Solving the Challenge of Future Emission Regulations and Decarbonization at the same time: A holistic Approach

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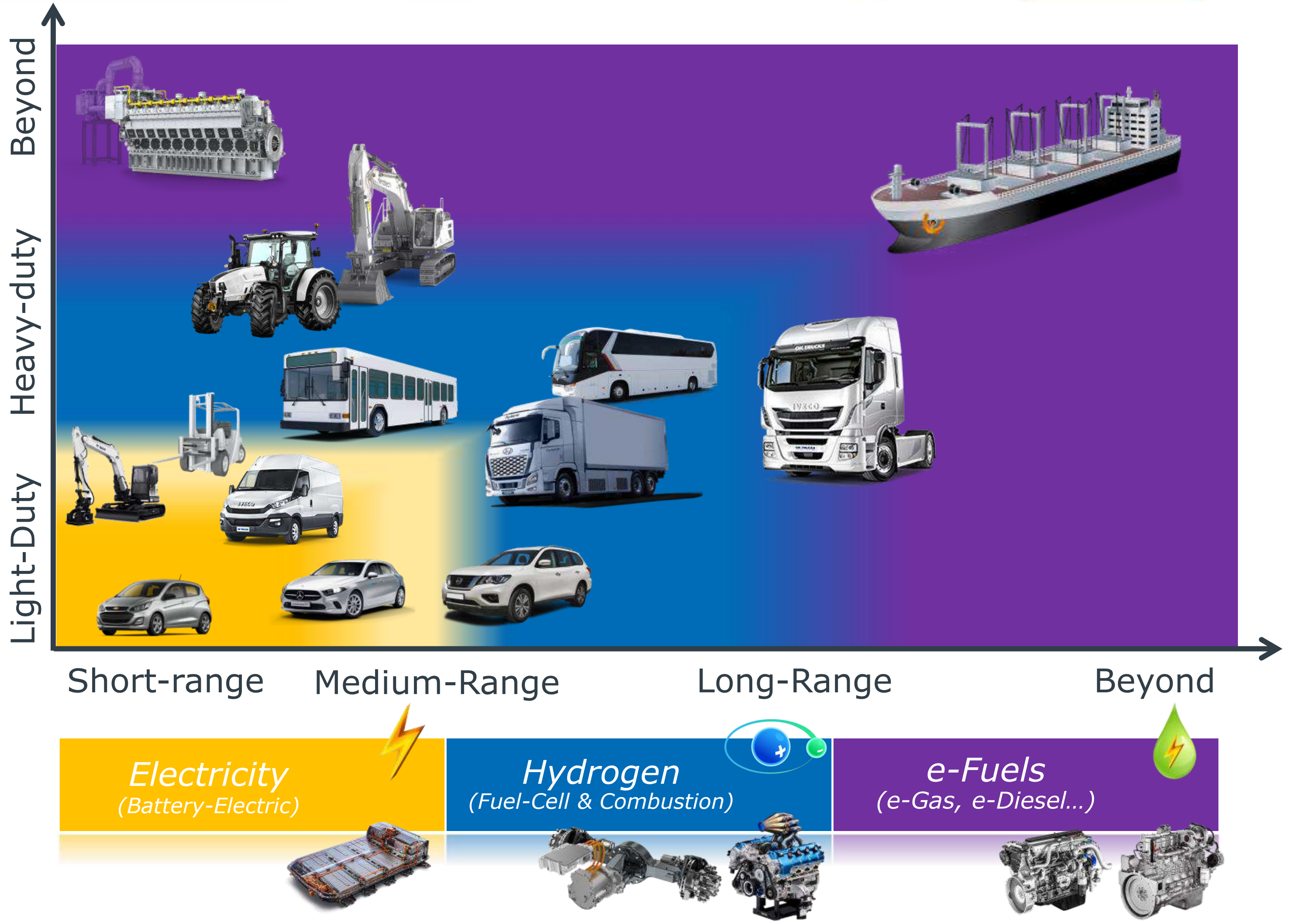
going the extra mile

Energy carriers Vs Applications
2050 outlook

The heavier the load and the longer the range, the less suitability for electrification & the more reliance on combustible fuels.

Take-aways:

- ✓ No silver-bullet technology
- ✓ Different energy carriers are suitable for different application requirements
- ✓ Renewable hydrogen is required to decarbonise transportation



Expansion of focus

going the extra mile

~~OR~~ AND

<u>Environmental concerns</u>

- All about pollutants in our environment
- Particles, HC, CO, NO_X, SO_x
- Health risk to people, animals and ecosystems
- Most often a local, regional concern (“the air we breathe”)

✓ BS7/Euro 7 HDV – 2028
✓ Tier 5 Offroad – 2029

<u>Climate concerns</u>

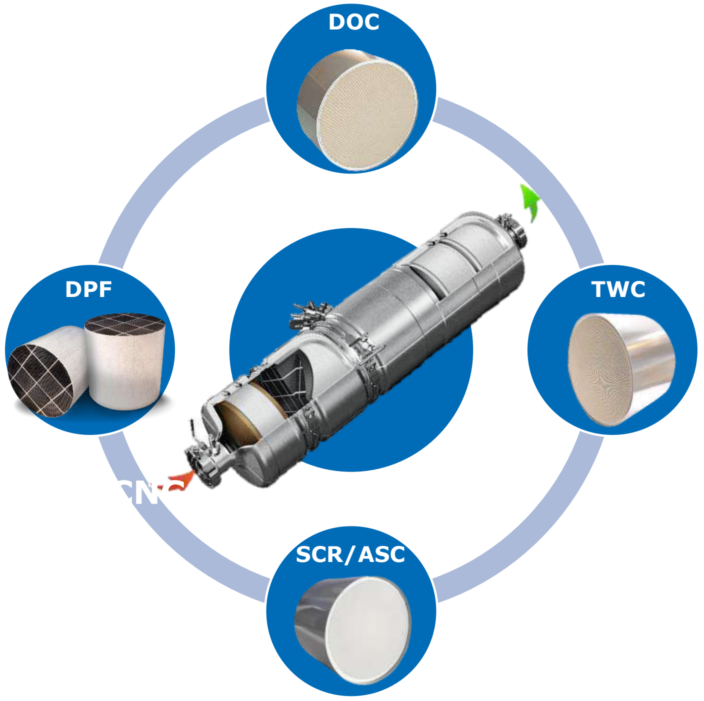
- All about greenhouse gases
- CO_2, CH_4, N_2O
- Harmless to the environment (relatively)
- A global concern leading to climate change

✓ Revised European Union CO_2 standards for Heavy-Duty vehicles
✓ EPA Phase 3 GHG standards

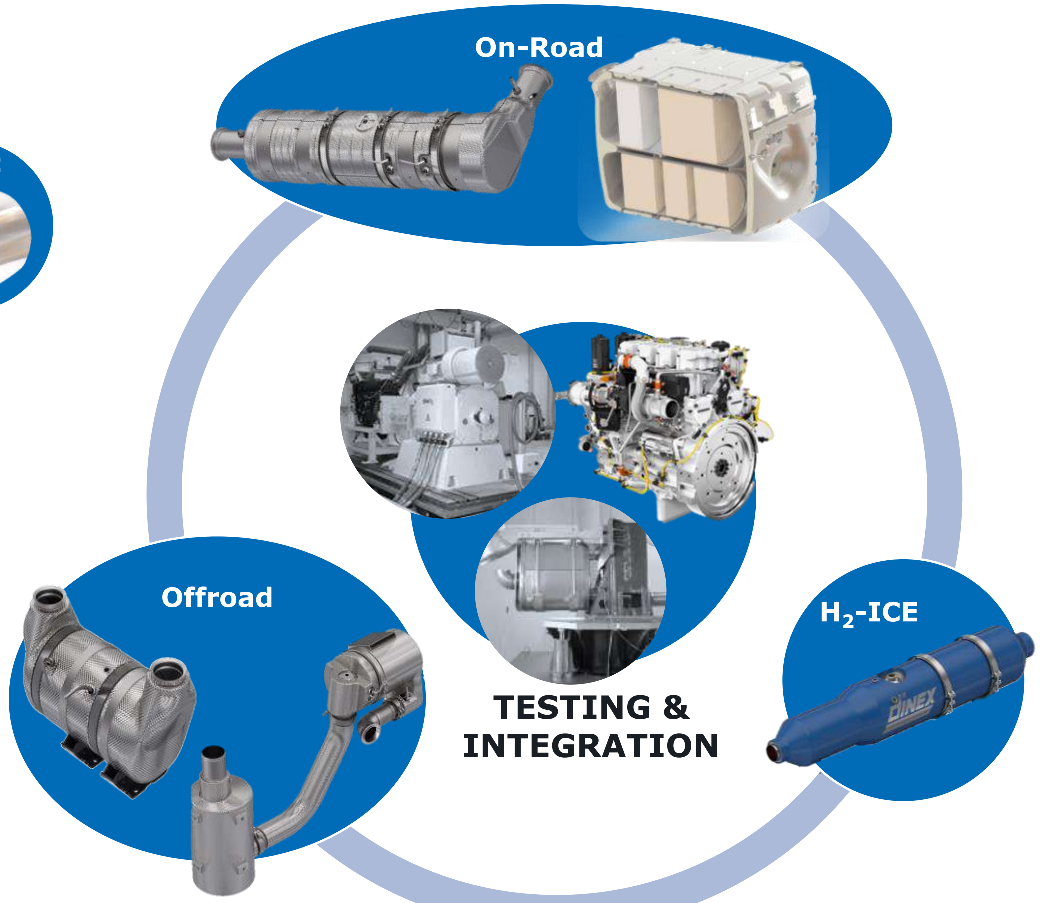
Dinex Product Portfolio

Catalyst & Canning Technologies under one roof

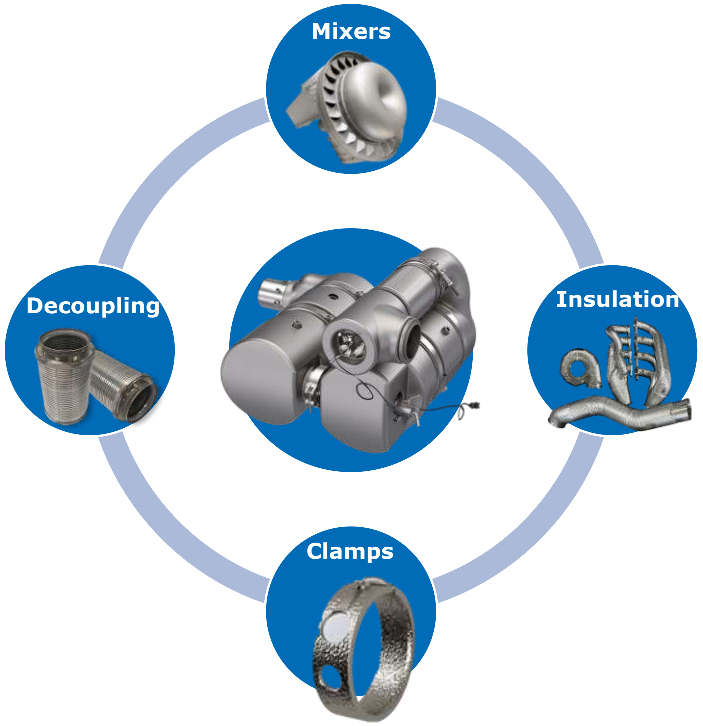
CATALYST – DIESEL, Natural Gas, H_2



ATS SYSTEMS



CANNING & PIPES



System approach allows for a holistic optimisation of the ATS to meet future standards at the best cost

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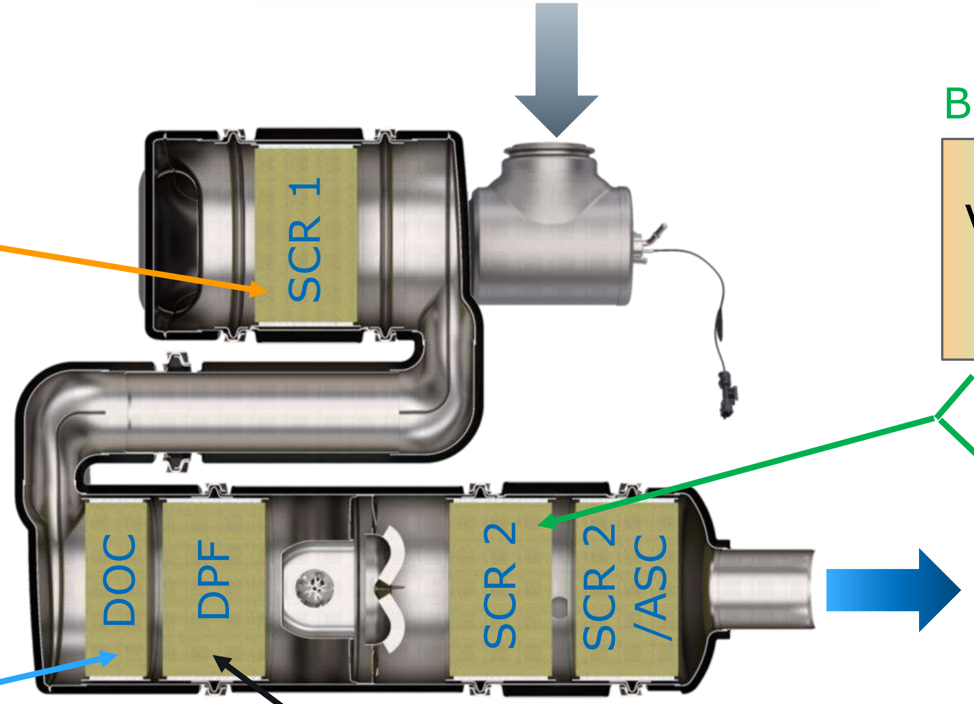
ATS layout for diesel engines

BS7/Euro 7 on-road & Tier 5 offroad ATS (>56kW)

going the extra mile



V-SCR

- ✓ V-SCR: XVO_4, where X represents Mn, Fe, Cu or Er or mixtures
- ✓ Low N_2O formation
- ✓ operated at ANR 0.7-0.9

DOC

- ✓ Silica stabilized Alumina, doted with Ceria and mixed metal oxides
- ✓ PGM load 10 – 20g/cft depending on regen. strategy

DPF

- ✓ Cordierite DPF at low pore size and porosity of 45%
- ✓ Optional adjustments via wash coat
- ✓ PGM load 1 – 3g/cft
- ✓ Alternative: Dinex high-porosity SiC filter

BS7/Euro 7 on-road

V-SCR & Cu-SCR | ASC

- ✓ Combination of V-SCR & Cu zeolite for simultaneous control of N_2O formation & high NOx conversion (best compromise Vs cost)

Tier 5 offroad

Fe/Cu-SCR | ASC

- ✓ Highest NO_x conversion
- ✓ Zeolite based SCR with high thermal durability, suitable for hot exhaust gas
- ✓ Control of N_2O formation via advanced Cu-zeolite or via Fe-/Cu-SCR formulation

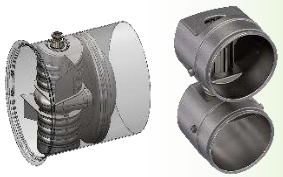
Technology requirements & Dinex innovation portfolio

going the extra mile

Cold performance concept

Low NO_x concept

Filtration concept



Main mixer
Swirl mixer for superior NH_3 UI & deposit performance with optimal backpressure

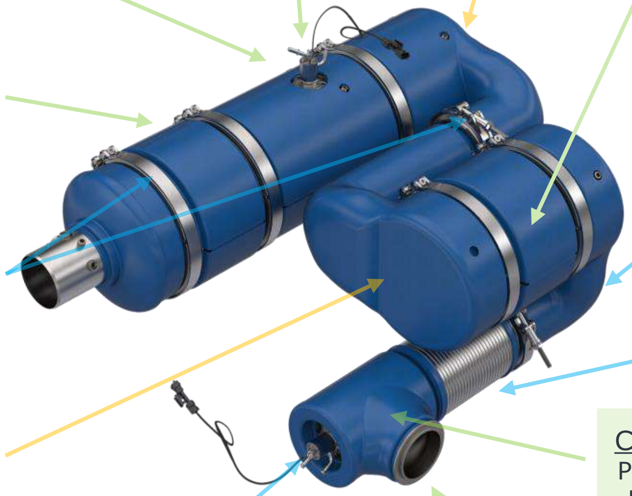
Fe/Cu SCR
High $deNO_x$, low N_2O & thermal durability at 2nd position

Insulated clamps/slip joint
To reduce heat losses & ensure serviceability

DOC
Optimal PGM loading, compatible with active & passive regeneration

1st urea dosing unit (optional heated)
Low temperature urea dosing for earlier $deNO_x$ & deposit-free operation

2nd urea dosing unit



DPF
High-porosity serviceable SiC filter or cordierite filter coating for PN10 filtration efficiency at low backpressure

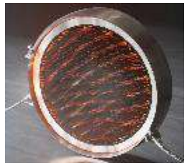
Vanadate SCR
Robust V-SCR at 1st position for ultra-low N_2O generation

Low thermal mass metal parts
Improved cold performance through faster heat-up (passive)

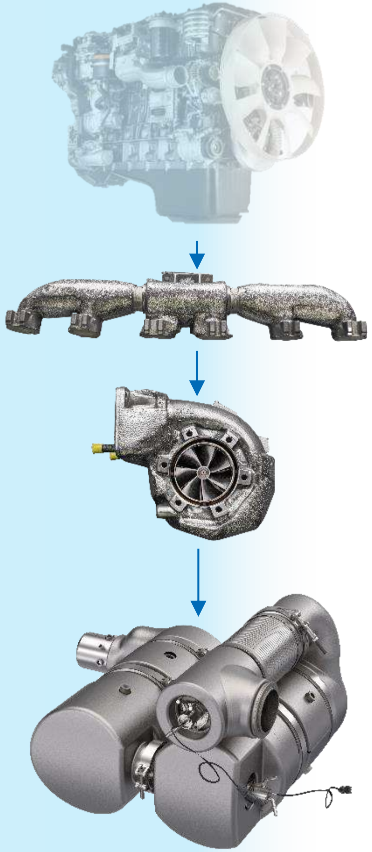
Dinex Insulated & Leak-Tight Decoupling
To avoid urea deposits & cold spots, with 0 leakage

Close coupled pipe mixer
Pipe mixer for superior NH_3 UI & deposit performance with optimal backpressure

E-heater
Active thermal management with integrated & serviceable e-heater

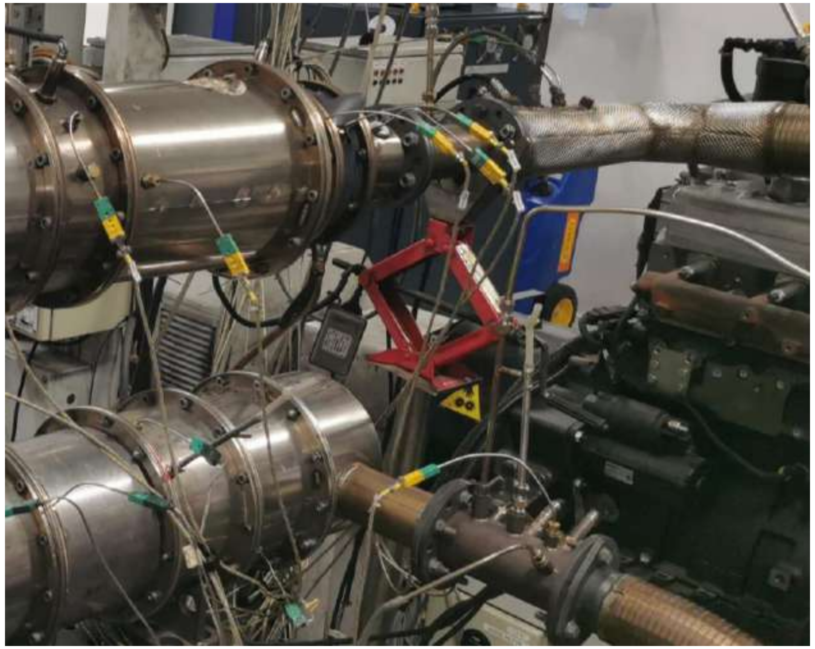


Exhaust manifold & turbocharger insulation
Insulation of complex geometries to minimise heat losses upstream of the ATS (passive)



Engine test setup
1- and 2-stage SCR

going the extra mile



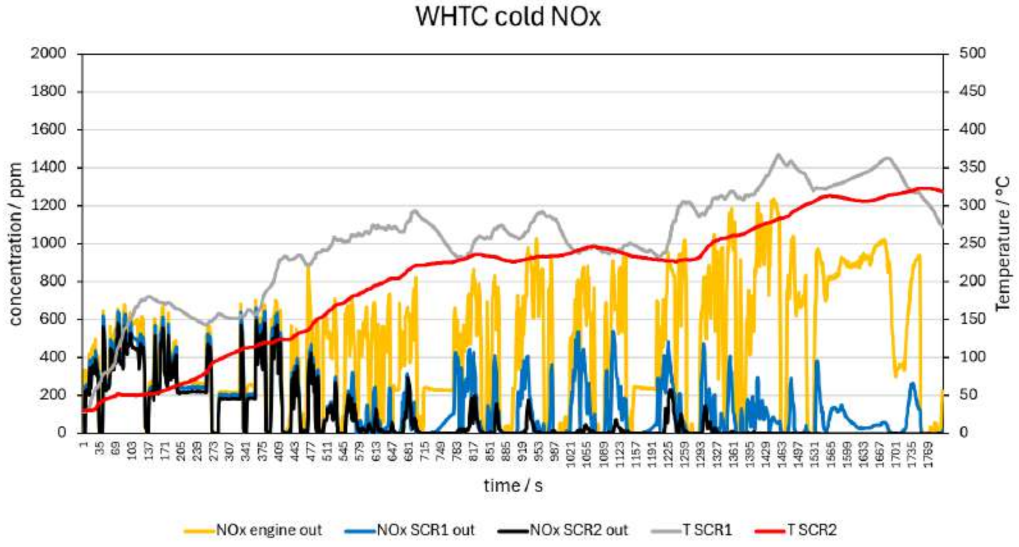
- 4.4L Tier 4f engine, no EGR, 120kW
- Engine out NO_x: 9 g/kWh in WHTC (Euro 7 expected at ~7g/kWh)
- 2 x multihole pressure-based urea dosing systems
- Simplified dosing strategy
- E-heater
- Flexible flanged design for fast exchange of catalyst samples (resulting however in high thermal mass)
- **Step 1:** Non-optimised ATS: no insulation, thick flanges, exhaust gas analyser modules → Worst case scenario in terms of emission performance, aiming to validate the ATS layout and new catalyst technology
- **Step 2:** Optimised ATS, more representative in terms of emissions

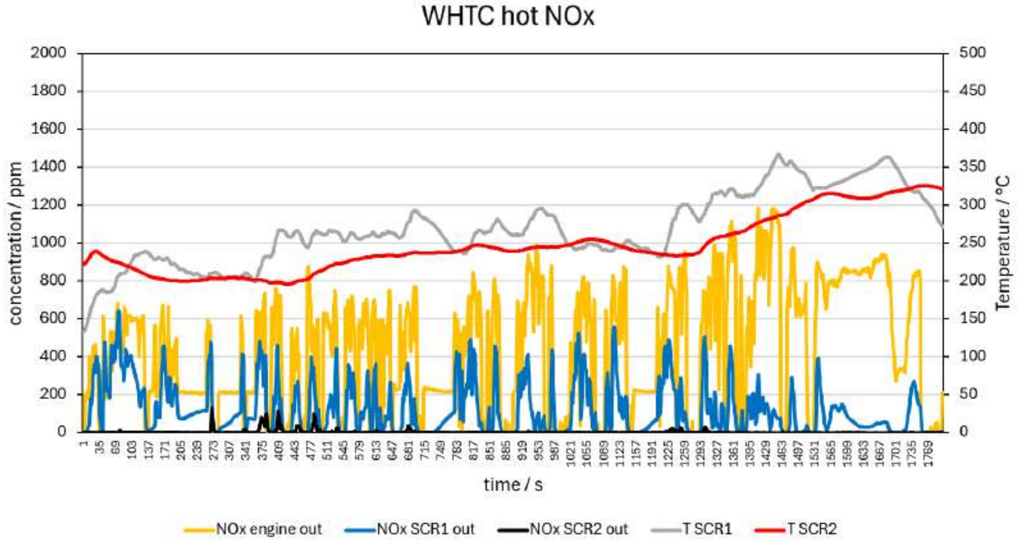
Catalyst setup:

- **SCR1:** 7.5"x5", 400/4, V-SCR
- **DOC:** 7.5"x5, 400/4, Pt:Pd (4:1), 10 g/cft
- **DPF:** 7.5"x8", 300/9, Pt:Pd (2:1), 3 g/cft
- **SCR2/1:** **1x** 7.5"x4", 400/4, Fe/Cu-SCR
- **SCR2/2,3:** **2x** 7.5"x4", 400/4, Cu-SCR
- **SCR2/4:** **1x** 7.5"x4", 400/4, Cu-SCR+ASC

All components pre-aged before start of test
V-SCR → 580°C / Fe/Cu→ 650°C – 50h

NO_x conversion performance





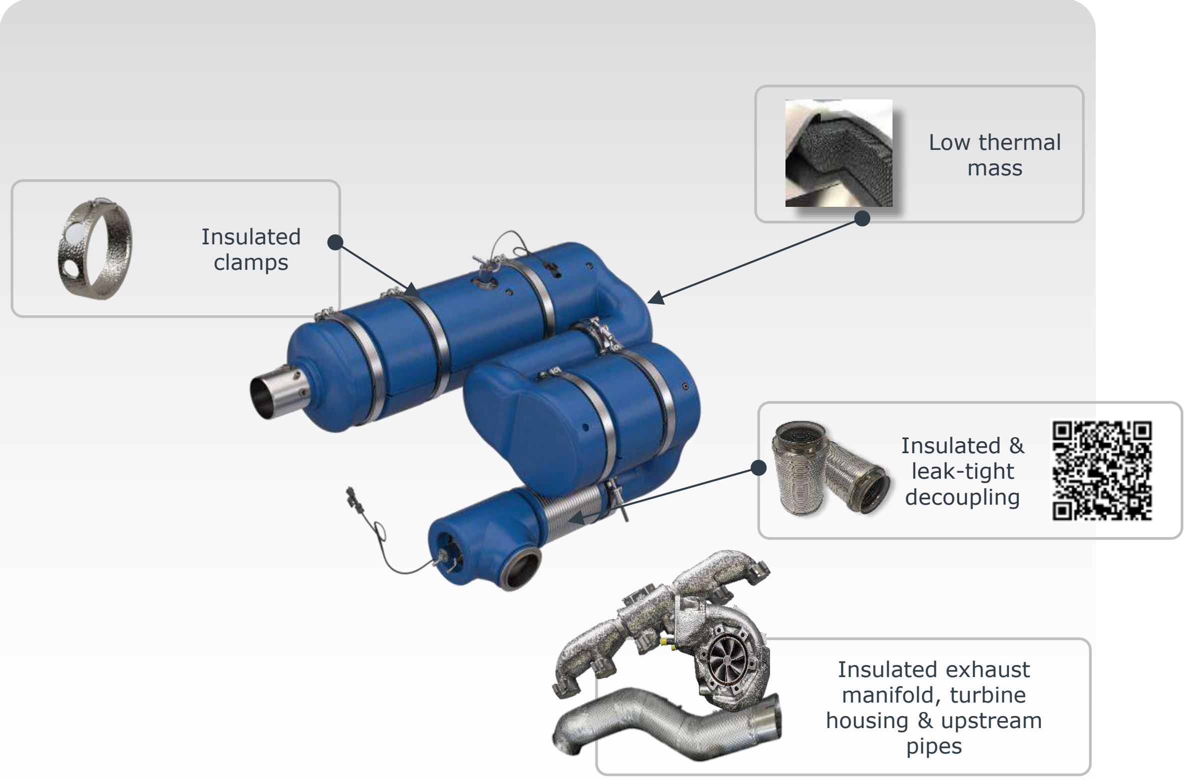
$t_{inj.\ start\ SCR1}$ = 138 s (effective 368s) $t_{inj.\ start\ SCR2}$ = 564 s

$t_{inj.\ start\ SCR1}$ = 29 s $t_{inj.\ start\ SCR2}$ = 0 s

Ø ANR SCR1: 0.75
Ø ANR SCR2: 1.20
inj. start Temp.: 180 °C

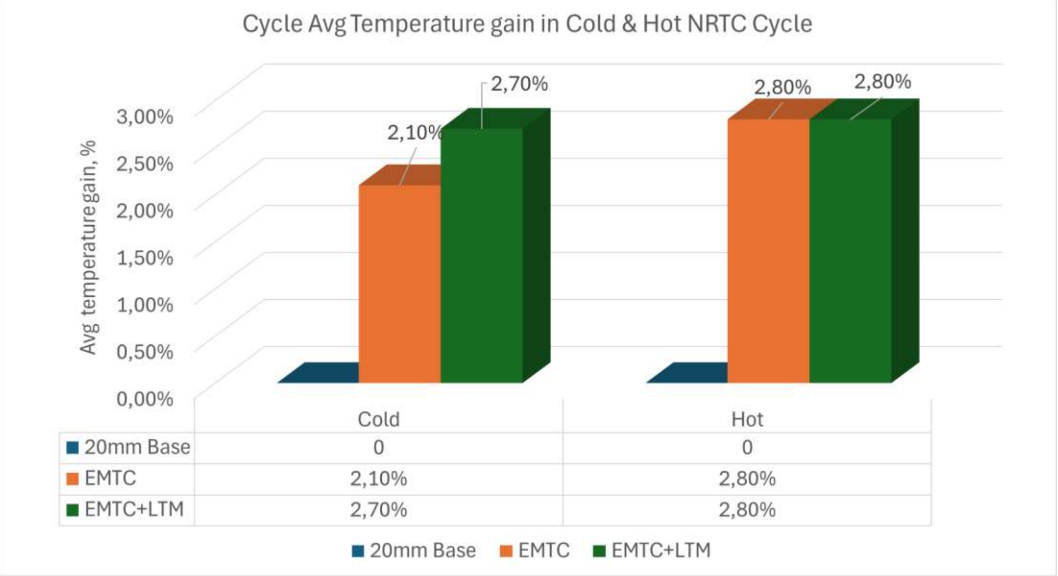
	NO_x cold	NO_x hot	NO_x combined 20:80	N_2O
Reduction after SCR1	70%	72%	**71.6%**	--
Reduction after SCR2	91.6%	99.3%	**97.8%**	--
TP emission, g/kWh	0.76	0.06	**0.20**	0.09

Passive thermal management
Temperature and deNOx efficiency gain

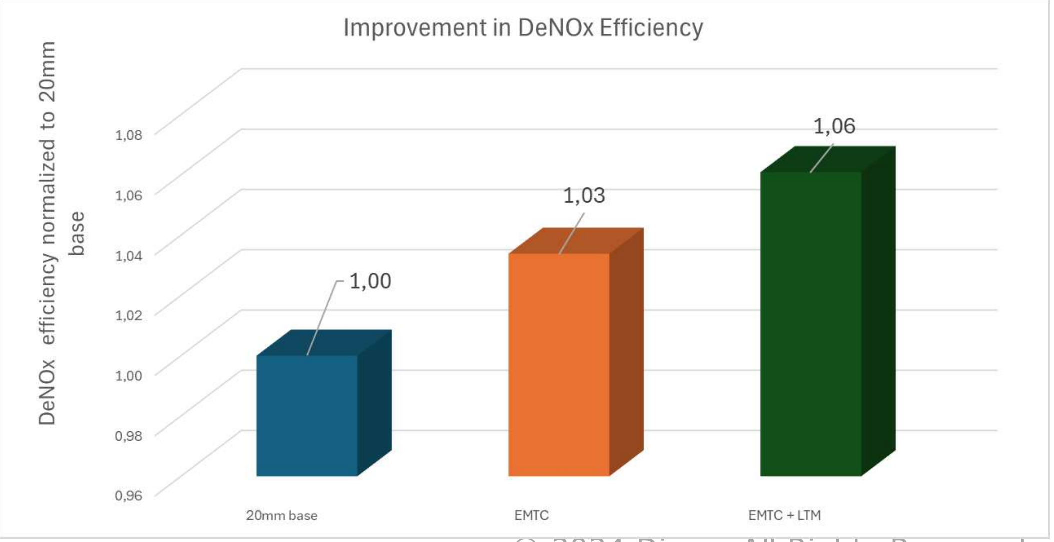


- Insulated & leak-tight decoupling (DLTD)
- Insulated clamps installed with EMTC + LTM setup
- 12mm insulation installed in LTM pipes and cones
- DeNOx efficiency calculated on 5:95 ratio between cold & hot

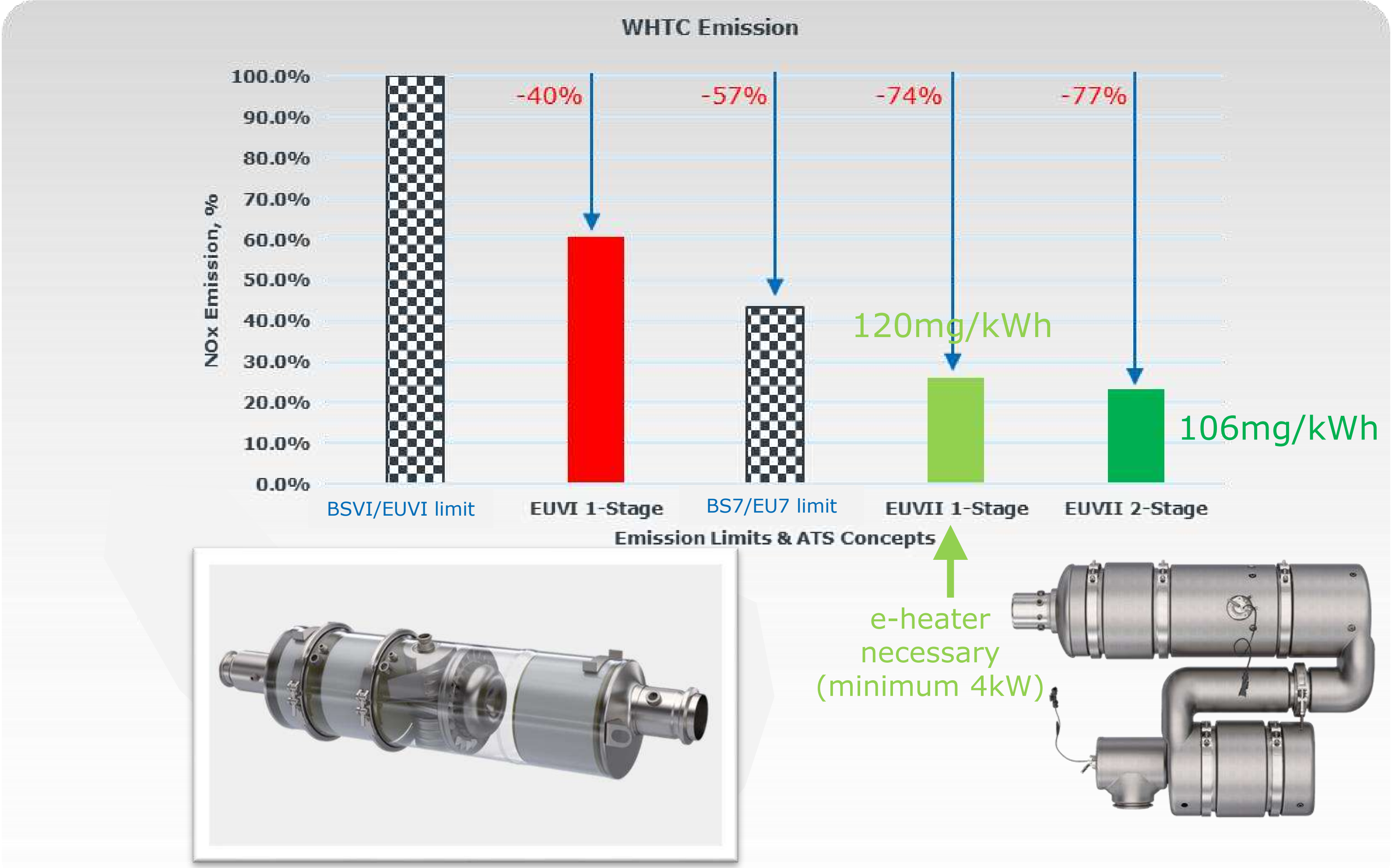
Note:
- 20mm is base insulation setup (20mm)
- Exhaust manifold & turbine housing insulation. (EMTC)
- Low thermal mass components (LTM)



	Cold	Hot
20mm Base	0	0
EMTC	2,10%	2,80%
EMTC+LTM	2,70%	2,80%



Summary of results after optimisation



- Engine raw emissions from Euro VI & Stage V / Tier 4 engine.
- Thanks to advanced insulation, temperature profile improved and earlier urea injection times were achieved (cold WHTC):
  - SCR1: 101s (effective 315s)
  - SCR2: 414s
- DPF regeneration strategy defines DOC, SCR design & dosing strategy
- Same total SCR volume between 1-stage & 2-stage SCR

Note: These ATS concept results are based on specific engine flow and temperature conditions and may vary with different customer-specific engine conditions.

Conclusions
BS7/Euro 7 & Tier 5 diesel ICE

going the extra mile

- Latest Dinex catalyst and canning technologies were tested on a 1-stage & 2-stage SCR dyno setup – introduction of Vanadate SCR, Fe/Cu SCR & low PGM DOC

- A 2-stage SCR system is necessary to meet Euro 7 on-road & Tier 5 offroad emission limits - it is possible without active thermal management

- For a 1-stage SCR and further reduction of NO_x and N_2O emissions in low load cycles, active thermal management (e-heater or heated urea injector) is required

- The PGM load on the DOC was at a low level, showing the potential of new washcoat development to reduce PGM load, but the DPF regeneration strategy will define the final design in respect of load and PGM ratio

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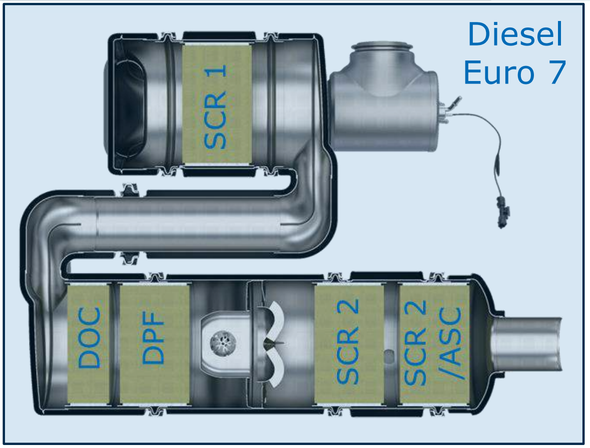
H_2 ICE - Key requirements on the ATS

going the extra mile

- ✓ Reach near-zero emissions, for example NO_x<15mg/kWh, as direct comparison against H_2 Fuel Cells is expected
- ✓ Overall lower raw emissions from the engines → Cost-effective and more compact ATS is expected
- ✓ No N_2O generation – zero-CO_2 technology
- ✓ High H_2O content in the exhaust → Selection of corrosion-resistive materials
- ✓ High H_2O content in the exhaust → Selection of catalytic coating which is more resistant to hydrothermal ageing → V-SCR Vs Cu-SCR
- ✓ Optimise development effort & cost by reusing ATS technology from diesel BS7/Euro 7/Tier 5 development, while adjusting to the specific attributes of the H_2 ICE

ATS layout for H_2 engines
From diesel to H_2 ATS



- ✓ Keep same SCR technology
- ✓ Keep advanced insulation
- ✓ Replace DOC by NSC or HOC
- ✓ Reuse filter technology (but simplify)

NSC or H_2 Oxicat

- ✓ Alumina/Ceria based wash coat
- ✓ PGM load 30 – 50g/cft
- ✓ NOx storage: 140µmol/g coating (HT aged 500°C / 100h)

V-SCR or Cu-SCR | ASC

- ✓ V-SCR: XVO_4, where X represents Mn, Fe, Cu or Er or mixtures
- ✓ Low N_2O formation

or

- ✓ Cu-Zeolite based SCR for highest $deNO_x$

Filter

- ✓ Cordierite filter at low pore size and porosity of 45% (GPF or high filtration DPF)
- ✓ Adjustments via wash coat
- ✓ No PGM

H2 ICE – ATS Concepts

Dinex H_2 ICE technologies for different ATS configurations

UDS | Mixing | V-SCR or Cu-SCR

H_2 OxiCat | UDS | Mixing | V-SCR or Cu-SCR

NO_x Storage Catalyst | UDS Optional heated | Mixing | V-SCR or Cu-SCR

LNT | Cu-SCR (passive)

WORK IN PROGRESS

H2 SCR

Small operation window
N_2O formation
high H_2 / NO_x ratio needed

V. Huth et al., 30th Aachen Colloquium Sustainable Mobility 2021, October 6, 2021

T. Wolff et al, FAD conference Nov. 2022

With heated injector: J. E. Bebe, AVL SimPulse conference for alternative fuels, Apr. 2024

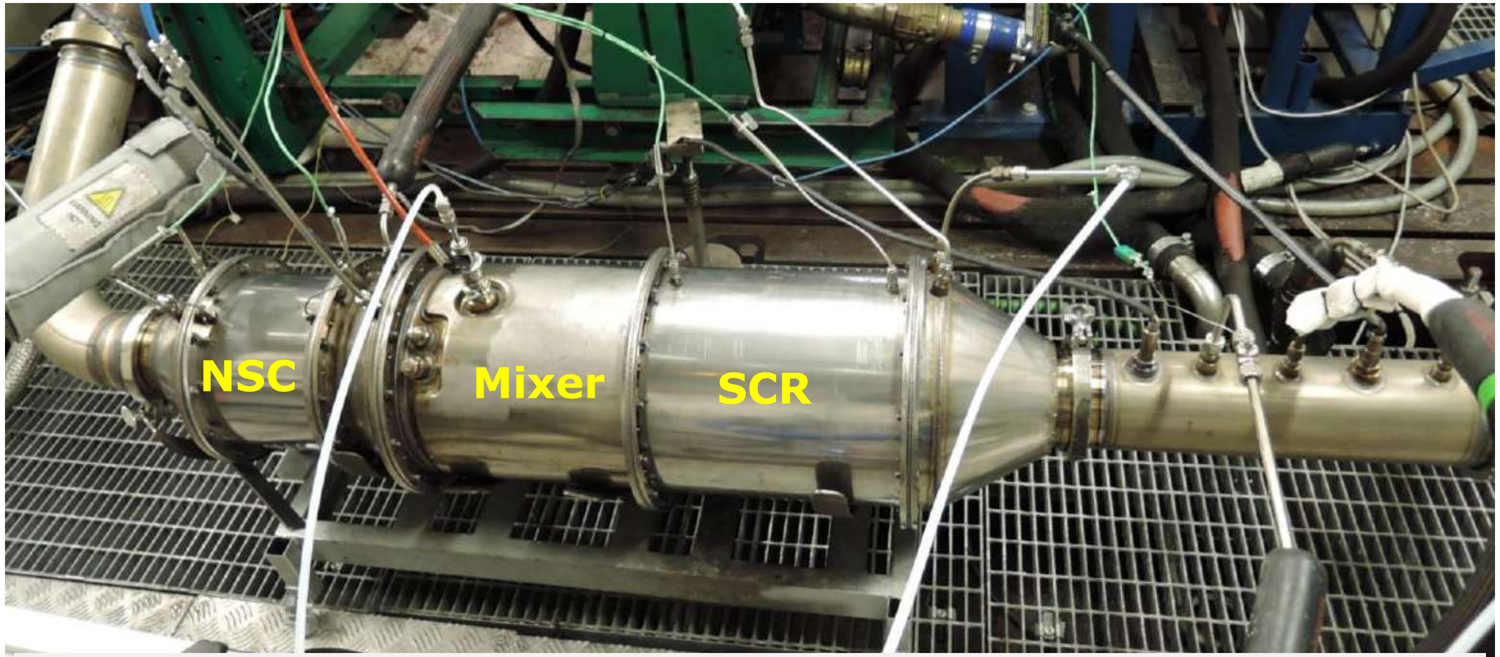
H_2 engine dyno setup
Catalyst test setup with NSC & SCR

Collaboration with **IFPEN** (Lyon) for ATS test campaign on H_2 ICE

Engine: 6 cyl, 8L, 210kW
Diesel converted to Hydrogen

Renault Truck Engine developed in the framework of „PLH2" Consortium[1]

NRTC: 660 mg/kWh NO_x



- **NSC:** 7.5"x5, 600/3 Pt 50g/cft, V = 3.62L
- **V-SCR:** 9.5"x7.5", 600/3, V-SCR+ASC, V = 8.71L
  or
- **Cu-SCR:** 9.5"x7.5", 600/3, Cu-SCR+ASC, V = 8.71L

[1] Walter et al. *H2 ICE technology development for medium-duty truck application: from concept to full calibrated engine prototype* SIA Powertrain 2024

Test results Cu-SCR & NSC/Cu-SCR

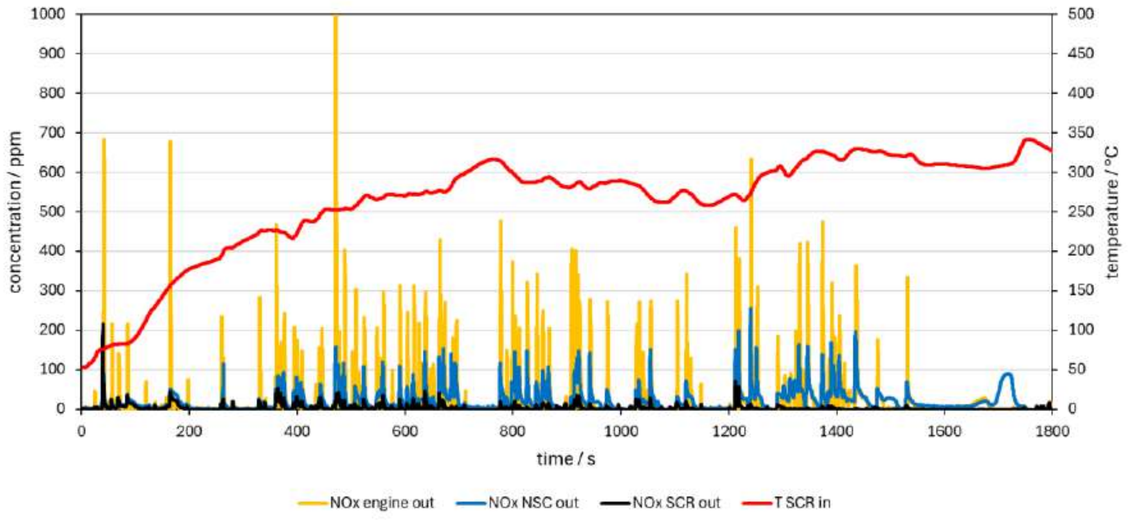
going the extra mile

TP emissions, mg/kWh, WHTC cold & hot

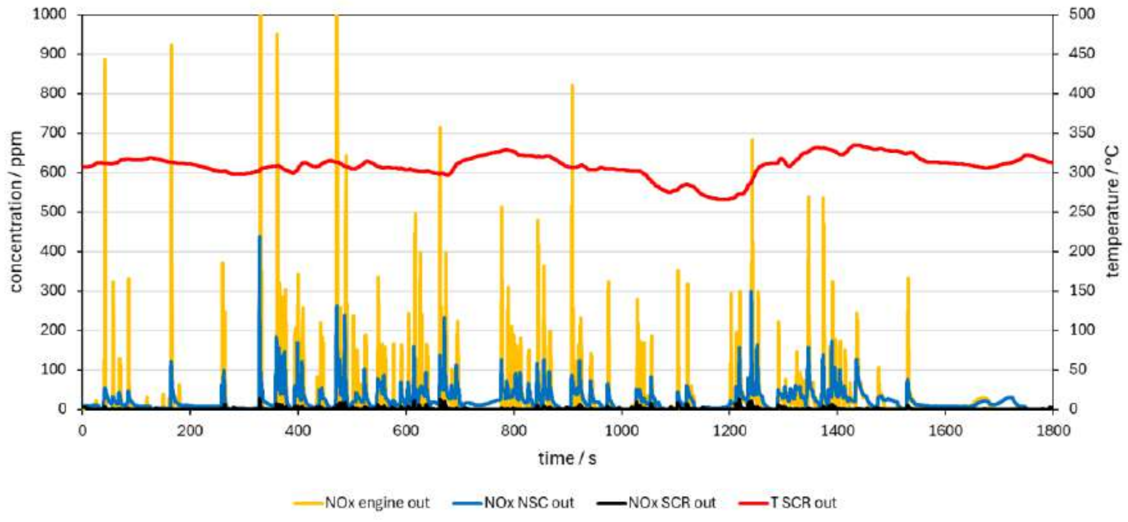
SCR catalyst empty at start of test (ANR ~ 1)

Catalyst setup	NO_x cold | hot	NO_x c:h = 20:80	N_2O cold | hot
SCR only	143 | 28	51	18 | 18
NSC + SCR	90 | 22	36	11 | 11

WHTC cold NSC+SCR



WHTC hot NSC+SCR



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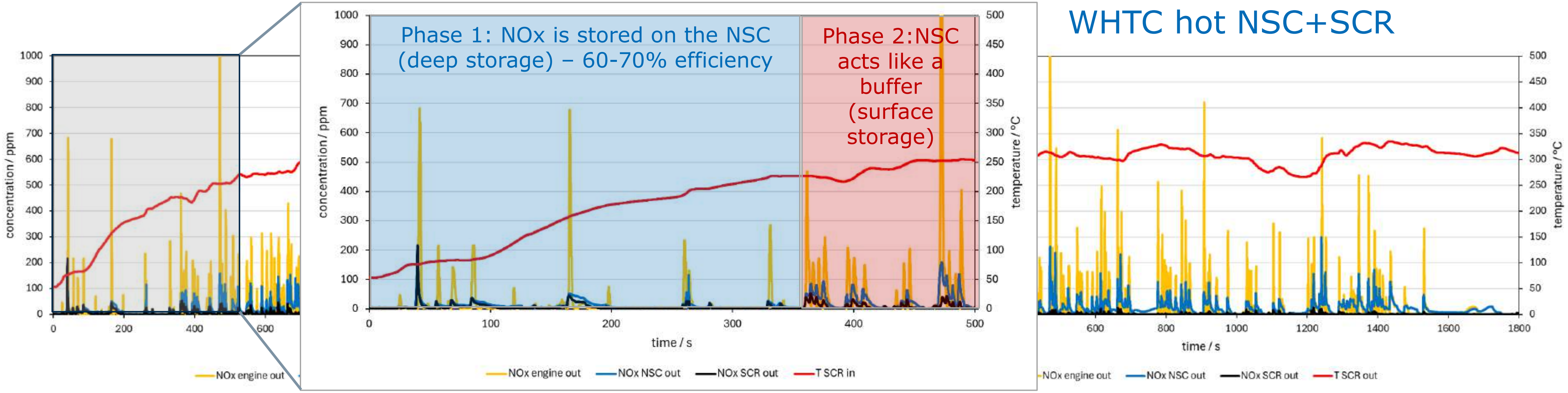
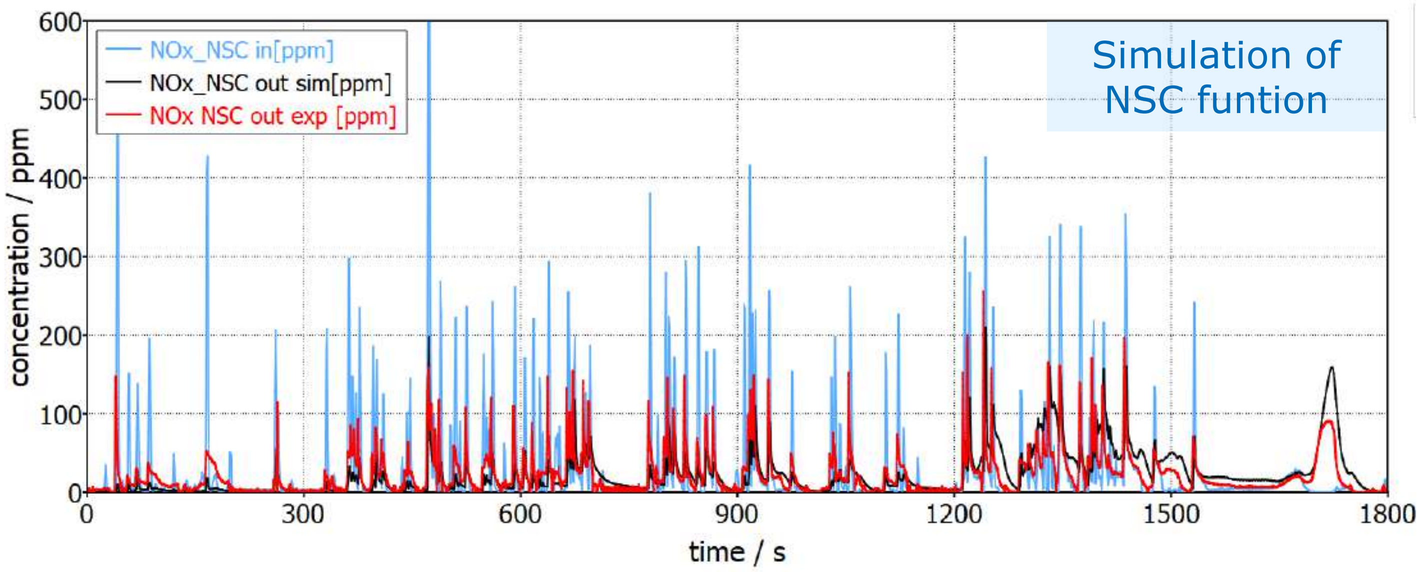


WHTC 1D Simulation results
Pre-filled SCR and optimized urea dosing

going the extra mile

Emissions mg/kWh	WHTC hot Cu-SCR only	WHTC hot NSC+Cu-SCR	WHTC cold NSC+Cu-SCR	WHTC 20:80 NSC+Cu-SCR
NO_x	21	14	68	25
N_2O	24	17	16	16



- Good match on NO_x storage and buffering effect between measurement and simulation
- With pre-filled SCR and optimised urea dosing, even lower NO_x is possible

Conclusions & outlook H_2 ICE

going the extra mile

- The SCR technology used to meet BS7/Euro 7 or Tier 5 emission standards for diesel engines can be used without further adaptions on the H_2 ICE, hence reducing development costs & effort
- The Cu-SCR has been tested on an engine bench setup as SCR only and in combination with an NSC
- The NSC shows a NO_x buffering effect over the entire test cycle, supporting hence the SCR and reducing N_2O emissions
- The SCR volume can be 2-3x lower on a H_2 ICE comparing to a diesel engine
- Near-zero NO_x emissions are possible on a H_2 engine with a relatively small ATS & optimized urea dosing
- Outlook: V-SCR as replacement of Cu-SCR will be tested on the dyno & simulated – the combination of LNT/pSCR as well

Many thanks to the colleagues from **IFPEN**
David Berthout, **Loic Rouleau**, **Bruno Walter** and **Geoffrey Bourrachot** for the H_2 ICE testing

and to the audience for your attention!