Repeatability of DPG Testing

This document sumarises validation data for several aspects of the repeatability of DPG performance.

1 Soot Rate Stability & Repeatability

The specified repeatability of the soot rate produced by the DPG over a test, excluding effects from changes in fuel specification and test filter coating, is ±20%, for soot rates from 2 g/h – 20 g/h. This variability does not directly affect the accuracy of backpressure or filtration efficiency characteristics vs. soot load, see section 3, and if more accurate loads must be placed on a filter then this can be achieved by two different automated techniques built into the DPG, see 1.1 & 1.2, below.

The soot rate stability has been validated by loading a filter for 5 sequential phases of 24 minutes each, weighing at the start and end of the sequence and between each period. This allows calculation of the soot load in each of the five phases. The whole sequence was repeated on five days to confirm the day to day repeatability of the system.

The soot loads measured from each of the phases are tabulated below:

Table 1: Soot loads phase by phase

	Day 1	Day 2	Day 3	Day 4	Day 5
Phase 1	3.6	3.6	3.7	3.8	3.7
Phase 2	3.5	3.8	3.9	3.7	3.6
Phase 3	3.7	3.5	3.5	3.7	3.5
Phase 4	3.7	4.0	3.8	3.8	3.5
Phase 5	3.6	3.6	3.6	3.7	3.5

The mean load was 3.66 g/phase (9.15 g/h). The deviation of the load in each phase from the mean is shown in table 2:

Table 2: Deviation of soot load from mean

	Day 1	Day 2	Day 3	Day 4	Day 5
Phase 1	-1.7%	-1.7%	+1.0%	+3.7%	+1.0%
Phase 2	-4.5%	+3.7%	+6.4%	+1.0%	-1.7%
Phase 3	+1.0%	-4.5%	-4.5%	+1.0%	-4.5%
Phase 4	+1.0%	+9.2%	+3.7%	+3.7%	-4.5%
Phase 5	-1.7%	-1.7%	-1.7%	+1.0%	-4.5%

The COV is 3.7%, the maximum deviation was 9.2% and the range of 13.7% of the mean.

Further validation data over a longer period is obtained from a series of 5 loads of 1.5 hours duration performed over a period of approximately 1 month. For these tests, the soot concentration was also monitored by the AVL415, discussed below. The data are below:

Table 3: Long Term Soot Loading Repeatability, 1.5 hour tests

Test date	Weighed Soot Mass (g)	Deviation from mean	Soot estimation from AVL415 (g)	Difference from weighed mass
7-Dec	15.7	-1.8%	15.4	-2.2%
20-Dec AM	16.8	+5.1%	16.7	-0.7%
20-Dec PM	16.3	+2.0%	15.9	-2.7%
22-Dec	15.8	-1.1%	15.6	-1.3%
05-Jan	15.3	-4.3%	15.2	-0.6%

The COV is 3.6% and the range 9.4% of the mean.

Over a longer timescale, the soot rate of the DPG may drift and should be monitored, and setpoints corrected if necessary, according to Cambustion instruction DPG016.

Note that the soot mass rate is affected by the fuel composition and also by the material of the filter under test and its coating:

- Biodiesel blends produce a significantly lower soot rate at the same settings as non-biodiesel due to the oxygenate content: with biodiesel proportions greater than 10%, the soot generation capability of the DPG will be limited.
- Catalytic filter coatings have been observed increase the absorption of gas phase constituents in the DPG flow, therefore increasing the soot mass rate measured by weighing, by up to around 5%.

1.1 Improved Total Soot Load by Monitoring with AVL415

If the DPG is being used to load filters for, for example, regeneration testing then it may be necessary to achieve a desired soot load on the filter more accurately than by relying on the soot rate discussed above. If an AVL415S is connected to the DPG then the system can be configured to measure the intake soot concentration periodically and estimate the soot deposited on the filter from this measurement. The system can automatically terminate the load when this estimated mass reaches the target level.

In the tests shown in Table 3, above, an AVL415 was connected and configured to measure the soot concentration every 5 minutes. The soot load on the filter estimated from these measurements is tabulated, along with the error from the weighed mass.

In these tests, the AVL415 estimate ranged between -0.6% and -2.7% from the weighed mass, a range of 2.1% around a mean of -1.5%. Loads triggered from the AVL415 estimate would therefore lie within around 2% of the average load. Absolute accuracy in achieving a desired soot load will be the sum of this variability plus any systematic calibration error in the AVL415 which can typically be held to less than 2% following the Cambustion procedure DPG016.

The use of the AVL to trigger the soot load may also remove the requirement for weighing the filter at the start and end of the load, allowing the whole load to run unattended.

1.2 Improved Total Soot Load by Top-up Load

To achieve the most accurate total soot load on a filter, the DPG has a built-in top-up load schedule. In this schedule, the filter is weighed three times: once when empty at the start of the test, once at an estimated 80% (or similar) of the desired soot load, and once at the end. The duration of the second phase is automatically adjusted on the basis of the soot load measured in the first phase.

The table below shows the accuracy of achieving a target soot load measured on six tests using the top-up schedule:

Table 4: Accuracy of Load via Top-up schedule

Test Date	Target Load (g)	Actual Load (g)	Error %
2011-04-07	31	31	0%
2010-10-22	32.9	32.6	-0.9%
2011-03-08	26.4	26.6	+0.8%
2011-04-06	37	36.8	-0.5%
2011-10-21	24.7	24.5	-0.8%
2011-02-25	32.7	32.6	-0.3%

The standard deviation in the error from the target load is 0.6% over these six tests, and the range is 1.7%: typically the soot load will be within 1% of the desired load using this technique.

2 Empty Filter Backpressure Repeatability

The backpressure measured by the DPG at a set flow on an empty filter is affected by the measurement of flow rate, backpressure, temperature and accuracy of the correction for variations in ambient pressure.

The accuracy specifications for these factors are: ±5% for the DPF flow (above 100 kg/h), ±1ºC ±1%

reading for the temperature and ±0.05 mbar ±1% reading for the backpressure measurement. In total, this could give an error of up to 7% in the measurement, but in practice the overall repeatability is much better than this.

Table 5 shows the measurement of backpressure made on 3 different parts, each measured 5 or 6 times. All measurements are made at 500 kg/h and 45ºC.

Table 5: Backpressure Measurements of Empty Filters @ 500 kg/h, 45ºC 2009-05-22

Part	1	2	3	
measured pressure mbar	37.76	36.75	38.85	
	37.83	36.90	39.04	
	37.93	36.99	38.85	
	37.77	37.11	39.09	
	38.03	37.12	39.16	
			39.20	
μ mbar	37.86	36.98	39.03	overall
σ mbar	0.11	0.15	0.15	0.14
COV	0.30%	0.41%	0.39%	0.37%

The overall COV for these measurements is 0.37% of the measured backpressure.

3 Loaded Backpressure Repeatability

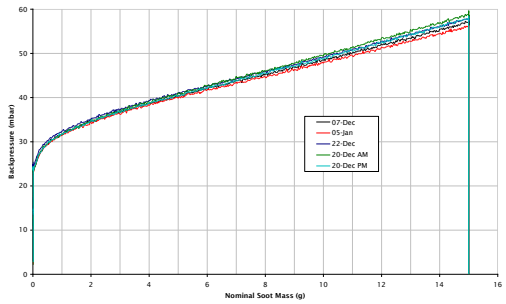
When the DPG is used to measure the backpressure at a given soot load, all the factors affecting empty filter backpressure measurement affect the measurement accuracy, as well as variability in the properties of the soot and errors in the estimation of soot mass on the filter.

In order to minimise the errors in the soot mass estimation, the filter is weighed at the start and end of the test and the nominal soot load thoughout the test is scaled to match the weighed mass. The standard test procedure is therefore to load to a slightly higher soot level than that of interest, reading the backpressure corresponding to the desired soot mass after making the mass correction. The DPG software automatically makes these calculations.

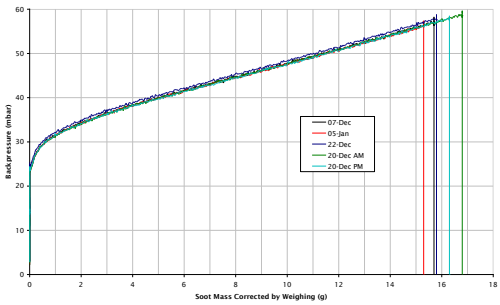
The effect of this soot rate correction is shown in Figure 1.

Figure 1: Comparison of Backpressure vs Nominal and Weighed Soot Mass

Backpressure vs Nominal Soot Mass



Backpressure vs Weighed Soot Mass



The backpressure measured from the five tests shown in table 3 are tabulated below:

Table 6: Backpressure results at 12g referred to weighed mass.

Test date	Backpressure at 12 g (mbar)	Deviation from mean
7-Dec	50.9	-0.1%
20-Dec AM	50.9	-0.1%
20-Dec PM	50.7	-0.4%
22-Dec	51.4	0.9%
05-Jan	50.7	-0.4%

The data show a COV in the backpressure measurement of 0.5%, with a range of 1.3% of the mean.

Note that the soot characteristics and hence backpressure are also dependent on the fuel used (and can cause variations of several percent in the loaded backpressure): the data above were all obtained with fuel from a single batch. Cambustion recommend that before and after a fuel batch is changed, a load is made on the same reference filter, to compare the fuel dependent characteristic.

4 Backpressure Reproducibility

Cambustion aims to achieve loaded backpressure measurements across different instruments within ±3% of the average. This is not a specification for the instruments alone and to achieve it requires good control of the whole measurement procedure.

The data below shows the backpressure at 2 g and 10 g for one filter tested on five different DPGs from May-June 2009. Units A, B and E were tested at Cambustion: other tests were performed on-site, but with Cambustion personnel in attendance.

Table 7: Backpressure Reproducibility at 2 g and 10 g Load

DPG Unit	Backpressure at 2 g (mbar)	Deviation from mean	Backpressure at 10 g (mbar)	Deviation from mean
A	38.0	+0.3%	62.6	+0.5%
B	38.1	+0.5%	61.7	-1.0%
C	37.2	-1.8%	61.8	-0.8%
A	37.4	-1.5%	62.3	0.0%
D	37.7	-0.6%	61.9	-0.7%
E	38.1	+0.5%	61.6	-1.1%
E	38.9	+2.6%	64.3	+3.2%
	μ = 37.9 mbar σ = 0.56 mbar	σ = 1.5% range = 4.5%	μ = 62.3 mbar σ = 0.95 mbar	σ = 1.5% range = 4.3%

One of these results is outside the ±3% target range: monitoring of units in the field and improvements to operating procedures are continuing.