DPF Durability and Control
DPF耐久性及控制

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第11届内燃机可靠性技术国际研讨会

SOUTHWEST RESEARCH INSTITUTE®

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Presentation Outline 报告内容

- Introduction 简介

- DPF Control DPF控制
  - Soot deposition algorithms 积碳算法
  - DPF regeneration control strategies DPF再生控制策略
  - OBD monitors OBD监测

The DPF Continues to Evolve DPF技术持续发展

- Fuel Efficiency 燃油效率
  - Reduction in active regenerations 减少主动再生
    - Better soot/ash loading prediction 更好的积碳/灰分加载预测
    - Passive regeneration strategies 被动再生策略
  - Reduced pressure drop减少压降
- Achieve Cost Reduction 成本降低
  - Downsizing 尺寸减小
  - Combining technologies (i.e. SCR-F) 组合技术（如SCR-F）
- Improved Filtration Efficiency (both PM and PN) （PM和PN）过滤效率提高
- Improved Thermal Survivability / Durability 热生存能力/耐久性提高

Stage	Test Cycle	CO	HC	NMHC	CH_4	NOx	PM	PN	NH_3
		mg/kWh						kWh^{-1}	ppm
China VI CI	WHSC	1500	130	-	-	400	10	8.0×10^{11}	10
	WHTC	4000	160	-	-	460	10	6.0×10^{11}	10
	WNTE	2000	220	-	-	600	16	-	-

DPF Required

DPF R&D and Application Roadmap DPF研发及应用路线

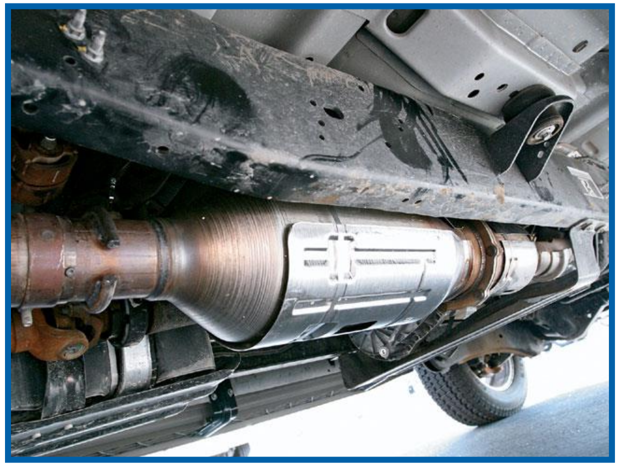
Performance 性能

- Filtration Efficiency 过滤效率
- Pressure Drop Performance 压降性能
- Soot Mass Limit 积碳质量限制
- Washcoat Compatibility 载体涂层兼容性

Component 零部件

Durability 耐久性

- Thermal Aging 热老化
- Thermal Durability 热耐久性
  - Thermal cycling 热循环
  - Thermal survivability 热生存能力
- Ash Accumulation 灰分累
- On-Vehicle Durability 整车 性



Assembly 总成

Validation 验证

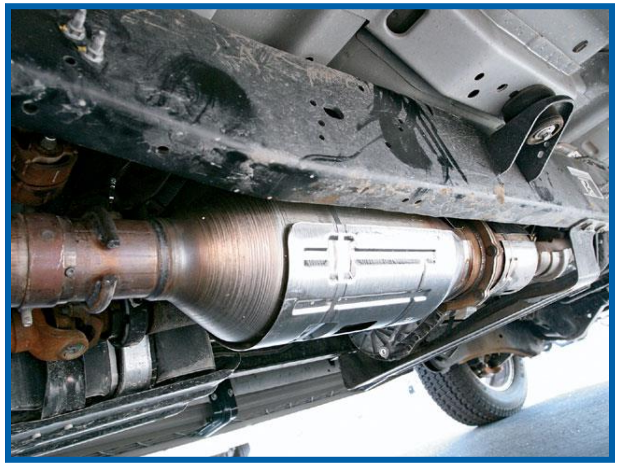
- Thermal & Mechanical 热和机械验证
  - "Hot vibration" 热振动
  - "Liquid spray" 液体喷淋

System 系统

Application 应用

- Control Strategy 控制策略
- Calibration 标定
- OBD
- System Compatibility 系统兼容

DPF R&D and Application Roadmap



Performance
- Filtration Efficiency
- Pressure Drop Performance
- Soot Mass Limit
- Washcoat Compatibility

Component

Durability
- Thermal Aging
- Thermal Durability
  - Thermal cycling
  - Thermal survivability
- Ash Accumulation
- On-Vehicle Durability

Assembly

Validation
- Thermal & Mechanical
  - "Hot vibration"
  - "Liquid spray"

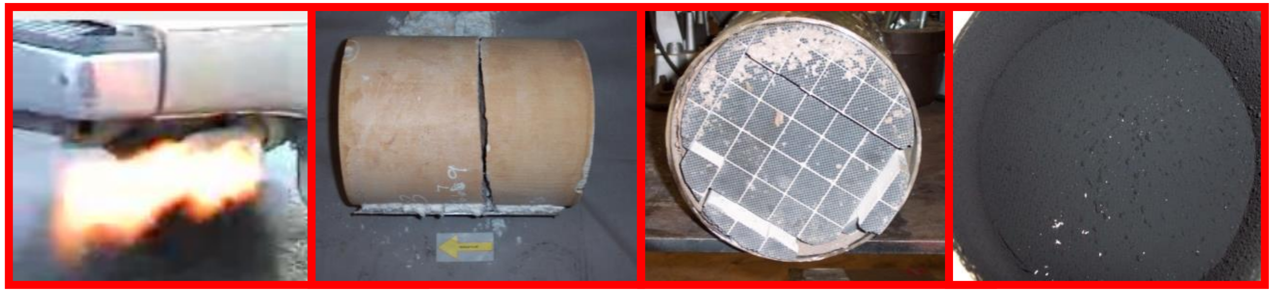
System

Application
- Control Strategy
- Calibration
- OBD
- System Compatibility

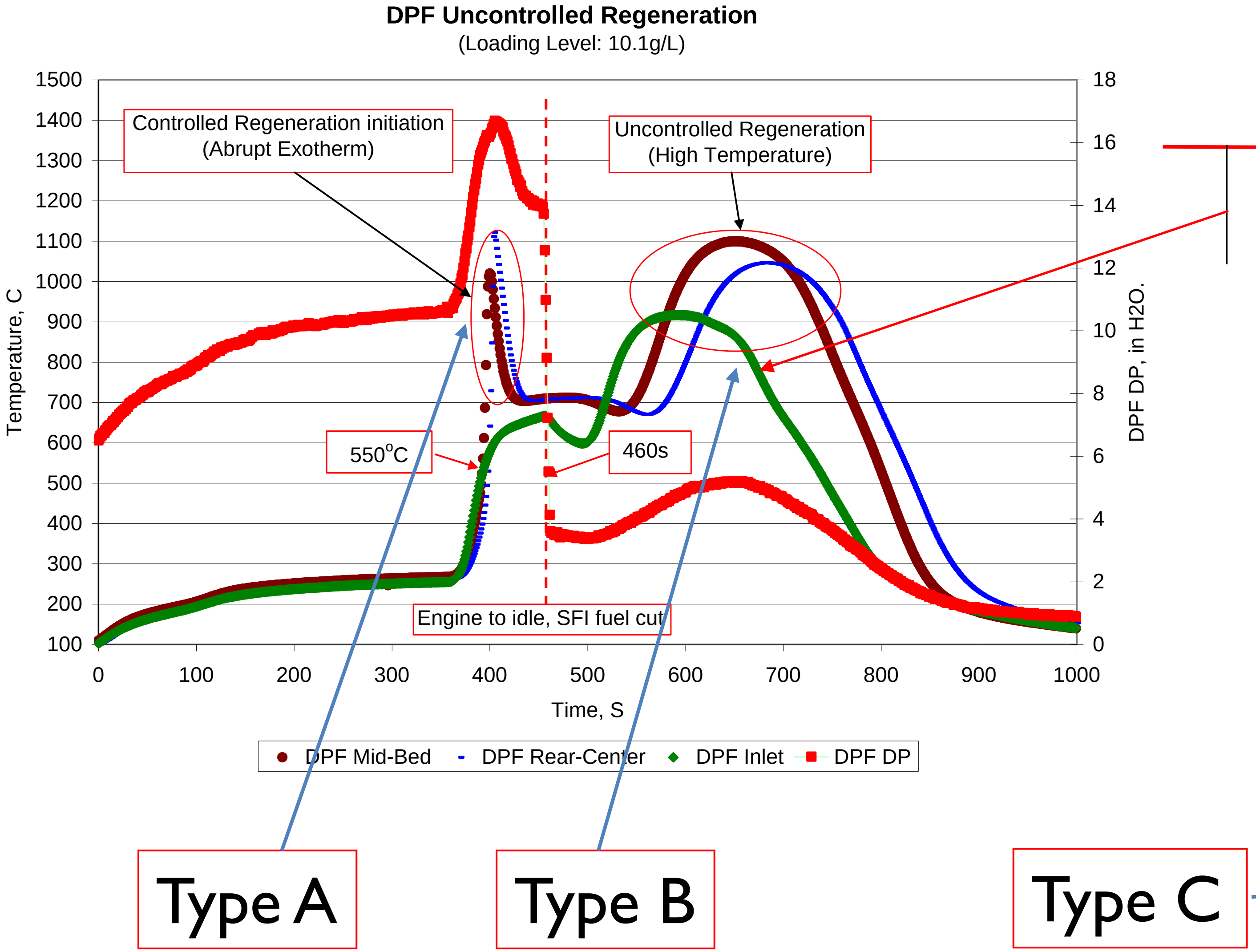
Control Strategies – Achieving Safe DPF Regeneration
控制策略-实现安全的DPF再生

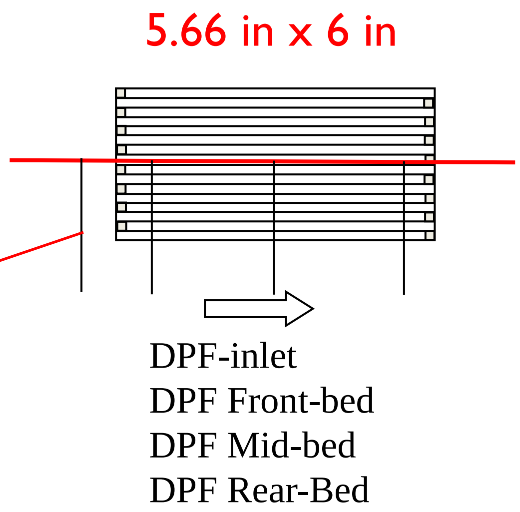
- Three Elements to "Light Fire" "点火"三要素
  - Fuel 燃油: Accumulated PM in DPF DPF中累积的颗粒物
  - Ignition Source 火源: Temperature of active regeneration 主动再生温度
  - O_2:氧气 Diesel engine operates lean 柴油机稀燃

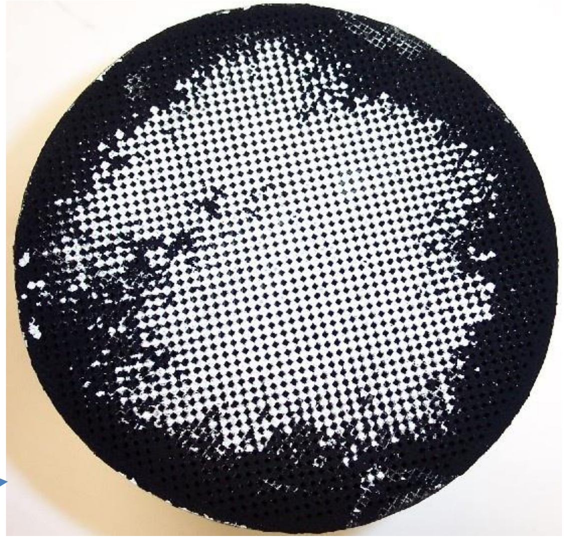
To prevent an uncontrollable fire in DPF, you need to control at least one element. 要防止DPF不受控着火，你需要至少控制1个要素



DPF Regeneration Related Failure Modes
DPF再生相关失效模式

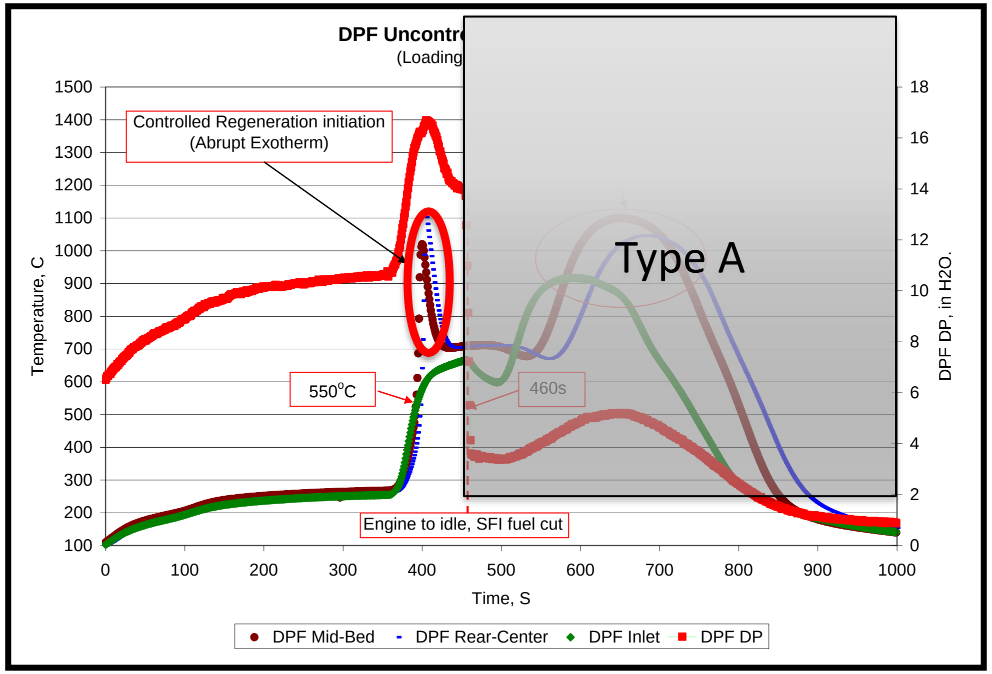






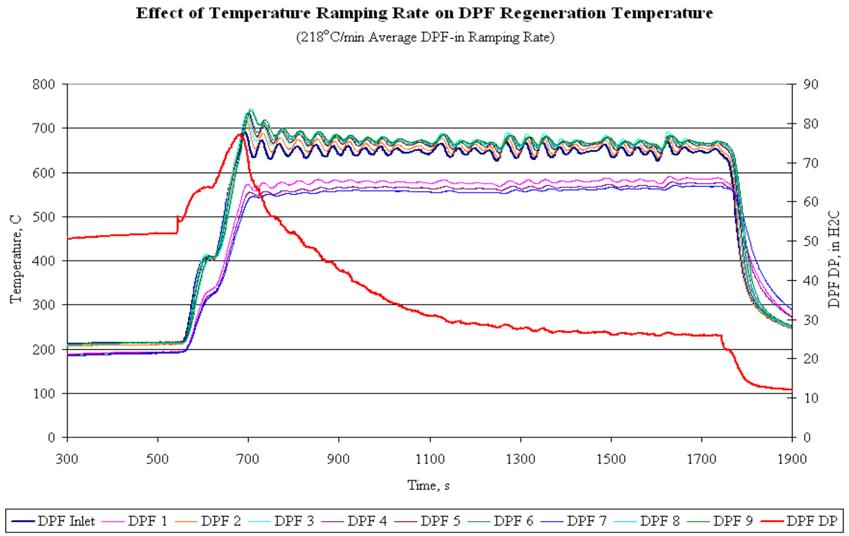
Classification of Failure Modes 失效模式分类

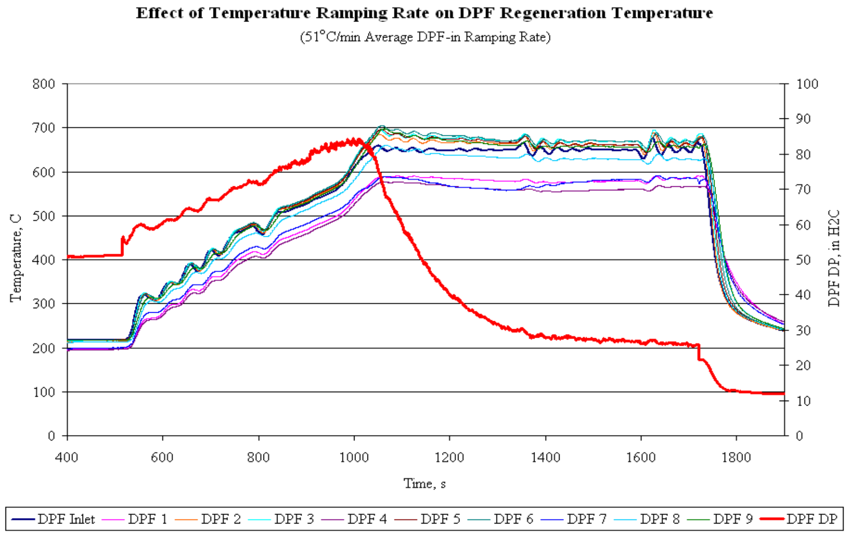
Type类型	Description 描述	Causes 原因	Solutions 解决办法
A	Abrupt exotherm at start of regeneration 再生开始时突然放热	1) High SOF content 高SOF溶度 2) High temperature ramp rate高升温速率	1) Close-coupled DOC 密耦合DOC 2) Control of temperature ramp rate 控制升温速率 3) Stepped regen 梯级再生

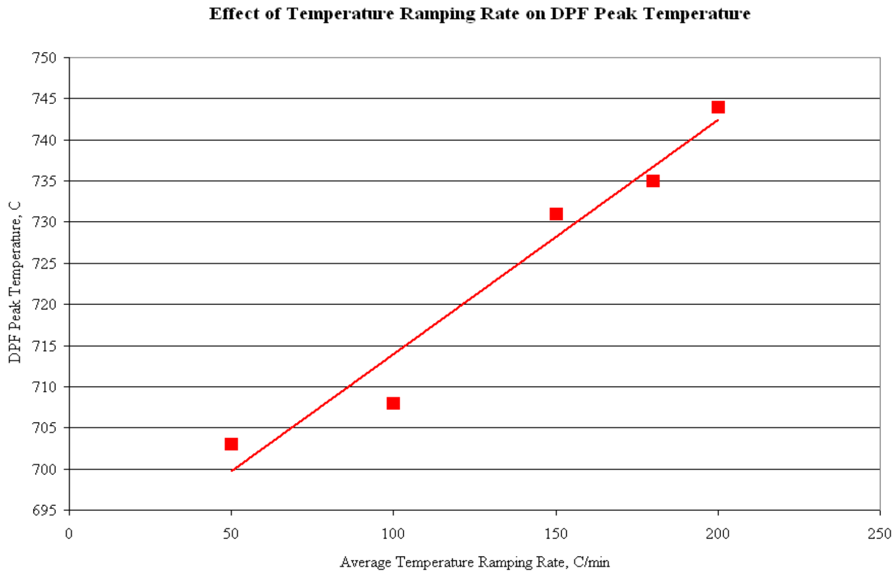


Control of Type A Uncontrolled Regeneration A类不受控再生控制

Effect of Temperature Ramp Rate (PSA DW-10, 5.66"X6" uncoated DPF)



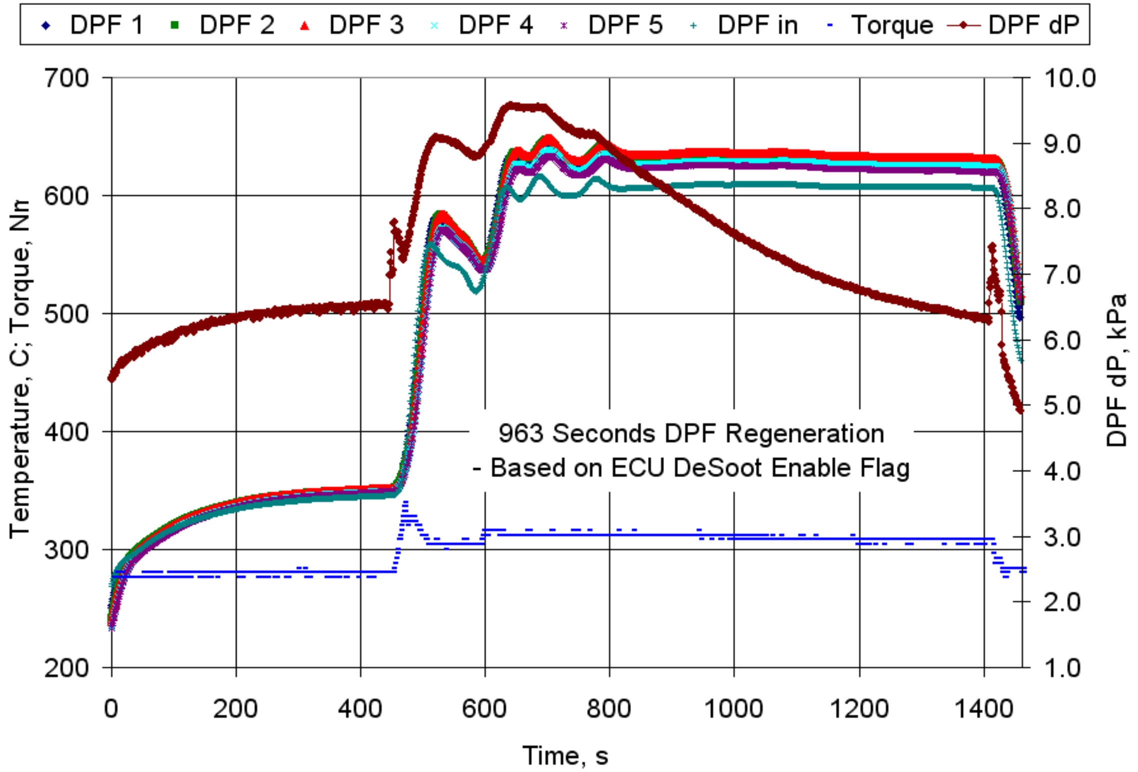




Control of Type A Uncontrolled Regeneration A类不受控再生控制

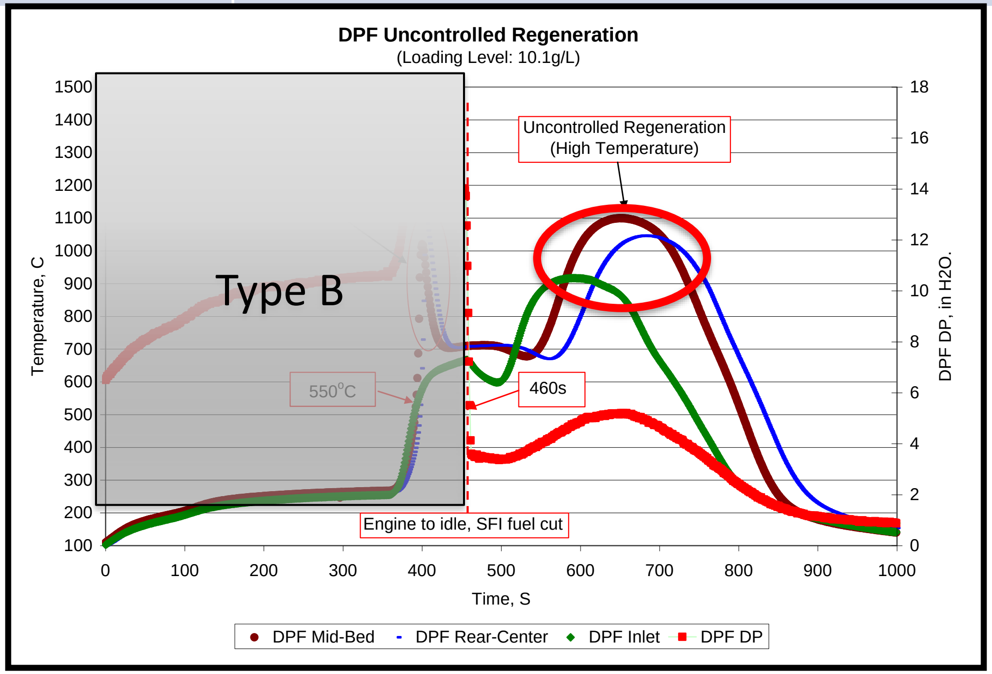
Real World Application 实际应用

- 2-Stage Temperature Ramping for DPF Regeneration DPF再生2级升温
  - Cummins ISB 6.7L Turbo Diesel, Equipped on Dodge Ram 2500/3500 康明斯ISB 6.7L 涡轮柴油机，装载在道奇Ram 2500/3500车上



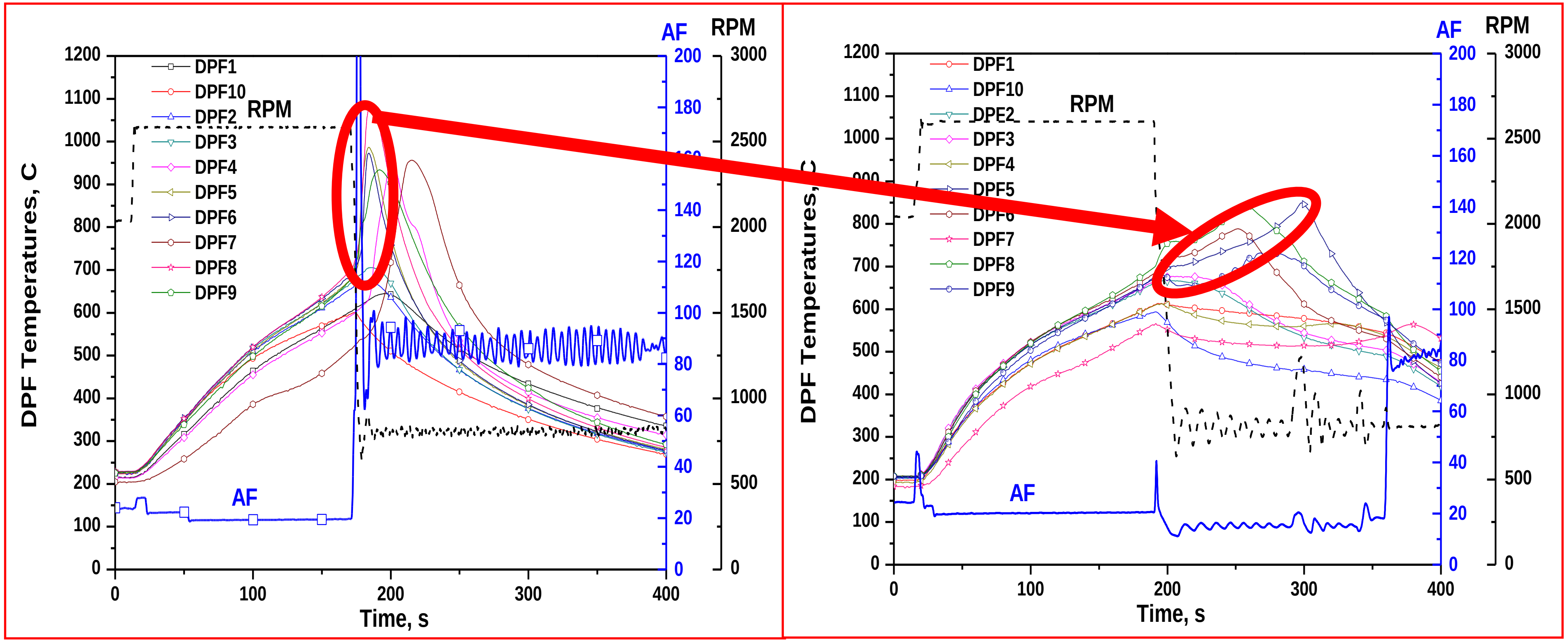
Classification of Failure Modes 失效模式类型

Type 类型	Description描述	Causes 原因	Solutions 解决办法
B	Temperature spike when "runaway regeneration" happens 逃逸再生发生时温度飙升	The combination of 多种原因: 1) Excessive PM loading 过度颗粒物加载 2) High O_2 concentration 氧浓度高 3) Low exhaust flow rate 低排气流量	Combination Of 结合: 1) High EGR rate 高EGR率 2) Intake throttle 进气节流 3) VGT 可变几何涡流增压 4) Other controls 其它控制措施



Control of Type B Uncontrolled Regeneration B类不受控再生控制

EGR Rate vs. Peak DPF Temperature EGR率 vs. DPF最高温度



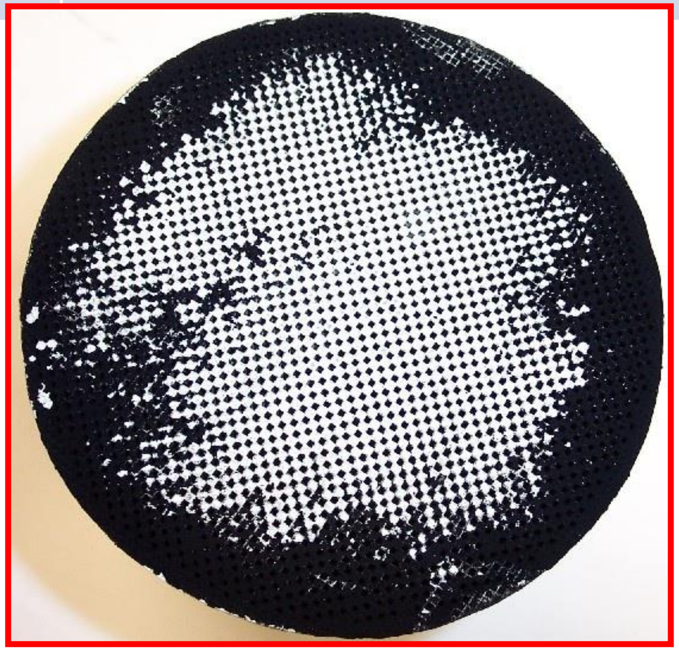
No EGR: Peak DPF temperature: 1080°C	High EGR: Peak DPF temperature: 846°C
Leaking channels observed (cracks)	No leaking channels observed (no cracks)
无EGR：DPF最高1080° C，观察到裂纹	高EGR：DPF最高846° C，未观察到裂纹

Control EGR, throttle and VGT to Control O_2 Concentration.

"Closed-Loop AFR" is Applied 控制EGR、节气门和VGT以控制氧浓度，采用"闭环空燃比"

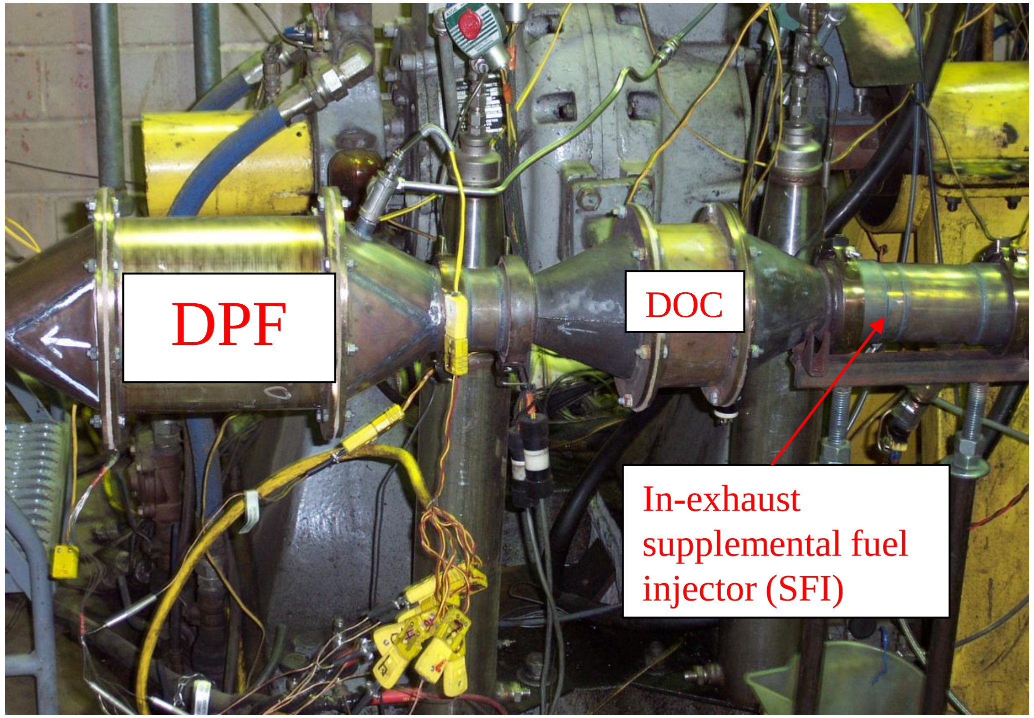
Classification of Failure Modes 失效模式分类

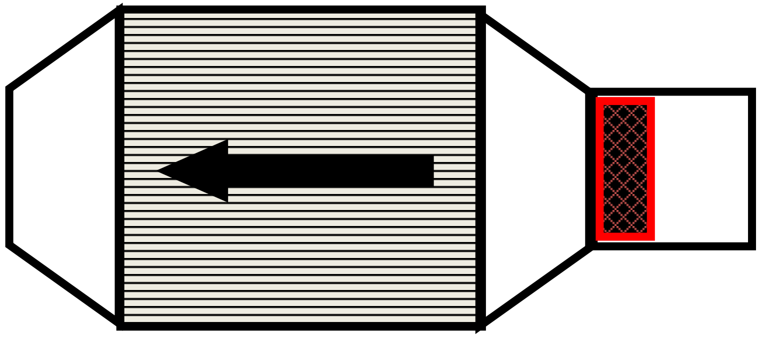
Type 类型	Description 描述	Causes 原因	Solutions 解决方法
C	Uneven temperature distribution during regeneration – “hot spot” 再生过程中温度分布不均-热点	1) Incomplete regeneration 不完全再生 2) Uneven flow and temperature distribution 流体和温度分布不均	Improve flow distribution 改善流体分布



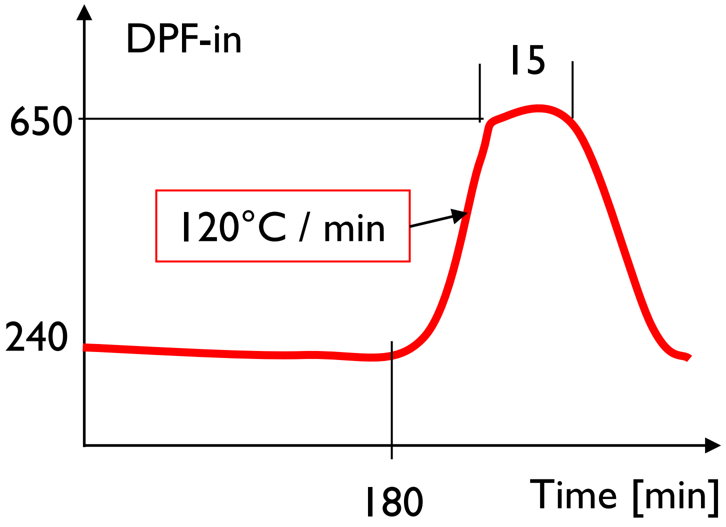
Control of Type C Uncontrolled Regeneration C类不受控再生控制

Test Setup and Procedure 试验装置及流程



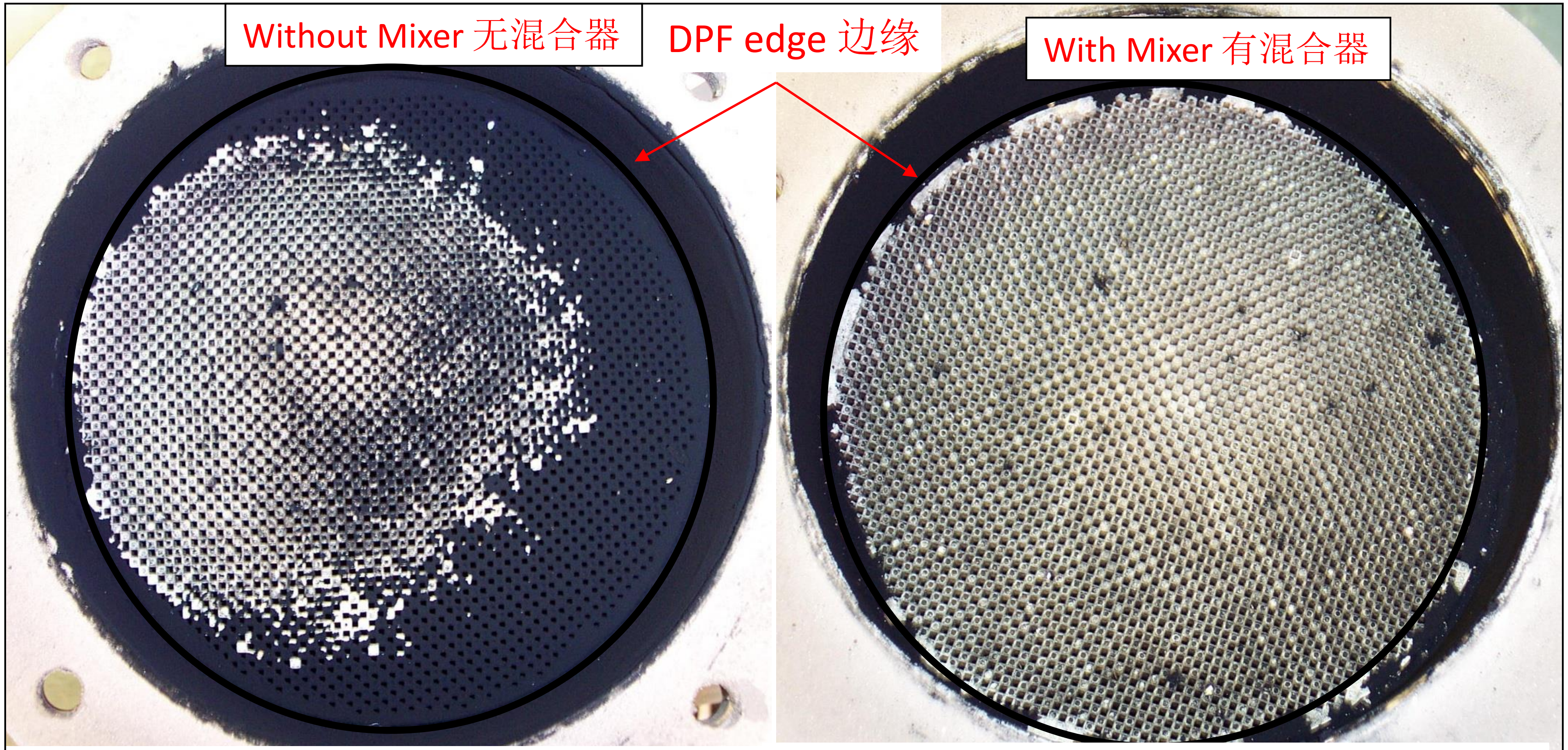


1. **PSA 2.0L Diesel Engine 柴油机**
2. **EGR:**
   - **HP-EGR (OEM 出厂配置)**
   - **LP-EGR (added 后装)**
3. **DOC-Out Soot Rate催化器出口积碳速率：6.5g/hr**



Control of Type C Uncontrolled Regeneration C类不受控再生控制

Impact on DPF Effective Size 对DPF有效尺寸的影响



After 10 DPF cycles 10个DPF循环后

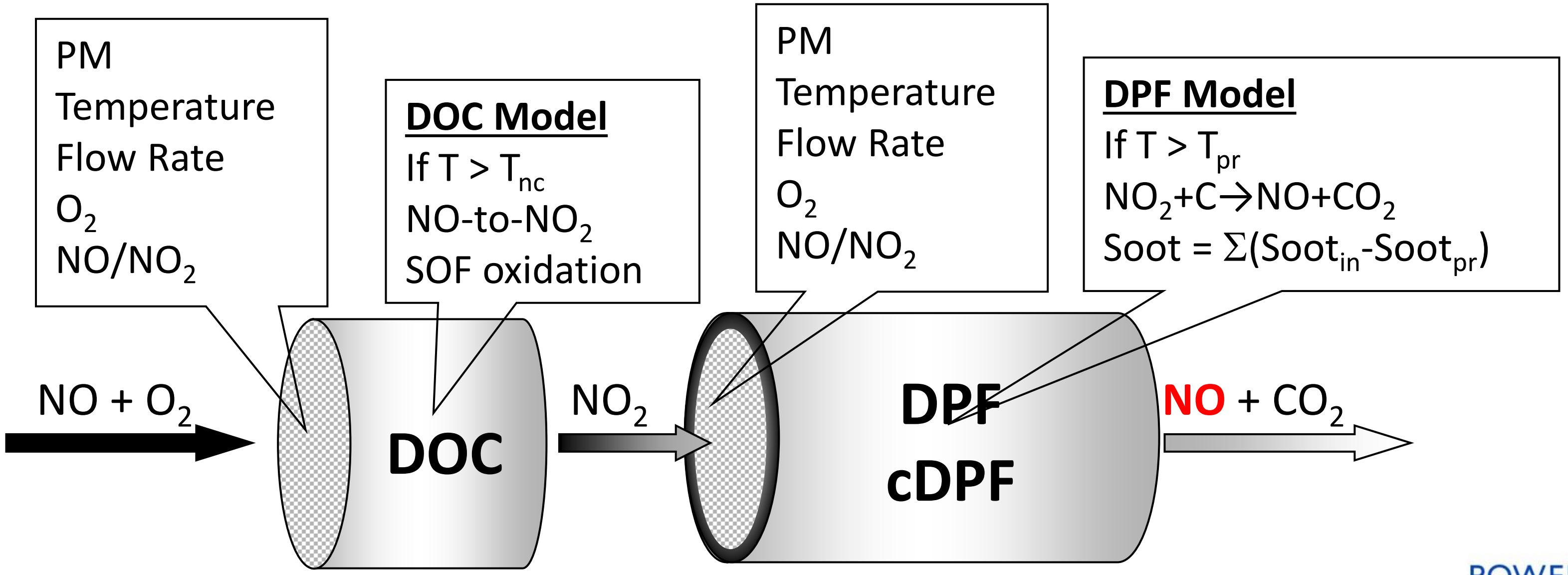
After 30 DPF cycles 30个DPF循环后

A well-designed mixer can reduce DPF size, improve DPF survivability, and it's LOW-COST!

混合器设计得好，可以减小DPF尺寸，提高DPF生存能力，且低成本。

Calibration 标定–
Predicting DPF Soot Loading 预测DPF积碳加载

- DPF Soot Loading Prediction DPF积碳加载预测
  - Integrate major elements: 整合主要因素
    - Steady-state 3-D (RPM, Torque, EGR) maps for 稳态3-D(转速、扭矩、EGR)迈普
    - EC / OC
    - NO_X (DOC out NO_2/NO_X)
    - Temperatures 温度 (DOC-in and DPF-in)
    - Exhaust Flow Rate 排气流量



Challenges 挑战–
DPF Controller Calibration DPF控制器标定

- Estimate Transient PM Rate (Driver Variability) 估计瞬态PM率 （驾驶习惯不同）–
  Most dominating factor! 主导因素
- Establish DOC Efficiencies (SOF, NO-to-NO_2) 建立DOC效率
- Establish DPF Soot Accumulation Rate 建立DPF积碳率
  - DOC-out rate minus DPF passive regeneration rate DOC出口率-DPF被动再生率
- Recalibrate System to Optimize NO_2 for SCR (NO/NO_2 = 1) 重新标定系统以优化SCR (NO/NO_2 = 1) NO_2
- Add Safety Factors - Build Control Models to Initiate DPF Active Regeneration 增加安全因素-构建DPF主动再生控制模型
- Integrate Controls to Avoid Uncontrolled Regenerations and Handle Incomplete Regenerations 集成控件，避免不受控再生并应对不完全再生

Calibration 标定 – Incorporating DOC / cDPF Aging 结合DOC / cDPF 老化

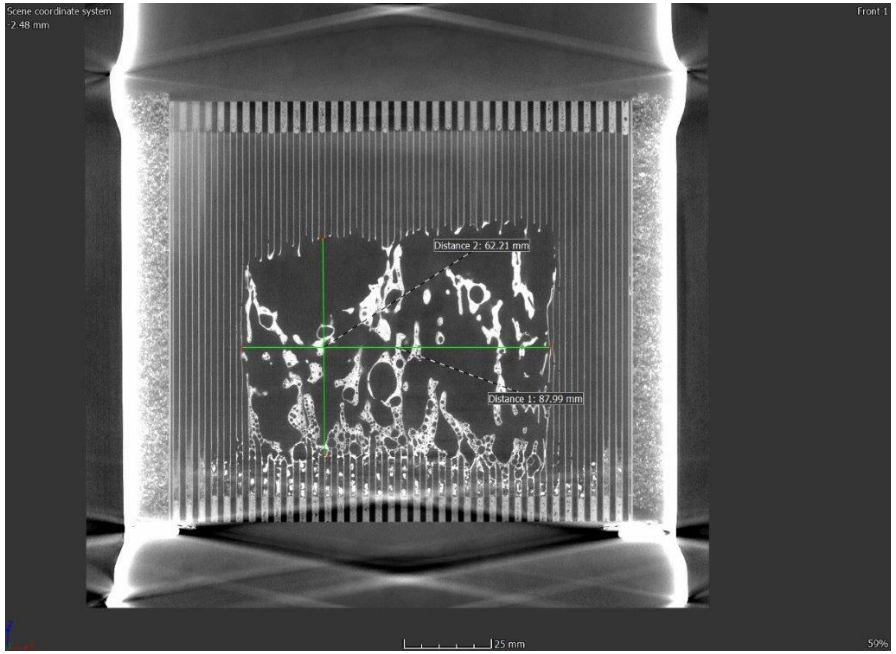
- cDPF Thermal Aging 热老化
  - Controlled regeneration 受控再生
  - Uncontrolled regeneration不受控再生
- DOC / cDPF Poisoning DOC / cDPF中毒
  - Lubricant poisoning and ash accumulation may affect 机油中毒和灰分累积可能影响
    - DOC light-off and efficiency (passive regeneration) DOC起燃和效率（被动再生）
    - cDPF efficiency (BPT) cDPF效率（BPT）
- Need Model That Incorporates Aging:模型中需要融入老化
  - Hydrothermal aging impact 水热老化影响
  - Oil consumption 机油耗

Challenges 挑战–
When to Trigger Active Regen? 何时触发主动再生

- Real-World DPF Regeneration Control (example): 实际DPF再生控制（实例）
  - Build multiple control layers to initiate DPF regeneration: 构建多个控制层启动DPF再生
    - Based on fuel consumption 基于油耗
    - Based on accumulated mileage (or time) 基于累计里程（或时间）
    - Based on DPF soot accumulation model 基于DPF积碳模型
    - Based on DPF-ΔP sensor (safety only) 基于DPF的压降传感器（安全用途）
  - “Deep-Clean” DPF regeneration 深度清洁DPF再生
    - Extended regeneration to ensure high soot oxidation efficiency延长再生，确保高积碳氧化效率
    - Used to adjust monitors for ash loading predictions 用于调整灰分加载监测

Challenges 挑战 –
DPF Regeneration Control at Low Speed 低速DPF再生控制

- Challenges: 挑战
  - Low exhaust flow rate (heat transfer issue) 低排气流量（传热问题）
  - High O_2 concentration (mass transfer control) 氧浓度高（传质控制）
  - “Critical” DOC or cDPF temperature (feed-back control) 临界DOC或cDFP温度（反馈控制）



On-Board Diagnostics (OBD) 车载诊断

- OBD Guidelines for PM Filter (EU Example): 颗粒过滤OBD指南（欧盟实例）
  - Filtration Performance过滤性能 = 0.025 g/kw-hr on WHTC (standard标准 is 0.01 g/kw-hr)
    - Need to target post "phase-in" monitor 需要对"分阶段"后进行监测
      - Soot sensor will be required 需要碳烟传感器
    - delta P-based "phase-in" monitor not in scope ΔP的"分阶段"监测不在此范围
  - Regeneration System (HC Doser and DOC) 再生系统（HC计量仪和DOC)
    - total functional failure only (temp sensors/exotherm) 全部功能故障（温度传感器/温升）
  - Regeneration Frequency 再生频率
    - monitored against manufacturer defined interval 按照厂家指定的周期进行监测
  - DPF Clogging (Incomplete Regeneration) DPF堵塞（不完全再生）
    - total functional failure only (delta P sensor) 全部功能故障（ ΔP传感器）
  - Missing Substrate 载体缺失
    - total functional failure only (temp sensors) 全部功能故障（温度传感器）

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