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Hydrogen Internal Combustion Engine
An additional Cornerstone for a future with clean mobility

ECT-Seminar

23rd of October 2024

India’s green hydrogen approach

Ambitious Plans for a Revolution in Mobility

INDIA’S “PANCHAMRIT” TO ACHIEVE NET-ZERO

1. Raising the non-fossil fuel-based energy capacity of the country to 500 GW by 2030.
2. Half of the energy requirements of the country would be met using renewable energy sources by 2030.
3. Reduce one billion tons of carbon emission by 2030.
4. The carbon intensity would be reduced to less than 45% by 2030.
5. By 2070, India would become carbon neutral and achieve net zero emissions.

Ambitious goals with high dedication to green hydrogen:

By 2030 reaching 500GW with renewable energy sources, which reduces the carbon emissions by one billion tons.

By 2070 India want to reach net zero emissions and be carbon neutral.

As of March 2024, already 190GW renewable energy sources are installed.

Source: https://static.pib.gov.in/WriteReadData/specificdocs/documents/2024/may/doc2024510336301.pdf

The Way of Industrialization for the H_2-ICE

What does Umicore offer for the great ambitions in India for the H_2-ICE?

- Umicore is a member of the Alliance Hydrogen Engine since the very beginning

- Early-stage discussions with a higher number of OEMs and engineering companies worldwide.
- Generation of catalyst technology performance data in H_2 environment (synthetic gas bench testing stationary and dynamic, e.g. driving cycles). Partly in combination with modelling in case the full engine data is not available yet.
- Active participation in several public funded projects together with various OEMs, e.g. in the H_2-Democar with DHL, Ford, Bosch, Purem and various partners.
    - 6 active projects in the field of light-duty, heavy-duty and Non-/Off-Road.

H_2-ICE – Cornerstone for clean mobility

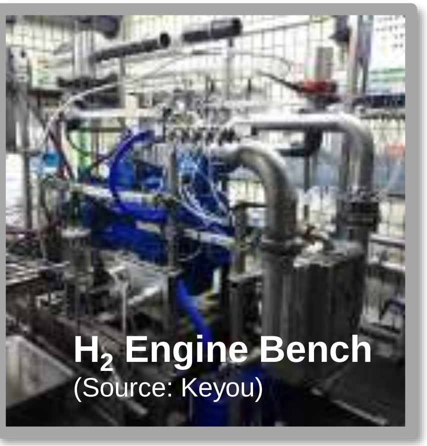
Difference of H_2-ICE to Diesel application (from EATS perspective)

General

- Temperature window tends to be narrower than for Diesel (200-450°C).
- Higher Exhaust Mass-flow compared to Diesel (≈ +30%).
- High water content (15-35%) → risk of condensation/flooding.
- Aging requirements expected to be like Diesel (except for potential physical H_2O effects).

Hydrogen H_2

- High H_2 concentration (>> 1000ppm) possible.
- Explosion limit is temperature dependent and can be << 4%.
- Oxidation catalyst is recommended for safety reasons.
- Oxidation catalyst can generate significant heat starting from ≈ 150°C (chemical heater).



H_2 Engine Bench

(Source: Keyou)

$DeNO_x$

- Varying NO_x levels, depending on OEM/application: <1 - 8 g/kWh (transient), in steady state significantly lower.
- High NO_x peaks (>1500ppm) can occur during acceleration phases.
- Cold start still challenging, but typically faster warm up, also assisted by oxidation catalyst.
- In case of Fuel-Cell fuel grade: very limited $DeSO_x$ requirements.

Soot / PN / filtration

- Soot mass ≈ 0, however PN limit requires filter.
- No regeneration requirement.
- Low impact of urea particulates due to lower NO_x and possible filter positioning downstream urea injection.
- Δp is important: $\Delta p \nearrow \rightarrow \lambda \searrow \rightarrow NO_x \nearrow$

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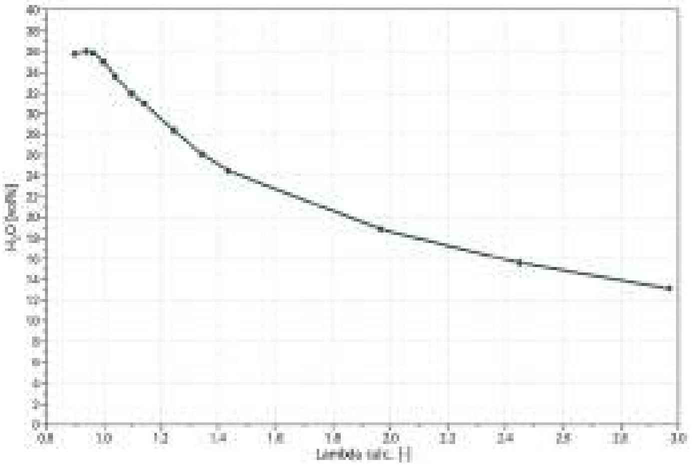
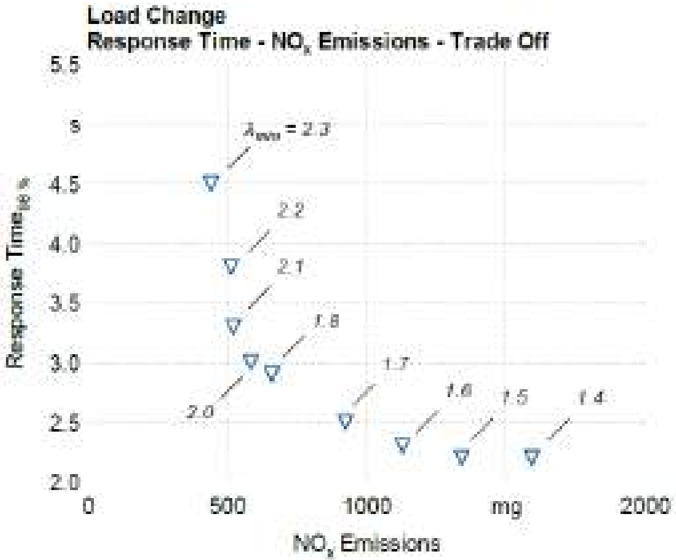
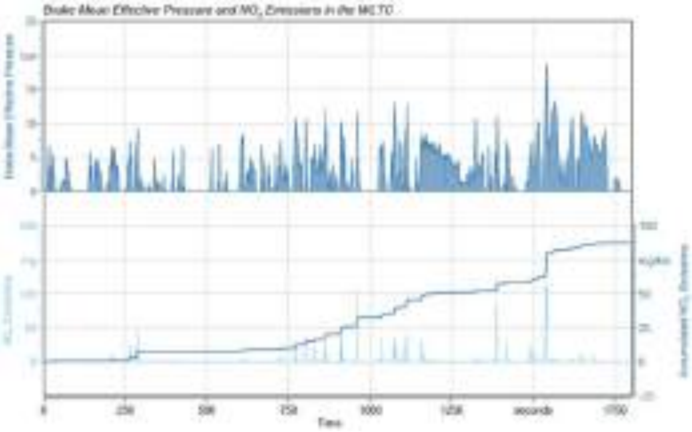
H_2-ICE – Cornerstone for clean mobility

Challenges for the H_2-ICE for the EATS





WLTC (started @ 25°C)
$NO_{x,raw}$ = 88 mg/km



Water Content

Strongly dependent on the operating Lambda.

Preferable Lambda > 1.6 for low water content and low NO_x Emissions.

Engine Response Time vs. NO_x-Emissions

Compromise between Dynamics & NO_x.

Challenges for air supply.

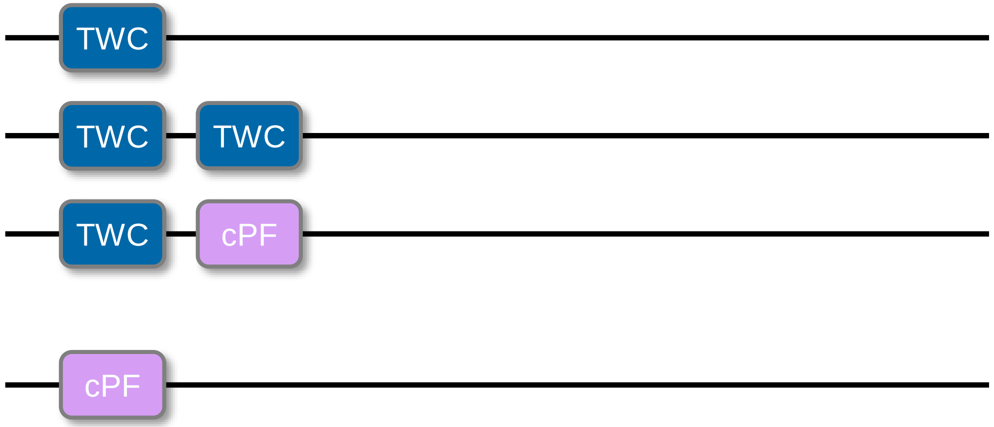
NOx-Emissions in Transient Operation

NO_x emissions primarily at load increase.

Nearly no emissions at low load.

H_2-ICE – Cornerstone for clean mobility

System Layouts for Lambda = 1

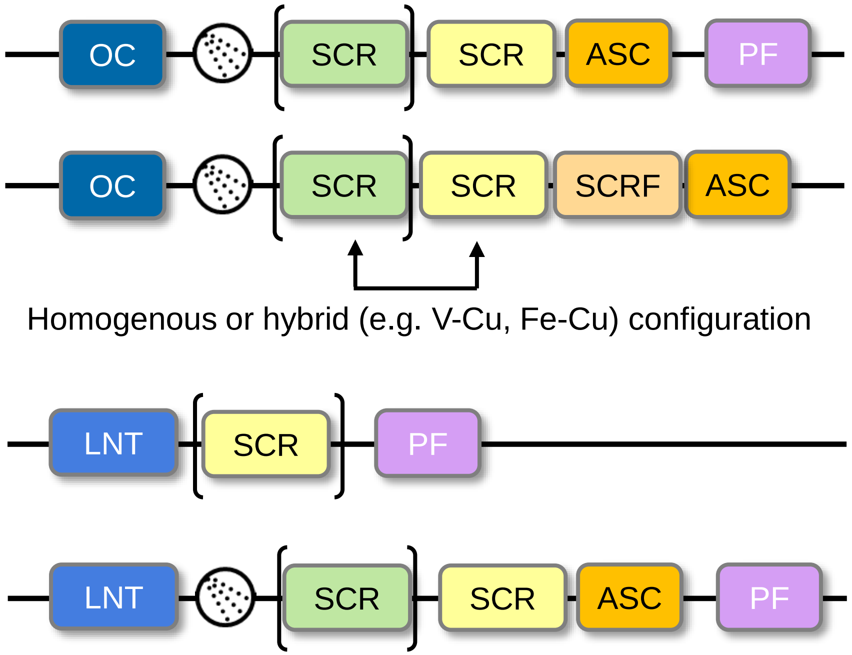


System design approach:

- NOx engine out emissions seen as like gasoline applications → TWC system volume comparable to gasoline.
- For certain legislations a concept with a coated filter only might be feasible.
- Dependent on the application coated or uncoated filter might be used in addition.

H_2-ICE – Cornerstone for clean mobility

System Layouts for lean operation



Homogenous or hybrid (e.g. V-Cu, Fe-Cu) configuration

SCR

- OC for H_2 oxidation, heat-up & NO_2 formation.
- Cu-Zeo with highest activity potential and best for dynamic requirements with extreme peaks.
- Combination of V- or Fe- and Cu-SCR
  → highest DeNOx @ lowest N_2O
- SCR function can be integrated on particulate filter (SCRF)

NO_x storage Catalyst

- Most attractive: avoid urea infrastructure
  → only feasible for $NO_{x,\ raw}$ << 3 g/kWh
- PGM << 50 g/ft³
- Little DeSOx requirements.
- Also “light” versions thinkable:
  trap NOx during cold start phase, passive or active release + active SCR

PF Particulate Filter: necessary for markets with PN regulation (remove PN derived from oil, ash, urea)

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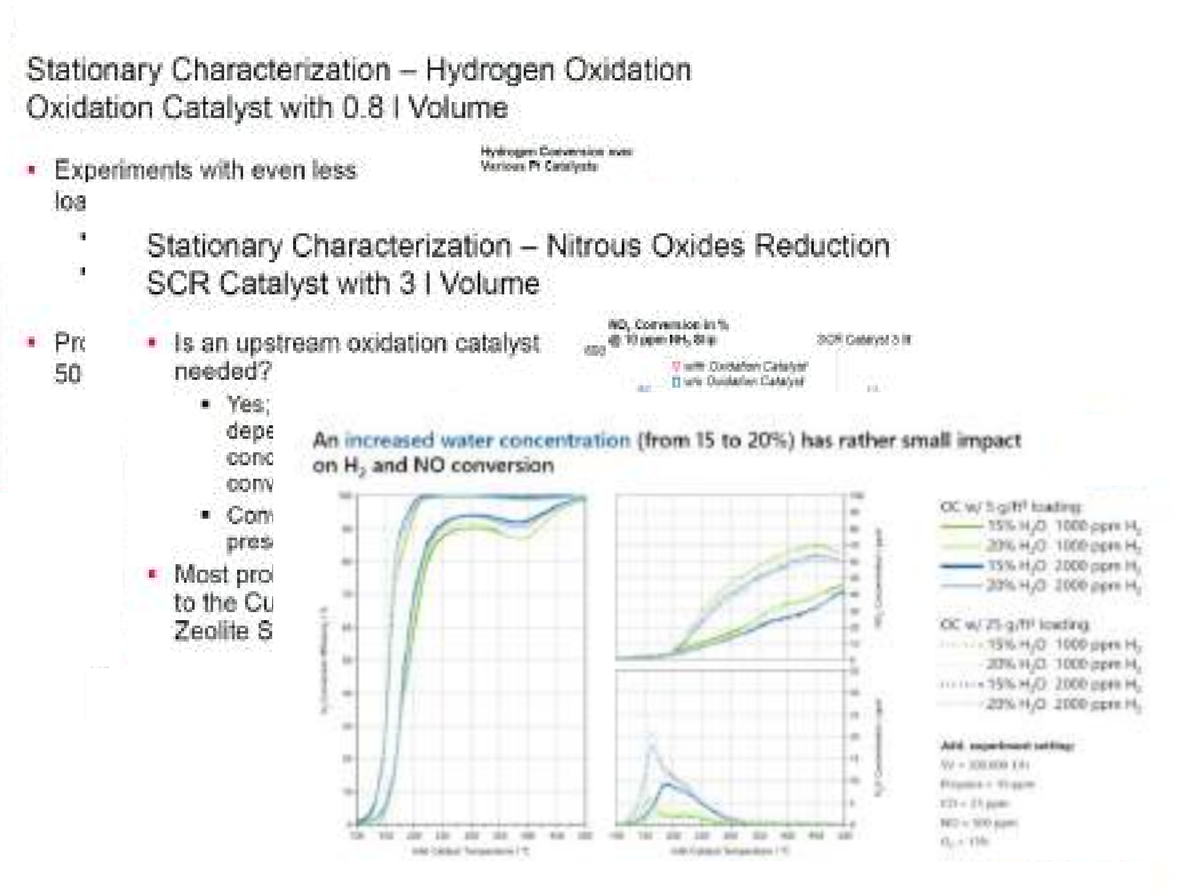
Summary of Learning’s
Oxidation Catalysts



Stationary Characterization – Hydrogen Oxidation
Oxidation Catalyst with 0.8 l Volume

- Experiments with even less loa
- Pr 50

Stationary Characterization – Nitrous Oxides Reduction
SCR Catalyst with 3 l Volume

- Is an upstream oxidation catalyst needed?
  - Yes; depe conc conv
  - Con pres
- Most pro to the Cu Zeolite S

An increased water concentration (from 15 to 20%) has rather small impact on H_2 and NO conversion

- Small volume with low PGM loading (loading dependent on the application) reaches more than 95% of H_2 conversion.
- Even a small volume of oxidation catalyst is beneficial for the following SCR catalysts for the NOx conversion (presence of H_2 reduces the NOx conversion).
- Lubricant emissions of HC and CO are reduced to the detection limit of the measurement devices.
- The higher water content has little to no impact on the catalyst performance.

✓ Main drivers for good performance are right sizing of the volume and PGM loading with regards to space velocity (<400k kh-1), temperature window and application (driving cycles, operation mode).

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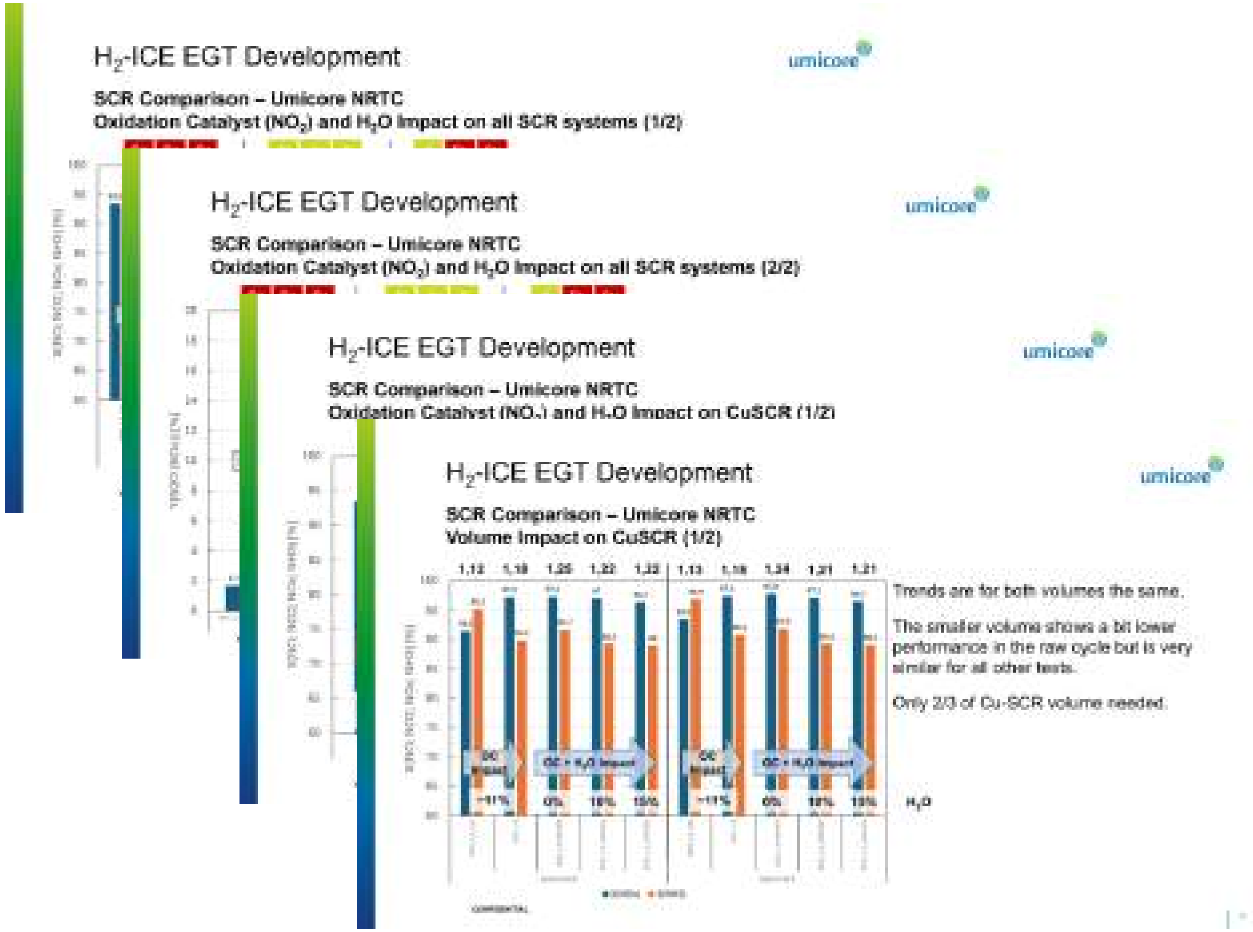
Summary of Learning’s
SCR Catalysts



H$_2$-ICE EGT Development

SCR Comparison – Umicore NRTC
Oxidation Catalyst (NO_2) and H_2O Impact on all SCR systems (1/2)

H$_2$-ICE EGT Development

SCR Comparison – Umicore NRTC
Oxidation Catalyst (NO_2) and H_2O Impact on all SCR systems (2/2)

H$_2$-ICE EGT Development

SCR Comparison – Umicore NRTC
Oxidation Catalyst (NO_2) and H_2O Impact on CuSCR (1/2)

H$_2$-ICE EGT Development

SCR Comparison – Umicore NRTC
Volume Impact on CuSCR (1/2)

Trends are for both volumes the same.

The smaller volume shows a bit lower performance in the raw cycle but is very similar for all other tests.

Only 2/3 of Cu-SCR volume needed.

- Cu-SCR technologies have advantages in the NO_x conversion due to the higher NH_3 storage compared to V-SCR → this is critical in high NO_x peaks, where dosing might not follow
- V-SCR reduces the N_2O formation.
- Combined systems with Fe- or V- and Cu-SCR, even with only a small part Fe- or V-SCR, offer low N_2O formation at nearly similar NO_x performance compared to a Cu-only system.
- Higher water content has little to no impact on the catalyst performance. At cold start the high water content slows down SCR catalyst heat-up and the has an impact on the cold start performance (investigations on-going).
- Relatively low interaction with H_2 (only low conversion). Some results indicate some negative impact on $DeNO_x$ performance.
- Compared to a diesel exhaust system ~50-70% of the SCR volume seems sufficient for most legislation requirements.

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