柴油机后处理系统典型排放失效模式研究

Study on the Typical Emission Failure Mode of ATS on Diesel Engines

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概 要 Outline

SPMC
Catalyst for clean air

我国移动源减排成效

Mobile emission reduction effectiveness in China

- **2001年我国开始实施汽车排放控制，短短20年，我国汽车标准从无到有，快速进入世界前列。**

  China has implemented vehicle emission control since 2001. China's automobile standards have grown from scratch and quickly entered the forefront of the world just within 20 years.

- **我国汽车保有量比20年前超过15倍，但汽车大气污染物的排放总量与2000年基本持平。**

  The total quantity of vehicles in China is more than 15 times that of 20 years ago, while the air pollutants from vehicles is basically the same as in year of 2000.

柴油机现阶段排放标准

Current emission standard of diesel engine

- **2021年7月1日我国开始实施重型柴油车国六排放标准。**

  The Stage VI emission regulations of heavy-duty vehicles implemented on Jul 1, 2021.

- **与国1排放相比，现阶段单车污染物排放量下降90%以上。**

  Compared with Stage I, the single-vehicle pollutant emissions have dropped by more than 90%.

车型	年份	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
轻型汽车	柴油车	无控制要求			国Ⅰ				国Ⅱ				国Ⅲ					国Ⅳ				国Ⅴ	国Ⅵ
	汽油车	无控制要求			国Ⅰ				国Ⅱ			国Ⅲ					国Ⅳ				国Ⅴ		国Ⅵ
	气体燃料车	无控制要求			国Ⅰ				国Ⅱ			国Ⅲ					国Ⅳ				国Ⅴ		国Ⅵ
重型汽车	柴油车		无控制要求			国Ⅰ			国Ⅱ				国Ⅲ					国Ⅳ			国Ⅴ		国Ⅵ
	汽油车			无控制要求			国Ⅰ			国Ⅱ				国Ⅲ						国Ⅳ			
	气体燃料车		无控制要求			国Ⅰ			国Ⅱ			国Ⅲ		国Ⅳ					国Ⅴ				国Ⅵ
摩托车	两轮和轻便摩托车			无控制要求			国Ⅰ				国Ⅱ						国Ⅲ						国Ⅳ
	三轮摩托车			无控制要求			国Ⅰ				国Ⅱ							国Ⅲ					国Ⅳ
三轮汽车						无控制要求				国Ⅰ							国Ⅱ						
低速货车						无控制要求				国Ⅰ					国Ⅱ							无此类车	

机动车排放法规实施进度/Implementation Schedule

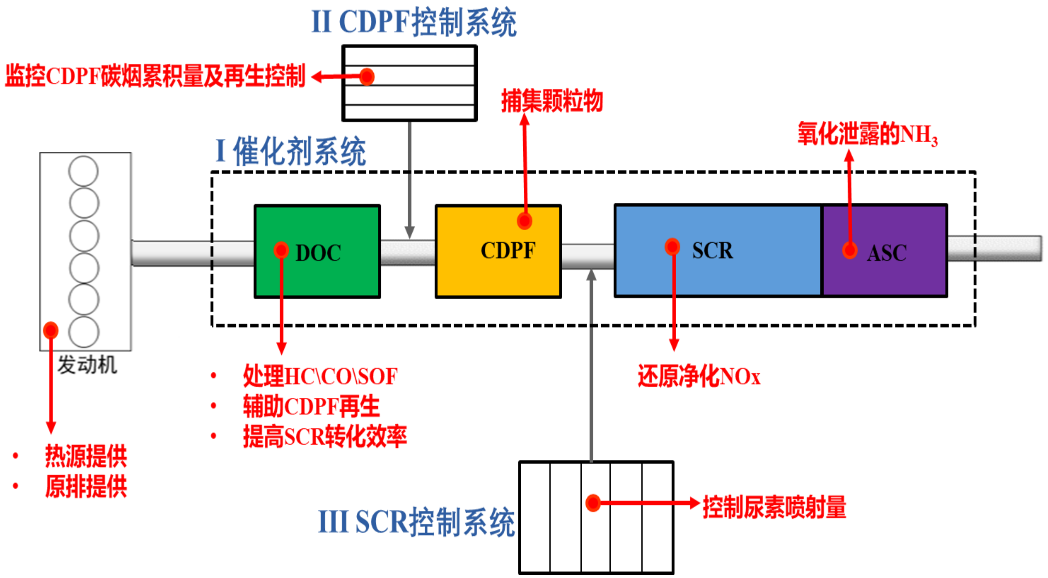
柴油机排放控制技术
Emission Control Technology

柴油机排放控制技术为系统工程，主要包括发动机、催化系统、后处理控制策略三大部分。

Diesel engine emission control is a systematic engineering, which mainly includes engine, catalytic system and ATS control strategy.

柴油机排放控制技术 Emission Ctrl. Tech.

- **发动机 Engine**
  - 发动机原排特性 Raw emission Characteristics
  - 发动机热管理 Engine thermal management
  - EGR等零部件 EGR and other parts
- **催化系统 Catalytic System**
  - 催化剂 Catalyst
  - 封装系统 Canning system
- **后处理控制系统 ATC Ctrl System**
  - CDPF再生控制策略 CDPF reg. ctrl strategy
  - 尿素喷射控制系统 Urea injection ctrl system



概 要 Outline

一 柴油机排放技术介绍
Introduction of Emission Technology

二 柴油机主要排放故障
Emission Failure of diesel engines

三 典型排放失效模式及失效机制
Typical Emission Failure mode and Mechanism

四 总结
Summary

柴油机主要排放故障

Emission Failure of diesel engines

国六/T4标准实施过程中最常见的排放故障包括NOx排放增高、PN排放增加、背压异常增加三方面问题。

The most common emission failures in the Stage VI /T4 include increased NOx, PN emission and abnormal increase of back pressure.

柴油机主要排放故障
Emission Failure of diesel engines

① NOx 排放故障
NOx emission failure

- **SCR催化剂性能下降**
  Performance degradation
  - 燃油硫含量高，催化剂硫中毒
    Sulfur poisoning
  - Fe、P等异物覆盖、堵塞，活性下降
    Foreign matter block
  - 催化剂稳定性不足
    Poor stability
  - 尿素水溶液质量不合格
    Unqualified urea solution
- **封装结构设计不合理**
  Unreasonable canning
  - 喷嘴设计、安装位置设计不合理，尿素结晶加剧
    Unreasonable nozzle design, installation, urea crystallization
  - 混合器设计不合理，无效有效发挥催化剂性能
    unreasonable mixer
  - 流场分布差，无法有效利用催化剂面积
    poor flow distribution, insufficient catalytic reaction area
- **发动机标定不合理**
  Unreasonable calibration
  - 尿素喷射策略与催化剂特性匹配不足 Unmatched urea injection strategy
- **零部件故障**
  Other parts failure
  - EGR EGR damage
  - NOx传感器损害 NOx sensor damage

柴油机主要排放故障
Emission Failure of diesel engines

SPMC
Catalyst for clean air

② PN排放故障
PN emission issues

DPF载体选型不合理

- **载体孔径偏大，运行过程再生后碳烟层消失，PN过滤效率下降**
  Unmatched pore size, layer disappeared after regeneration during operation, and the PN filtration efficiency decreases
- **载体芯体与皮层热膨胀系数差异大，长期热环境下，出现破裂**
  The thermal expansion coefficient difference, and rupture occurs in the long-term high-temp. environment

CDPF破裂、烧熔

- **主动再生时，DOC出口超温**
  DOC outlet over-temperature during active regeneration
- **CDPF内部碳烟超量、不均匀**
  excessive uneven soot loading inside CDPF
- **大量未燃HC沉积**
  poor HC combustion, massive unburned HC
- **Fe锈熔化烧蚀**
  The pipe was corroded by S and water, CDPF ion coverage that led to high temp. during reg.

柴油机主要排放故障
Emission Failure of diesel engines

SPMC
Catalyst for clean air

③ 背压高、再生里程短
High B.P. and short regenerative mileage

- **PN再生效率差**
  Poor reg. efficiency
  - **主动再生温度不足**
    Poor HC light off
  - **再生不完全**
    Poor regeneration
- **Fe、S、P、等过量不可燃灰分堵塞**
  Massive soot/ash block

概 要 Outline

典型排放失效模式及失效机制
Typical Emission Failure mode and Mechanism

SPMC Catalyst for clean air

三大典型失效模式
Typical failure mode

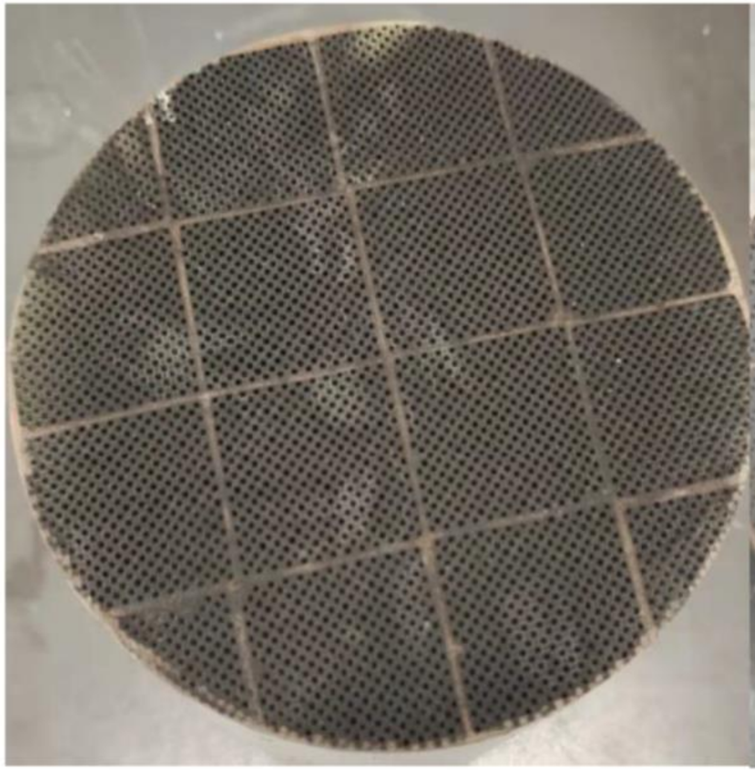
- **S、Fe污染**
  Sulfur or ion pollution
- **未燃HC覆盖**
  Unburned HC coverage
- **流场均匀性差**
  Poor flow distribution

典型排放失效模式及失效机制
Typical Emission Failure mode and Mechanism

S、Fe污染 → 排放故障1：背压高、动力不足
High back pressure and underpowered

- **整车运行过程中出现背压过高报警问题。**
  High back pressure alarm occurs during vehicle operation

外观/appearance



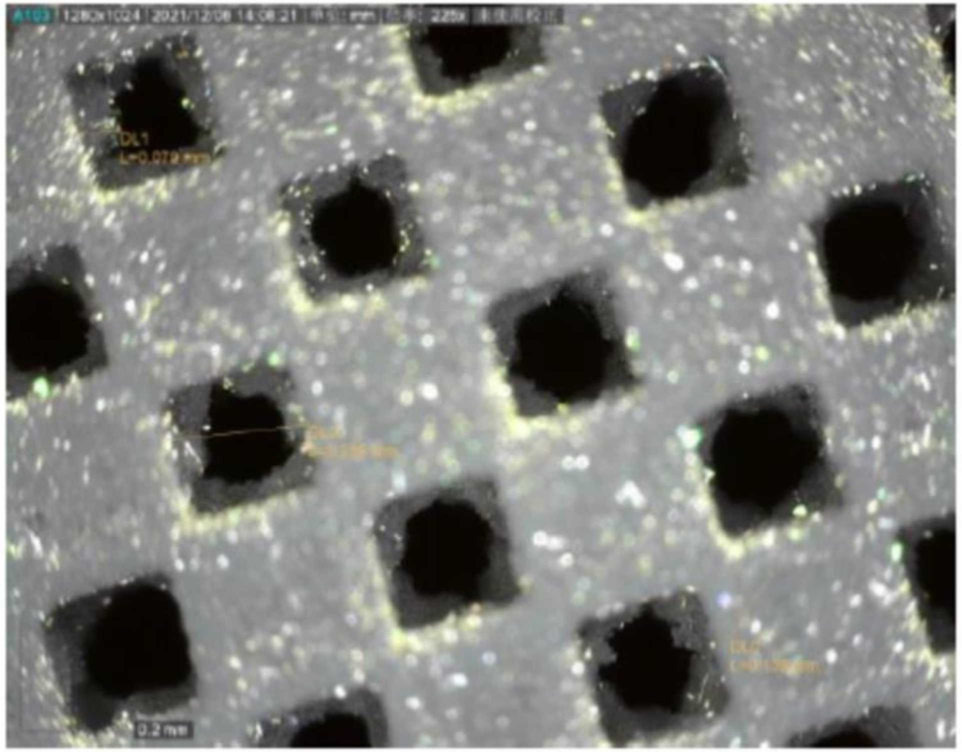
进气端/inlet

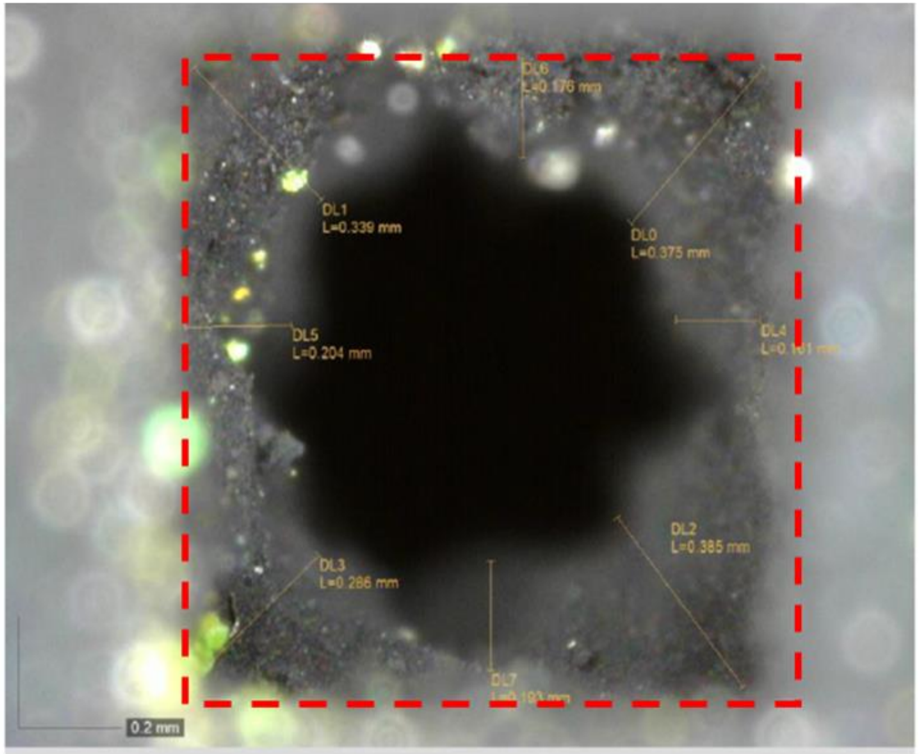
出气端/outlet

典型排放失效模式及失效机制
Typical Emission Failure mode and Mechanism

Catalyst for clean air

S、Fe污染 → 排放故障1：背压高、动力不足
High back pressure and underpowered





入口端微距放大图/Macro view of the inlet face

端面可见：孔道显著变小，约50%的体积被碳烟覆盖。
Visible on the face: the pore becomes significantly smaller, and about 50% of the volume is covered by soot.

典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

S、Fe污染 → 排放故障1：背压高、动力不足

High back pressure and underpowered

气流吹扫孔道/air sweeps

孔道的碳烟（煅烧前）/soot

600℃，1h煅烧的碳烟/ash

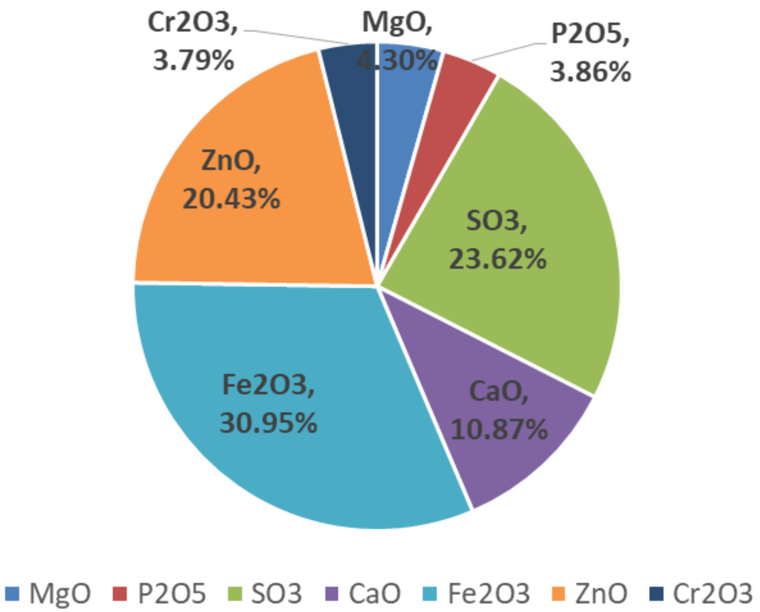
- **CDPF内部孔道部分被碳烟完全堵塞，导致背压急剧增加。**
  The pores were partially blocked by soot, resulting in a sharp increase in back pressure.
- **碳烟经600℃，1h煅烧后仍留存大量红褐色灰分。**
  After calcination at 600℃ for 1h, the soot still retained a large amount of reddish-brown ash.

典型排放失效模式及失效机制

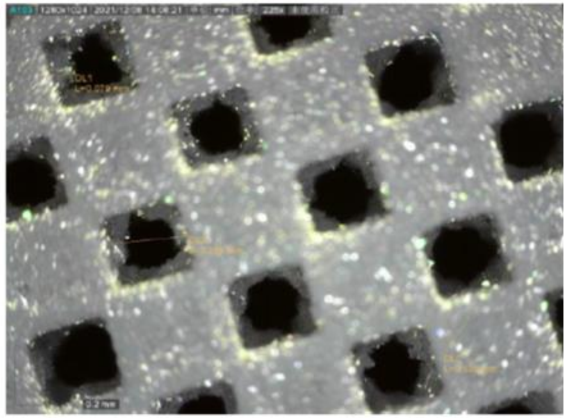
Typical Emission Failure mode and Mechanism

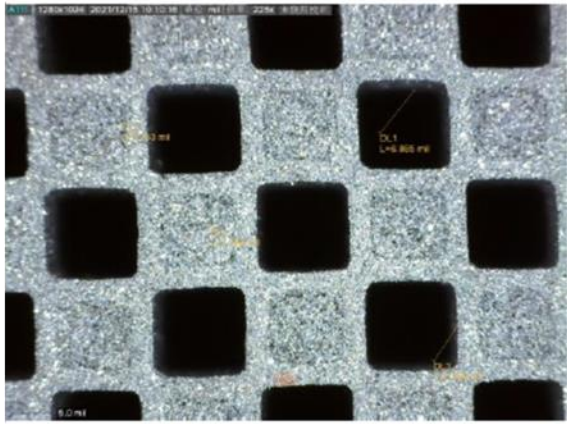
S、Fe污染 → 排放故障1：背压高、动力不足

High back pressure and underpowered



红褐色物质成分





煅烧前重量：2518g

累碳63g

处理后重量：2455g

- **红褐色灰分主要成分为Fe、S、Zn。**
- **通过煅烧、吹扫，CDPF可完全恢复。**

→ **失效机制：大量Fe、S、Zn等不可燃污染物堵塞所致。**

典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

S、Fe污染 → **排放故障2：NOx排放异常增加、超标**

Increase of NOx emission

- **整机运行1000公里，OBD报警，NOx超标。**
  OBD alarm, NOx exceeds the standard within 1000 km operation

返回件封装外观/appearance

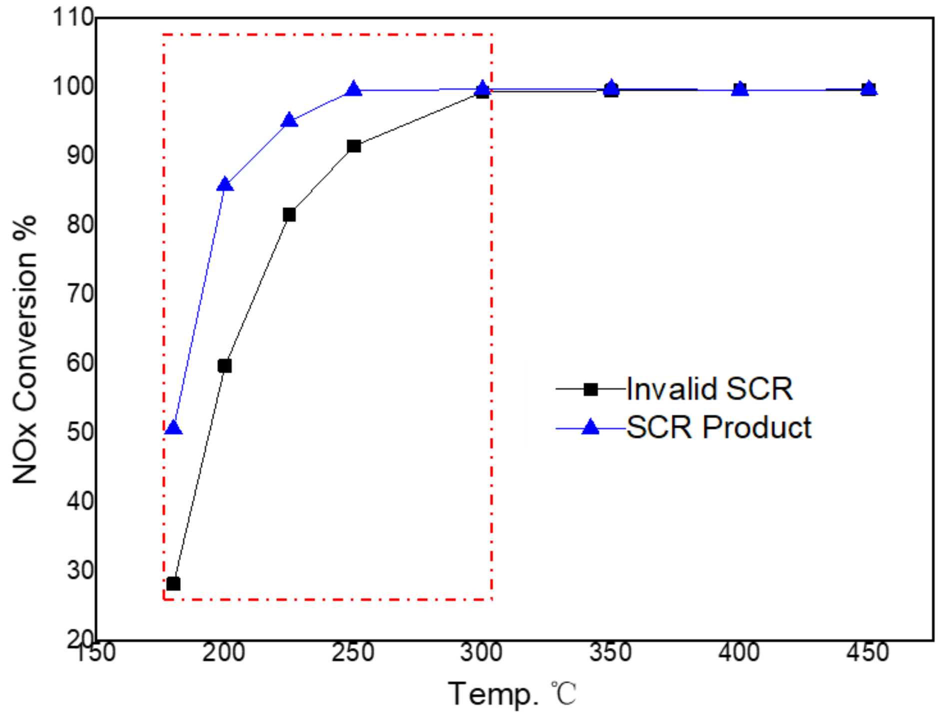
SCR催化剂返回件/failure part

典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

S、Fe污染 → 排放故障2：NOx排放异常增加、超标

Increase of NOx emission



成分	含量（%）	
MgO	4.818	载体涂层
Al2O3	19.366	载体涂层
SiO2	64.424	载体涂层
P2O5	0.033	污染物
SO3	8.285	污染物
CaO	0.082	污染物
Cr2O3	0.130	污染物
Fe2O3	1.211	污染物
CuO	1.053	涂层

性能测试显示，故障件低温区转化效率下降超过20%。

The NOx conversion dropped by 20% within the low-temperature range.

成分分析显示，催化剂含有大量的S，可判断催化剂遭受S、Fe中毒，导致活性下降。

Catalyst suffered from S and Fe poisoning, resulting in a decline in activity.

典型排放失效模式及失效机制

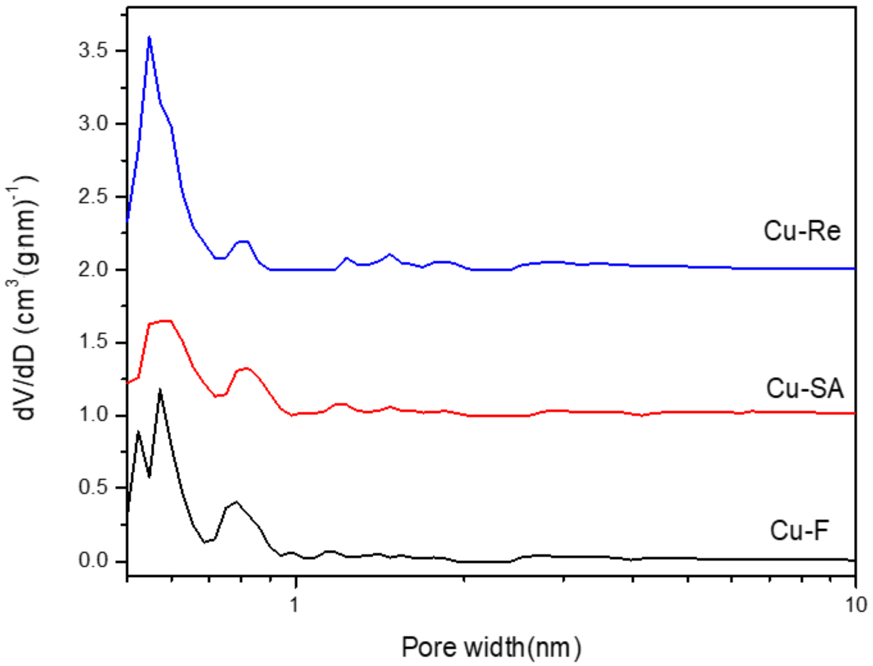
Typical Emission Failure mode and Mechanism

S、Fe污染 → 排放故障2：NOx排放异常增加、超标

Increase of NOx emission

SO_2浓度：200ppm

S影响机制



中毒前后孔径分布图/pore distribution

催化剂	比表面积 m2/g	总孔容cc/g	平均孔径 nm	硫元素含量 %
Cu-F	580.24	0.62	1.199	0
Cu-A	378.34	0.56	0.365	0.94
Cu-Re	575.65	0.36	1.129	0

硫中毒能够导致催化剂载体堵塞，降低总孔容，导致活性下降。

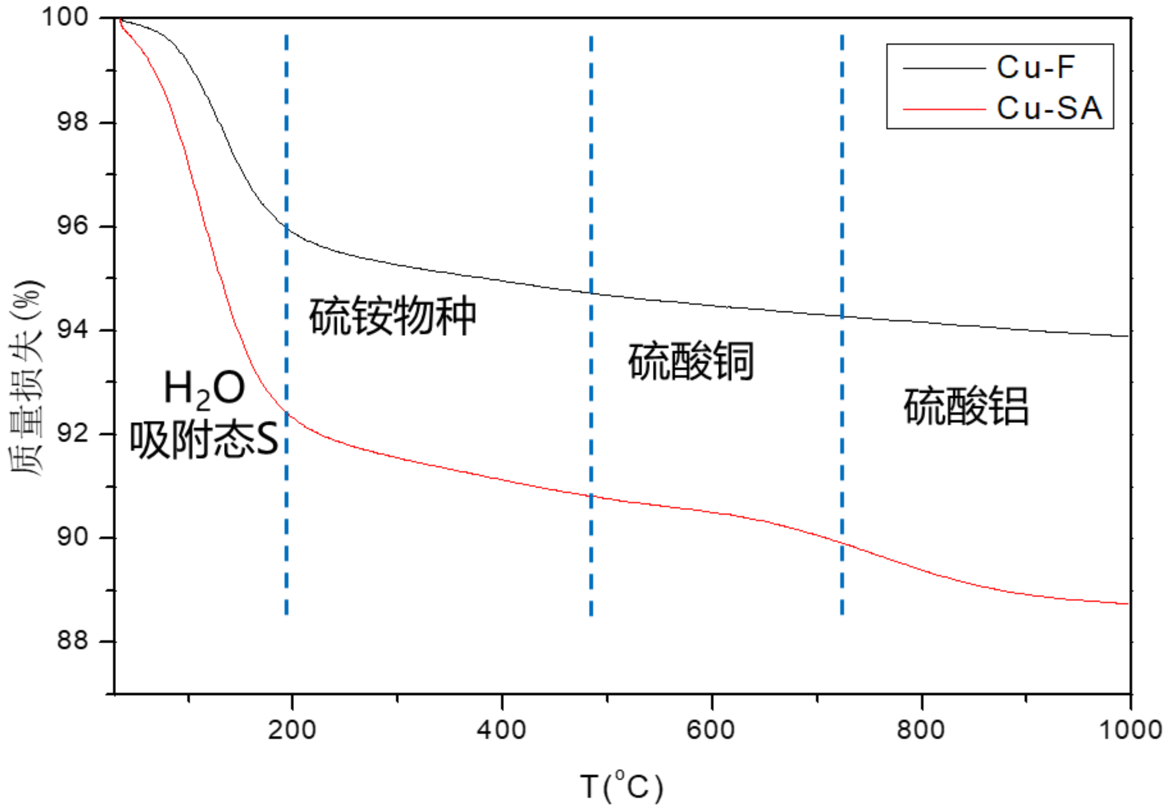
Sulfur poisoning led to block of support and decrease of total pore volume, resulting in decreased activity.

典型排放失效模式及失效机制
Typical Emission Failure mode and Mechanism

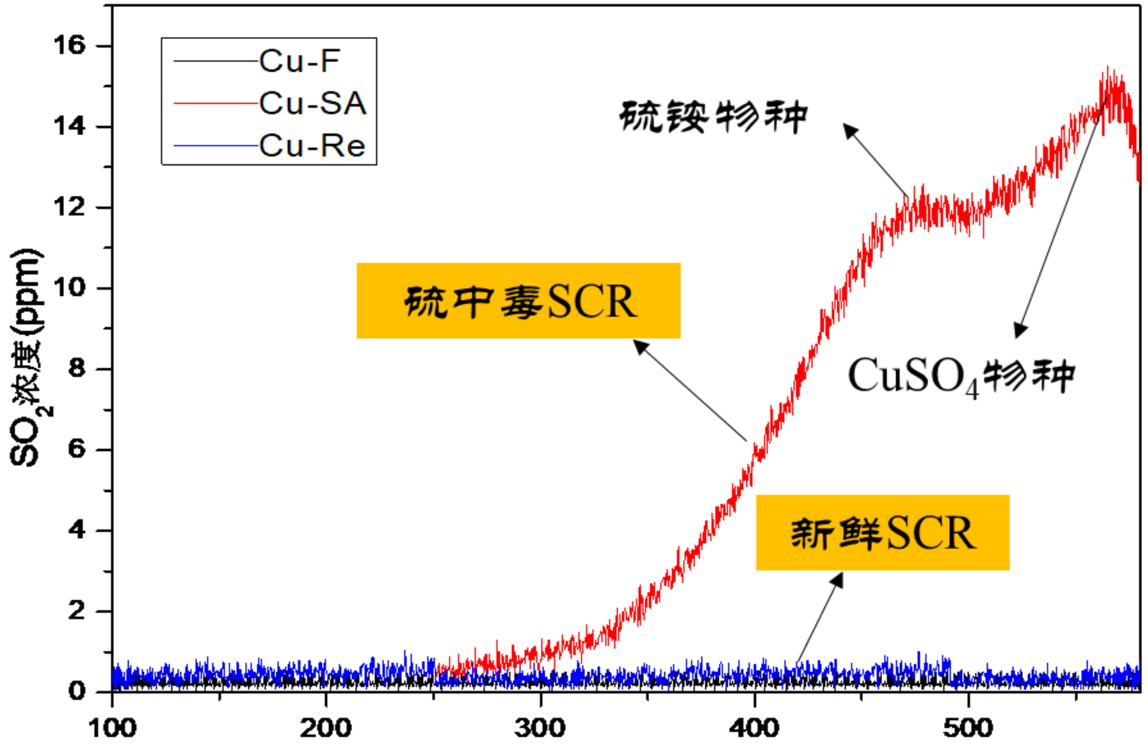
SO$_2$浓度：200ppm

S、Fe污染 → 排放故障2：NOx排放异常增加、超标
Increase of NOx emission

S影响机制



TGA曲线



脱附曲线

硫与氨、Cu、Al反应生成了系列硫酸盐，导致孔道堵塞、酸性变化、活性位降低，导致性能下降。

Sulfur reacts with ammonia, Cu and Al to form a series of sulfates, which leads to pore block, acidity change, active site and performance degradation.

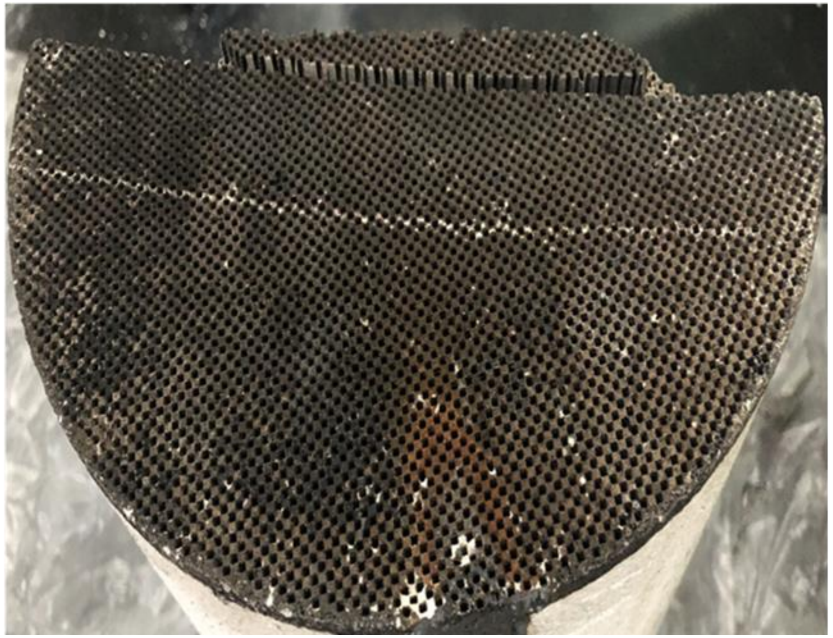
典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

S、Fe污染 → 排放故障3：PN排放超标

PN emission issues

- PN排放超标，OBD报警 OBD alarms due to PN emission issues



进气端/inlet

出气端/outlet

DPF内剖面/channels

DPF外观无裂纹、破裂等异常失效模式。

No apparent cracks on the surface while the channels all cracked.

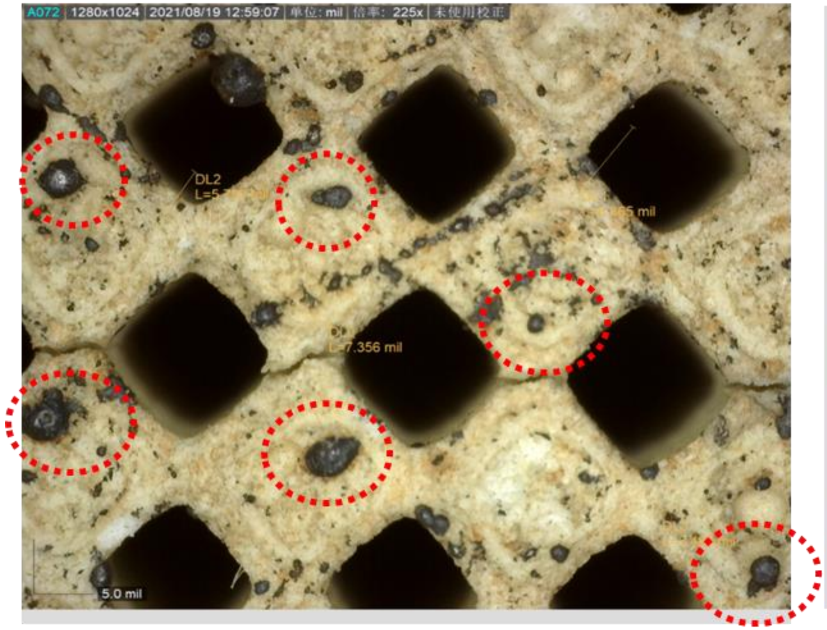
典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

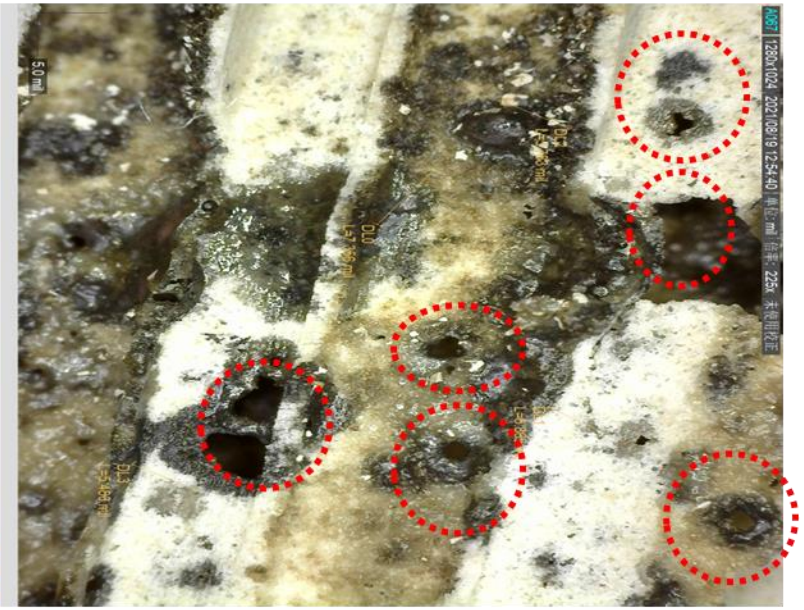
S、Fe污染 → 排放故障3：PN排放超标

PN emission issues

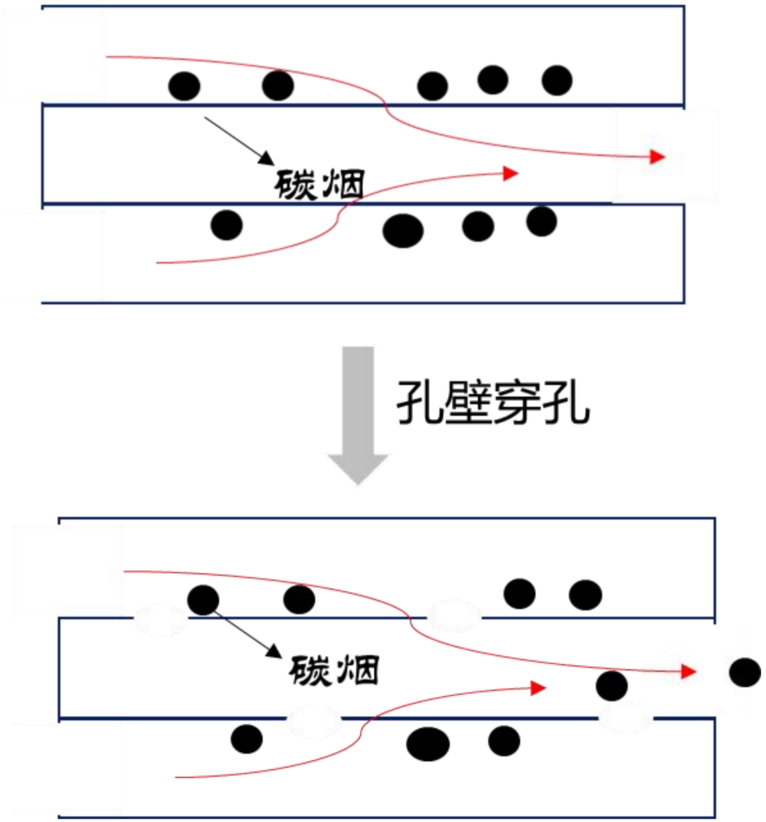
故障原因



入口端面微距图



内壁微距图



DPF端面和内部有大量的烧蚀孔洞，尤其是内壁出现大量穿孔，导致PN大量泄漏。

Massive ablative holes inside in the DPF which lead to PN emission issues.

典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

S、Fe污染 → 排放故障3：PN排放超标

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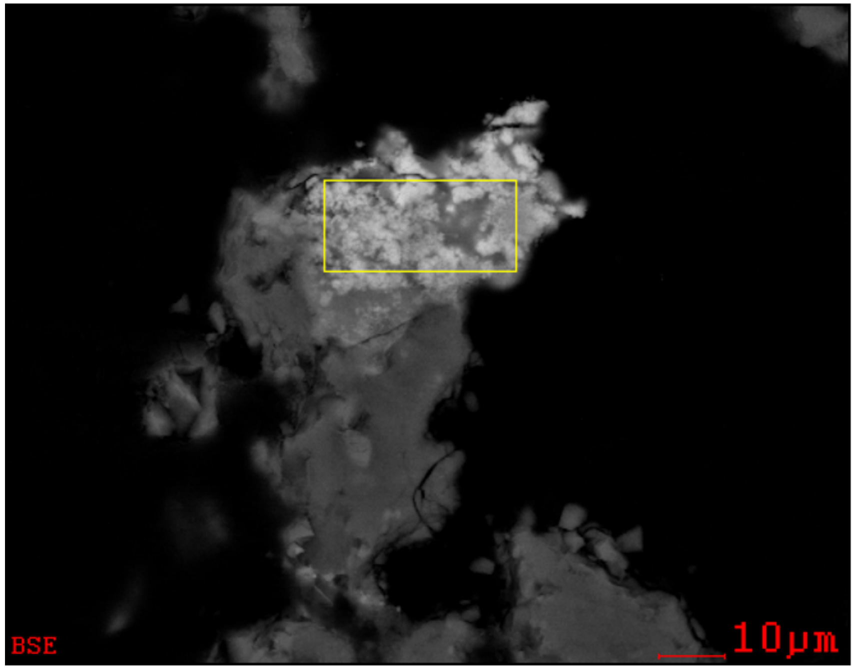
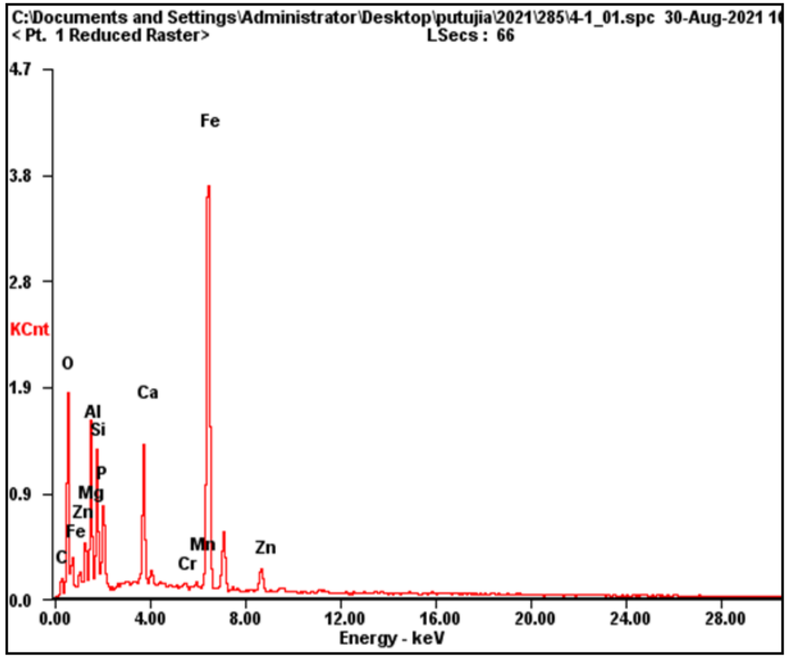
故障原因





Element	Wt %	At %
C K	11.01	19.87
O K	30.63	41.48
MgK	04.97	04.43
AlK	16.49	13.24
SiK	16.95	13.08
K K	00.37	00.21
CaK	00.53	00.28
CrK	00.56	00.23
FeK	18.50	07.18

载体 (C K – SiK)

杂质 (K K – FeK)

- **通过能谱分析，可判断载体壁穿蚀为Fe所致。**
  It can be concluded that the carrier erosion was caused by ion from EDS results.

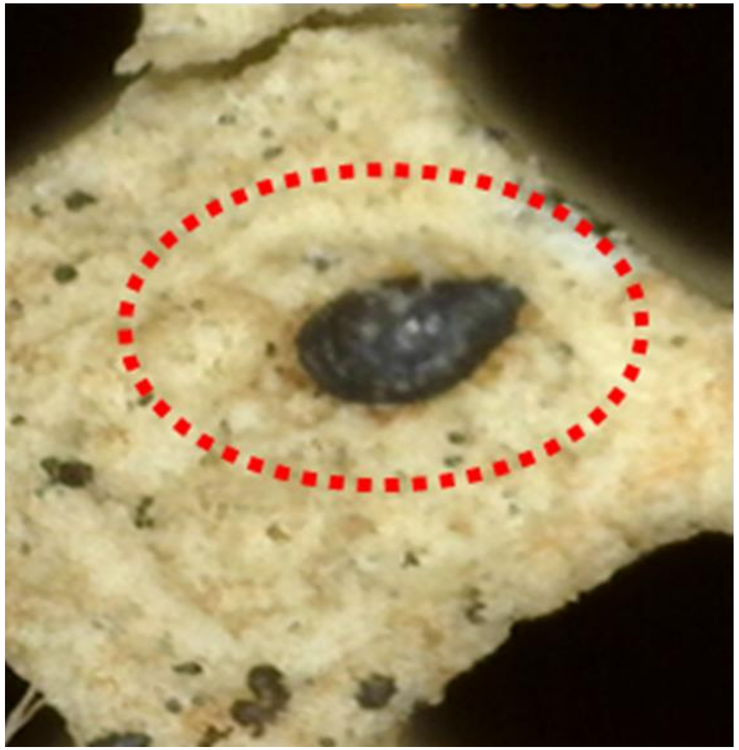
典型排放失效模式及失效机制

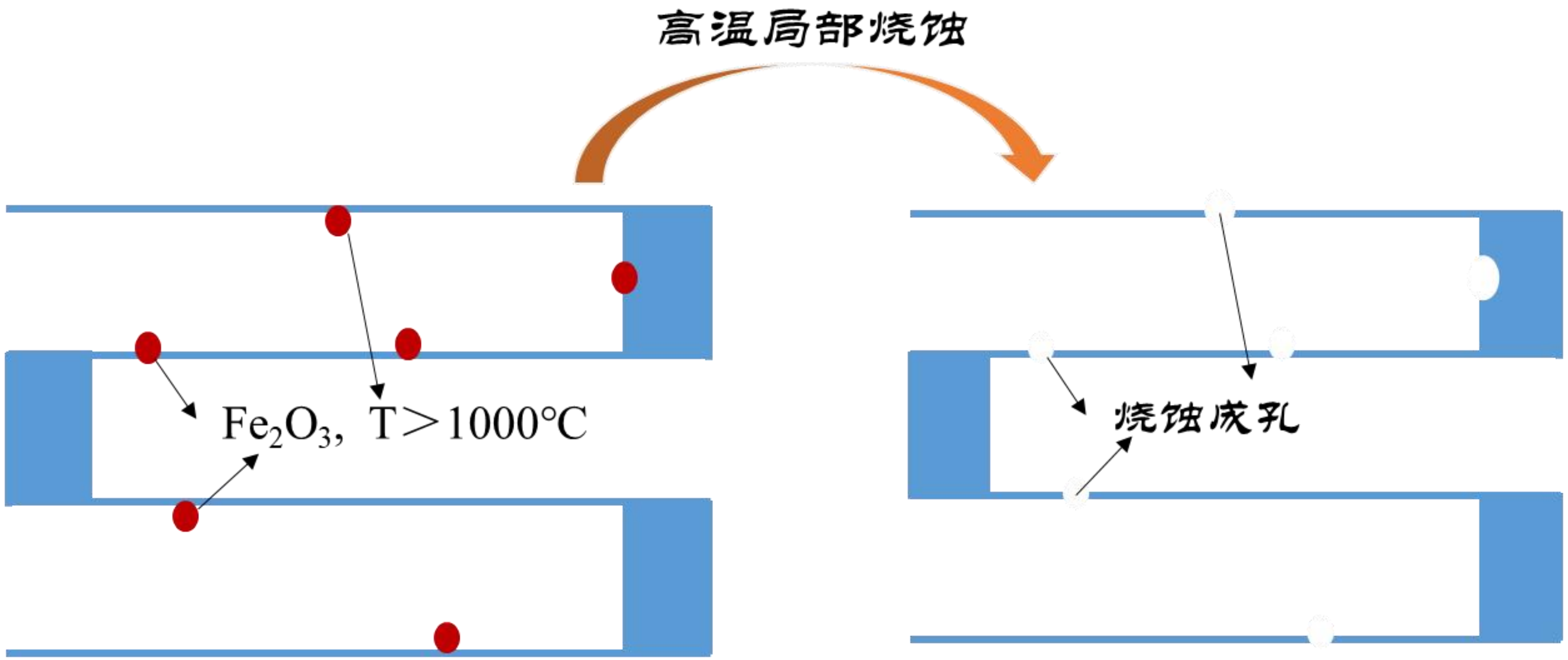
Typical Emission Failure mode and Mechanism

S、Fe污染 → 影响机制

排放故障3：PN排放超标

PN emission issues





主动再生时，床体最高温度将超过900℃， Fe_2O_3细粒子因吸热使得自身温度将超过1000℃，导致载体局部高温熔化。

During active regeneration, the highest temperature of the bed could exceed 900℃, and the temperature of fine Fe_2O_3 particles exceeded 1000℃, resulting in melting.

典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

S、Fe污染 → Fe、S 从何处来?
where are the ion and sulfur from?

S来源：主要来源于燃油。

Fe来源：

水腐蚀：发动机尾气含水，尤其是国六尿素水溶液的使用，使得管道内水含量极高，在高温、高水环境，管道腐蚀生锈，生成Fe污染物。

硫腐蚀：SO2尤其是SO3的存在，会与水生成硫酸，加剧腐蚀管道，从而生成更多的Fe物种。

硫中毒几乎都伴随Fe中毒， 但Fe中毒可单独存在。
Sulfur poisoning was almost always accompanied by ion, but Fe poisoning can be isolated.

典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

S、Fe污染 → 小结 summary

S、Fe中毒的影响与再生
Influence and regeneration

- **NOx排放增加**
  NOx emission issues
  - 单纯S中毒：可逆,高温再生（＞450℃）
    Sulfur only: reversible by heat treatment(great than 450 degrees)
  - 单纯Fe中毒：不可逆
    ion only: irreversible
  - S、Fe复合中毒：不可逆
    Sulfur and ion: irreversible
- **PN排放增加**
  PN emission issues
  - 不可逆，无法再生
    irreversible
- **背压增加**
  Increase of back pressure
  - 不可逆，需高温煅烧+清灰处理
    Irreversible, heat + and cleaning treatment

典型排放失效模式及失效机制
Typical Emission Failure mode and Mechanism

流程均匀性差 → 故障1 NOx排放高 NOx emission issues

- **产品一致性抽查，其中一套出现NOx排放偏高。**
  Product consistency check, one set of NOx emission appears high.

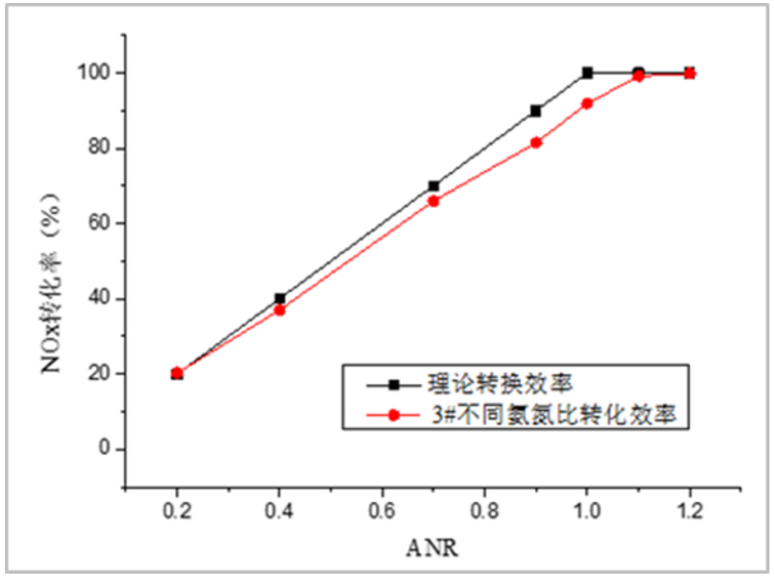
典型排放失效模式及失效机制

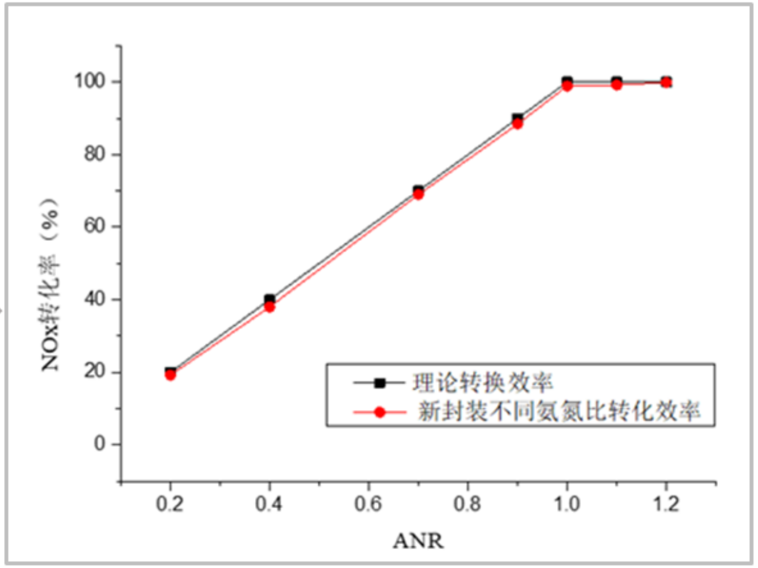
Typical Emission Failure mode and Mechanism

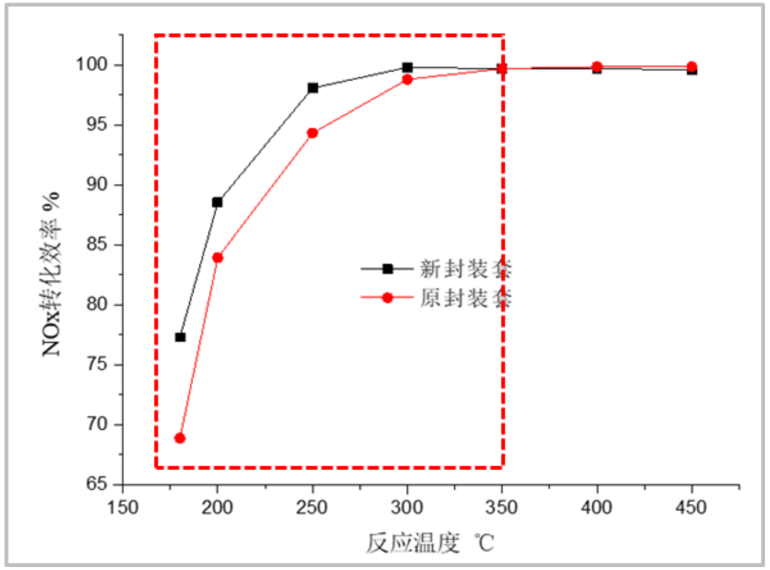
流程均匀性差 → 故障1 NOx排放高

NOx emission issues

故障原因







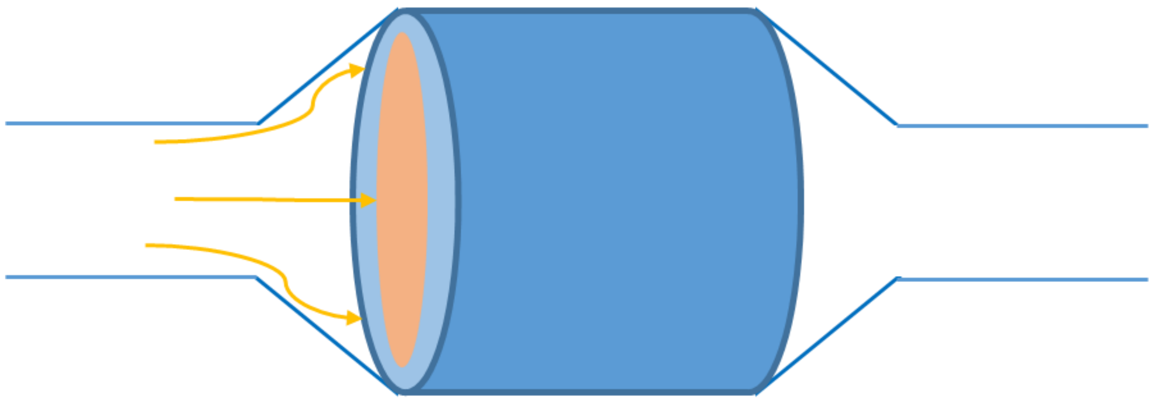
流程均匀性显著影响NOx转化效率，尤其低温转化效率，降幅可达10%以上。

Flow distribution significantly influenced the NOx conversion, especially the low temperature conversion efficiency, which could be reduced by more than 10%.

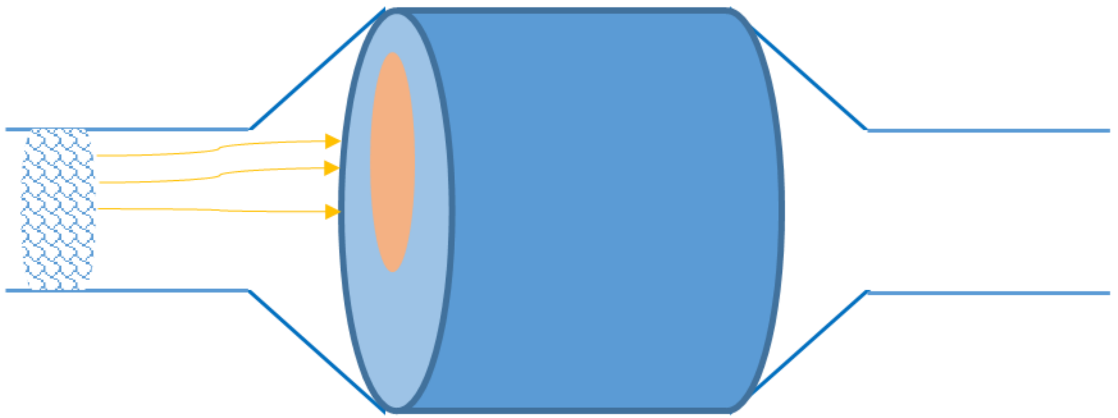
典型排放失效模式及失效机制
Typical Emission Failure mode and Mechanism

流程均匀性差 → **故障1 NOx排放高**
NOx emission issues

影响机制



锥度设计不合理/unreasonable taper design



混合器设计不合理/unreasonable mixer design

进入催化剂的气流无法均匀分布在载体端面，导致有效反应面积减少，活性下降。
The air flow could not be evenly distributed in the carrier, resulting in a decrease in the effective reaction area and activity.

典型排放失效模式及失效机制

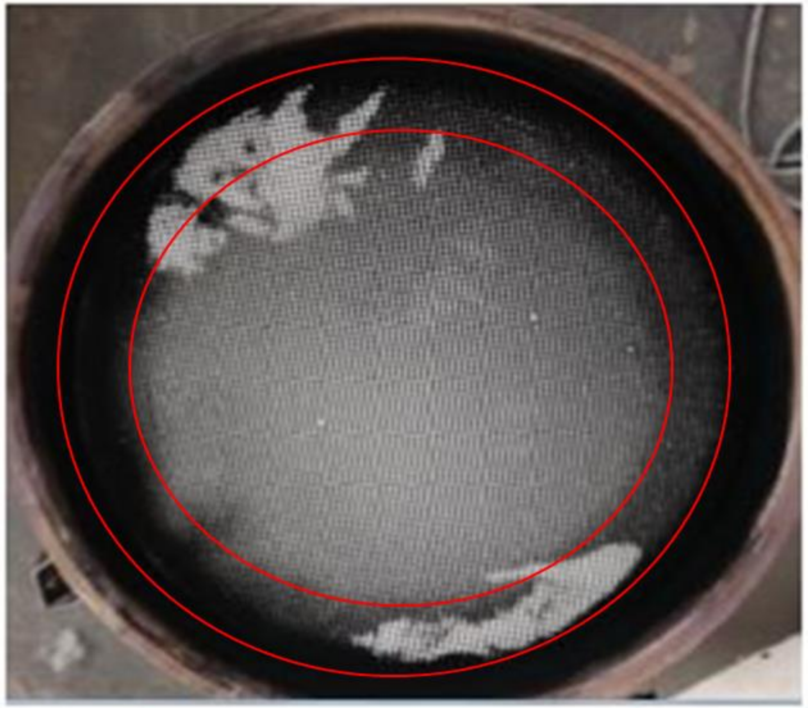
Typical Emission Failure mode and Mechanism

流程均匀性差 →故障2 背压高、再生里程不足

High back pressure and insufficient regeneration mileage

高原整车运行中，出现再生里程短，PN再生效率低问题；

CDPF外圈肉眼可见，大量PN存在。



典型排放失效模式及失效机制

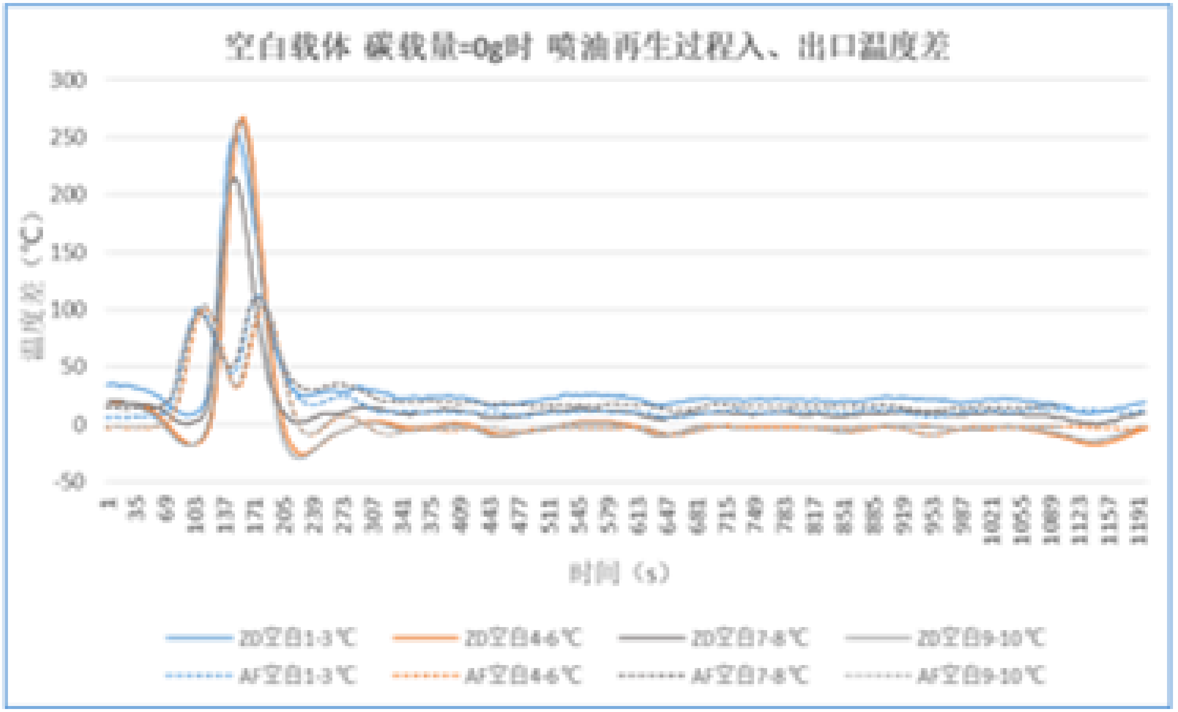
Typical Emission Failure mode and Mechanism

SPMC
Catalyst for clean air

流程均匀性差 → 故障2 背压高、再生里程不足

High back pressure and insufficient regeneration mileage

故障原因



- 中心与边缘温差：40℃-66℃
- 外缘温度不足导致再生不彻底

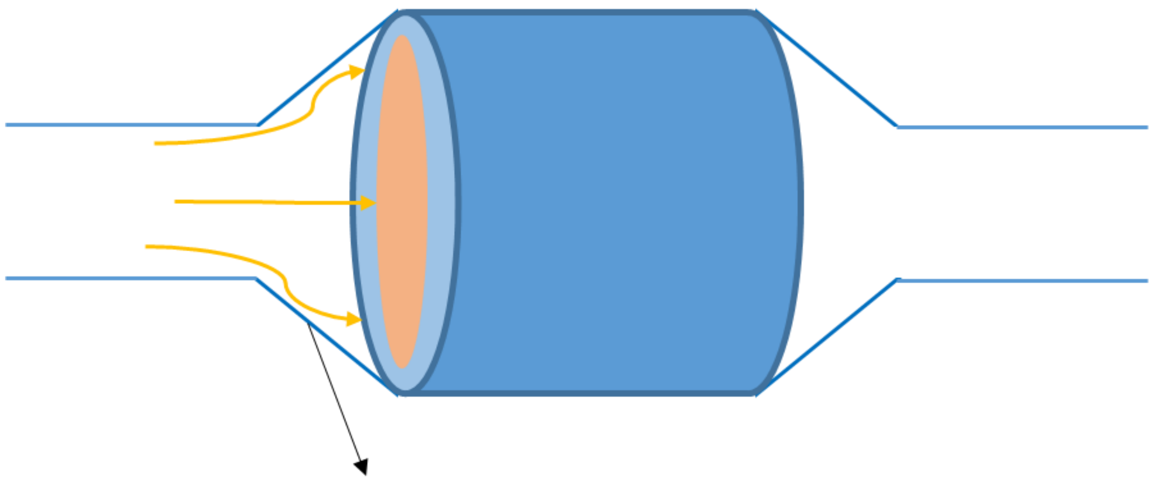
典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

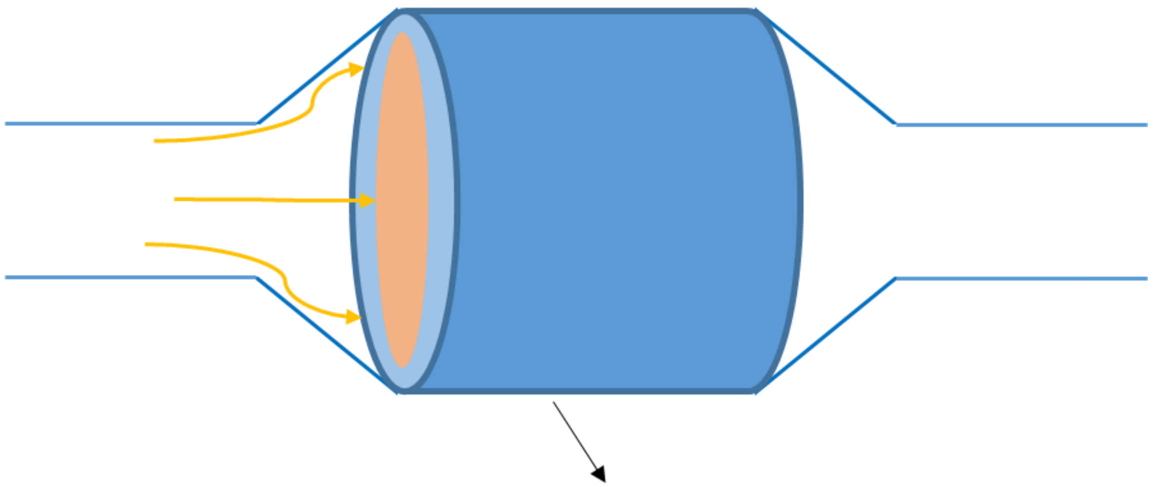
流程均匀性差 → 故障2 背压高、再生里程不足

High back pressure and insufficient regeneration mileage

影响机制



锥度设计不合理，温度集中内圈
Unreasonable taper design and the temperature concentrated in the inner ring



保温不合理，外缘散热太快
Unreasonable heat preservation, outer edge heat dissipation too fast

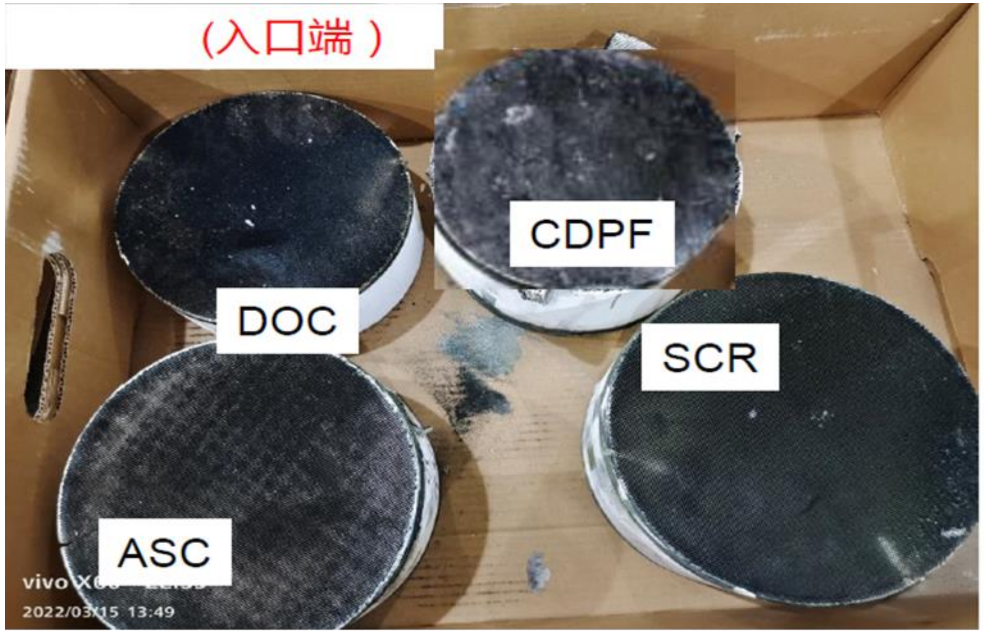
典型排放失效模式及失效机制

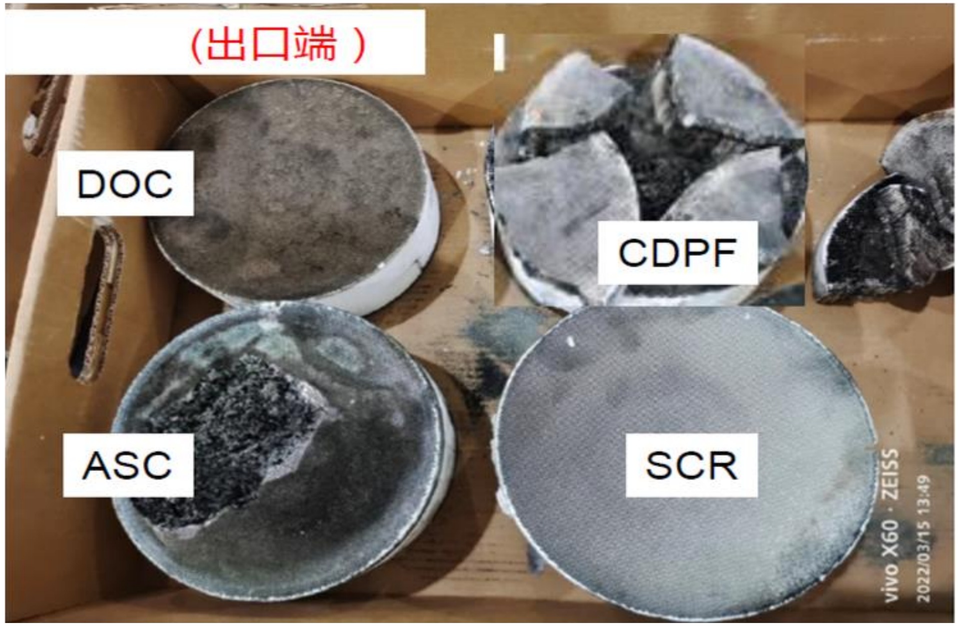
Typical Emission Failure mode and Mechanism

末燃HC覆盖→ 故障 PN超标、NOx超标

PN and NOx emission issue

- 整车在东北冬季运行时出现PN、NOx排放超标。





外观可见四颗催化剂端面都沉积大量碳烟 DOC、CDPF、ASC均被烧蚀。

Massive soot loading, CDPF and ASC all erosion.

所有催化剂均遭受了1000℃以上的高温。

All catalysts were subjected to high temperatures of more than 1000℃.

典型排放失效模式及失效机制

Typical Emission Failure mode and Mechanism

末燃HC覆盖→ 故障 PN超标、NOx超标

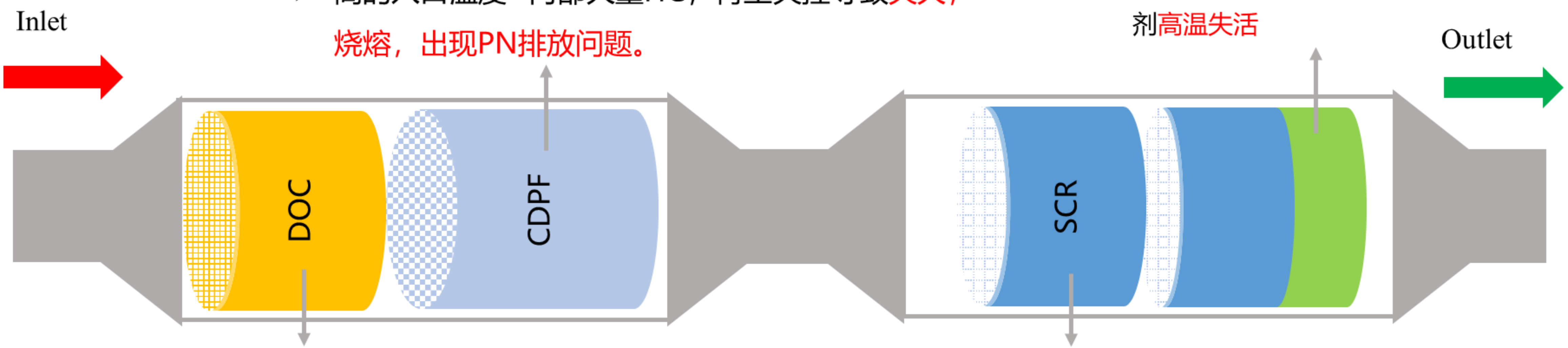
失效机制　　PN and NOx emission issue

HC覆盖为连锁反应，会导致系列严重排放问题发生。

HC coverage is a chain reaction, which will lead to a series of serious emission problems.

未燃HC会随着气流沉积到各催化剂内部，导致各催化剂均受影响。

Unburned HC will deposit into each catalyst with the gas flow, which will affect all catalysts



- 高的入口温度+内部大量HC，再生失控导致失火，烧熔，出现PN排放问题。
- 高的入口温度+放热反应，导致催化剂高温失活
- DOC内部含有大量HC和燃油，自动再生燃烧剧烈，烧熔，出口超温。
- 高的入口温度+内部HC燃烧，导致催化剂高温失活，出现NOx排放问题。

概 要 Outline

总结 Summary

柴油机排放可靠性为系统工程，单一排放故障涉及多种失效模式和失效机制。

Diesel engine emission reliability is system engineering, and single emission failure involves multiple failure modes and failure mechanisms.

为实现柴油机后处理系统的高排放可靠性，需强调发动机、催化剂、后处理控制系统及应用环境的协同设计。

In order to realize the high emission reliability of diesel after-treatment system, it is necessary to emphasize the collaborative design of engine, catalyst, after-treatment control system and application environment.

谢　谢!

Thanks!