Development of A Microwave Assisted Particulate Filter Regeneration System

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DEER
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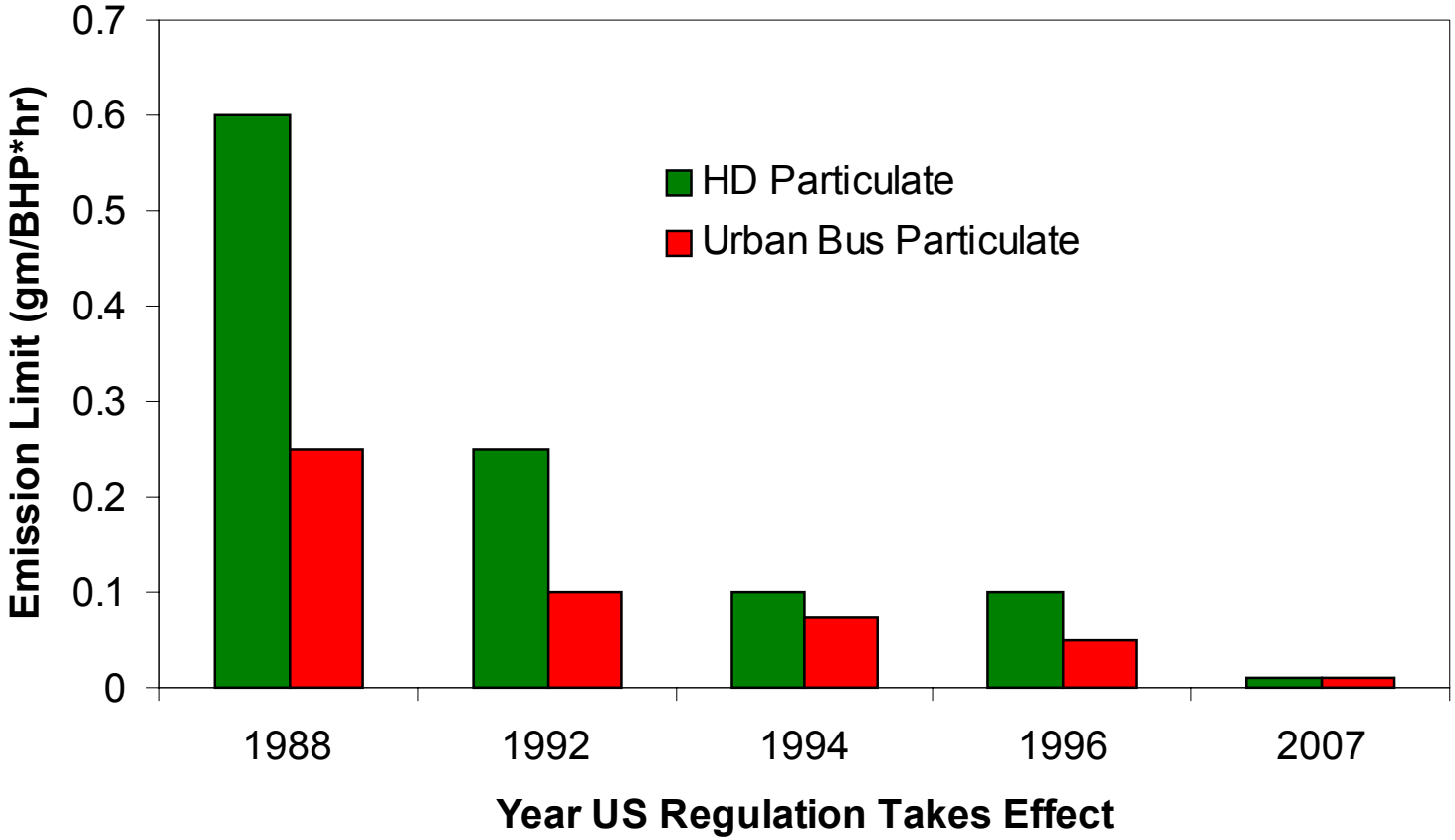
US Particulate Emissions Standards History



Filtration is the only proven method for meeting the 2007 standards

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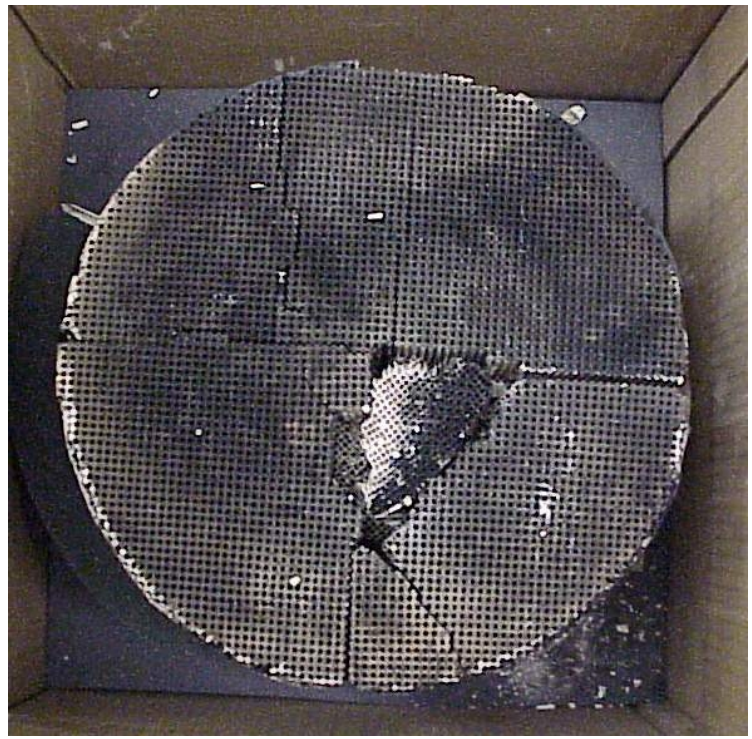
Results of High Soot Loads

Excessive Peak Temperatures - Melting



Excessive Temperature Gradients - Fracture

Removal of accumulated soot (regeneration) is a major issue

Regeneration Approaches

- Passive Regeneration:
  - Typically catalytic oxidation
  - Make combustion temperature equal exhaust temperature
  - Will not work for all duty cycles, particularly light and medium duty
- Active Regeneration:
  - Addition of energy to remove soot from a soot filter
  - May increase initial cost and fuel penalty
  - Common Approaches:
    - Burner system (Deutz)
    - Electrical (Donaldson)
    - Engine Management and Fuel Additive (Peugeot)
    - Microwave

Microwaves - Background

- Heating characterized by the dielectric constant

$$\varepsilon = \varepsilon' + j\varepsilon''$$

$$p = 2\pi f \varepsilon_0 \varepsilon'' E_{in}^2$$

$$D_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}} \frac{1}{\sqrt{\left[1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right]^{0.5} - 1}}$$

Sample	ε'	ε''
Soot	8.6	7.4
Cordierite	1.0008	0.00006

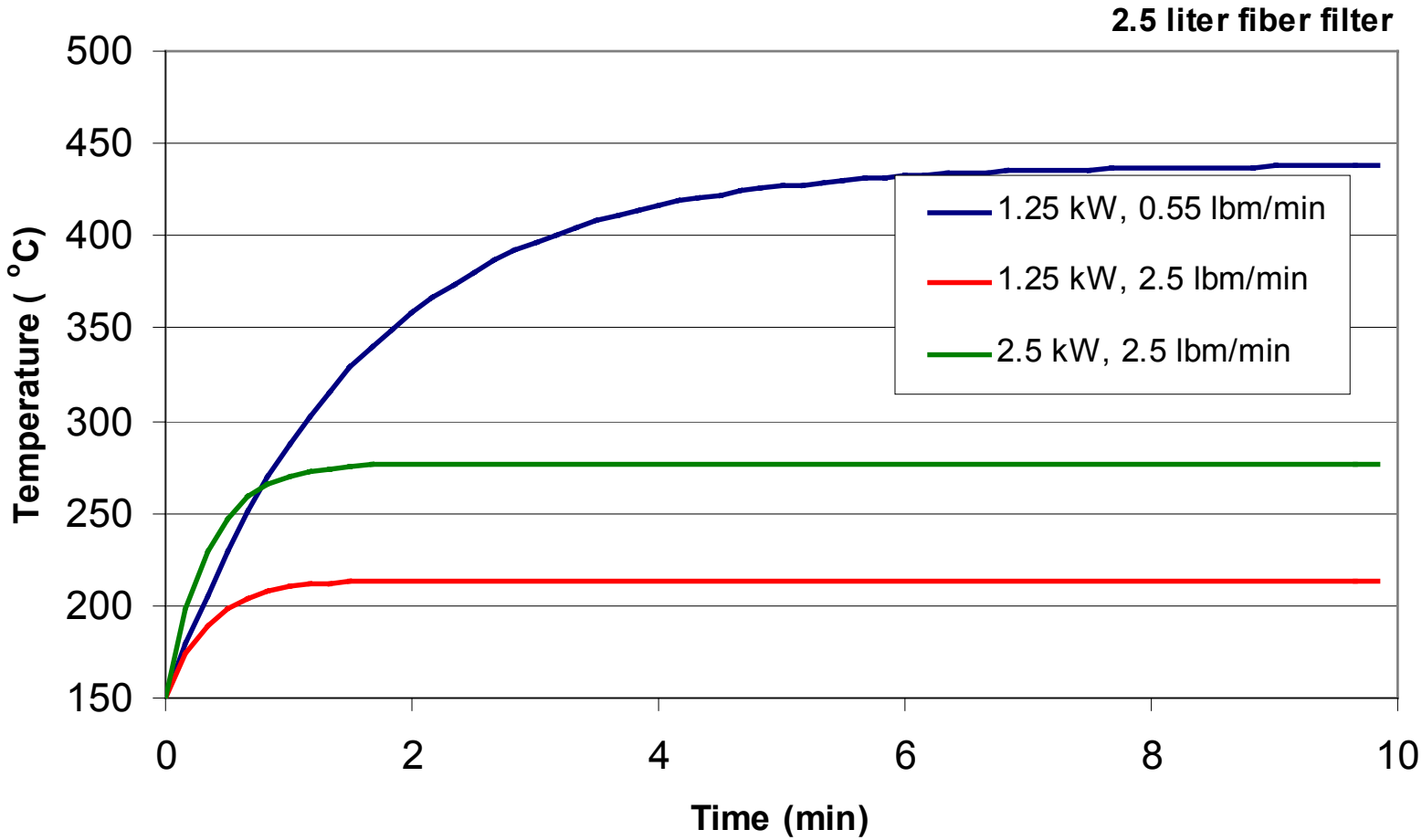
**Source: Babu, V. Suresh., Popuri, S., Gautam, M., Seehra, M.S., (1996), "Thermal and Microwave Characteristics of Diesel Particulate Matter in Relation to Microwave Regeneration of Traps", J. Applied Occ. and Environ. Hygiene, Vol. 11, No. 7, pp 799-803.*

Microwave Heating

From the equations on the previous slide it is readily apparent that:

- Soot absorbs 100,000 times more energy than cordierite in the same electric field
- Microwaves penetrate and can heat inner portions of solid materials

Heating Exhaust Increases Power Requirement



Low Exhaust Flow Increases Heating Efficiency

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Objective

Develop an efficient active soot filter regeneration system

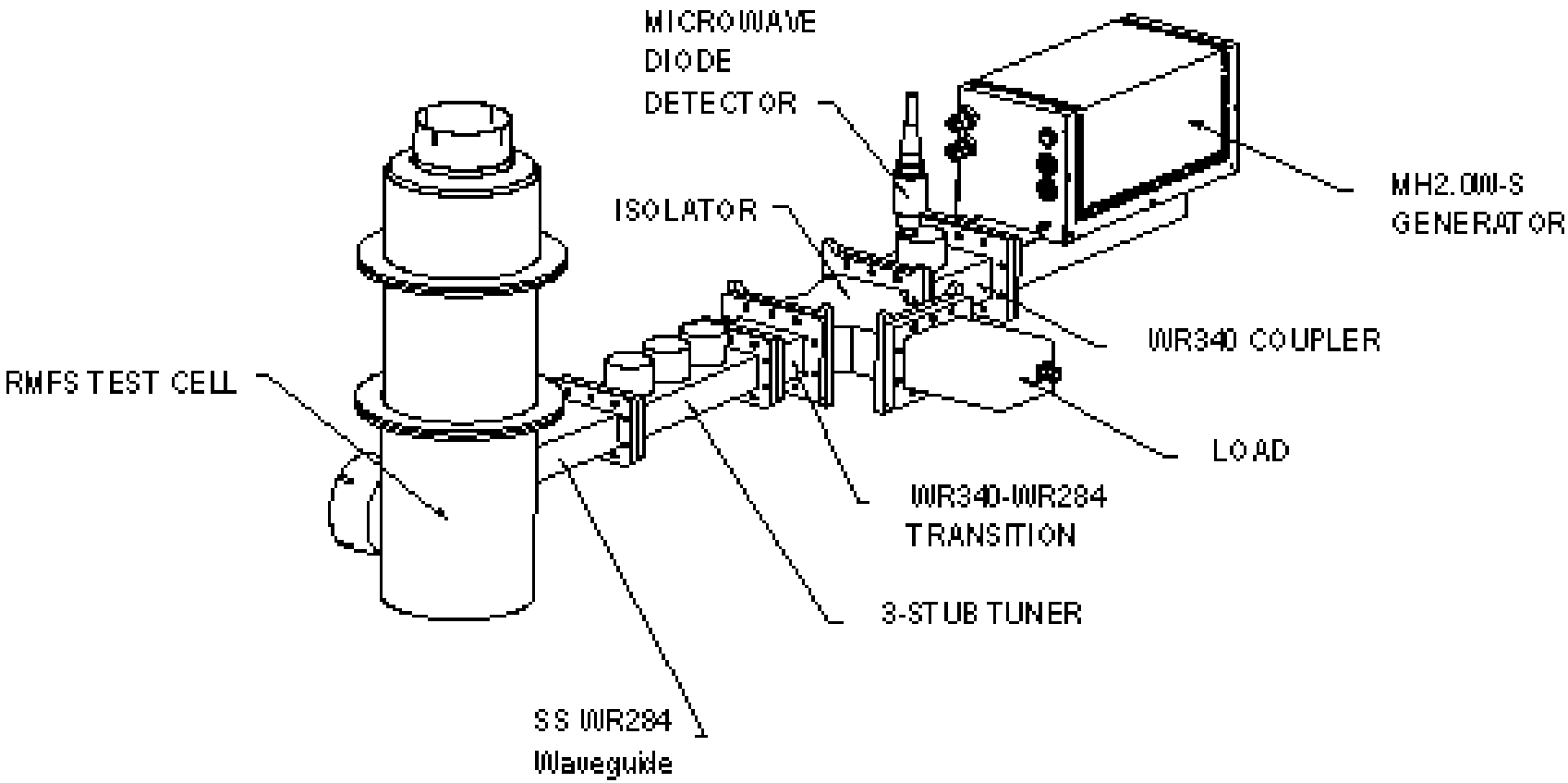
Why Microwave Heating?

- Direct and selective heating of soot/catalyst/susceptor
- Microwaves penetrate
  - Volumetric heating allows greater temperature uniformity
  - Energy (heat) delivery is more rapid than conduction or convection
- No electrical connections in the exhaust stream
- Exhaust flow is not heated directly

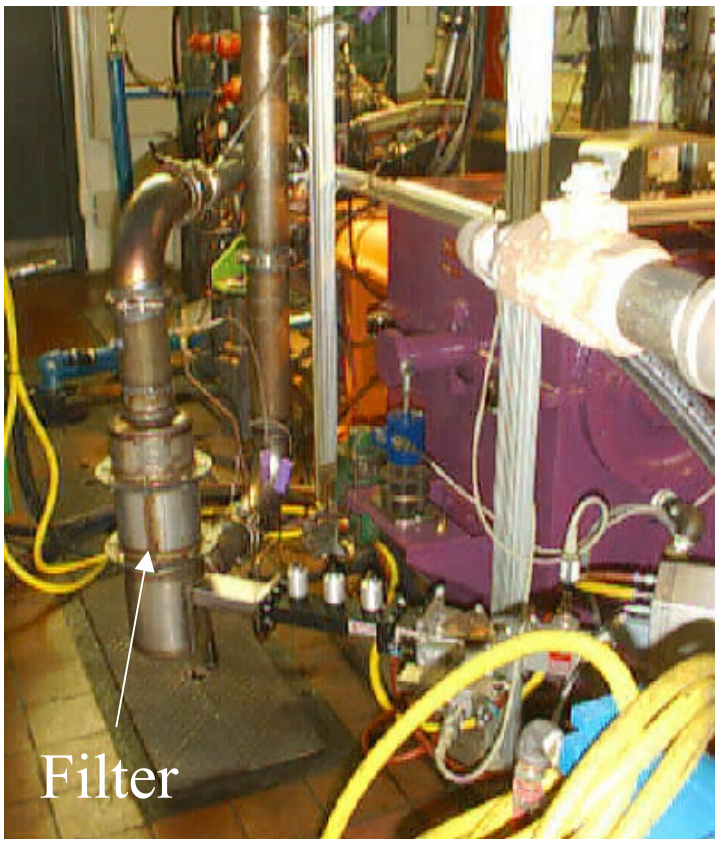
System Development Path

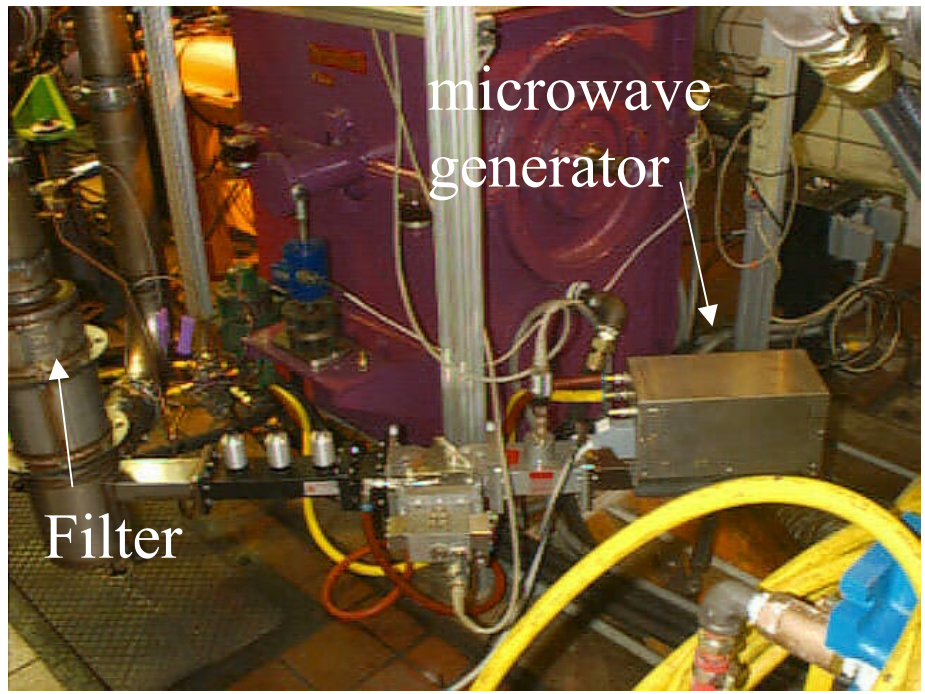
- Microwave system development
  - Off-the-shelf microwave generator, waveguide, and power supply
  - Cavity optimization
    - modeling
    - bench scale testing
    - test-cell performance
  - Dielectric property measurement
- Particulate filter development
  - Low thermal mass
  - Meet or beat performance of conventional wall-flow filter
- Overall system development
  - Determine optimal operating conditions
  - Control strategy development

Microwave Equipment

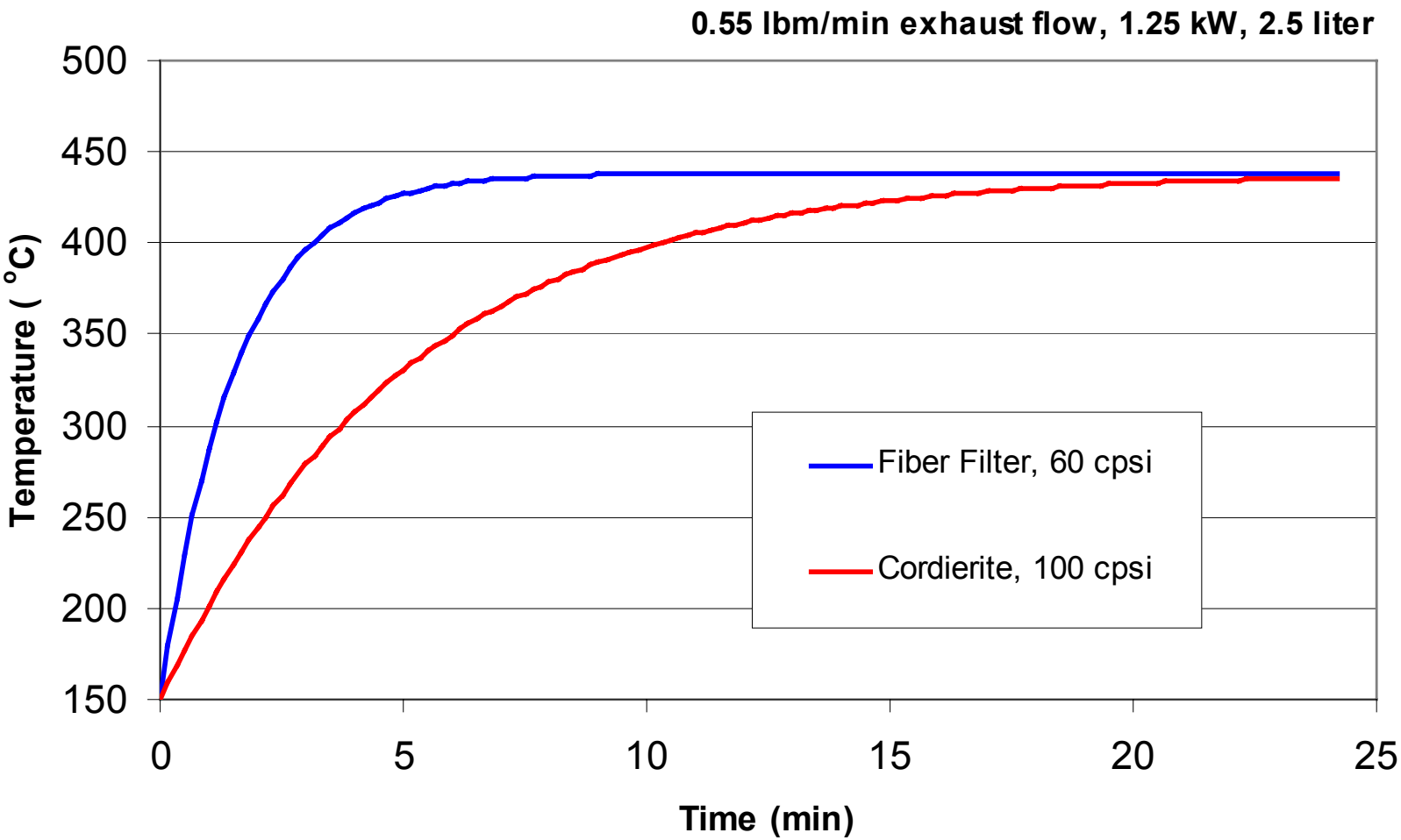


Microwave Equipment





Filter Development - Modeling



Low Filter Mass Increases Heating Efficiency

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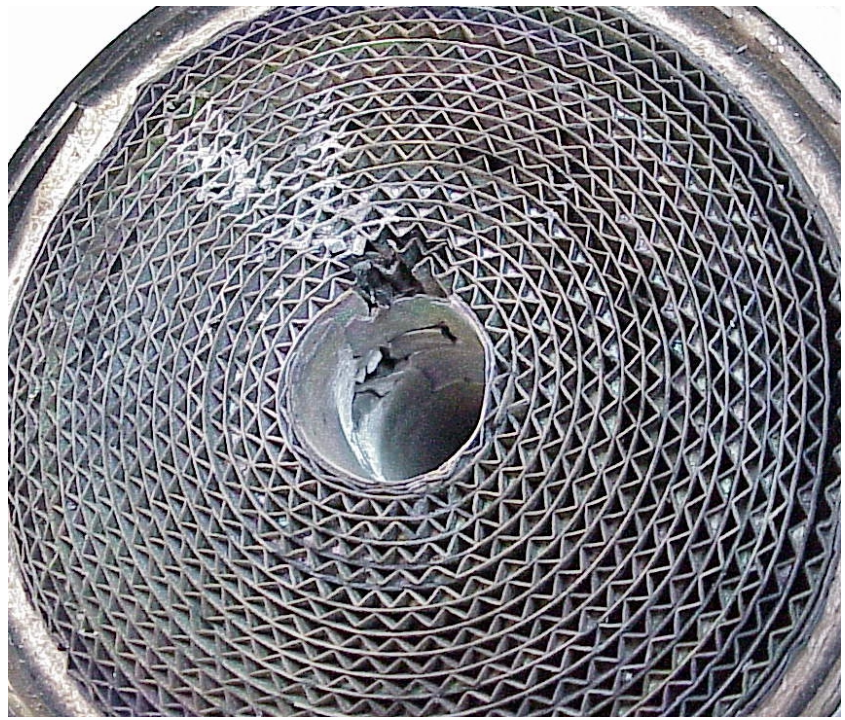
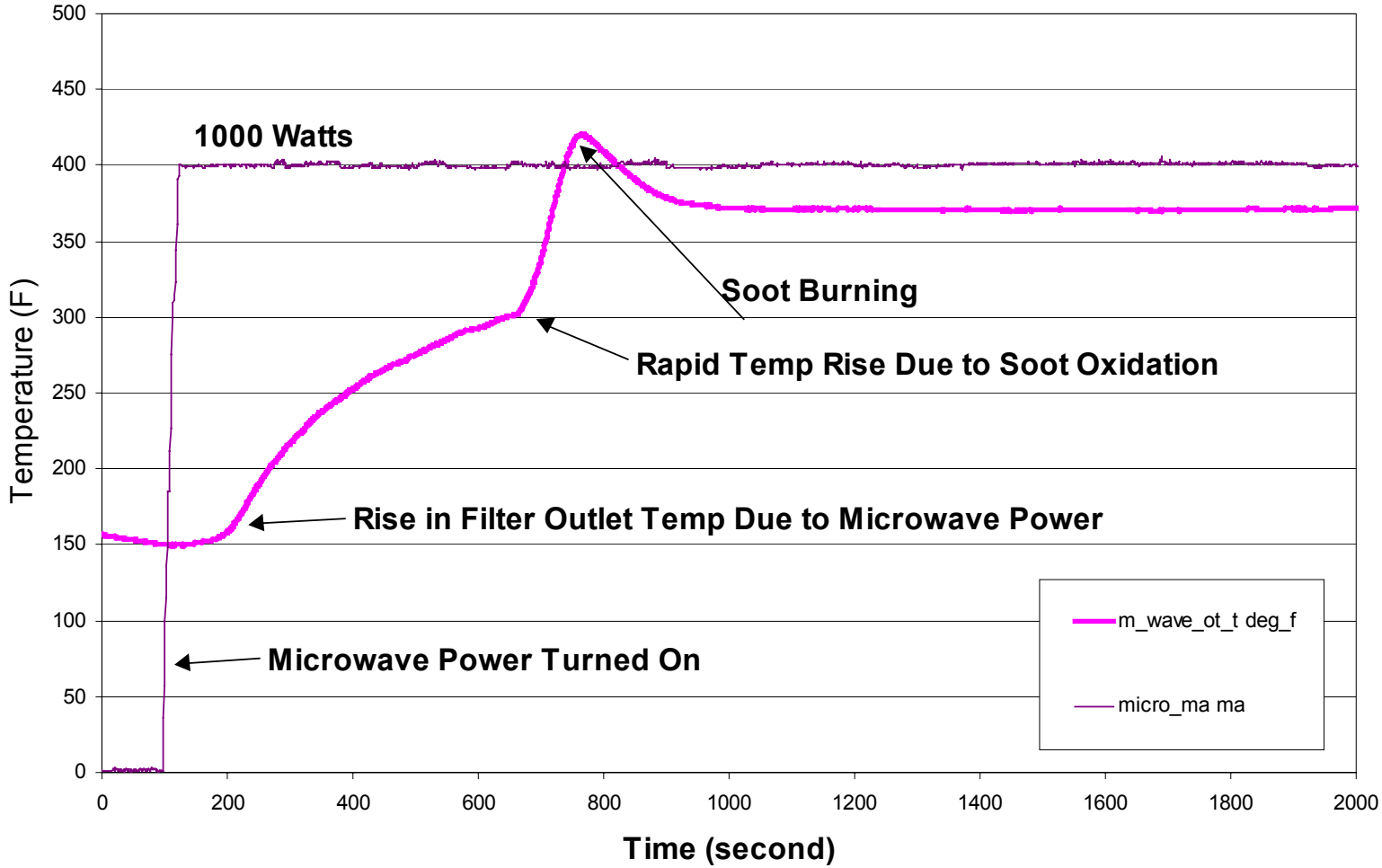
CVD/SiC Bonded Fiber Filter

- Lab scale CVD SiC coatings provided tough, uniform coatings
- Production CVD SiC coatings
  - insufficient uniformity for microwave regenerated PM filters
  - poor temperature uniformity
  - low strength



Test Cell Results

DPF - Active Regeneration with Microwave



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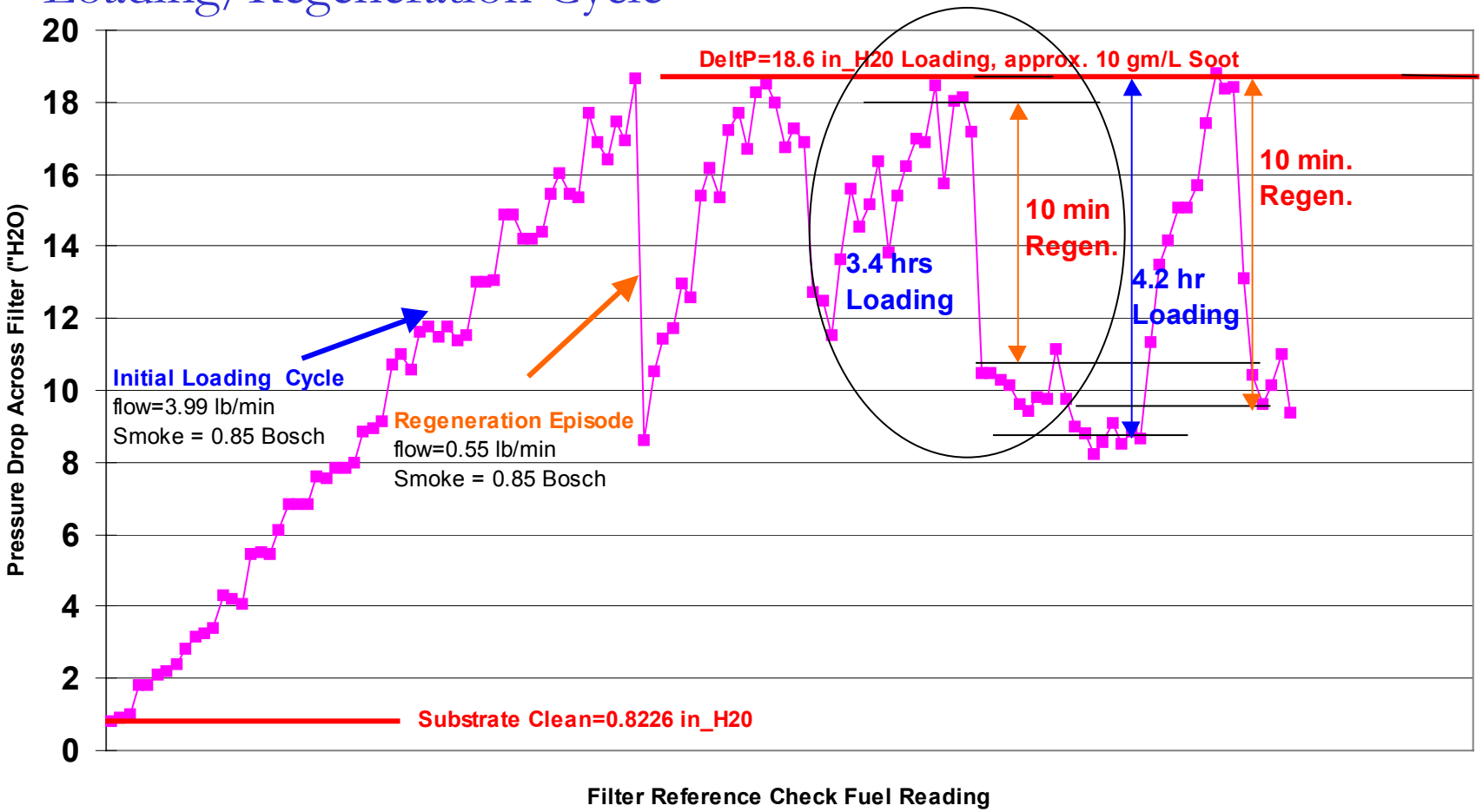
Test Cell Results

Loading/Regeneration Cycle



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Test Cell Results

- The current microwave system and waveguide components are more robust than earlier systems.
- >100 hours of engine operation with microwave regenerable filter.
- Regeneration with as few as 10 minutes heating
- Exhaust temperature increase up to 260°C during microwave heating
- Demonstrated seven regeneration events

Current Tasks

- A parametric study is underway involving the following key parameters to define the optimal operating conditions
  - Soot loading level
  - Oxidant flow rate
  - Microwave heating time
  - Microwave power level
  - Oxidant inlet temperature (for supplemental air source)
- Assessment will be made for the need and significance of using supplemental air source as oxidant supply as opposed to engine exhaust
- Optimization of cavity and filter material are underway utilizing fundamental studies on bench scale testing and modeling