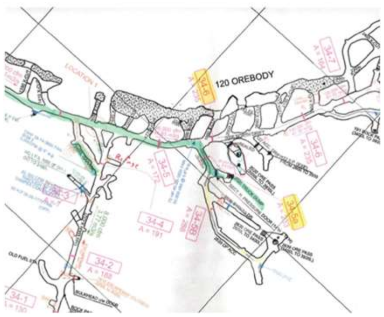
Phase 2: Underground In-Use Tests

- Installed the SEMTECH on-board emissions analyzer on the truck deck. Connected to the engine ECU datalink.
- Emissions measured pre- and post-DPF during normal haul operations. Gases and particulate mass (DPM) emissions.

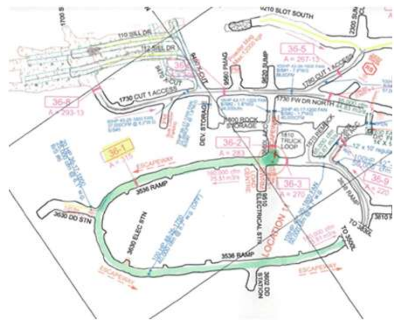


Haul Cycle

- The truck was side-loaded by LHD on 3650 level and then hauled up to the 2020 ore pass on 3400 level.
- Our station was in 3400 shop where we checked filters and sample probes.



3400 Level (2020 Ore Pass)



3650 Level Loading

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Underground Test Results

- Diesel Particulate Matter (DPM filtration)

Gravimetric DPM Samples (1.7 L/m sample flow)						
Filter	Location	Mass (mg)	Time (min)	Volume (m^3)	DPM (mg/m^3)	Reduction (%)
VM-07	Pre DPF	5.017	40	0.0680	73.8	
VM-08	Post DPF	0.023	35	0.0595	0.4	99.5
VM-06	Pre DPF	4.064	38	0.0646	62.9	
VM-04	Post DPF	0.052	34	0.0578	0.9	98.6

Filter	Location	Organic Carbon (mg/ m^3)	Elemental Carbon (mg/ m^3)	Total Carbon (mg/ m3)	Reduction (%)
EC/OC1	Post DPF	0.175	0.025	0.200	
EC/OC2	Pre DPF	17.209	28.298	45.507	99.6
EC/OC3	Post DPF	0.085	0.098	0.183	
EC/OC4	Pre DPF	14.560	25.396	39.955	99.3

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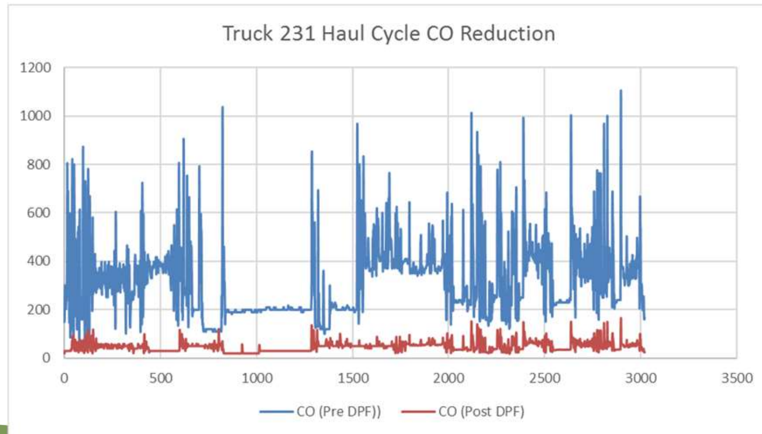
Underground Test Results

- Carbon Monoxide (catalyst performance)



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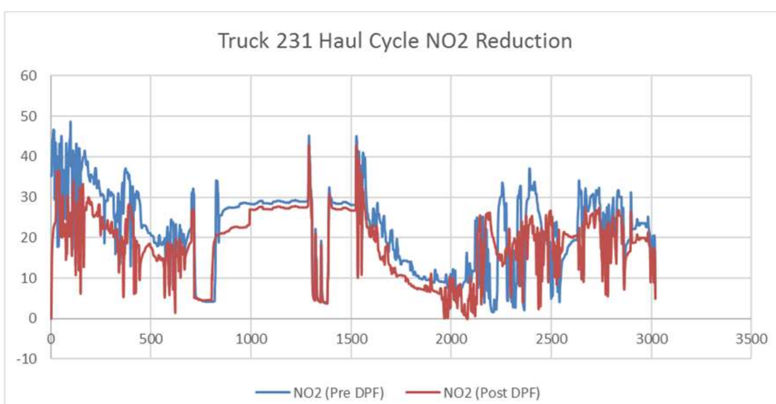
Underground Test Results

- Nitrogen Dioxide (NO_2 catalyst performance)



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Conclusions Phases 1/2

- The stationary workshop tests conducted by CANMET are consistent with Vale's own internal data.
- The Mammoth DPF can achieve its claimed performance in-service by reducing the mass of particulate emissions by 98-99% without an increase in NO_2 emissions.
- In fact NO_2 emissions were reduced by 17% and CO emissions were reduced by 85% over the haulage cycle.
- The DPF system performance is consistent with other advanced catalyst systems known to CANMET.
- The Mammoth DPF was removed and sent to CanmetMINING for laboratory engine tests in Phase 3.

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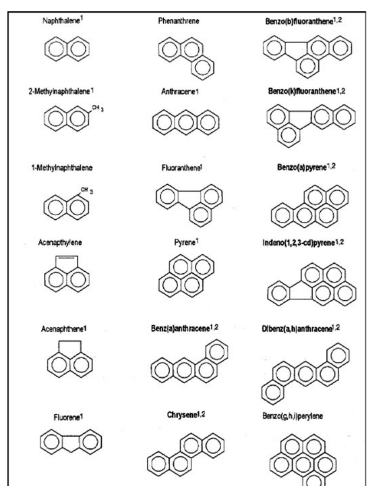
Phase 3 – VOC / D-F / PAH / nPAH Tests

- A comprehensive study of the emissions performance of the DPF system took place in June at the CanmetMINING diesel engine certification facility in Ottawa.
- Regulated emissions similar to the in-mine test were measured including CO, CO2, O2, NO, NO2, and DPM.
- Secondary emissions from the engine and DPF were also measured to include volatile organics (VOC), Dioxins/Furans, polycyclic aromatic hydrocarbons (PAH) and nitrated (nPAH).



Notes: [1]PAHs are on the EPA RBC List (EPA, 1999a).
[2]PAHs identified as probable human carcinogens by the EPA (shown in **bold**).
Source: Bjorseth, 1983

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Secondary emissions tests

- Secondary emissions analyzed during the course of this test were selected from the EPA, VERT, and NATO lists.
- The engine test procedure was the ISO8178 C1 cycle.
- The sampling was to EPA Method 5 / TO-15/11A/23; Environment Canada EPS 1/RM/2&3 and CARB 430.
- Analysis to SwRI procedures with surrogate injection for quality control.
- Comprehensive full test in June 2022
- Preliminary data received Sept 2022

Volatile Organic Compounds	
Benzene	Formaldehyde
1,3-Butadiene	Acetaldehyde

Dioxins and Furans (total as TEQ)
2,3,7,8 Tetrachlorodibenzo-p-dioxin (2,3,7,8 T_4CDD)
1,2,3,7,8 Pentachlorodibenzo-p-dioxin (1,2,3,7,8 P_5CDD)
1,2,3,4,7,8 Hexachlorodibenzo-p-dioxin (1,2,3,4,7,8 H_6CDD)
1,2,3,6,7,8 Hexachlorodibenzo-p-dioxin (1,2,3,6,7,8 H_6CDD)
1,2,3,7,8,9 Hexachlorodibenzo-p-dioxin (1,2,3,7,8,9 H_6CDD)
1,2,3,4,6,7,8 Heptachlorodibenzo-p-dioxin (1,2,3,4,6,7,8 H_7CDD)
Octachlorinated dibenzo-p-dioxin (O_8CDD)
2,3,7,8 Tetrachlorodibenzofuran (2,3,7,8 T_4CDF)
1,2,3,7,8 Pentachlorodibenzofuran (1,2,3,7,8 P_5CDF)
2,3,4,7,8 Pentachlorodibenzofuran (2,3,4,7,8 P_5CDF)
1,2,3,4,7,8 Hexachlorodibenzofuran (1,2,3,4,7,8 H_6CDF)
1,2,3,6,7,8 Hexachlorodibenzofuran (1,2,3,6,7,8 H_6CDF)
1,2,3,7,8,9 Hexachlorodibenzofuran (1,2,3,7,8,9 H_6CDF)
2,3,4,6,7,8 Hexachlorodibenzofuran (2,3,4,6,7,8 H_6CDF)
1,2,3,4,6,7,8 Heptachlorodibenzofuran (1,2,3,4,6,7,8 H_7CDF)
1,2,3,4,7,8,9 Heptachlorodibenzofuran (1,2,3,4,7,8,9 H_7CDF)
Octachlorinated dibenzofuran (O_8CDF)

Polynuclear Aromatic Hydrocarbons (PAHs)	Nitrated Polynuclear Aromatic Hydrocarbons (nPAHs)
Pyrene	1-nitro-naphthalene
Fluoranthene	2-nitro-naphthalene
Chrysene	3-nitro-phenanthrene
Benz(a)-anthracene	9-nitro-phenanthrene
Benzo(b)-fluoranthene	9-nitro-anthracene
Benzo(k)-fluoranthene	3-nitro-fluoranthene
Benzo(a)-pyrene	1-nitropyrene
Indene(1,2,3- cd) pyrene	1-nitro-naphthalene
Naphthalene	
1-Methyl naphthalene	
2-Methyl naphthalene	
Acenaphthene	
Acenaphthylene	
Phenanthrene	

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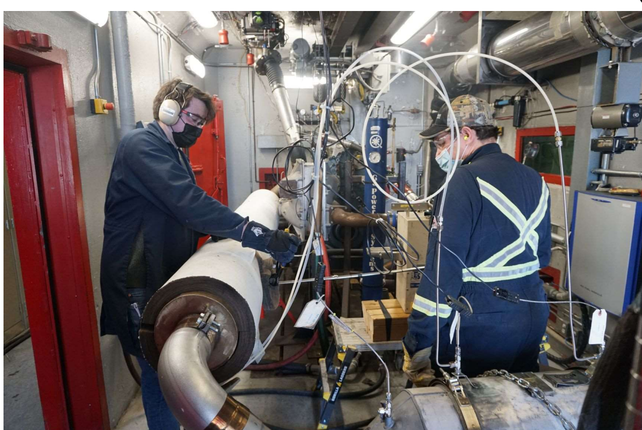
Phase 3 - Test cell configuration



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Method 5 - Sample trains

Phase 3 – Preliminary Results VOC

- Not all results are in yet.
- Still waiting for VOC/SVOC species and certain PAH/nPAH
- Expected in October

SetPoint	Date	1,3-Butadiene Emissions (μg/s)				Benzene Emissions (μg/s)			
		Inlet	Outlet Average	Outlet to Inlet Difference	Outlet to Inlet % Difference	Inlet	Outlet Average	Outlet to Inlet Difference	Outlet to Inlet % Difference
SetPoint 1	19-Jul-22	0.44	0.44	0.00	0.00	21.8	20.9	-0.89	-4.07
SetPoint 2	20-Jul-22	0.39	0.39	0.00	0.00	11.9	8.18	-3.72	-31.2
SetPoint 3	21-Jul-22	0.31	0.31	0.00	0.00	12.2	5.63	-6.57	-53.8
SetPoint 4	22-Jul-22	0.22	0.22	0.00	0.00	27.2	20.2	-7.06	-25.9
SetPoint 5	25-Jul-22	0.28	0.28	0.00	0.00	9.37	6.72	-2.65	-28.3
SetPoint 6	26-Jul-22	0.22	0.22	0.00	0.00	5.57	2.16	-3.41	-61.2
SetPoint 7	27-Jul-22	0.13	0.13	0.00	0.00	24.2	20.9	-3.25	-13.4
SetPoint 8	28-Jul-22	0.18	0.18	0.00	0.00	5.21	1.25	-3.95	-75.9

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Phase 3 – Preliminary Dioxins/Furans

- All dioxins / furans data received for all eight modes.
- TEQ pending for all eight modes.

Congener	Inlet Run 2 20-Jul-22 14:14 - 16:42		Outlet Run 2A 20-Jul-22 09:35 - 12:15		Outlet Run 2B 20-Jul-22 14:12 - 17:02		Outlet Averages		Difference in Emissions (Outlet from Inlet)	% Difference in Emission Rates (Outlet from Inlet)
	(pg/m^3)	(ng/s)	(pg/m^3)	(ng/s)	(pg/m^3)	(ng/s)	(pg/m^3)	(ng/s)	(ng/s)	
2,3,7,8 - T_4CDF*	5.96	2.32E-03	2.07	6.94E-04	1.98	6.38E-04	2.02	6.66E-04	-1.66E-03	-71.3
1,2,3,7,8 - P_5CDF	1.85	7.20E-04	1.93	6.48E-04	1.77	5.73E-04	1.85	6.10E-04	-1.10E-04	-15.2
2,3,4,7,8 - P_5CDF	1.85	7.20E-04	1.93	6.48E-04	1.77	5.73E-04	1.85	6.10E-04	-1.10E-04	-15.2
1,2,3,4,7,8 - H_6CDF	1.79	6.97E-04	1.86	6.24E-04	1.71	5.51E-04	1.78	5.88E-04	-1.09E-04	-15.6
1,2,3,6,7,8 - H_6CDF	1.49	5.80E-04	1.72	5.78E-04	1.54	4.97E-04	1.63	5.38E-04	-4.27E-05	-7.4
2,3,4,6,7,8 - H_6CDF	1.85	7.20E-04	1.96	6.59E-04	1.77	5.73E-04	1.87	6.16E-04	-1.04E-04	-14.4
1,2,3,7,8,9 - H_6CDF	2.03	7.89E-04	2.14	7.17E-04	1.94	6.27E-04	2.04	6.72E-04	-1.17E-04	-14.9
1,2,3,4,6,7,8 - H_7CDF	1.07	4.18E-04	1.31	4.39E-04	1.37	4.43E-04	1.34	4.41E-04	2.34E-05	5.6
1,2,3,4,7,8,9 - H_7CDF	1.37	5.34E-04	1.62	5.43E-04	1.71	5.51E-04	1.66	5.47E-04	1.34E-05	2.5
O_8CDF	1.31	5.11E-04	1.48	4.97E-04	1.37	4.43E-04	1.43	4.70E-04	-4.06E-05	-7.9
2,3,7,8 - T_4CDD	1.76	6.85E-04	2.14	7.17E-04	1.94	6.27E-04	2.04	6.72E-04	-1.30E-05	-1.9
1,2,3,7,8 - P_5CDD	1.52	5.92E-04	1.28	4.28E-04	1.37	4.43E-04	1.32	4.36E-04	-1.57E-04	-26.4
1,2,3,4,7,8 - H_6CDD	1.43	5.57E-04	1.96	6.59E-04	1.44	4.65E-04	1.70	5.62E-04	4.73E-06	0.8
1,2,3,6,7,8 - H_6CDD	1.25	4.88E-04	1.69	5.67E-04	1.27	4.11E-04	1.48	4.89E-04	1.10E-06	0.2
1,2,3,7,8,9 - H_6CDD	1.31	5.11E-04	1.79	6.01E-04	1.34	4.32E-04	1.57	5.17E-04	6.04E-06	1.2
1,2,3,4,6,7,8 - H_7CDD	1.43	5.57E-04	1.38	4.63E-04	1.47	4.76E-04	1.43	4.69E-04	-8.82E-05	-15.8
O_8CDD	1.58	6.15E-04	2.14	7.17E-04	1.61	5.19E-04	1.87	6.18E-04	2.62E-06	0.4

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Dioxins / Furans

- TEQ is a single weighted average toxicity for all D/F compounds related to the most toxic species.
- Developed by the WHO/EPA and NATO.
- Significant reduction in TEQ by the DPF.

			Trial Test Engine Out 14:30 - 16:40				Trial Test DPF Out 14:35 - 16:45			
			WHO		NATO		WHO		NATO	
Congener	WHO-TEF Factors	NATO-TEF Factors	TEQ Max (pg)	TEQ Min (pg)	TEQ Max (pg)	TEQ Min (pg)	TEQ Max (pg)	TEQ Min (pg)	TEQ Max (pg)	TEQ Min (pg)
2,3,7,8 - T_4CDF	0.1	0.1	14.1	14.1	14.1	14.1	3.0	3.0	3.0	3.0
2,3,7,8 - T_4CDF*	0.1	0.1	2.6	2.6	2.6	2.6	3.0	3.0	3.0	3.0
1,2,3,7,8 - P_5CDF	0.03	0.05	0.52	0.52	0.87	0.87	0.17	0.17	0.28	0.28
2,3,4,7,8 - P_5CDF	0.3	0.5	10.1	10.1	16.8	16.8	1.7	0.87	2.9	1.5
1,2,3,4,7,8 - H_6CDF	0.1	0.1	4.5	4.5	4.5	4.5	0.80	0.80	0.80	0.80
1,2,3,6,7,8 - H_6CDF	0.1	0.1	1.5	1.5	1.5	1.5	0.39	0.20	0.39	0.20
2,3,4,6,7,8 - H_6CDF	0.1	0.1	1.8	1.8	1.8	1.8	0.44	0.22	0.44	0.22
1,2,3,7,8,9 - H_6CDF	0.1	0.1	0.32	0.16	0.32	0.16	0.44	0.22	0.44	0.22
1,2,3,4,6,7,8 - H_7CDF	0.01	0.01	0.29	0.29	0.29	0.29	0.07	0.07	0.07	0.07
1,2,3,4,7,8,9 - H_7CDF	0.01	0.01	0.046	0.023	0.046	0.023	0.038	0.019	0.038	0.019
O_8CDF	0.003	0.001	0.013	0.006	0.004	0.002	0.021	0.010	0.007	0.003
2,3,7,8 - T_4CDD	1	1	3.6	1.8	3.6	1.8	3.7	1.9	3.7	1.9
1,2,3,7,8 - P_5CDD	1	0.5	3.4	3.4	1.7	1.7	4.3	2.2	2.2	1.1
1,2,3,4,7,8 - H_6CDD	0.1	0.1	0.31	0.16	0.31	0.16	0.34	0.17	0.34	0.17
1,2,3,6,7,8 - H_6CDD	0.1	0.1	0.27	0.14	0.27	0.14	0.29	0.15	0.29	0.15
1,2,3,7,8,9 - H_6CDD	0.1	0.1	0.27	0.14	0.27	0.14	0.27	0.14	0.27	0.14
1,2,3,4,6,7,8 - H_7CDD	0.01	0.01	0.060	0.060	0.060	0.060	0.059	0.030	0.059	0.030
O_8CDD	0.0003	0.001	0.003	0.003	0.011	0.011	0.003	0.002	0.010	0.005
WHO-TEQ (Primary Column)			41.0	38.6			16.1	10.0		
WHO-TEQ (Second Column)			29.5	27.1			16.1	10.0		
NATO-TEQ (Primary Column)					46.4	43.9			15.2	9.7
NATO-TEQ (Secondary Column)					34.9	32.4			15.2	9.7

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Phase 3 – Preliminary PAH / nPAH

- Still waiting for comprehensive modal PAH / nPAH data.
- PAH results shown here.
- Conventional PAHs significantly reduced by DPF.

Compound	<	Trial Test Engine Out 14:30 - 16:40 (ng)	<	Trial Test DPF Out 14:35 - 16:45 (ng)
Naphthalene		33,600		21,400
2-Methylnaphthalene		28,500		4,530
1-Methylnaphthalene		15,700		1,980
2,6 & 2,7-Dimethylnaphthalene		11,900		500
Acenaphthylene		364		27
Acenaphthene		399		45.4
Fluorene		1,020		91
Phenanthrene		3,300		1,530
Anthracene		103	<	1.0
2,3,5-Trimethylnaphthalene		1,800		62.8
1-Methylphenanthrene		322		159
Fluoranthene		542		438
Pyrene		824		226
Benz(a)anthracene		43.0		6.7
Chrysene		78.1		13.2
Benzo(b)fluoranthene		18.4		4.7
Benzo(k)fluoranthene		18.3		3.6
Benzo(e)pyrene		47.6	<	1.0
Benzo(a)pyrene	<	1.0	<	1.0
Perylene	<	1.0	<	1.0
Indeno-1,2,3(c,d)pyrene		11.3		10.5
Benzo(g,h,i)perylene		46.5		62.5
Dibenz(a,h)anthracene	<	1.0	<	1.0

Phase 3 – Preliminary PAH / nPAH

- Nitrated PAH (nPAH) data show increases of some species by the DPF.
- Unlike VOC, SVOC, Dioxins Furans and PAHs, only about half of the nPAHs are reduced by the DPF system.
- 1-Nitronaphthalene, 2-Nitronaphthalene, 3-Nitrophenanthrene are increased by the DPF.

Compound	<	Trial Test Engine Out 14:30 - 16:40 (ng)	<	Trial Test DPF Out 14:35 - 16:45 (ng)
1-Nitronaphthalene		27.5		440
2-Nitronaphthalene		205		414
9-Nitroanthracene		3.70		1.24
9-Nitrophenanthrene		2.54		1.63
3-Nitrophenanthrene		3.51		5.14
3-Nitrofluoranthene		2.21		1.25
1-Nitropyrene		8.20		3.32

Surrogate Recovery for this compound was noted to be low by the analytical laboratory

Preliminary Results:

- Lab engine testing of primary emissions (CO, CO_2, NO, NO_2 and DPM) confirmed similar reductions seen in the field tests.
- Secondary emissions of VOC, SVOC, Dioxins/Furans and PAH/nPAH showed reductions in most species – with the exception of nPAH where some showed increases across the DPF.
- This is similar to other DPF systems where catalytic activity is known to promote nitration.
- Overall the DPF application appears to be a net benefit for emissions reduction.
- Comprehensive results will be available in Oct/Nov for a full report.

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