Non-Destructive In-The-Can X-ray measurement of soot, ash, wash coat and regeneration damage in DPFs

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Joint Exploratory Project between 3DX-Ray and ORNL

- This presentation describes March-April 2008 work at ORNL
- Goal: exploratory work to demonstrate the ability to:
- Make through-the-can evaluations of the distribution of
  - *Soot*
  - *Ash*
  - *Thermal damage*
- Quantify the distribution of individual or multiple wash-coats

Overview

- Aim of 3DX & ORNL Collaboration
- Introduction to 3DX-Ray Ltd (3DX)
- X-ray Imaging Background (MDXi Systems)
- 3DX History (Washcoat Distribution)
- Initial Results – Visualisation of:
  - *Soot Distribution*
  - *Ash Distribution*
  - *Substrate Damage*
- Future work
- Conclusion

Introduction to 3DX-Ray Ltd

Global Supplier of X-ray systems for security and industrial applications

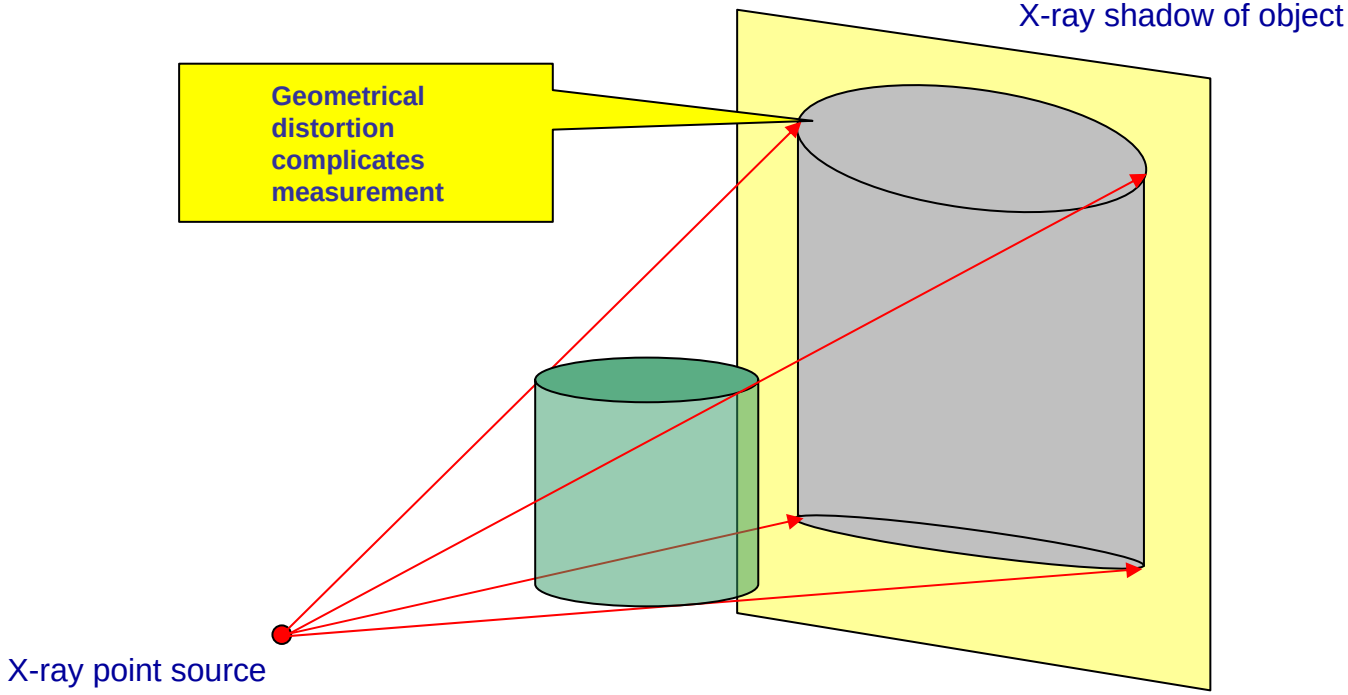
Security → Industrial

Introduction to 3DX-Ray Ltd

Core Expertise:

- Design and delivery of advanced x-ray solutions to the security and industrial sectors
- Specialised in extracting useful information from x-ray images
- Major global supplier of x-ray inspection systems for diesel filter manufacturing

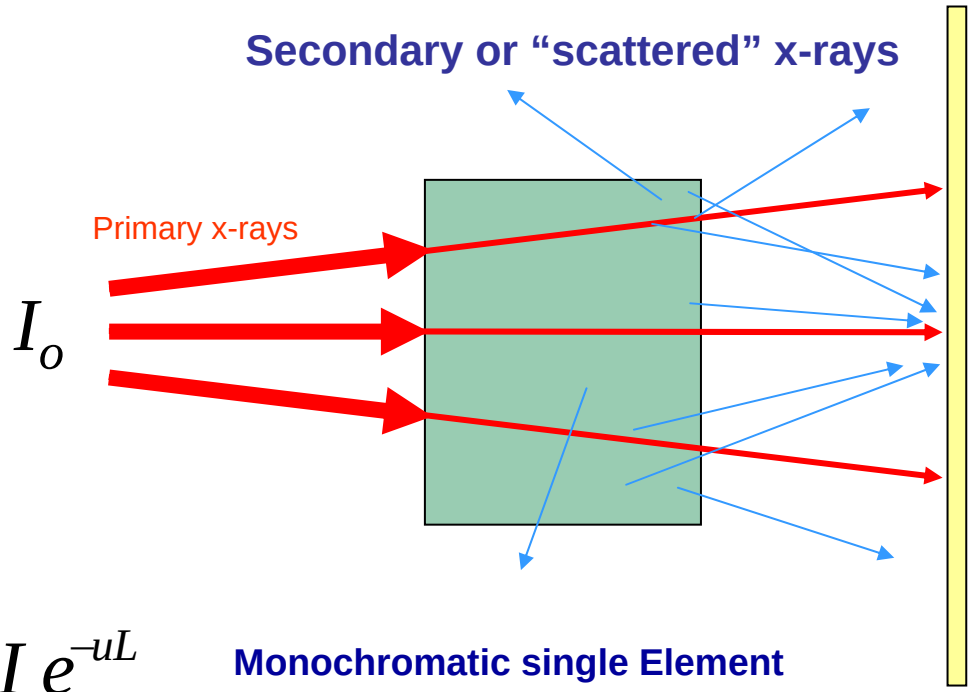
Basics of X-ray Imaging



X-rays create "shadowgraph" images

Basics of X-ray Imaging

Conventional full-field X-ray imaging



Blurring of image due to scattered radiation

Loss of information due to scatter noise

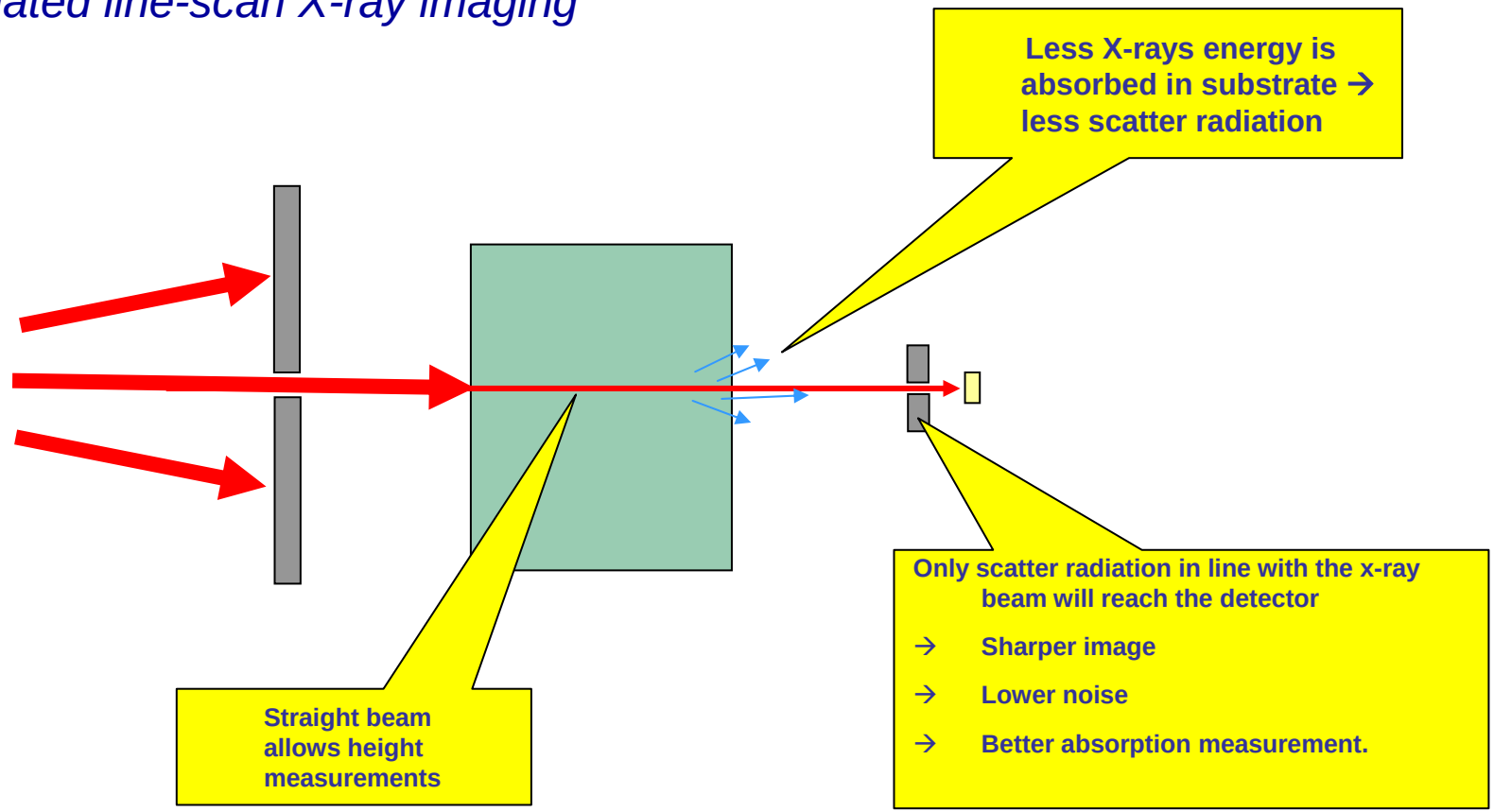
Poor x-ray attenuation measurement.

$$I_x = I_o e^{-uL}$$ **Monochromatic single Element**

$$I_x = \int_S I_o(s)\, e^{-\sum_E u(s)\,L}\, ds$$ **Polychromatic multiple Elements**

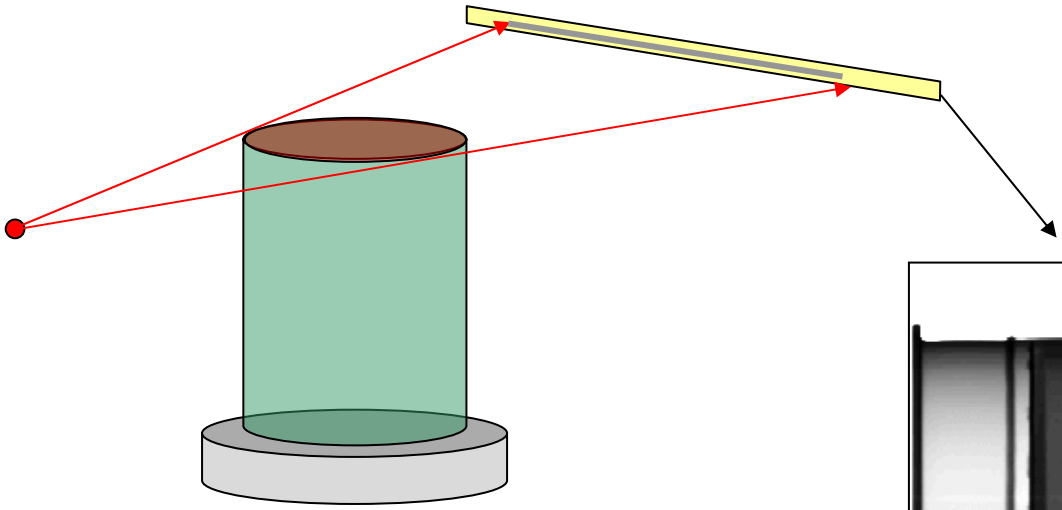
Basics of X-ray Imaging

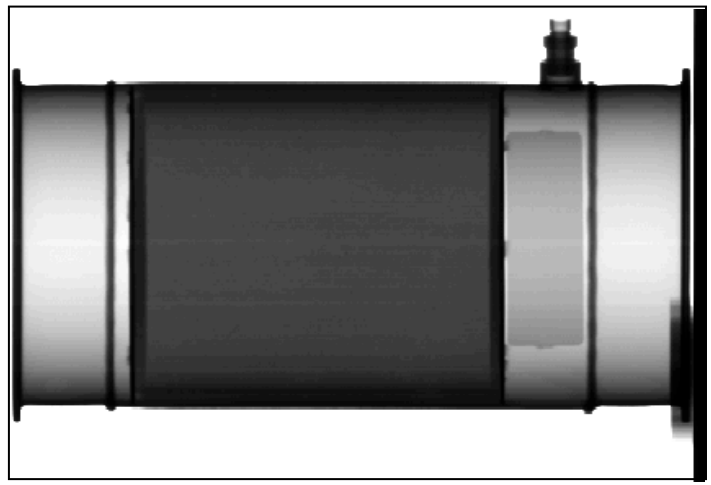
Collimated line-scan X-ray imaging



Basics of X-ray Imaging

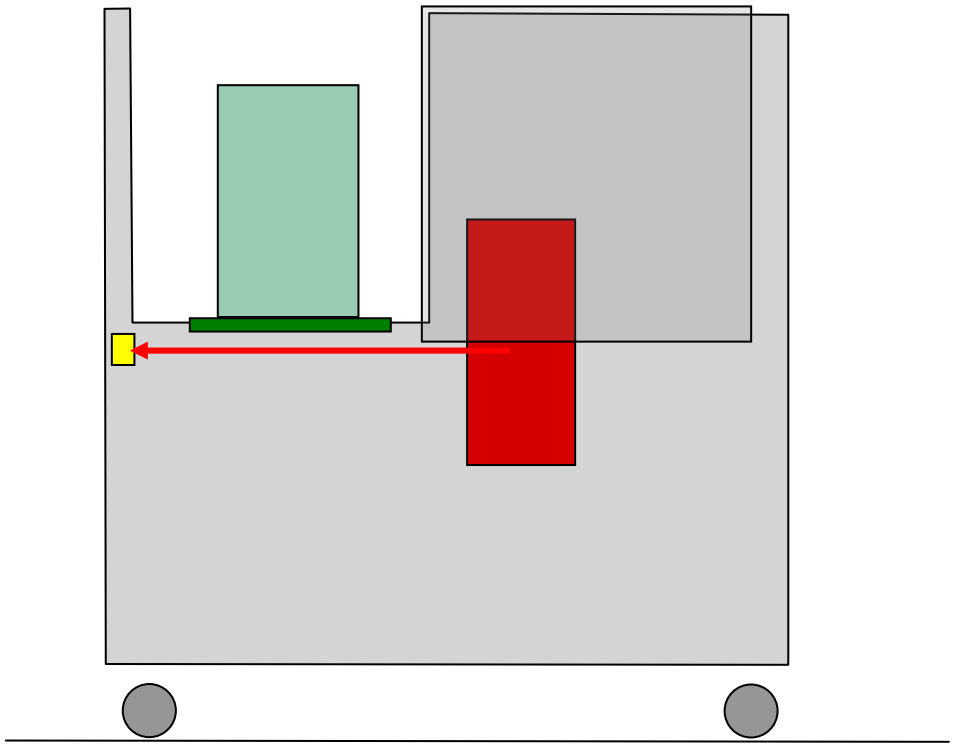
Object is scanned line by line and data is reconstructed in computer memory





Collimated line-scan imaging

MDXi Concept



MDXi 400 Lab Machine

This technology is currently in use in more than 20 DPF and CAT production lines and laboratories world wide.

- **150kV X-ray source.**
- **Linear low noise detector**
- **Control over sample height**
- **Control over sample angle**
- **Automatic batch file capability**

X-ray Measurement Issues

Primary Factors

- X-rays are mainly attenuated by electrons in X-ray path
- The X-ray attenuation is affected by
  - *Type of material (Z number)*
  - *Amount of material (mass)*
- The challenge is to separate the effects of one variable of interest

Are x-ray techniques sensitive enough to detect subtle differences such as soot and ash build up inside a DPF?

X-ray Measurement Issues

Secondary Factors

- X-ray source drift
- X-ray detector stability and drift
- X-ray photon noise
- Mechanical stability

How will these effect reproducibility and repeatability of results?

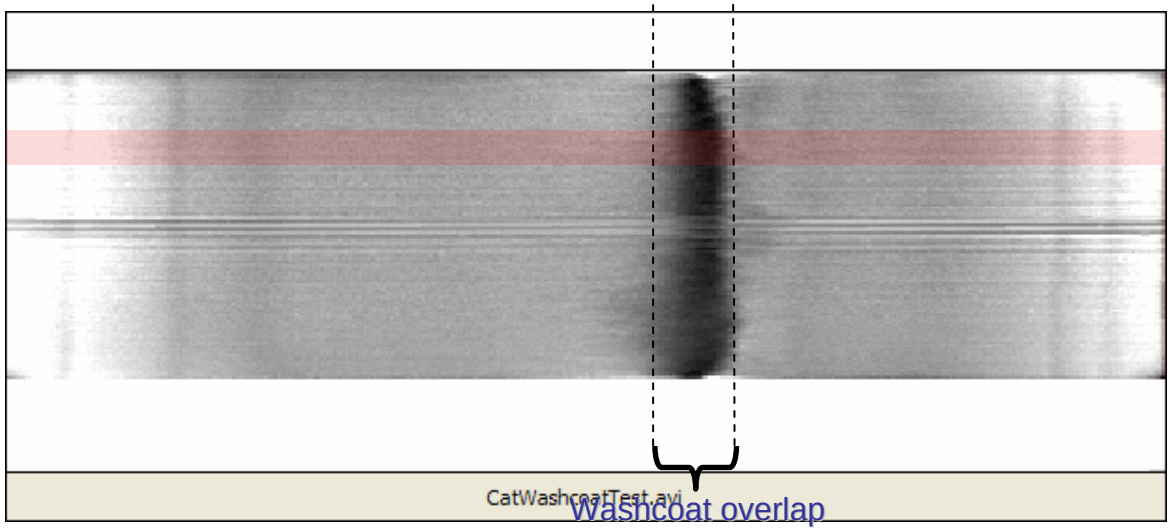
3DX History

WASHCOAT DISTRIBUTION

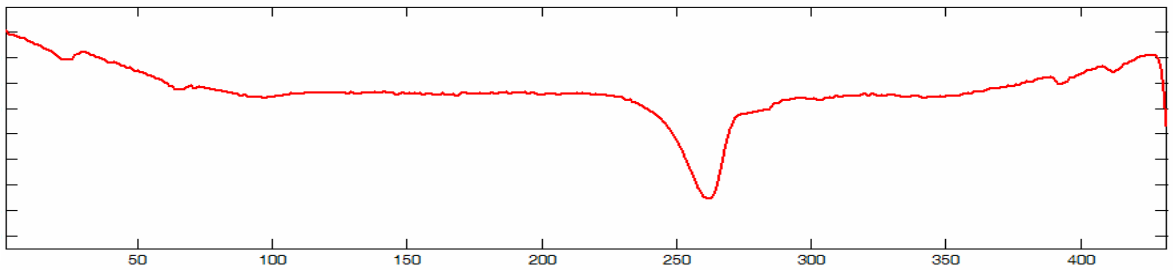
- Non Destructive characterisation of washcoat distribution.
- Used in Process Development.
- Cost reduction by non destructive QC.

Washcoat Distribution

Catalytic Converter with two overlapping washcoats



WASHCOAT DISTRIBUTION PROFILE



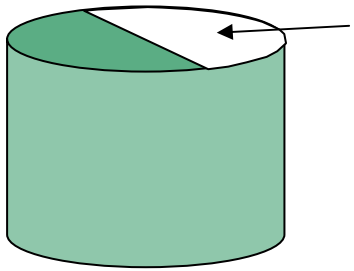
MEASUREMENT OF SOOT DISTRIBUTION IN A DPF

Initial Results

Imaging & Data Analysis of:

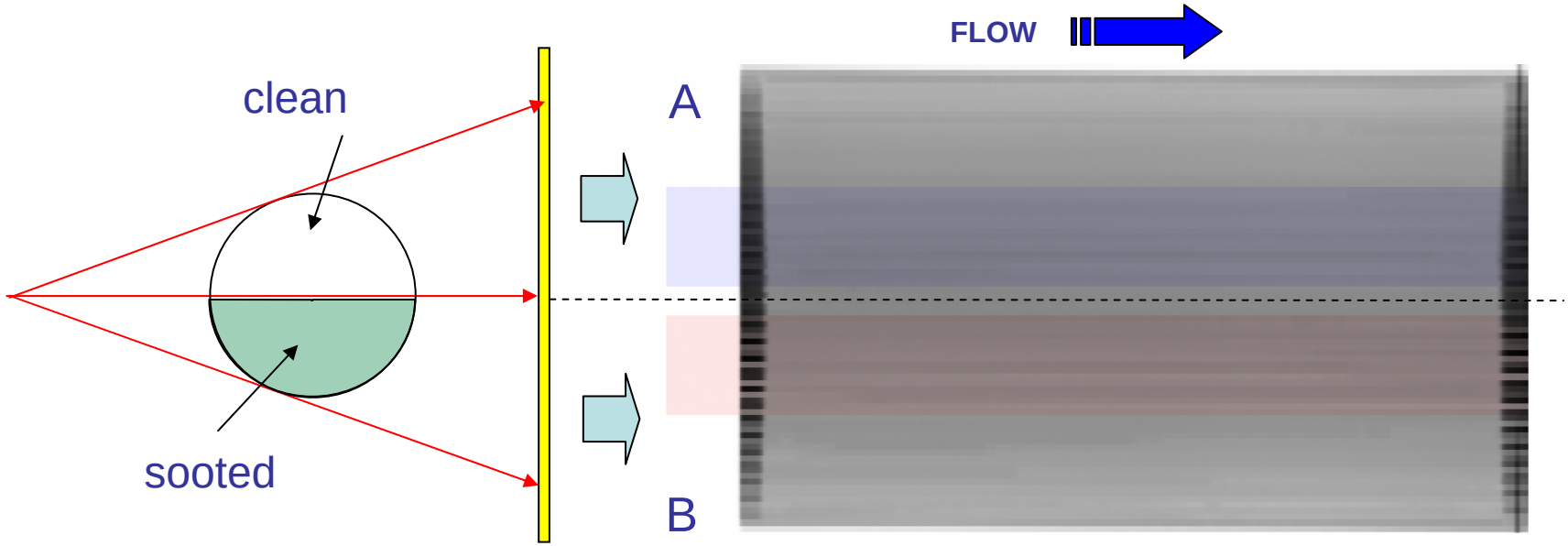
- Partially filled un-canned uncoated filter, filled in stages.
- Calibration – X-ray attenuation vs. soot mass.
- Canned filter (clean, sooted and acclimatised).

Un-Canned Soot Measurement



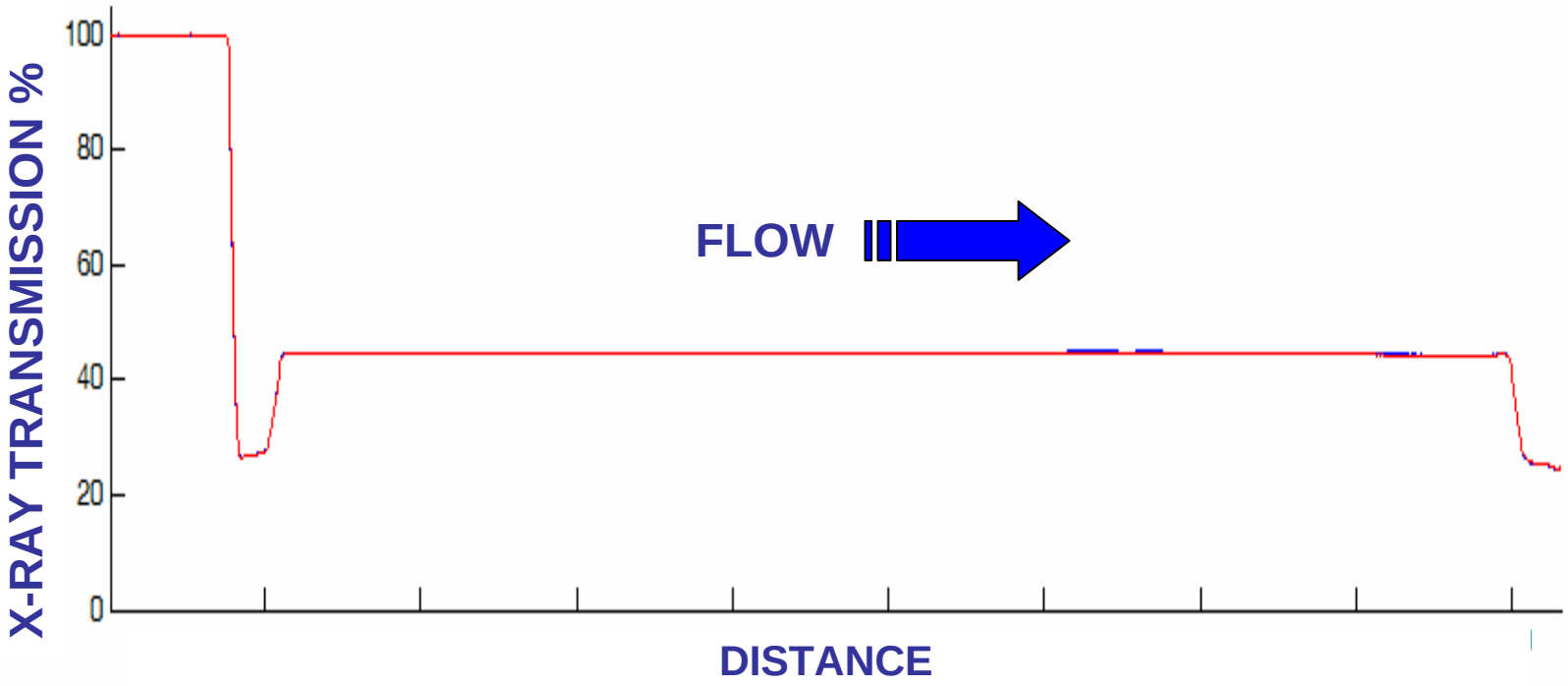
75mm (0.6L) Uncoated Cordierite Brick
Artificially vacuum loaded
One half sooted (0.3L), other half clean (masked off)
Soot slightly ash-laden.

	Added Weight	Loading
0	reference	0.00 g/L
1	0.59g	1.97g/L
2	1.16g	3.87g/L
3	1.77g	5.90g/L

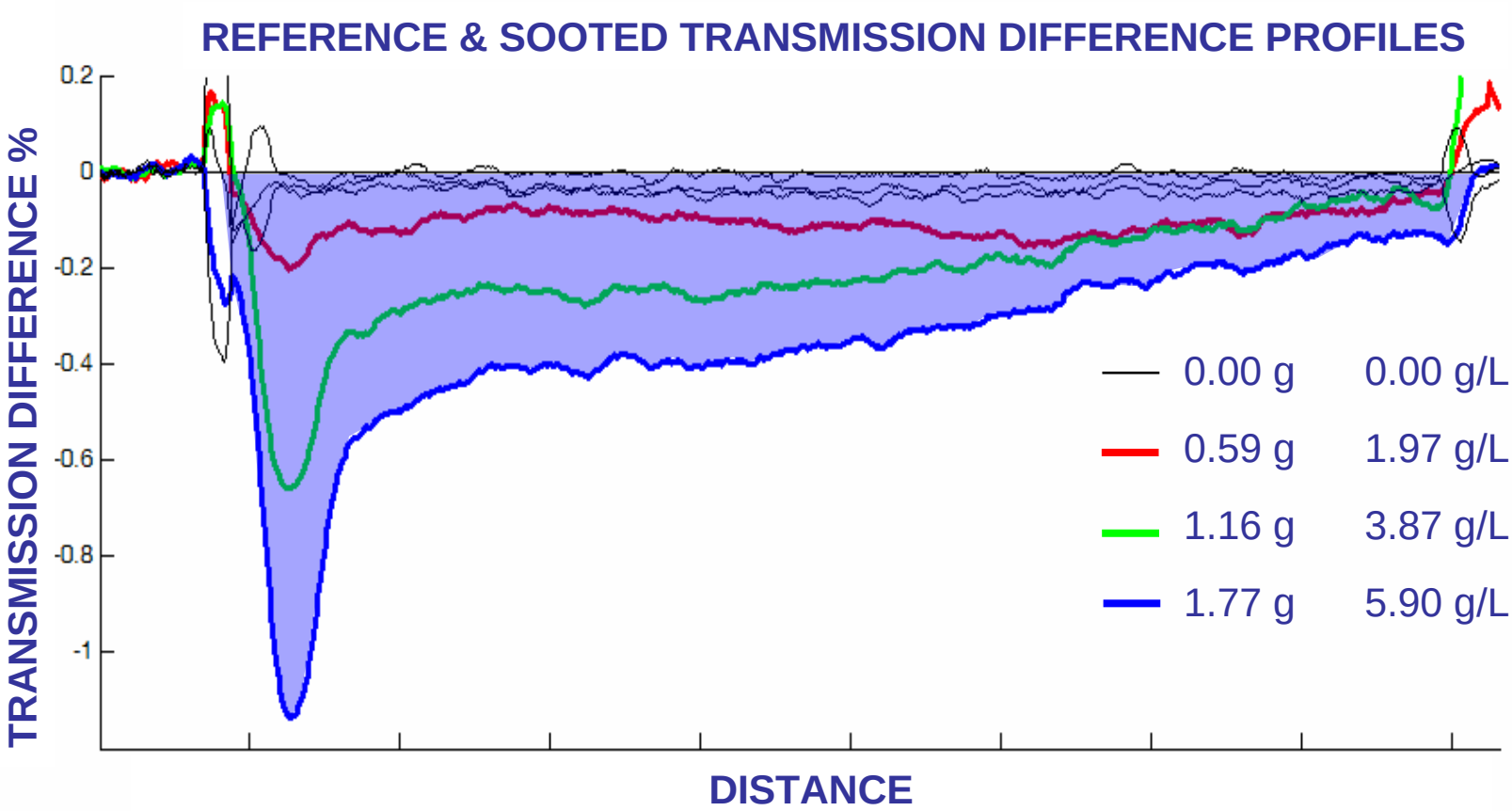


Un-Canned Soot Measurement

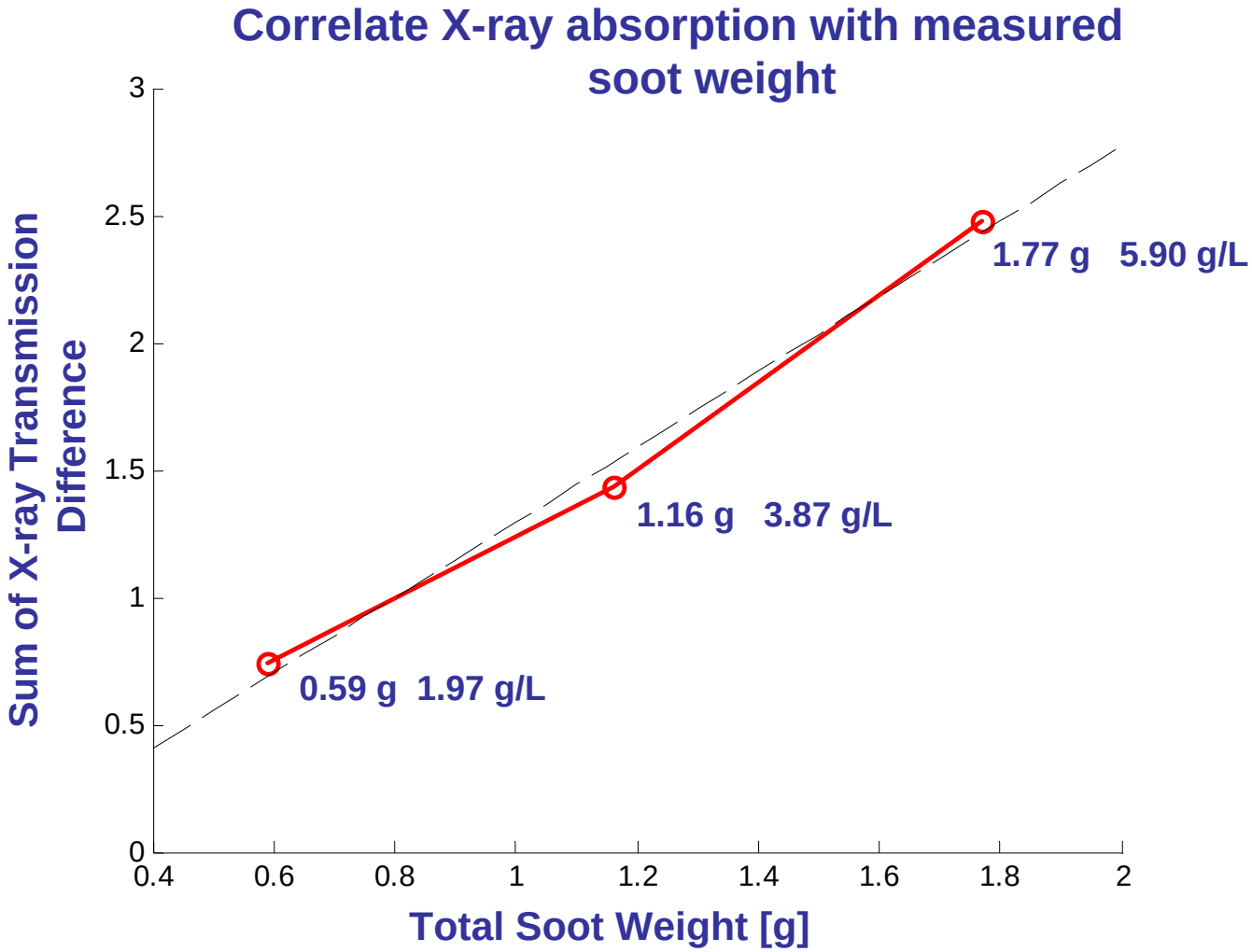
REFERENCE & SOOTED TRANSMISSION PROFILES



Un-Canned Soot Measurement



Un-Canned Soot Measurement



In The Can Soot Measurement

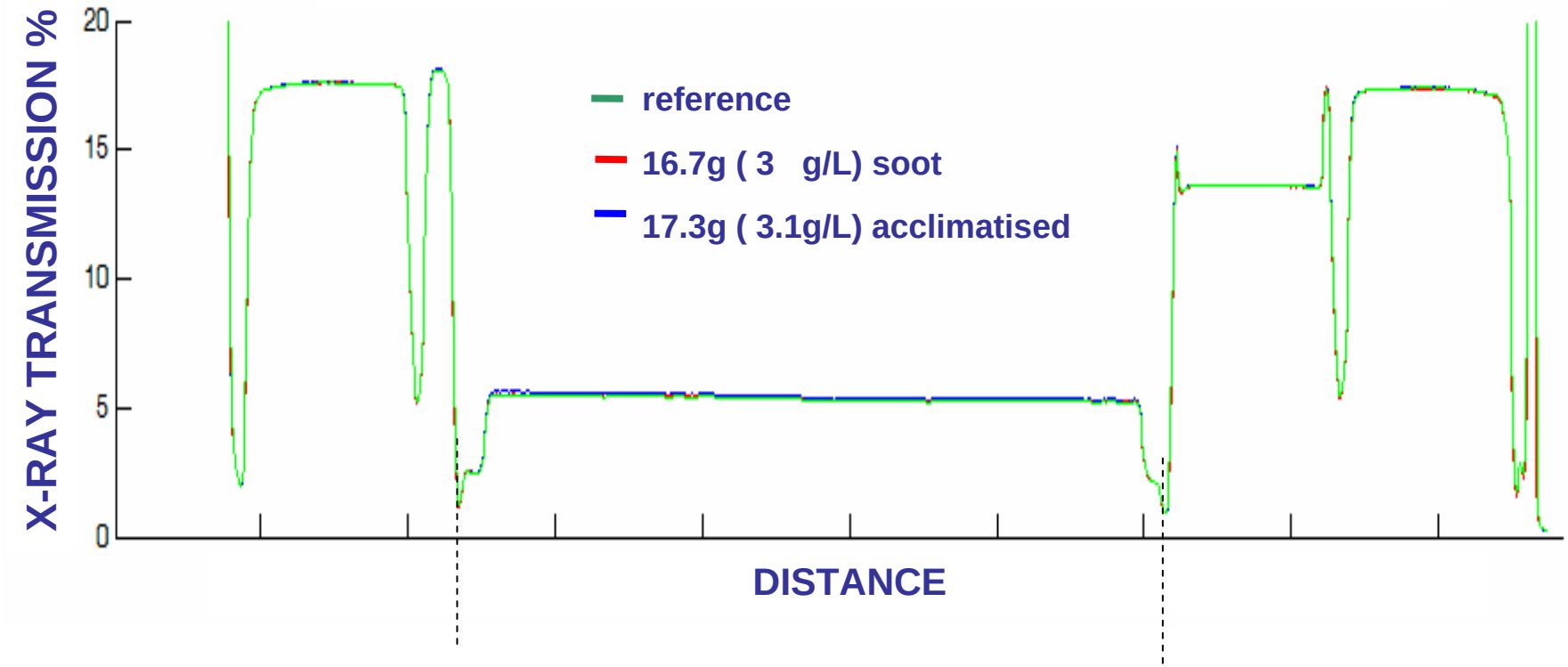
FLOW

NGK 558 5.66”x6” (~5.6L) Cordierite DPF.
Filled in 5 hours @ 2300rpm, 4.2bar BMEP, ULSD fuel, FSN 1.44

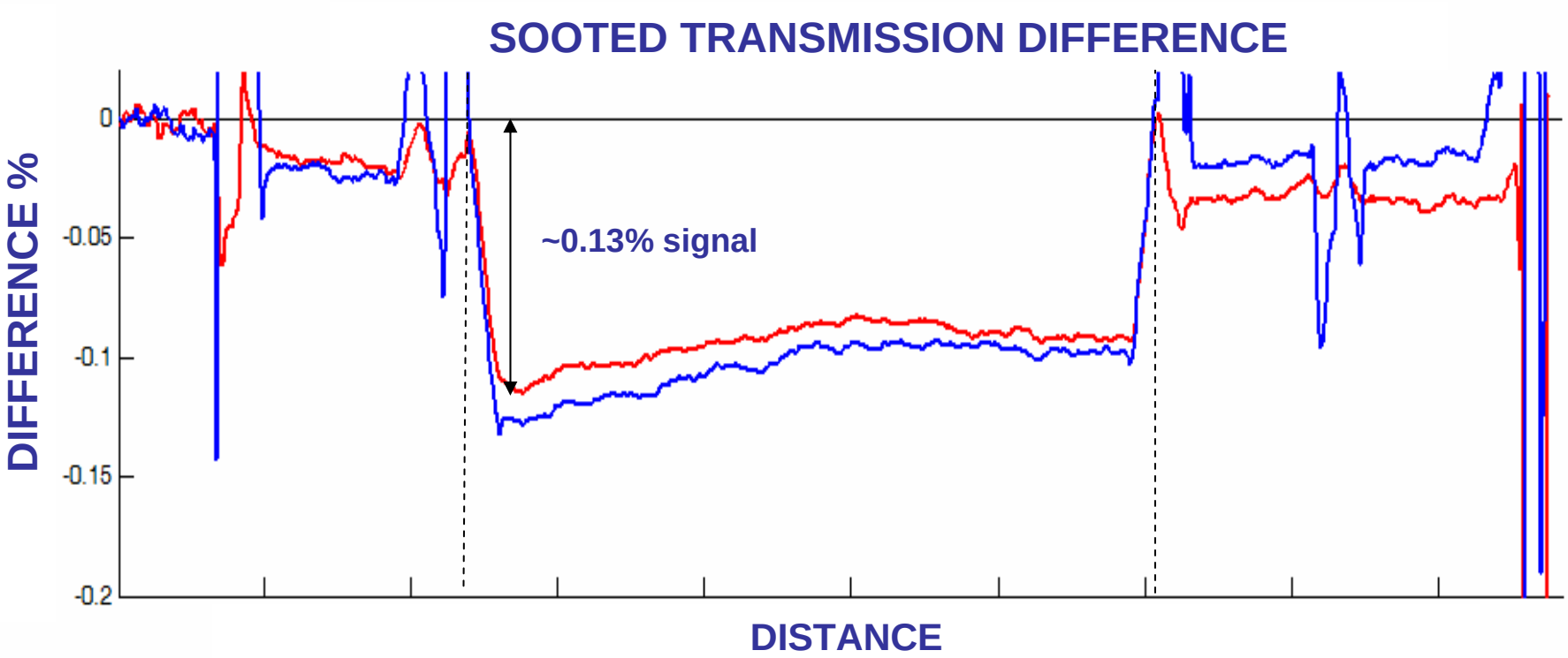
Condition	weight	soot	density	comments
Clean Filter	3473.7	0.0g		
Three days after run	3490.4	16.7g	(~3 g/L)	(bagged after run)
Acclimatised	3491.0	17.3g	(~3.1 g/L)	(one week acclimatised)

Digital scale 32000g full scale.

In The Can Soot Measurement



In The Can Soot Measurement



16.7g (3 g/L) soot

17.3g (3.1g/L) acclimatised

Initial Results

ASH DISTRIBUTION

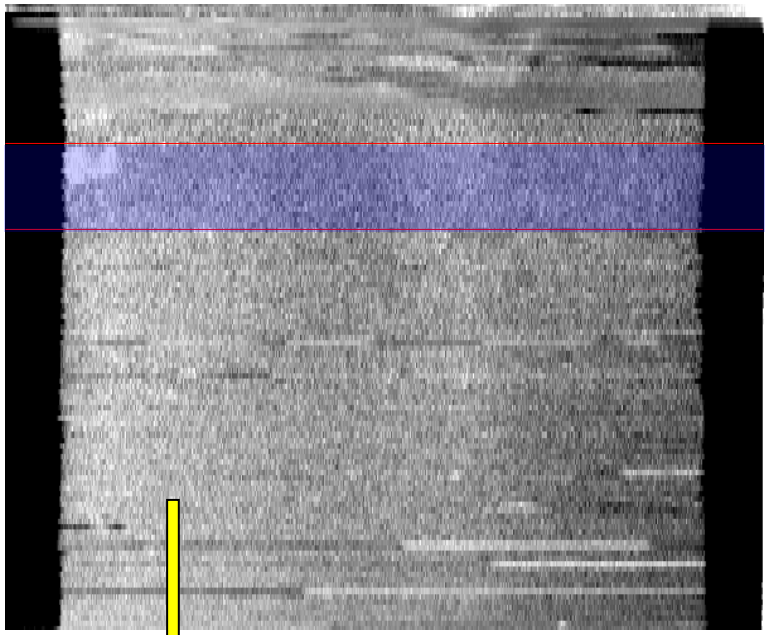
- Imaging
- Data Analysis

Ash Deposits

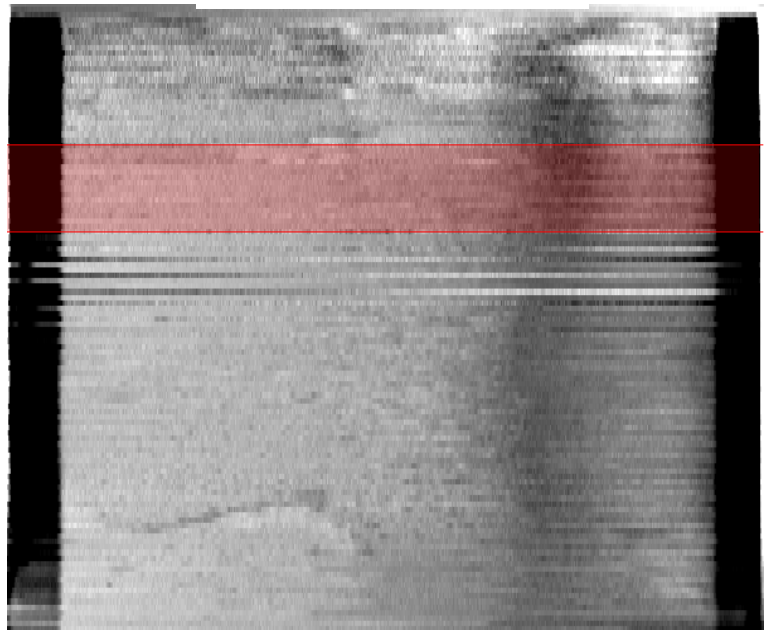
- Segmented half DPF
  - *Clean DPF for referencing*
  - *Filled DPF for testing*
- Filled DPF for testing

Ash in Segmented DPF

Clean

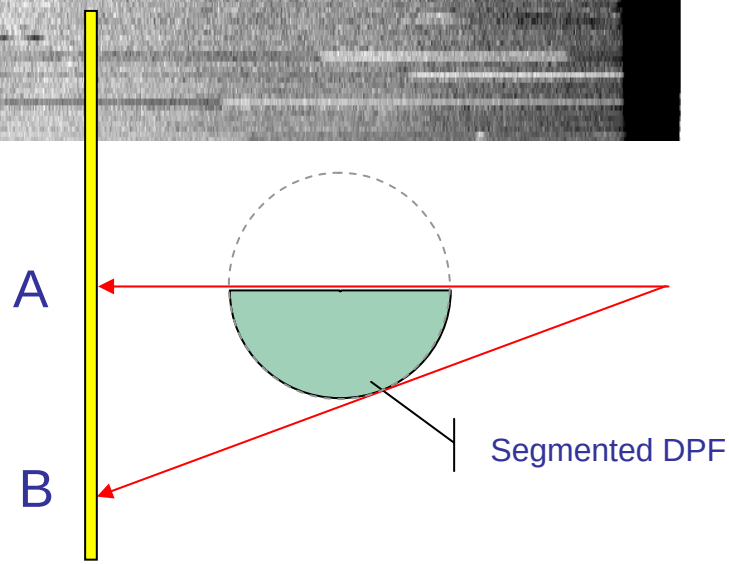


Ash loaded



A

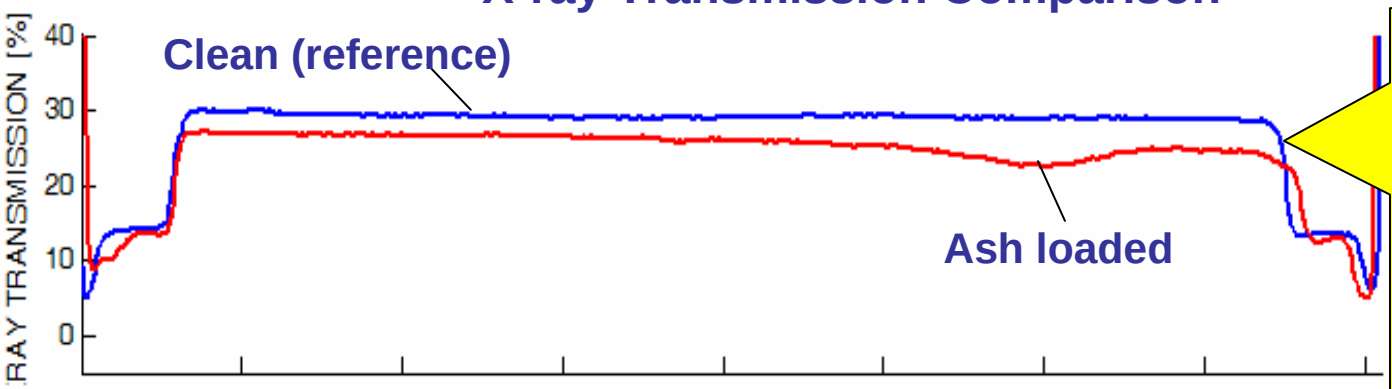
B



FLOW

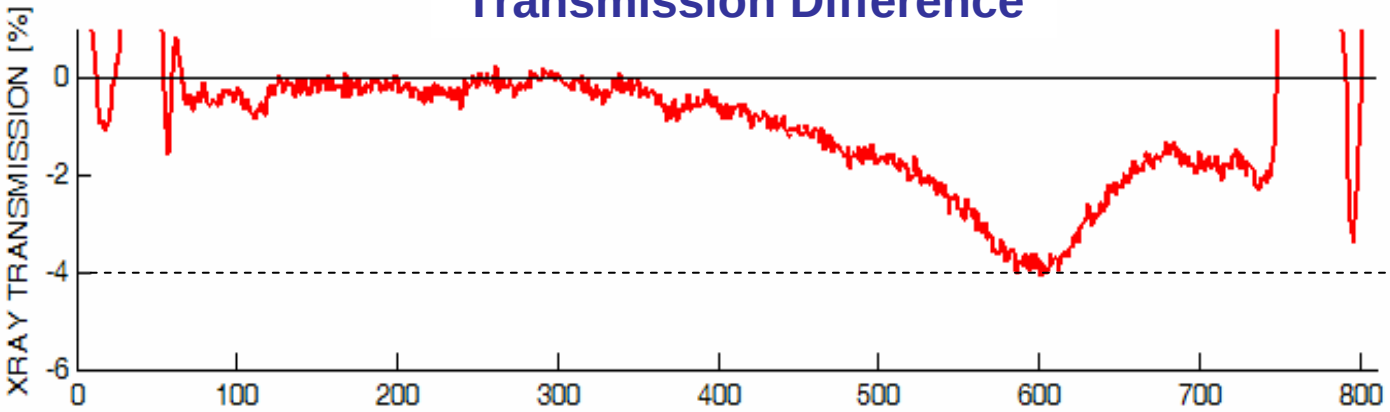
Ash in Segmented DPF

X-ray Transmission Comparison



~4% signal bias between reference and loaded filter → substrates have different absorption

Transmission Difference



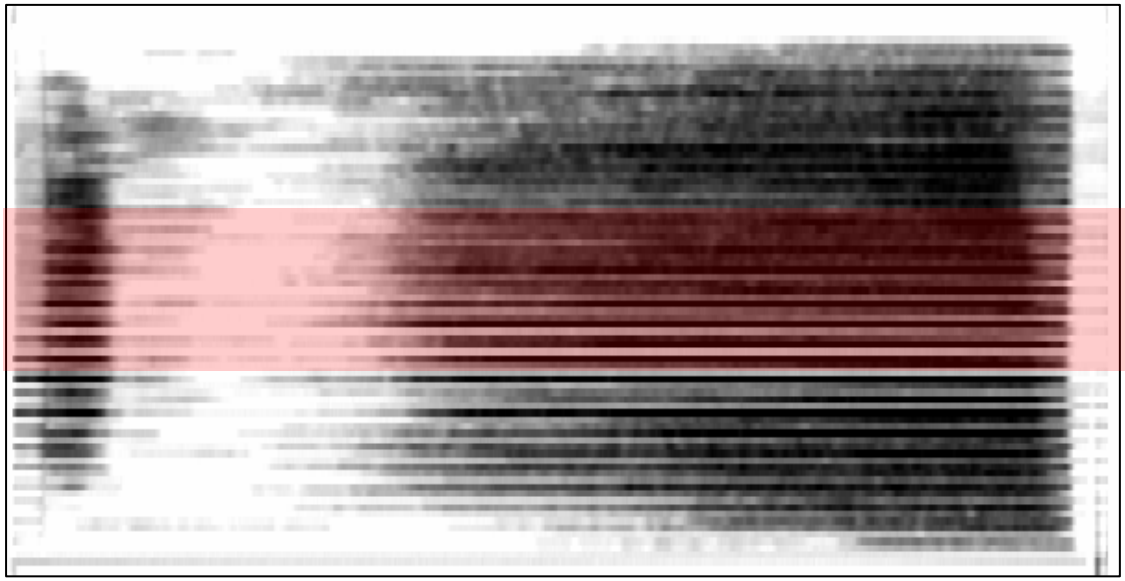
~4% signal

Ash in whole DPF

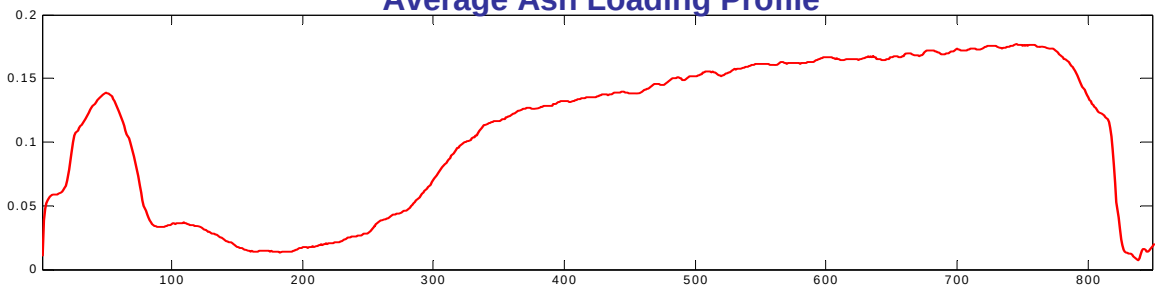
Vacuum loaded DPF

FLOW

X-Ray Transmission Image



Average Ash Loading Profile



Soot and Ash Measurement Summary

	X-ray Transmission	Signal
Ash	30-40%	4-7%
Soot	30-40%	~1.0%
Soot in can	~5%	~0.13%

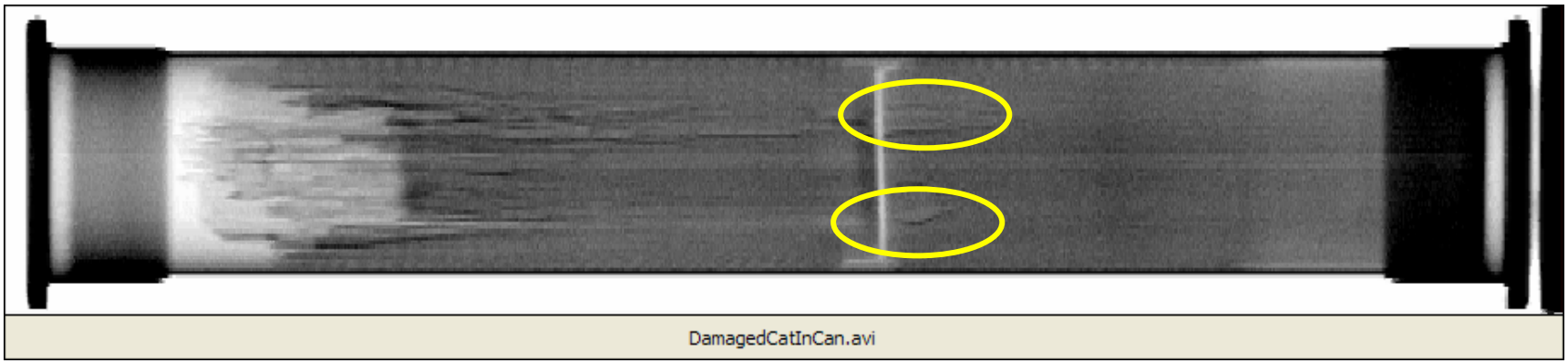
Initial Results

SUBSTRATE DAMAGE

- Thermal Damage

CAT Thermal Damage

FLOW



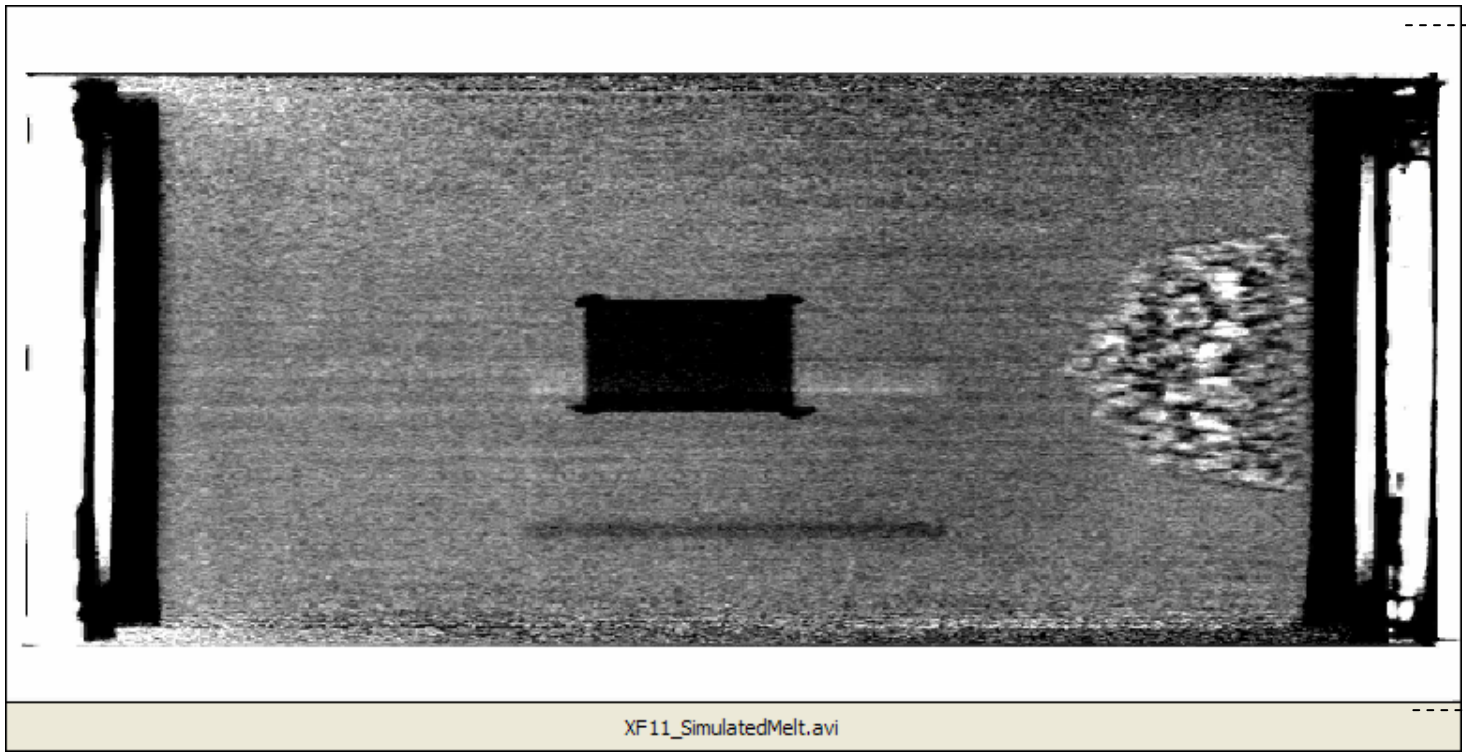
DamagedCatInCan.avi

Thermal Damage Inside Can

Simulated melt inside canned Cordierite DPF

340mm

FLOW

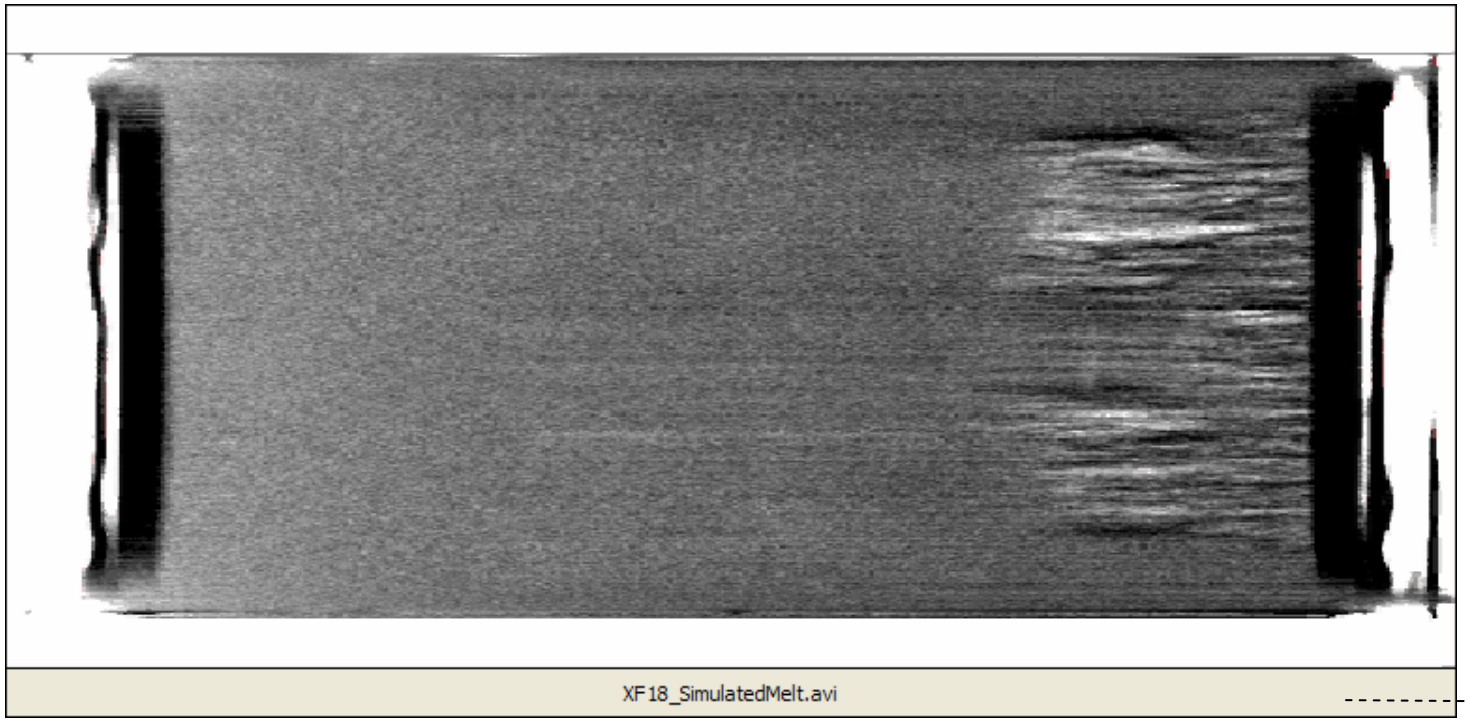


300mm

Thermal Damage Inside Can

Melt inside canned Cordierite DPF

340mm



300mm

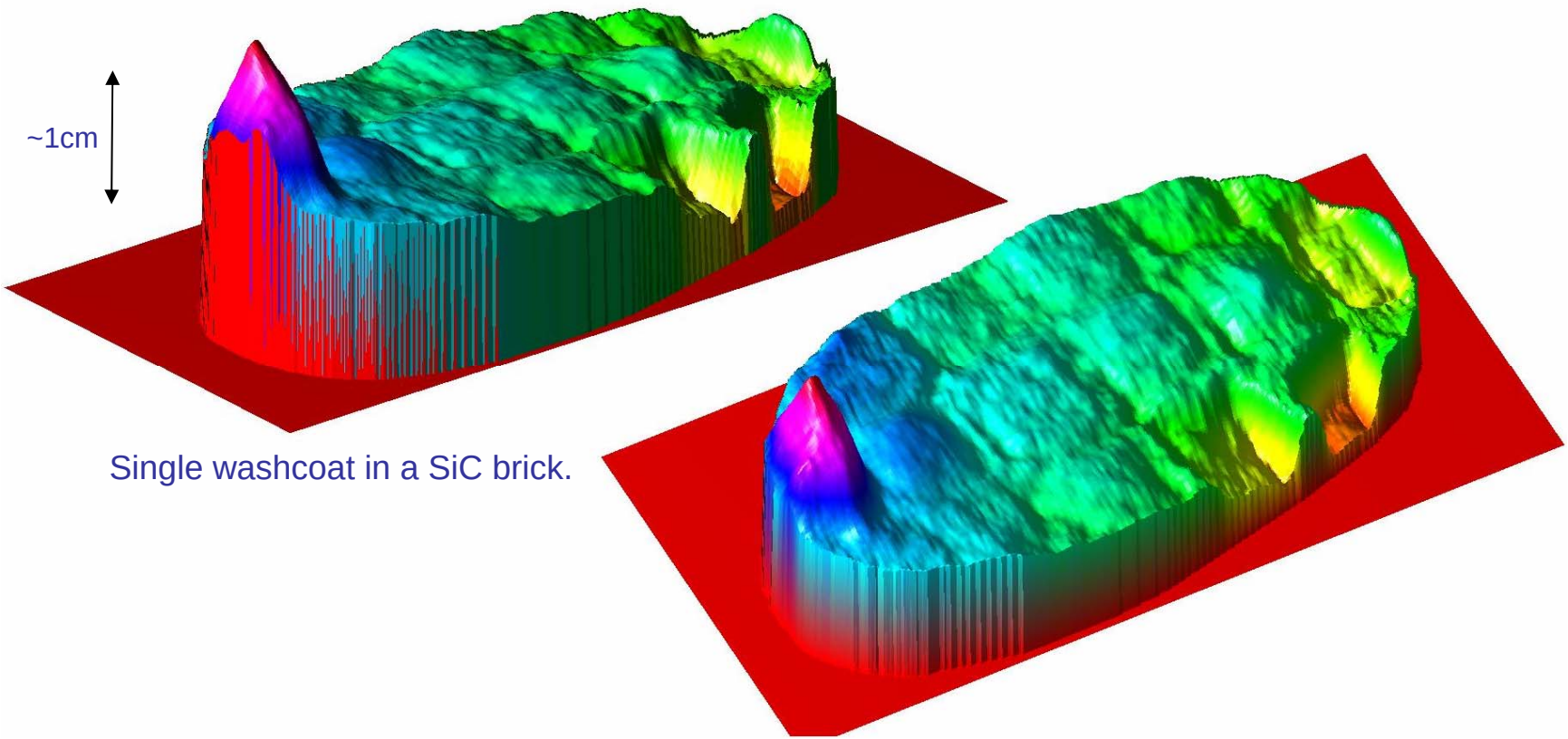
FLOW

Future Work

- Simplify calibration for Soot and Ash measurement
- Better estimate of added mass and density
- Rerun tests to produce error bars
- Substrate crack detection
- Characterisation and measurement of thermal damage
- 3D Soot, Ash and Damage representation

Future Work 2D to 3D

3D Washcoat Distribution



Single washcoat in a SiC brick.

3D Soot, Ash and Damage Representation.

Conclusion

3DX-Ray has powerful non-destructive inspection tools for DPFs suitable for R&D, Production and QA labs. We have demonstrated:

- DPF soot distribution can be detected and measured outside the can.
- X-ray soot mass estimates correlate well with measured soot weight.
- Soot distribution can be detected inside the can. More work is required to test the measurement capability.
- Ash deposits are clearly visible and can be interpreted and measured.
- Thermal damage is clearly visible through the can and can be measured in size and position.
- The new X-ray based method depends on careful experimental procedures designed to isolate the variable to be measured.
- These procedures could be performed in any well staffed, well equipped emissions laboratory.

Contact:

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