# SUMMARY REPORT

## EVALUATION OF DONALDSON DURA-LIFE ETV TEST RESULTS OF OCTOBER 2011

Michael Kosusko, July 23, 2012

This report summarizes the APCT Center's evaluation of 2011 verification test results for Donaldson Company, Inc.'s Dura-Life #0701607 Filtration Media. It also documents decisions made by the APCT Center concerning publication of these test results.

Verification testing of the Dura-Life filtration media was performed during the period of October 20–28, 2011, at the test facility of ETS Incorporated in Roanoke, VA. Donaldson provided samples of its Dura-Life product. The product is a 10.5 ounce per square yard, polyester felt, self-supported filter media. The APCT Center quality manager reviewed the test results and the quality control (QC) data and concluded that the data quality objectives given in the generic verification protocol and test/QA plan were attained.

### THE PROBLEM

Donaldson is concerned that the 2011 ETV results do not accurately reflect the performance of its product for capture of Total PM and $PM_{2.5}$. Over several years, Donaldson had tested this product four times at ETS. Results for three screening tests (2004, 2004, and 2010) and one ETV test (2001) are presented in Table 1. Results from the 2011 ETV test are also presented. The screening test (ETS) differs from the EPA/ETV test. It evaluates one fabric sample rather than the three required by ETV's generic verification protocol. Also, some of the ETV QA checks are not performed for the screening test.

The average $PM_{2.5}$ outlet concentration for the ETV test was 0.0001289 g/dscm. The concentration for the screening and early ETV samples ranged from 0.0000250 to 0.0000479 g/dscm. The 2011 ETV test resulted in outlet concentration values three to five times as high as the earlier non-ETV tests. Similar results were obtained for Total PM.

**Table 1. Summary of Dura-Life Test Results (2001 – 2011)**

| ETS, Inc. Test Summary | 2001 | 2004 | 2004 | 2010 | 2011 |
|---|---|---|---|---|---|
| | EPA/ETV | ETS | ETS | ETS | EPA/ETV |
| | Durapex | Dura-Life #1 | Dura-Life #2 | Dura-Life | Dura-Life #0701607 |
| Test Date | 9/25/2001 | 03/01/2004 | 03/18/2004 | 11/10/2010 | 10/28/2011 |
| Mean Outlet Particle Conc. $PM_{2.5}$ (g/dscm) | 0.0000423 | 0.0000479 | 0.0000250 | 0.0000324 | 0.0001289 |
| Mean Outlet Particle Conc. Total Mass (g/dscm) | 0.0000676 | 0.0000556 | 0.0000250 | 0.0000324 | 0.0001745 |

In January 2012, a thorough review of the test records and procedures for the 2011 test found no meaningful anomalies. It was observed that the reference dust used in the test, Pural NF, had a significant change in particle size distribution (PSD) during 2011. However, the changed PSD was still within the test protocol's quality specifications. This PSD has persisted since the change and PM outlet concentration results for other fabrics tested under ETV do not appear to have been impacted.

The APCT Center and ETS agreed with Donaldson that additional testing might explain these results. Donaldson contracted with ETS to run screening tests with a new piece of the 2010 sample swatch and of the median sample from the 2011 ETV test (i.e., the sample with the median outlet concentration from the 2011 test). Test results are shown in Table 2. For the 2011 ETV sample, the $PM_{2.5}$ penetration fell to 0.0000282 g/dscm (i.e. by a factor of four) and into the historical range. At the same time, the 2010 screening sample's penetration fell to below the 0.0000167 g/dscm Method Detection Limit for this test. This value is below the historical range and less than the 2010 result by a factor of two (or more). The additional screening tests did not clarify anything. It appears that the new results are just shifted downward by a factor of three to four. The 2010 screening sample retested just as far outside of historical range as did the 2011 ETV test, but on the low side. The retested 2011 ETV sample still performed worse than the retested 2010 sample.

**Table 2. Dura-Life Retest Results (2011 – 2012)**

| **ETS, Inc. Test Summary** | 2010 | 2012 | 2011 | 2012 |
|---|---|---|---|---|
| | ETS | ETS | EPA/ETV | ETS |
| | Original | Retest of 2010 | Original | Retest of 2011 |
| Test Date | 11/10/2010 | 1/28/2012 | 10/28/2011 | 1/28/2012 |
| Mean Outlet Particle Conc. $PM_{2.5}$ (g/dscm) | 0.0000324 | 0.0000047* | 0.0001091 | 0.0000282 |
| Mean Outlet Particle Conc. Total Mass (g/dscm) | 0.0000324 | 0.0000125* | 0.0001668 | 0.0000315 |

* Below Method Detection Limit of 0.0000167 g/dscm

## APCT CENTER DISCUSSION ABOUT NEXT STEPS

After discussions with EPA management about funds for additional testing, the center proposed that we complete two tasks to resolve 2011 ETV test result issues and to allow completion of the Donaldson Dura-Life verification report. In order to justify a retest per ETV Program precedent, the unexpected results need to be caused by either a product quality issue (manufacturer error) or by a test methodology (testing) problem. Evaluations were initiated to explore each of these:

1. Physical property testing to identify variations of sample cloth quality both within each sample swatch and between swatches.

2. Statistical evaluation of twelve years of ETV data to determine whether the 2011 Donaldson Dura-Life results are statistically different than earlier results and to find a way to explain the differences.

## PHYSICAL PROPERTY TESTING

Following discussions with RTI, ETS performed the following set of tests:

1. Visual inspection of the swatches to identify obvious defects or irregularities,
2. Measurement of fabric permeability, which directly impacts filtration performance,
3. Mullen Burst test of each fabric's bursting strength, which is not a direct indication of filtration performance, and
4. Measurement of fabric weight or density.

The full physical property testing report is attached as Appendix A. The language in this section was excerpted from Appendix A.

The following conclusions were made from physical property testing:

- There were no obvious visual differences between the ten swatches examined.
- Variability in fabric weight and permeability within a given swatch was relatively minor.
- Variability in fabric weight and permeability across the ten swatches was substantial.
- Of the tests run in this series, the permeability is the most directly relatable to filtration performance. It is reasonable to suspect the low permeability of the 2010 swatch and the relatively high permeabilities of the three ETV-tested swatches could have contributed, at least partially, to the discrepancy in filtration performance (downstream $PM_{2.5}$ concentration) between the 2010 non-ETV and 2011 ETV tests. This suspicion is supported by the similar performance ratio between the two swatches that were retested in 2012.
- The results presented here do not seem to explain why the 2010 and 2011 swatches both performed substantially better when retested in 2012 relative to the original 2010 and 2011 results, respectively. This discrepancy suggests there was another factor which affected the filtration performance results, perhaps an as yet unidentified variability in the test method itself.

## STATISTICAL EVALUATION OF ETS TEST DATA

In many cases, manufacturers retest filter material when their verification statements expire after 3 years. Sets of retest data were analyzed for a statistical check of test method variability. The analysis of variance confirmed statistically significant differences among different fabric products for both $PM_{2.5}$ and Total PM. Comparisons of the two Donaldson samples to the other three fabrics are more relevant to the problem at hand. These individual comparisons were all statistically significant. The indicated conclusion is that the large Donaldson $PM_{2.5}$ and Total PM values cannot be explained by process (i.e., testing) variation, but rather suggest a real difference. However, the available data are not sufficient for pinpointing the reason for that difference.

Data from the physical properties report allowed an in-depth look at the relationship between $PM_{2.5}$ and permeability for the Donaldson test-retest results. The statistical analysis confirms (and quantifies) the relationship between $PM_{2.5}$ and permeability. In other words, $PM_{2.5}$ increases as permeability increases in both the test and retest data. Although the $PM_{2.5}$

values from the 2012 retests are lower, the evidence that this difference is statistically significant is not strong. This is not surprising in light of the small sample size.

There is no “smoking gun” in these results. The observations related to permeability and dust particle size distribution suggest some hypotheses to explore if additional testing is undertaken. However, it should be kept in mind that the only factors that could be investigated are those for which data were available. There are sources of variation that we do not have sufficient data to assess. The draft statistics report is attached as Appendix B. The language in this section was excerpted from Appendix B.

## CONCLUSIONS AND NEXT STEPS

In consultation with APPCD and ETV management and considering the results described above, it has been decided that EPA will not pay for retesting Donaldson's media. Reasons include:

1. ETV Program precedent. After extensive reviews of data and discussions with the testing organization, ETS, there is no evidence that the October 2011 ETV tests were flawed and there is no compelling evidence that Donaldson sent flawed or atypical production samples.
2. Special treatment. A retest at EPA expense without evidence of flawed testing would comprise special treatment of Donaldson's Dura-Life division.
3. Likely benefit to EPA and ETV. Retesting would provide little benefit to EPA and the ETV Program and is unlikely to clarify whatever may have happened during this test.

Our second decision is that the APCT Center should treat this as a typical verification. As such:

1. Donaldson can decline publication of a verification statement.
2. Donaldson has the option of preparing a rebuttal section for the verification report.
3. The APCT Center will report its typical data analyses, achievement of DQOs and DQIGs, and other QA issues.

## APPENDIX A:

# Donaldson Dura-Life 0701607 Physical Property Test Results

Jay Hill
March 15, 2012

## Introduction

On March 13, 2012, ETS performed a series of tests to examine the physical properties of the nine fabric swatches of the 0701607 filtration media provided by Donaldson for the 2011 ETV tests as well as the single swatch Donaldson provided for a non-ETV test in 2010. The purpose of the tests was to identify any variability in sample fabric quality that may have impacted the filtration performance test results. This brief report describes ETS' results (which are shown infull at the end of this report) along with RTI's interpretation of those results.

Following discussions with RTI, ETS performed the following set of tests:

1. Visual inspection of the swatches to identify obvious defects or irregularities,
2. Measurement of fabric permeability, which directly impacts filtration performance,
3. Mullen Burst test of the fabrics' bursting strength, which is not a direct indication of filtration performance, and
4. Measurement of fabric weight or density.

The 2010 fabric swatch was identified by the code EX22841B, while the 2011 ETV fabric swatches were identified as 0701607-[#] where [#] was a number from 1 through 9. For reference, the three swatches randomly selected by ETS for verification testing in 2011 were 0701607-3 (identified as 5V6-R2 in the draft verification report), 0701607-4 (5V6-R3), and 0701607-6 (5V6-R1). Additionally, fabrics EX22841B and 0701607-6 underwent additional repeat filtration performance testing at Donaldson's request in January 2012.

ETS and RTI agreed that at least one sample from each of the ten fabric swatches should be evaluated as part of this test series to identify variability across different swatches. Additionally, two swatches were selected for triplicate testing to identify variability within the swatch: EX22841B and 0701607-3.

## Test Results

It has been standard practice for ETS to visually inspect fabric swatches prior to filtration performance testing to check for damage or obvious defects. As such, the 2010 and 2011swatches were inspected prior to those tests. As part of the series of tests described in this report, the swatches were examined again. ETS did not observe any defects in the fabric swatches, and they could not visually identify any variation between the ten swatches.

The full set of quantitative results for fabric density, permeability, and burst strength are shown in ETS' test report (copied at the end of this report). To aid in interpretation of the results, the two sets of triplicate tests are shown separately below.

Triplicate tests of 2010 non-ETV fabric EX22841B

| Fabric ID | Weight ($oz/yd^2$) | Permeability (FPM) | Mullen Burst (psi) |
|---|---|---|---|
| EX22841B-1 | 9.7 | 26.8 | 405 |
| EX22841B-2 | 10.4 | 25.7 | 445 |
| EX22841B-3 | 10.1 | 25.4 | 405 |
| average | 10.1 | 26.0 | 418 |
| std dev | 0.4 | 0.7 | 23 |
| COV | 3% | 3% | 6% |

Triplicate tests of 2011 ETV fabric 0701607-3

| Fabric ID | Weight ($oz/yd^2$) | Permeability (FPM) | Mullen Burst (psi) |
|---|---|---|---|
| 0701607-3-A | 9.7 | 38.2 | 355 |
| 0701607-3-B | 9.7 | 37.2 | 370 |
| 0701607-3-C | 9.8 | 36.0 | 374 |
| average | 9.7 | 37.1 | 366 |
| std dev | 0.1 | 1.1 | 10 |
| COV | 1% | 3% | 3% |

For each set of triplicate tests, the variation within the swatch was minimal as the coefficients of variation for both weight and permeability were in the 1-3% range. However, there was a substantial difference in permeability between these two swatches.

By grouping the average results from the triplicate tests along with the other eight swatches which were tested only once, the variation over the full set of ten swatches was examined. These results are shown below. This set of results shows substantial variation in the permeability measurement, with a COV of 13%. Additionally, the fabric weight had a COV of 5%.

The three swatches selected for use in the 2011 ETV verification tests are also presented separately below for easier comparison to the 2010 swatch results. Out of all ten samples, the 2010 non-ETV sample EX22841B had the second-lowest permeability at 26.0 FPM, which is well below the ten-sample average of 29.4 FPM. In contrast, the three swatches randomly selected for the 2011 ETV tests happened to have three of the four highest permeabilities, all of which were substantially above the permeability of the 2010 non-ETV swatch.

Summary of all ten 2010 and 2011 fabrics

| Fabric ID | Weight ($oz/yd^2$) | Permeability (FPM) | Mullen Burst (psi) |
|---|---|---|---|
| EX22841B (avg) | 10.1 | 26.0 | 418 |
| 0701607-1 | 11.7 | 25.9 | 440 |
| 0701607-2 | 10.8 | 26.5 | 440 |
| 0701607-3 (avg) | 9.7 | 37.1 | 366 |
| 0701607-4 | 10.9 | 31.7 | 425 |
| 0701607-5 | 10.1 | 33.8 | 405 |
| 0701607-6 | 10.9 | 29.3 | 445 |
| 0701607-7 | 10.9 | 27.6 | 410 |
| 0701607-8 | 11.1 | 27.0 | 405 |
| 0701607-9 | 10.4 | 29.1 | 375 |
| average | 10.7 | 29.4 | 413 |
| std dev | 0.58 | 3.7 | 27 |
| COV | 5% | 13% | 6% |

The three fabrics randomly chosen for 2011 ETV tests

| Fabric ID | Weight ($oz/yd^2$) | Permeability (FPM) | Mullen Burst (psi) |
|---|---|---|---|
| 0701607-3 (avg) | 9.7 | 37.1 | 366 |
| 0701607-4 | 10.9 | 31.7 | 425 |
| 0701607-6 | 10.9 | 29.3 | 445 |
| average | 10.5 | 32.7 | 412 |
| std dev | 0.7 | 4.0 | 41 |
| COV | 6% | 12% | 10% |

In the table below, the results of these physical property tests are shown alongside the filtration performance results from the 2010 non-ETV test, the 2011 ETV test, and Donaldson's 2012 repeat test. It is clear the permeability and pressure drop values for sample EC22841B are noticeably higher and lower, respectively, than the three ETV samples. It is a reasonable expectation that for similar fabrics lower permeability results in lower penetration of aerosol particles (improved filtration efficiency). Note the pressure drop was measured at constant face velocity while the permeability was measured at constant pressure drop.

Also of note is the similarity in pressure drop and mass gain measurements for sample 0701607-6 but the factor of 4-5 difference in downstream aerosol concentration when comparing the 2011ETV test to the 2012 non-ETV retest. The full results of 2010 non-ETV test of EX22841B are not shown here as they have not been made available to RTI. However, it is known that downstream $PM_{2.5}$ concentration from that test was 0.0000324 g/dscm, also several times higher than the 2012 non-ETV retest of the same swatch.

| | 2010 non-ETV test | 2011 ETV Test | | | 2012 non-ETV re-test | |
|---|---|---|---|---|---|---|
| | | 5V6-R1 | 5V6-R2 | 5V6-R3 | | |
| Fabric ID | EX22841B | **0701607-6** | 0701607-3 (avg) | 0701607-4 | EX22841B | **0701607-6** |
| Weight (oz/yd$^2$)* | 10.1 | 10.9 | 9.7 | 10.9 | 10.1 | 10.9 |
| Permeability (FPM)* | 26.0 | 29.3 | 37.1 | 31.7 | 26.0 | 29.3 |
| Mullen Burst (psi)* | 418 | 445 | 366 | 425 | 418 | 445 |
| $PM_{2.5}$ (g/dscm) | 0.0000324 | 0.0001091 | 0.0001792 | 0.0000983 | 0.0000047** | 0.0000282 |
| Total PM (g/dscm) | -- | 0.0001668 | 0.0002085 | 0.0001482 | 0.0000125** | 0.0000315 |
| Average residual Δ P (cm w.g.) | -- | 2.03 | 2.03 | 2.09 | 2.50 | 2.04 |
| Initial residual Δ P (cm w.g.) | -- | 1.92 | 1.90 | 2.01 | 2.46 | 1.89 |
| Residual Δ P increase (cm w.g.) | -- | 0.19 | 0.24 | 0.17 | 0.13 | 0.25 |
| Mass gain of sample filter (g) | -- | 1.88 | 2.05 | 1.84 | 1.23 | 1.80 |
| Average filtration cycle time (s) | -- | 158 | 159 | 181 | 186 | 181 |
| Number of cleaning cycles | -- | 137 | 136 | 119 | 116 | 119 |

*Tested in 2012 on different punches from the same fabric swatches used in the filter performance tests
**Below the method detection limit of 0.0000167 g/dscm

## Conclusions

Based upon the data presented above, the following conclusions can be made:

- There were no obvious visual differences between the ten swatches examined.
- Variability in fabric weight and permeability within a given swatch was relatively minor.
- Variability in fabric weight and permeability across the ten swatches was substantial.
- Of the tests run in this series, the permeability is the most directly relatable to filtration performance. It is reasonable to suspect the low permeability of the EX22841B swatch and the relatively high permeabilities of the three ETV-tested swatches could have contributed, at least partially, to the discrepancy in filtration performance (downstream $PM_{2.5}$ concentration) between the 2010 non-ETV and 2011 ETV tests. This suspicion is supported by the similar performance ratio between the two swatches that were retested in 2012.
- The results presented here do not seem to explain why swatches EX22841B and 0701607-6 both performed substantially better when retested in 2012 relative to the original 2010 and 2011 results, respectively. This discrepancy suggests there was another factor which affected the filtration performance results, perhaps an as yet unidentified variability in the test method itself.

# ETS Test Report

Terry Williamson

March 13, 2012

Objective: The purpose of testing identify any variability between the 2010 Donaldson ASTM 6830 test samples and the 2011 Donaldson ETV test samples.

Test Program: The following tests were performed:

- Visual Inspection
- Permeability
- Mullen Burst
- Fabric Weight

The 2010 sample and one of the 2011 samples were tested in triplicate to demonstrate repeatability. All other samples from the 2011 set were single tests.

SUMMARY OF RESULTS

Visually no variations between the 2010 and 2011 samples could be determined. The fabric weight, permeability and Mullen burst strength are shown below.

| Fabric ID | Weight ($oz/yd^2$) | Permeability (FPM) | Mullen Burst (psi) |
|---|---|---|---|
| EX22841B-1 | 9.7 | 26.8 | 405 |
| EX22841B-2 | 10.4 | 25.7 | 445 |
| EX22841B-3 | 10.1 | 25.4 | 405 |
| | | | |
| 0701607-1 | 11.7 | 25.9 | 440 |
| 0701607-2 | 10.8 | 26.5 | 440 |
| 0701607-3-A | 9.7 | 38.2 | 355 |
| 0701607-3-B | 9.7 | 37.2 | 370 |
| 0701607-3-C | 9.8 | 36.0 | 374 |
| 0701607-4 | 10.9 | 31.7 | 425 |
| 0701607-5 | 10.1 | 33.8 | 405 |
| 0701607-6 | 10.9 | 29.3 | 445 |
| 0701607-7 | 10.9 | 27.6 | 410 |
| 0701607-8 | 11.1 | 27.0 | 405 |
| 0701607-9 | 10.4 | 29.1 | 375 |

CONCLUSIONS

The test results showed that the 2010 sample had a lower permeability value than most of the 2011 samples. This was particularly notable with 2011 sample 0701607-3 which had the highest permeability, the sample that exhibited the highest emission results during the 2011 ETV tests. Sample 0701607-3 also exhibited the lowest bursting strength value and lowest weight of the 2011 samples. These results show that there are variations in strength and flow properties from sample to sample thus variations in filtration performance are plausible.

**APPENDIX B:**

**To:** Mike Kosusko

**From:** Len Stefanski

**Subject:** Final Report on Donaldson Data Review

**Date:** May 16, 2012

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# 1 Introduction

This report summarizes my examination of the data and information relevant to the question of determining the aberrant Donaldson test results. The data I examined are from three sources: the *ETS Test Report* by Terry Williamson, March 1, 2012; the report *Donaldson Dura-Life 0701607 Physical Property Test Results* by Jay Hill, March 15, 2012; and the spreadsheet "Testing Pairs-418.xlsx" compiled here at EPA.

The statistical methods used are common analysis of variance models supplemented with graphical analysis. The available data are informative but are neither extensive or as directly relevant for the problem at hand as they would be if resulting from a designed experiment. Thus the findings from them are suggestive, but not confirmative.

# 2 Analysis of the ETS Test Report Data

For the analyses reported on in this section I used data from the document *ETS Test Report* by Terry Williamson, March 1, 2012.

## 2.1 Analysis of Variance

Using standard statistical analysis of variance methods I analyzed the data contained in the table of the report cited above for the purpose of assessing the variability among fabrics in Weight, Permeability, and Mullen Burst measurements.

The analysis of variance resulted in no statistically significant evidence of among fabric variability for the Mullen Burst measurements ($p$-value $> .1$); moderately strong statistical evidence of fabric-to-fabric variability for Weight ($p$-value $< .05$); and strong statistical evidence of fabric-to-fabric variability for Permeability ($p$-value $< .01$).

I also compared the average values for the 2011 Fabrics 3, 4, and 6 versus the average values for all other fabrics. Differences for Weight and Mullen Burst were not statistically significant (both $p$-values $> .2$); however, the difference for permeability was highly statistically significant ($p$-value $< .002$).

The results of these statistical analyses are consistent with the visual observations in the report and thus support the report's conclusions.

# 3 Analysis of the Physical Property Test Results

For the analyses reported on in this section I used data from the report *Donaldson Dura-Life 0701607 Physical Property Test Results* report by Jay Hill, March 15, 2012.

## 3.1 PM2.5 Permeability Relationship

Using data from the last table in the report cited above I took a more in-depth look at the relationship between PM2.5 and Permeability for the test-retest results displayed in the table. My analyses are summarized and presented in the attached Figure 1. The red crosses and interpolating line are the four initial test results (EX22841B, 0701607-6, 0701607-3, 0701607-4); and the green crosses and line are for the two 2012 retest results (EX22841B, 0701607-6). The blue lines are statistical "best-fitting" lines determined by least squares analysis under the assumption that slopes are equal for the test and retest data.

The statistical analysis confirms (and quantifies) the relationship between PM2.5 and Permeability. In other words, PM2.5 increases as permeability increases in both the test and retest data. And to the extent that can be determined from the data, the rates of increases are not different.

However, for the problem at hand the vertical distances between to the two lines is more relevant. It suggests that the retest PM2.5 values were systematically smaller than those from the initial tests, even after accounting for differences related to permeability. However, the vertical distance between the two lines is borderline *non-statistically* significant ($p$-value = .0788). In other words the PM2.5 values from the retests are lower, but the evidence that this difference is statistically significant is not strong. Note that the fact that the statistical analysis does not reveal a statistically significant difference is not surprising in light of the small sample size.

# 4 Analysis of Data from the Spreadsheet "Testing Pairs-418.xlsx"

## 4.1 Analysis of Variance of non-ND Data

The large number of below-detection limit values in the data set limit the analyses that can be meaningful done with these data. However, as a statistical check on the apparent disparity of the Donaldson data I culled the PM2.5 and Total Pm data for the four nearly complete sets of fabric tests: Set 5, BWF America (first block); Set 6*, Donaldson, and the two blocks of Polymer Group test results. The one Polymer Group ND value was replaced by 0.0000167.

The analysis of variance enables a rigorous comparison of fabric-to-fabric differences relative to the variation of repeated measurements of the same fabric. The analysis of variance confirmed statistically significant differences among fabrics for both PM2.5 and Total PM ($p$-values $<$ .02). More relevant to the problem at hand are comparisons of

Donaldson to the other three fabrics. These individual comparisons were all statistically significant (all $p$-values $< .006$). The indicated conclusion is that the large Donaldson PM2.5 and Total PM values cannot be explained by process variation, but rather suggest a real difference. However, the data are not sufficient for pinpointing the reason for that difference.

### 4.2 Graphical Analysis of PM and Related Measurements

After replacing all ND values by the detection limit 0.0000167, I plotted PM2.5 and Total PM versus AVG. RESIDUAL PRESSURE DROP (cm w.g.), MASS GAIN OF SAMPLE FILTER (g), MEAN DUST DIA. (1.5 1.0 um), Percent < 2.5 um (40 -90%), Filter Wt. Gain (1.12 0.45 g), and MAX DP (0.60 0.24 cm w.g.). The purpose here is simply to get a better picture for how the Donaldson data compare to those for the other fabrics. This is not a formal statistical analysis, but rather is intended only to facilitate discussion and possibly conjectures on explanations for the Donaldson results.

For these plots I excluded the two Polymer Group fabric tests as they have some unusual values in the auxiliary measurements (and were performed at different filtration velocities).

These plots appear in Figures 2 and 3. The Donaldson PM2.5 and Total PM data points are apparent by their magnitude. One observation that may be relevant is that the Mean Dust value for the Donaldson tests was much higher than the mean dust values for the other tests, and the percentage of small dust particles was much lower.

## 5 Summary

There is no "smoking gun" in these results. The observations related to permeability and dust particle size distribution suggest some hypotheses to explore if additional testing is undertaken. However, it should be kept in mind that the only factors that could be investigated are those for which data were available.

There are sources of variation that we do not have sufficient data to assess. On the manufacturing side there is inevitable product variation at different scales. The physical properties of the fabric vary both in time of the production run, and spatially across the expanse of the fabric. Whether that variation is large enough, and whether it affects key properties of the fabric (e.g., permeability), and whether variation in a key factor could be the cause of poor test results are all unknown.

On the testing side, there is also inevitable variation in the conduct of the tests. The data suggest that the particle size distribution of the dust changed at some time. It is possible that other components that affect the test procedure are also not perfectly static. Even though the dust particle size distribution is with specifications, we do not have any information on how robust test results are across the range of allowable size distributions.

The possibility exists that some fabrics are fairly robust to minor variations in the test conditions whereas other fabrics are more sensitive. I say this not based on subject-matter knowledge specific to this case, but based on general statistical experience analyzing data having similar structure. Interactions between factors (e.g., in this case the factors are "fabric" and "dust particle size") are commonly seen in experimental data.

My understanding is that it is very unlikely that we can do extensive testing of either Donaldson's fabric variability, of the test method variability (which would go a long way to understanding things). However, that it may be possible to retest the Donaldson fabric in conjunction with one or more other fabrics. If this is the case, then there are experimental designs that could be used to effectively study, and control for, the effects of testing variation of the results for the Donaldson fabric. Based on our conversations this may be the cost-effective way to shed the most light on the problem.

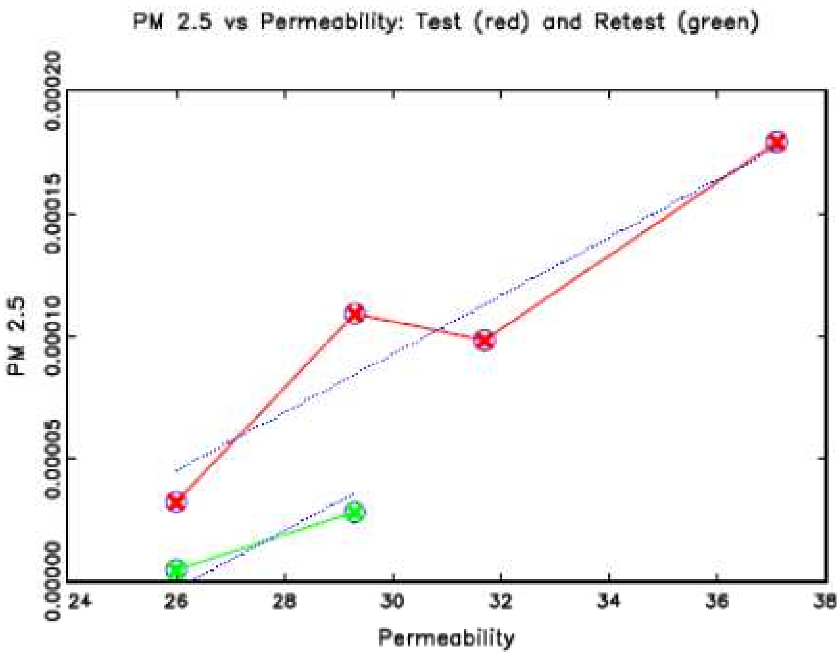


Figure 1: Relationship of PM2.5 to permeability. Initial test results: red crosses and interpolating line; Retest results: green crosses and interpolating line. Blues lines are best-fitting least squares lines assuming lines with equal slopes but different intercepts.

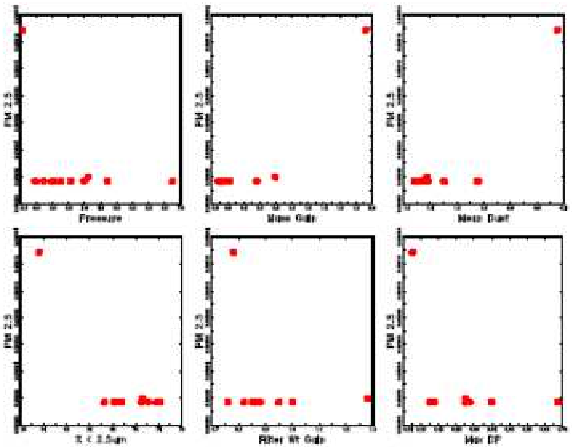


Figure 2: Plots of PM2.5 versus six auxiliary variables.

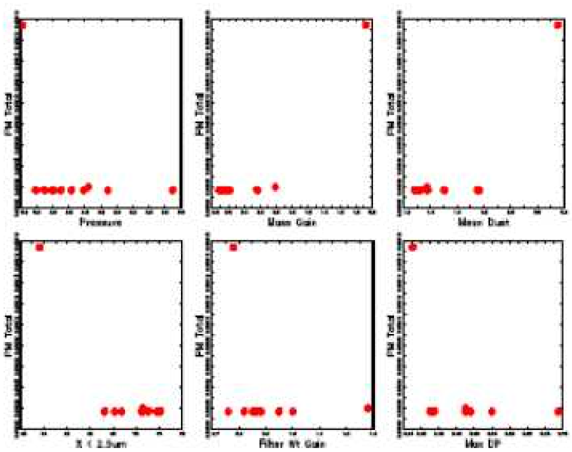


Figure 3: Plots of Total PM versus six auxiliary variables.