Thermal Management in Porous Ceramic Particulate Filters

Opportunities and Consequences of Plasma Technology Solutions for Particulate Filter Regeneration

Presentation Outline

1. Introduction
2. Particulate Filter Substrates
3. Plasma Thermal Regeneration
4. Plasma Heat Generation Measurements
5. Substrate Limits and Damage
6. Physical Regeneration

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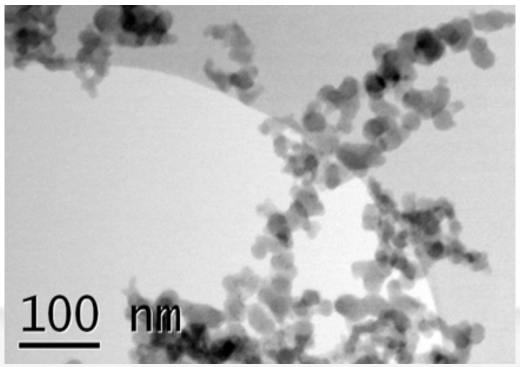
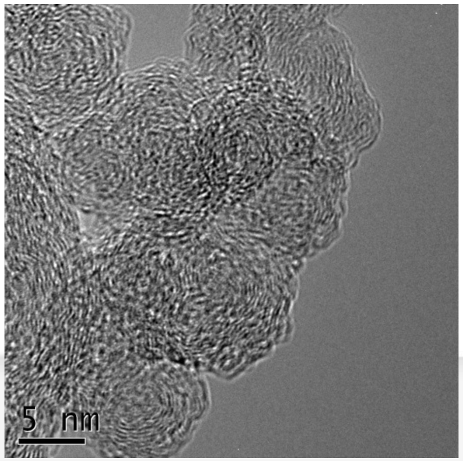
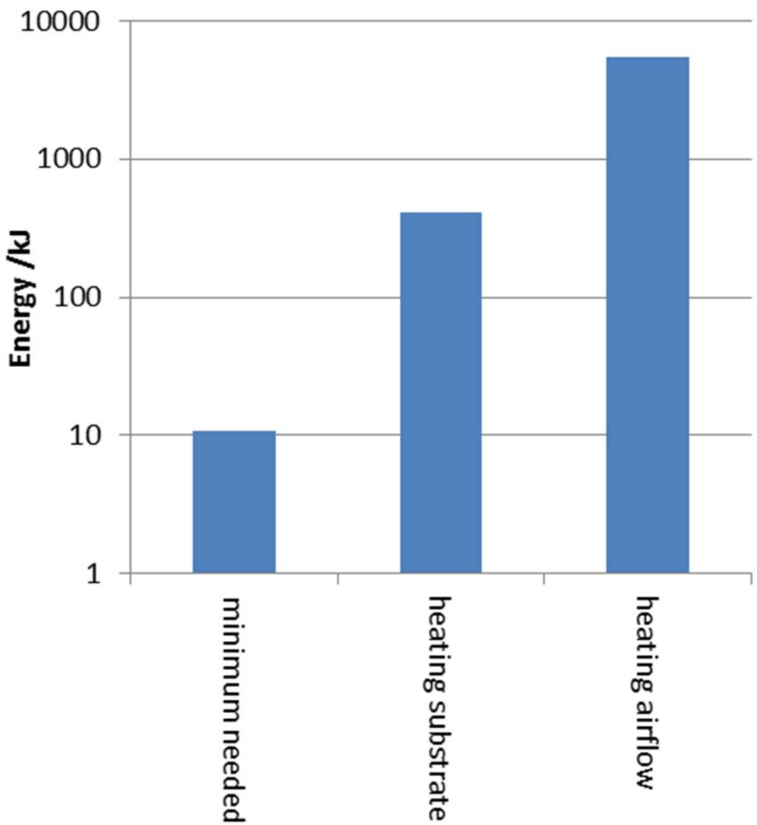
Introduction

- Particulates from combustion sources are considered harmful and are therefore regulated.
- Particulate filters are proven technologies capable of >99% reduction of particulate emissions, at the expense of fuel consumption and cost.
- Filters typically require frequent regeneration (cleaning) to maintain acceptable pressure drops which is commonly achieved through heating (oxidation).
- Direct heating of the particulates should offer a lower energy solution than heating the air which flows through the substrate.







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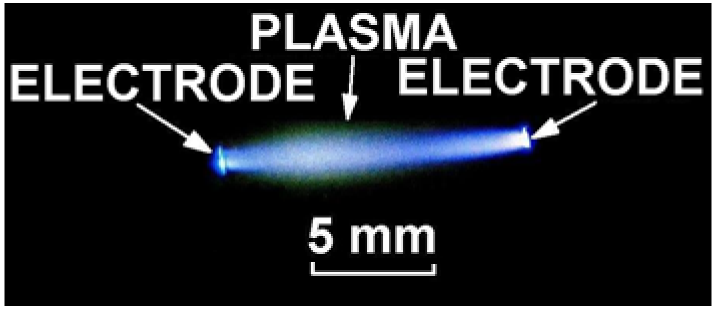
Introduction

- Prof. Colin Garner explored microwave heating in the mid 1980s
- Prof. Garner and Dr John Harry explore opportunities for electrical plasma regeneration
- 3 major projects and 4 PhDs since 2000 contributed to two unique regeneration methods

Acknowledgements:
Prof. Jon Binner, Prof. Colin Garner, Dr Karola Graupner, Dr John Harry, David Hoare, Prof. Mike Kong, Dr Karim Ladha, Dr Davide Mariotti, Dr John Proctor.

Microwave Regeneration:
Focuses energy in PM;
Slow (electrical power limits);
Requires bypass.

Electrical Plasmas:
High power density;
Rapid heating therefore no bypass needed;
Low power;
Low cost.



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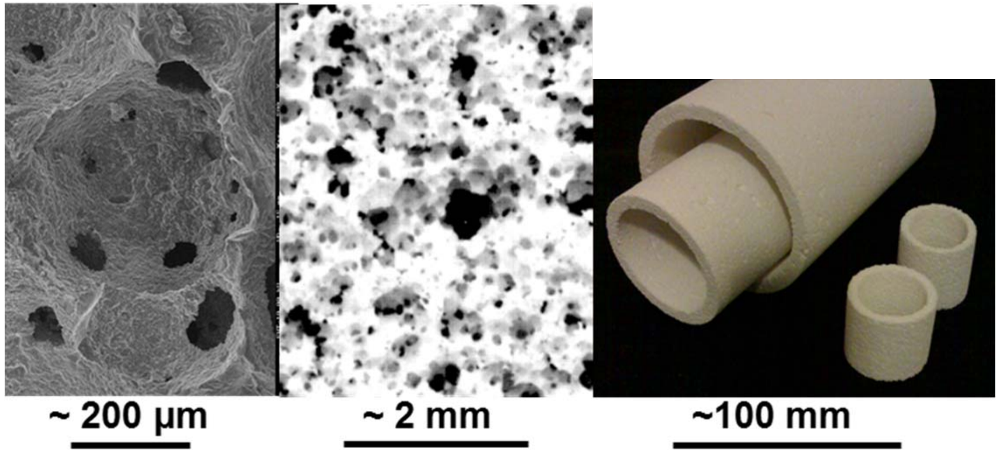
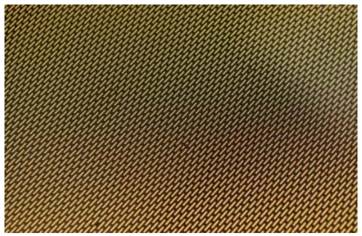
Background: Particulate Filter Substrates

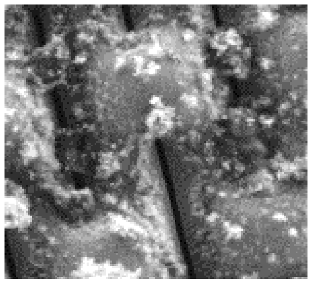
Gelcast Ceramic Foams

Analysis and Optimisation of Gelcast Ceramic Foam Diesel Particulate Filter Performance. A.M. Williams, C.P. Garner and J.G.P. Binner. IMechE Part D: Journal of Automobile Engineering Vol 222, No D11



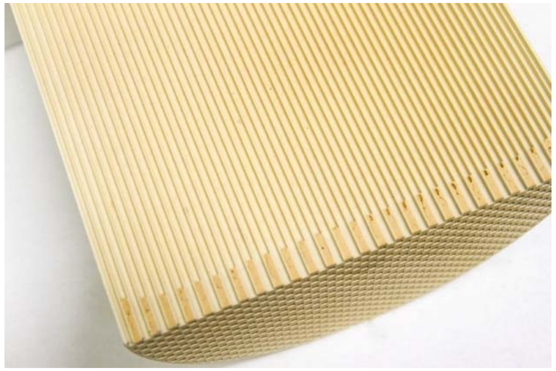
Metallic Membranes



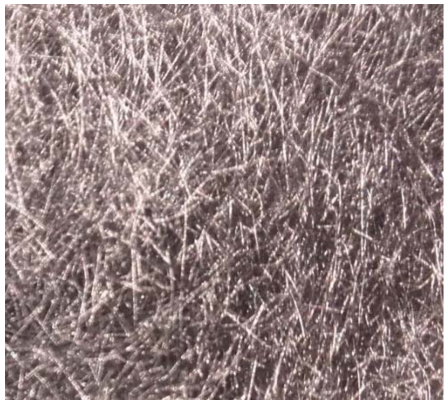


Performance of Slotted Metallic Membranes as Particulate Filters. C. Lin, B. Hillman and A.M.Williams. SAE Technical Paper 2014-01-2807.

Monolithic Wall Flow Filters



Fibrous Filters



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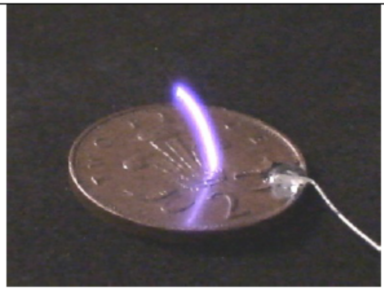
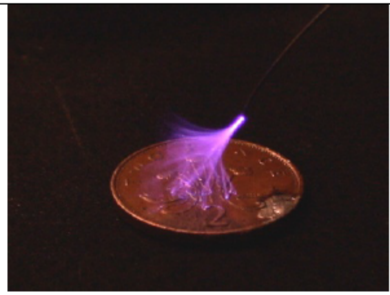
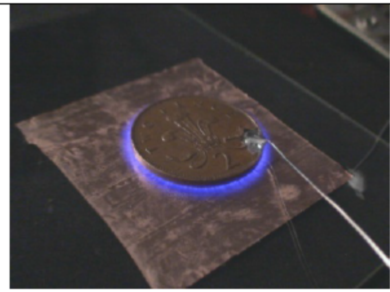
Background: Plasma Regeneration of Filters

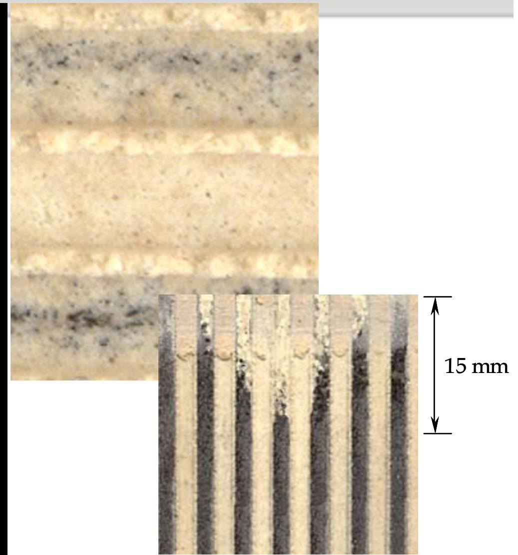
Glow Discharge	Corona Discharge	Dielectric Barrier
single current path	multiple current paths	multiple current paths
two discharge roots	one well defined root	no discharge roots
well defined discharge column	divergent discharge column	no visible discharge column

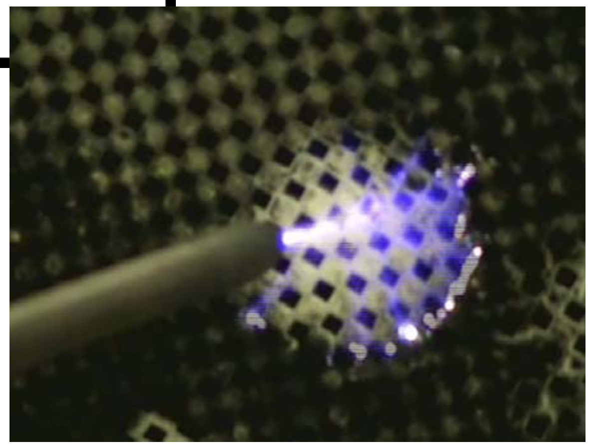


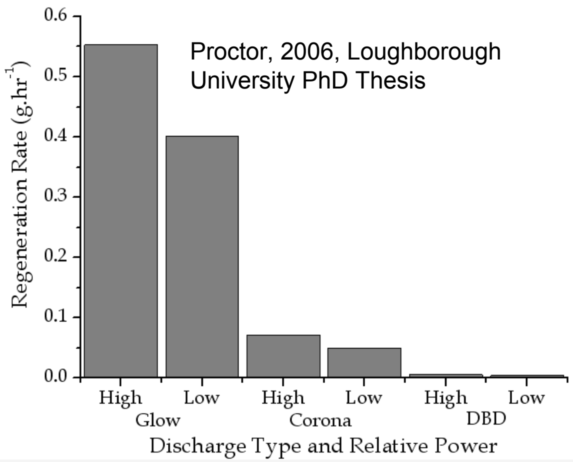


Ladha, 2010, Loughborough University PhD Thesis

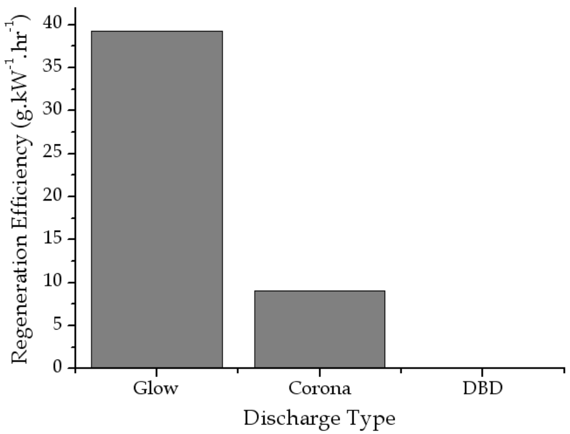




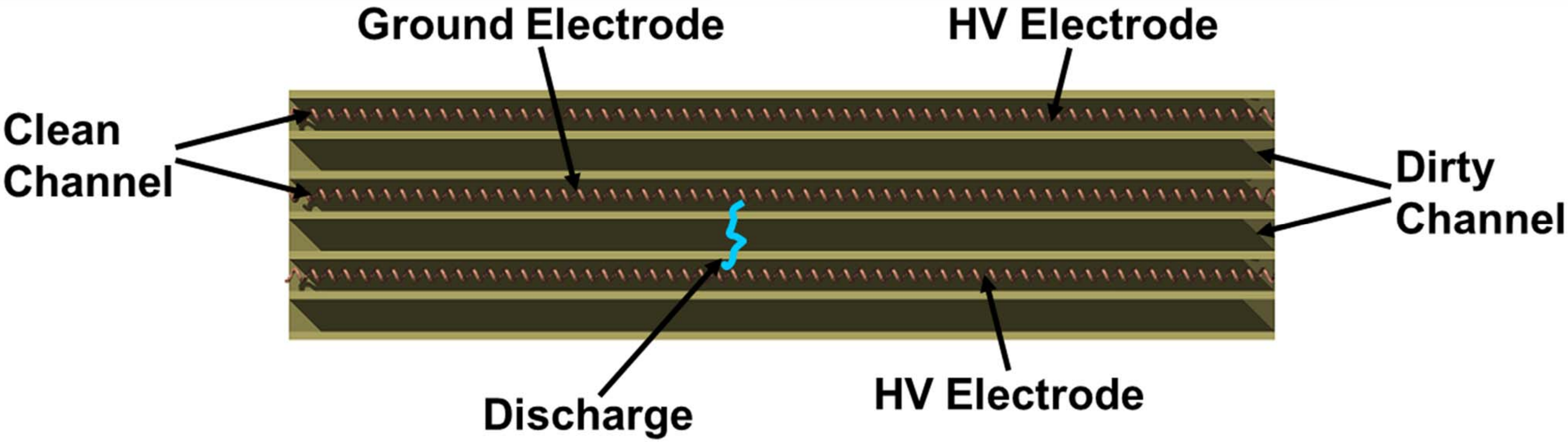




Proctor, 2006, Loughborough University PhD Thesis



Background: Plasma Regeneration of Particulate Filters



- Inserted electrodes and Autoselectivity of electrical plasmas enables regeneration (cleaning) of almost all of the filter volume.

Non-thermal Particulate Filter Regeneration Using Rapid Pulsed Electric Discharges, Mason A *et al* SAE Technical Paper 2013-01-0518, 2013

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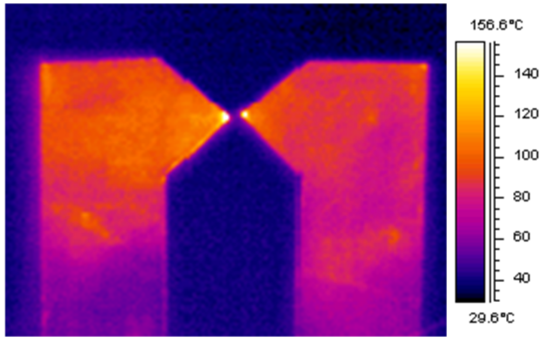
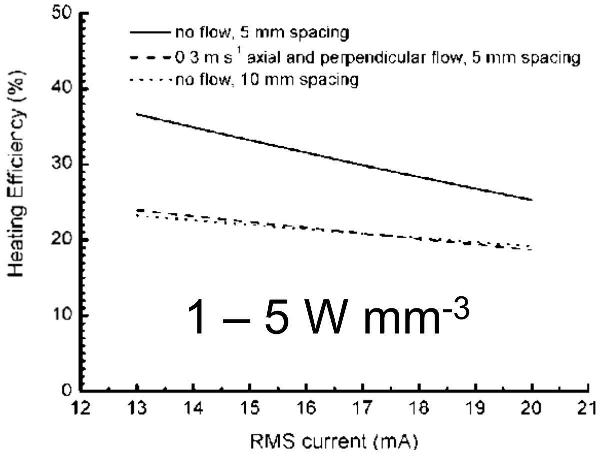
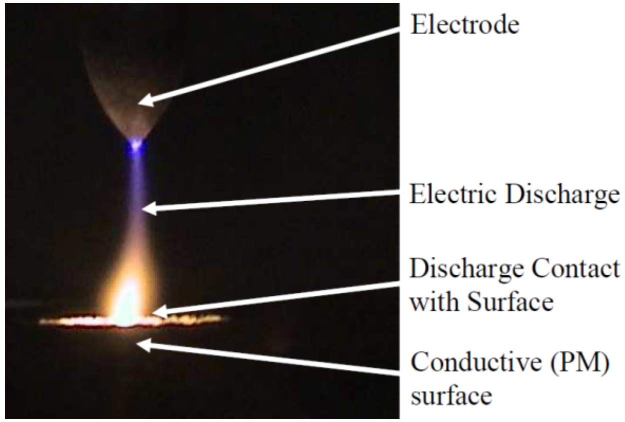
Plasma Heat Generation Measurements

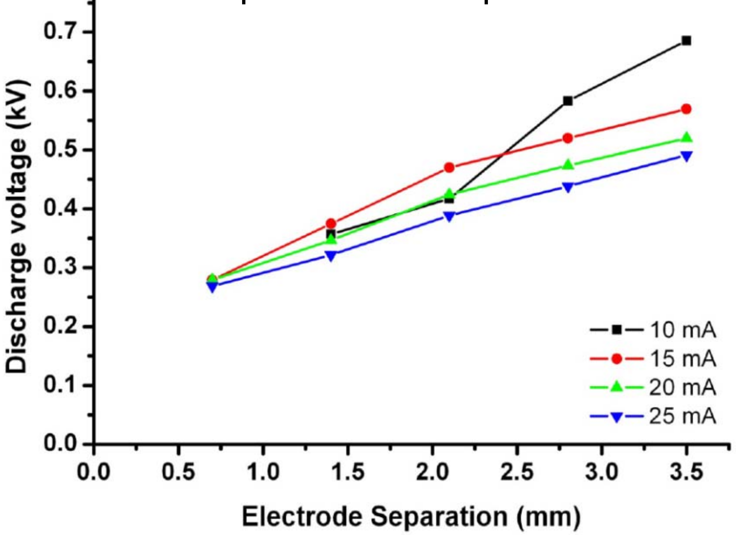
Calorimetric measurements:

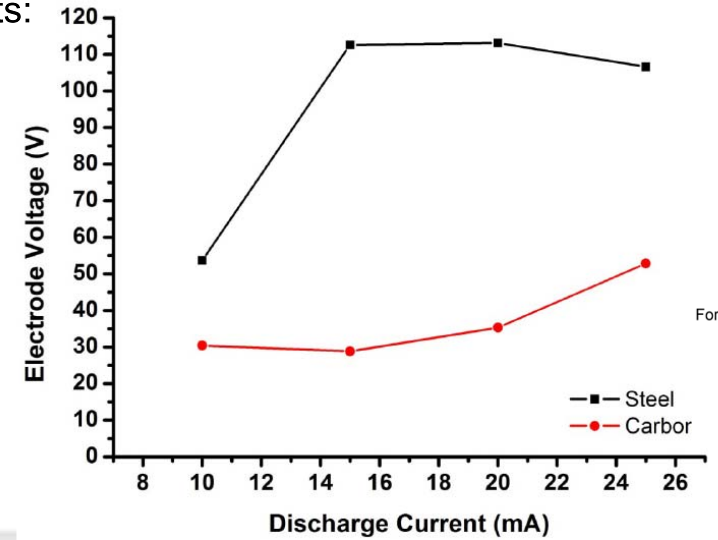


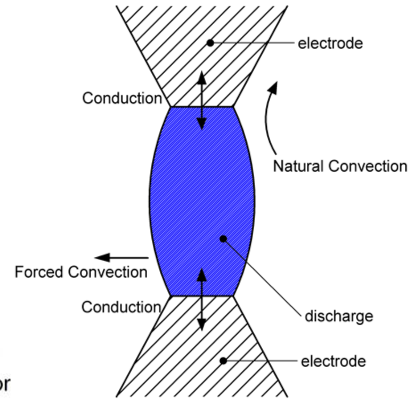




Electric power consumption measurements:







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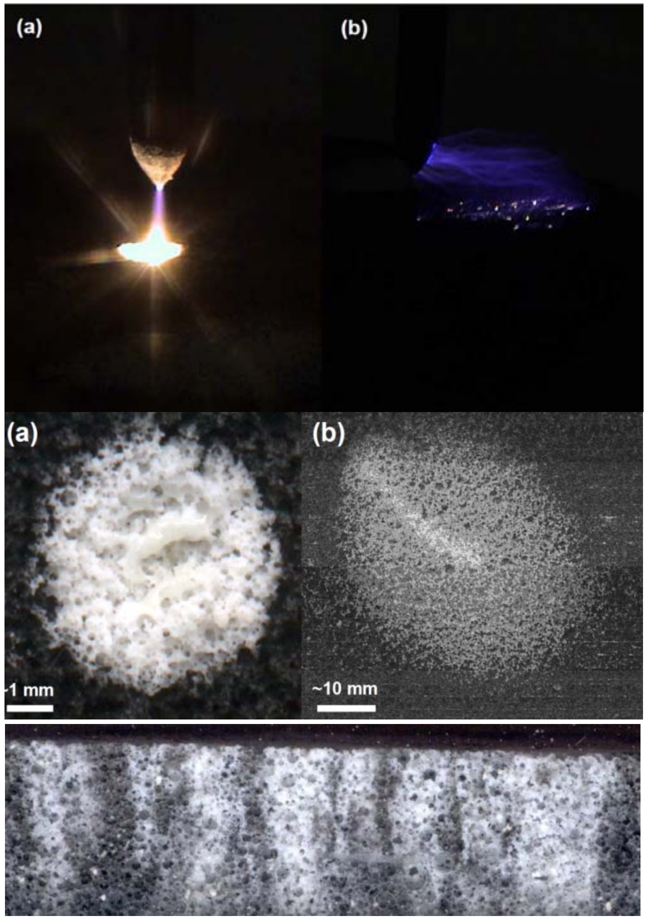
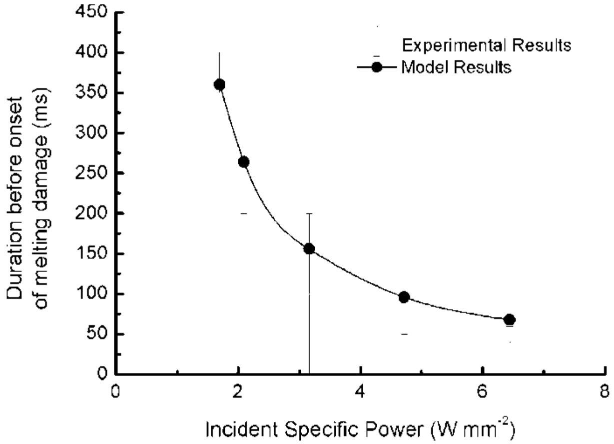
Ceramic Foams: Damage

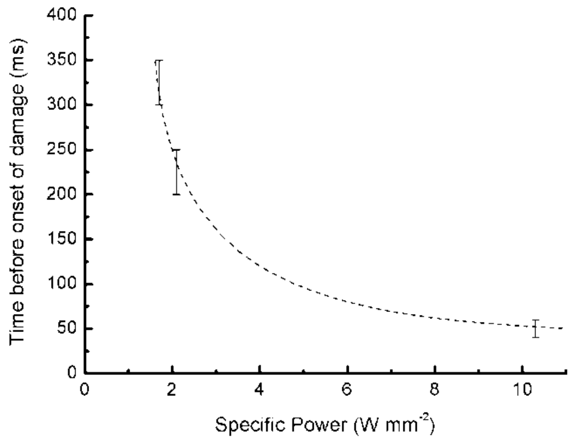


- In a 2000 hour powertrain system life with 200 regenerations, any location in the filter will be exposed to the plasma for ~60 seconds
- Failure modes of interest are typically those which can occur in a single exposure

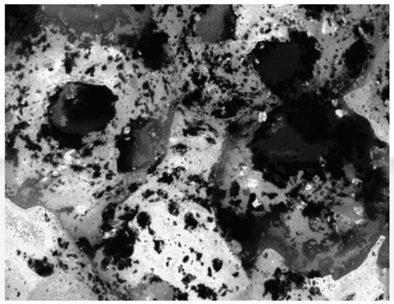
Melting in Cordierite samples:



Thermal shock in Alumina:



Distributed PM means heating of the substrate is unavoidable:



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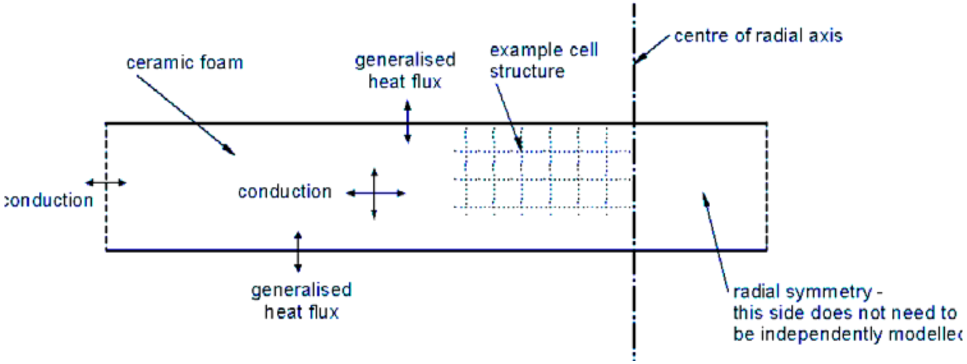
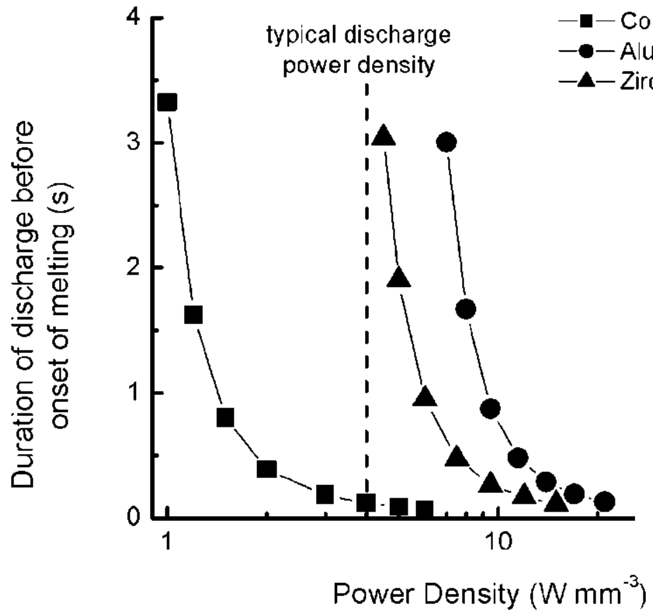
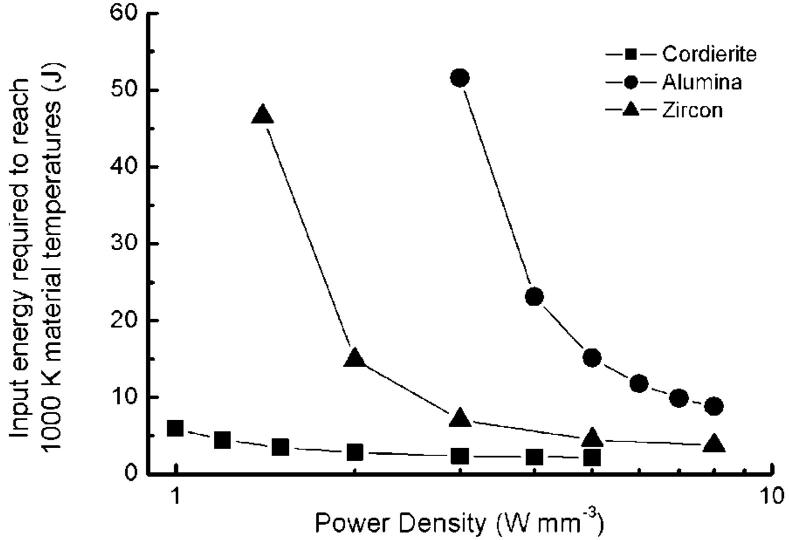
Potential for Damage

Material	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	Density ($kg\ m^{-3}$)	Specific Heat Capacity ($J\ kg^{-1}\ K^{-1}$)	Melting Temperature (K)
Cordierite	1.59	2100	753.6	1650
Alumina	8, 6.3	3980	1103.4	2050
Zircon	4.2	4600	538	2400
Silicon Carbide	59.8	3210	31.4	2700
Cordierite Foam	0.25	420	754.1	1650
Alumina Foam	1.17	796	1103.3	2050
Zircon Foam	0.62	920	538.4	2400
Silicon Carbide Foam	8.57	642	32.6	

Sources:- CRC Handbook of Chemistry and Physics (2003), Shackelford and Alexander (2001), Ahrens (1995)







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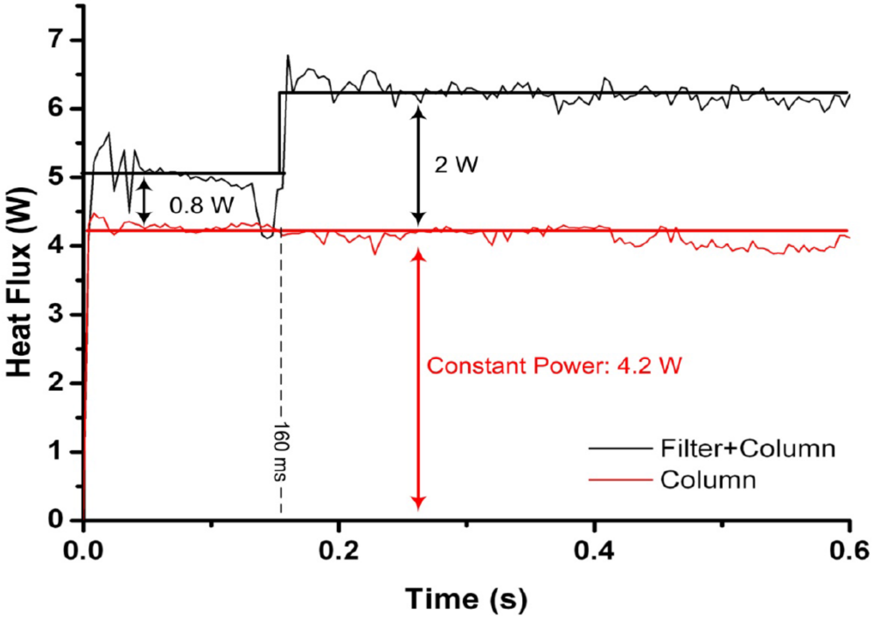
Heat Generation in Constricted Plasma

Region	Input Heat Flux (W.m^{-3})
Discharge column (constant)	2.72×10^{9}
Through-filter ($0 \le t < 160$ ms)	1.48×10^{10}
Through-filter ($t \ge 160$ ms)	3.70×10^{10}



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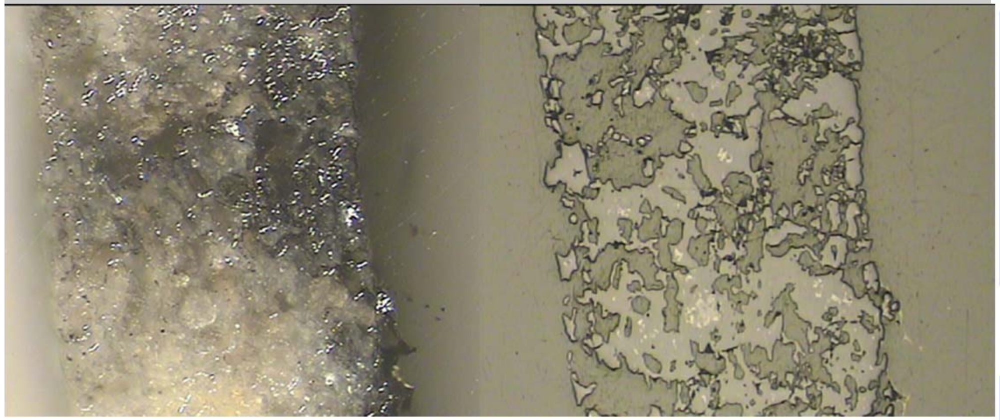
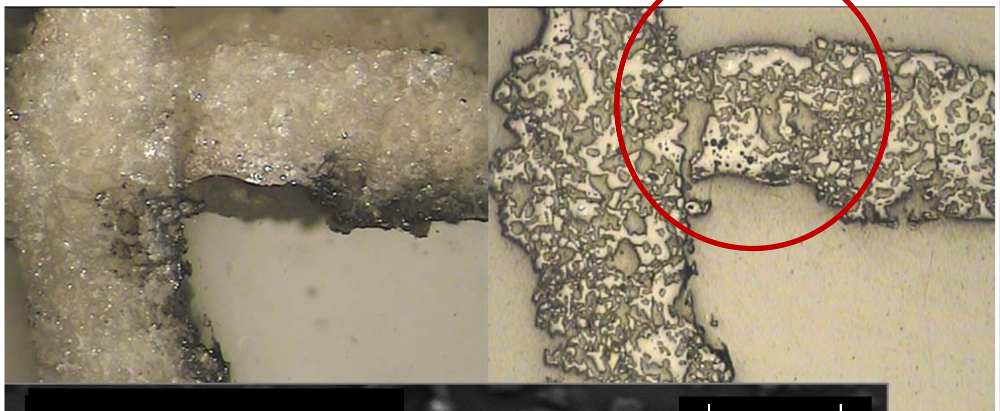
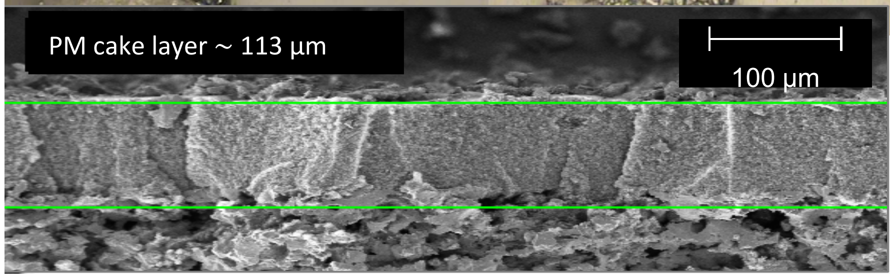
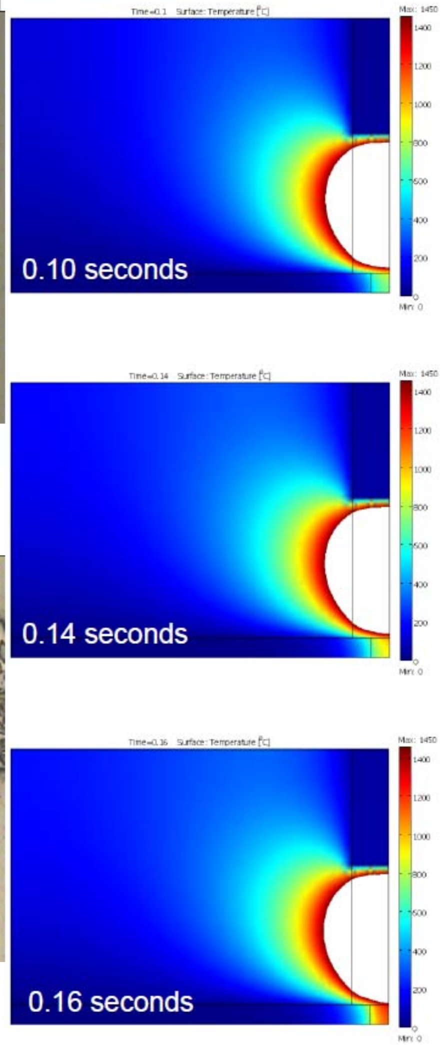
Wall Flow Filters: Damage

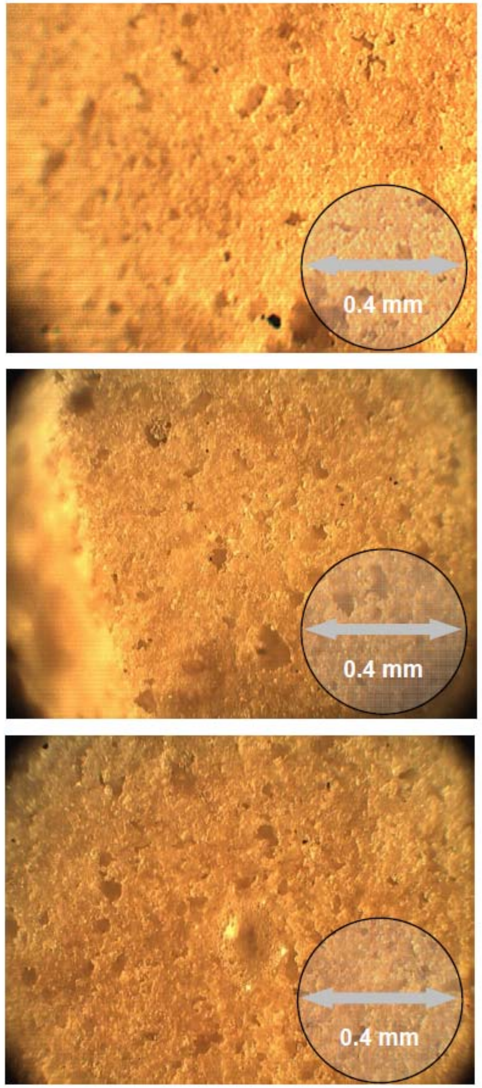


Melting leads to collapse of porous structure affecting filtration as well as plasma power consumption









Thermal lag in the substrate allows more rapid PM heating than substrate.

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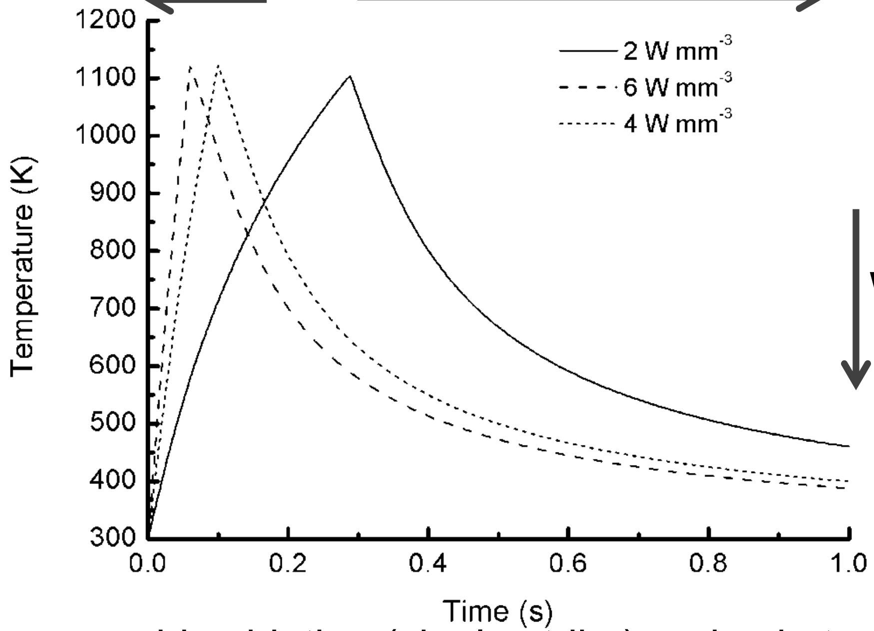
Thermal Regeneration: Challenges and Opportunity

Rapid heating desirable for efficiency

Cooling needed for autoselectivity recovery

Useful temperatures



Wasted energy

- Small margins exist between rapid oxidation (single strike) and substrate damage due to variations in pore and flow structures
- Higher working temperatures will give more margin and therefore allow fewer discharge events for a given regeneration
- Typical electrical power consumptions are still too high: ~2 kW for automotive filters.

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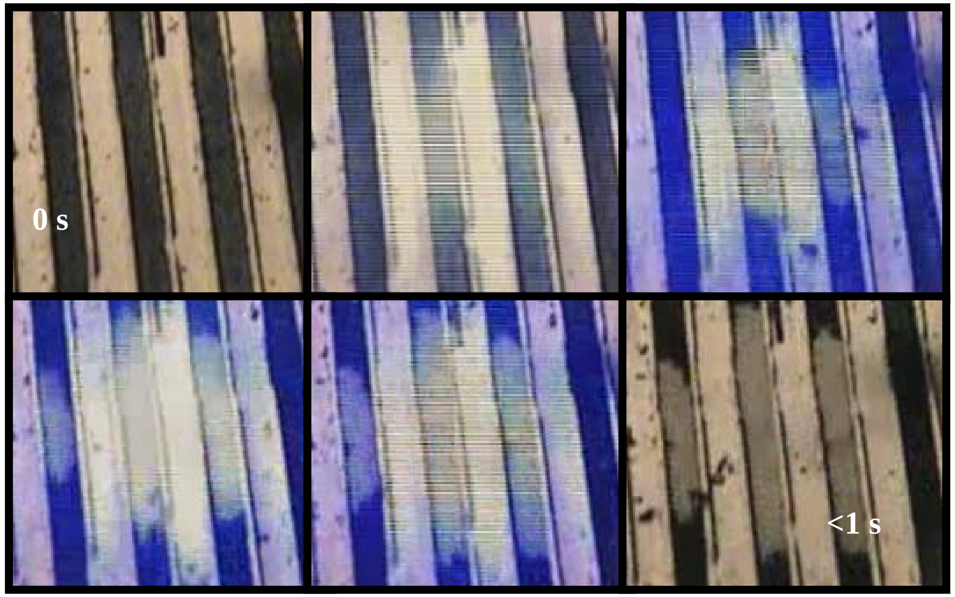
Physical Regeneration



Opportunities arise from:

- ➢ Removed need for high operating temperatures
- ➢ Removed existing packaging constraints
- ➢ Removed ash constraints
- ➢ Maintains high filtration efficiency after regeneration

Pulsed Discharge Regeneration of Diesel Particulate Filters, Graupner *et al,* Plasma Chemistry and Plasma Processing Volume 33 (No 2):467-477 (11 pages) Apr 2013

Summary

- Regeneration of particulate filters is needed to maintain acceptable pressure drops.
- For oxidation, we want to heat the PM and adjacent air. Typically we expend our energy heating the bulk air flow unnecessarily.
- Localised rapid heating with electrical plasmas allows rapid regeneration, however to be effective, alternative non electrically conductive substrates are needed that can operate at higher temperatures.
- Pulsed plasmas enable physical regeneration thereby removing the need for heating and opening an avenue for new, lower temperature, lower cost substrates.

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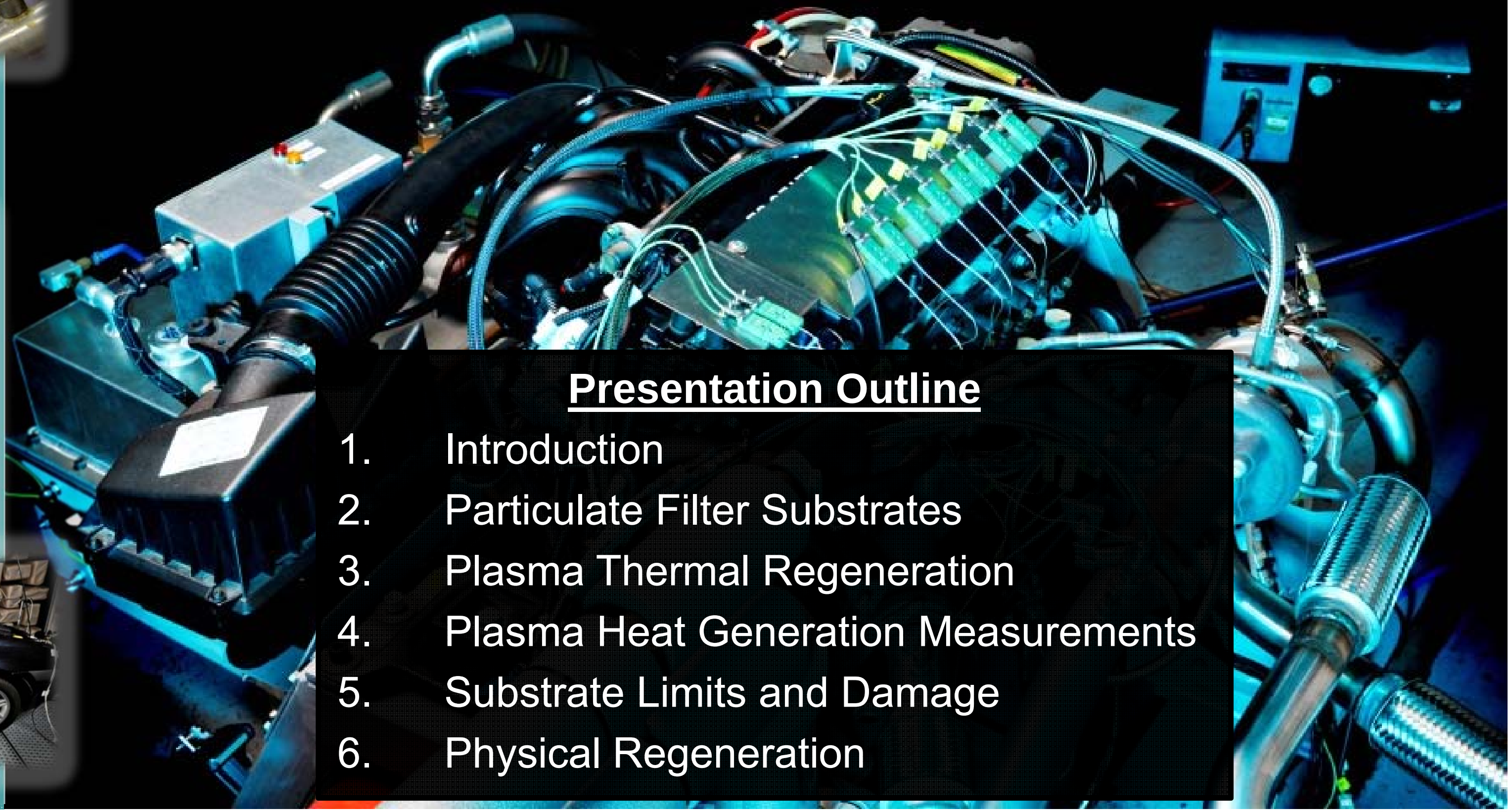
Opportunities and Consequences of Plasma Technology Solutions for Particulate Filter Regeneration



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