

PARTICLE NUMBER · UNDERGROUND MINING

Counting What Matters Underground

Particle number counters to verify diesel particulate filters on mining equipment: from opacity to PN testing — technologies, test protocols, calibration and verification

4th Annual Mining Vehicle Powertrain Conference · October 6–8, 2026

WORKSHOP: MEASUREMENT OF AMBIENT AIR QUALITY, TAIL PIPE EMISSIONS AND EMISSION CONTROL DEVICE PERFORMANCE

Robert Fraser and VERT Association

Agenda

From a blind test method to a working DPF verification program for mines

1

The problem

Diesel particles underground, and why opacity cannot find a failed DPF

2

Dieselgate to NPTI

How Europe proved PN testing at scale — including off-road machinery

3

Technologies

CPC and DC counters, instruments and field lessons

4

Test protocols for mines

Adapting the road test to mining machines and workshops

5

Calibration & verification

Metrology chain, aerosols, error limits, harsh conditions

6

Results & way forward

Machine failure rates, the dirty tail, exposure, recommendations

Diesel Particles Underground

Confined air, full-shift exposure and a fleet that depends on filters

1

Confined air

Ventilation dilutes exhaust, but one machine with a failed filter can load a whole drift

2

Full-shift exposure

Miners breathe the same air for 8 hours or more — exposure limits are set as 8-hour averages

3

Filter-dependent fleet

Tier 4 Final and Stage V machines rely on DPFs; a crack or removal is invisible to the operator

8-hour DPM limits, underground mines

EU **0.05 mg/m³ EC**

Dir. 2019/130, mining from Feb 2026

Ontario **0.12 mg/m³ EC**

O. Reg. 854, since Sept 2023

USA (MSHA) **0.16 mg/m³ TC**

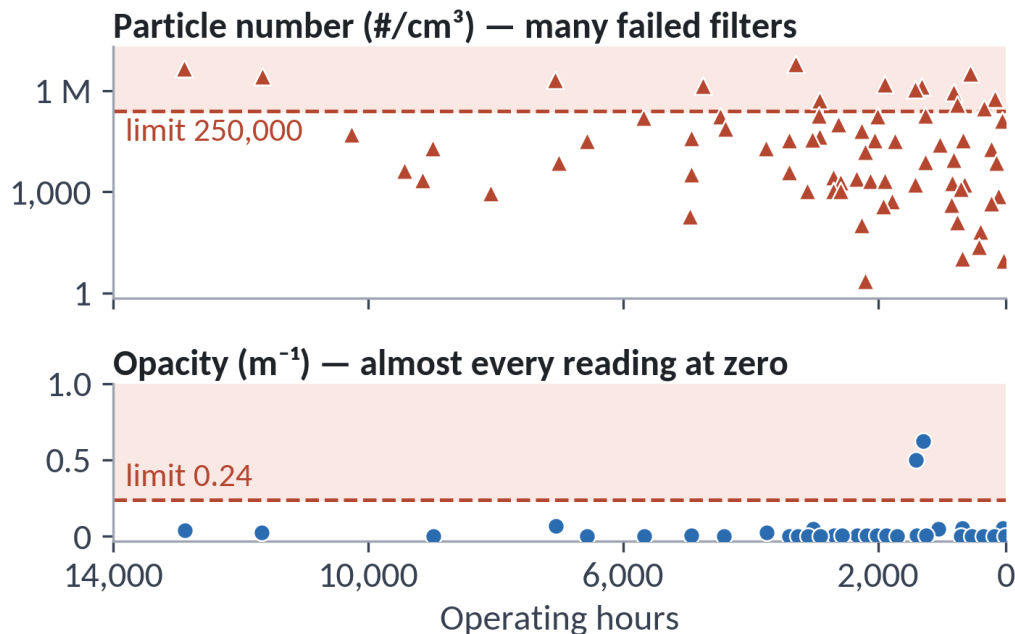
30 CFR 57.5060, metal/non-metal

Chile **No DPM limit**

DS 132 regulates gases and ventilation

Opacity Cannot See a Failed Filter

Opacity estimates mass from light absorption — it was designed for the smoke of pre-filter engines



Same DPF machines: PN at high idle vs opacity at free acceleration

Why opacity fails

- Opacity meters respond mainly to particles larger than about 300 nm
- Exhaust from modern diesels has a mean diameter below 100 nm
- A DPF removes up to 90% of mass but 99.5% of particle number
- Every opacity reading sits at zero — whether the filter works, is cracked or removed

The Evidence Against Opacity

Swiss field study: 107 DPF-equipped construction machines (FOEN / AFHB, 2017)

3% → 22%

failure rate when the same machines are tested with PN instead of opacity

20%

of machines that passed opacity failed the PN test (250,000 #/cm³)

0

failed filters detected by opacity on Stage IIIB and newer engines

Opacity is obsolete for testing filters. The study concludes that switching to nanoparticle measurement is “a necessity”.

“Opacity meters ... are only sensitive to particles larger than about 300 nm ... they cannot be used to measure the exhaust particles of modern [engines].”

— K. Vasilatou, METAS

Why Count Particles, Not Weigh Them

The health risk is in the number of ultrafine particles, not their mass

< 100 nm

Ultrafine particles reach deep into the lungs and bloodstream

Group 1

Diesel exhaust classified carcinogenic to humans by IARC (WHO) since 2012

Working DPF

$\sim 10,000 \text{ \#/cm}^3$

A good filter emits about as much as clean ambient air

Failed or removed DPF

$> 1,000,000 \text{ \#/cm}^3$

Cracked, removed or tampered filters jump by two to three orders of magnitude

A binary signal. Unlike a catalyst, a DPF does not wear out gradually — it works until it fails. PN counting separates the two states cleanly.

From Dieselgate to NPTI

A decade from scandal to national inspection standards

2012

Switzerland introduces a PN standard for off-road machinery

2015

Dieselgate: type-approval tests fail to reflect real emissions

2016

VERT NPTI working group: authorities, manufacturers, JRC

2019–21

NMi publishes Dutch protocol; VERT instrument spec TA-024

2022

Belgium (Flanders) is first to enforce PN-PTI

2023

Netherlands, Switzerland, Germany; EU Recommendation 2023/688

Fleet field tests

- Switzerland 2017: 107 construction machines · Belgium 2020: ~600 diesel cars in Brussels (TRUE)
- Belgium, Germany, Portugal, Serbia 2020–22: 618 diesel cars · Chile 2021: 989 light-duty vehicles in a Santiago PRT

Proven at Scale in Europe

First-year figures reported in March 2024 — today over 20 million PN tests in Europe

Country	In force	Limit (#/cm ³)	Scope	Tests to 3/2024	Rejection
Belgium	2022	1,000,000	Euro 5+ light-duty	1,995,251	9.3%
Netherlands	2023	1,000,000	Euro 4–6 / VI	970,000	6.5%
Switzerland	2023	250,000	Euro 5b, Euro VI, Stage V NRMM	6,300 (Thurgau)	10–15%
Germany	2023	250,000	Euro 6 / VI	1,911,451	4.8%
EU Rec. 2023/688	2023	250,000 (to 1,000,000)	Euro 5b and Euro VI	—	—

33,903

counters calibrated for Germany

> 15,000

already recalibrated in the 2nd annual cycle

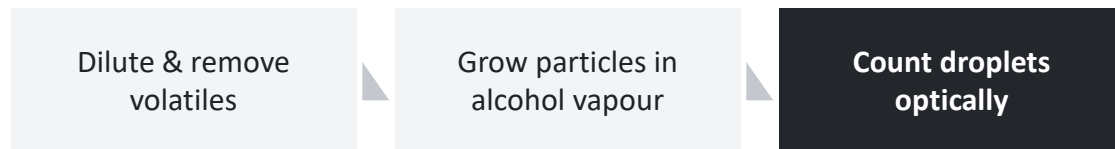
8 months

with hardly any equipment failures

Two Ways to Count: CPC and DC

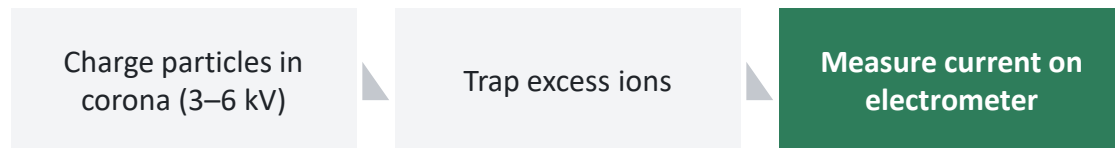
Both are approved in Europe; most PTI counters in service today are diffusion chargers

CPC — Condensation Particle Counter



Counts every particle directly; response largely independent of particle material. Needs working fluid, sensitive to humidity and cold starts.

DC — Diffusion Charger



Robust and fluid-free; dominant in PTI. Infers number from charge, so it assumes a size distribution and needs material correction.

Switzerland's Rules for Machinery Counters

TECHNOLOGIES

Ordinance on Exhaust Gas Analysers (VAMV, SR 941.242) — in force since 2013 for construction machines

Measurement

- Range 50,000 – 5,000,000 #/cm³
- Efficiency: < 50% at 23 nm, > 40% at 41 nm, 70–130% at 80 nm, < 300% at 200 nm
- Volatile droplets (30 nm tetracontane) counted < 5%
- Result in < 10 s; data logged at 10 Hz

Built for the field

- Portable, for outdoor use
- Ambient pressure 860–1060 hPa; mechanical class M2
- Must tolerate spray water, dust, corrosive gases, 300 °C probe heat, very high counts and soot build-up
- Warns and blocks the result if a disturbance invalidates it

Official test & upkeep

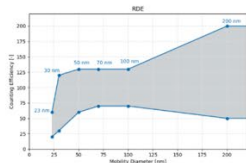
- Fully automated — no operator influence
- 15 s wait, then 3 × 5 s readings with 5 s pauses; mean is the result
- Durable record: date, time, mean, duration
- Annual verification by METAS or an authorised body, plus annual maintenance

Counting Efficiency and Error Limits

Each country approves instruments against its own efficiency band and tolerance

Germany

Counting efficiency



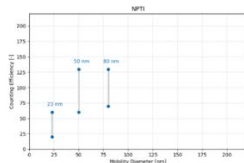
Status of approval
AVL DiTEST COUNTER



+/- 75%

Netherlands

Counting efficiency



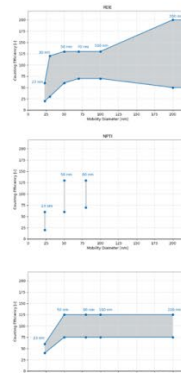
Status of approval
AVL DiTEST COUNTER



+/- 25%

Belgium

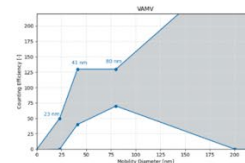
Counting efficiency



+/- 25%

Switzerland

Counting efficiency



Status of approval
AVL DiTEST COUNTER



+/- 30%

Key points

- 23 nm is the common cut-off (Euro 6 type approval)
- EU: $\pm 25\%$ at reference, $\pm 50\%$ in the field; $\pm 25,000 \text{ \#/cm}^3$ absolute
- Best reference uncertainty $\sim \pm 7\%$
- Germany $\pm 75\%$, moving to $\pm 50\%$

Example: approval of the AVL DiTEST Counter in each country, with its counting-efficiency band (efficiency vs mobility diameter) and maximum permissible error.

Homologated Instruments

Approved by METAS (CH), PTB (DE) or NMI (NL)

18

instruments certified for PTI

13 DC

diffusion charger models

5 CPC

condensation counters



TEN AEM (DC)



Capelec CAP3070 (DC)



TSI NPET 3795 (CPC)

Choosing an instrument

- Check that the whole instrument is approved — sometimes only a sensor module is
- Require secure, encrypted data transfer to the national database
- Plan maintenance and spare parts for local test volumes before purchase

Instrument Lessons from Field Trials

Santiago inspection plant (2021) and Swiss construction workshops (2017)

Humidity & cold

CPC units lost counts from wet wicks and filters; at -1 to 4°C warm-up took up to two hours

Self-check daily

A faulty unit read 5 million $\#/\text{cm}^3$ in clean air; another read 90,000 until cleaned — check ambient air every day

Agreement

Pass/fail agreement between instruments ranged from 59% to 97% at $250,000 \#/\text{cm}^3$

Workshop use (CH)

Humidity above 90% triggered errors; connectors wore out; mechanics were confused by “E” notation

318 vs 19

tests per month per station in Chile vs the Netherlands — heavy use wears counters fast

At that volume one DC unit would need service every 4 days instead of every 2 months. For busy mine workshops: choose the best technology, not the cheapest, and scale maintenance to use and failure rate.

The PN Test, Step by Step

Based on EU Recommendation 2023/688 — about one minute, engine warm

1

Identify

Machine,
emission stage,
DPF fitted; no
active
regeneration

2

Condition

Coolant > 60 °C;
idle or rev to
2,000 rpm

3

Zero & insert

Automatic zero
check, probe
centred in
tailpipe

4

Stabilise

15 s with probe in
place

5

Measure

≥ 15 s mean
concentration

6

Decide

Pass / fail vs limit;
abort at 2× limit
to protect the
sensor

Does the protocol matter? One 15-second reading and the mean of three gave the same pass/fail results in Chile. Switzerland, Belgium, the Netherlands and Germany use different sequences with no reported difference in outcomes.

Adapting the Test to Mining Machines

Switzerland already tests Stage V machinery — its rule is the natural starting point

1

High idle, no load

More particles than at low idle, so good and failed filters separate clearly — far better than opacity

2

Every outlet

Mining machines can have 2 exhausts; test each and take the highest reading

3

Warm engine

Coolant above 60 °C; avoid testing during or right after an active regeneration

4

In the workshop

Take the portable counter to the machine at its underground workshop or bay — about one minute

5

All diesel equipment

Haul trucks, loaders, drills, locomotives and stationary plant

Suggested limits

250,000

#/cm³ pass/fail limit

< 50,000

maintenance target — a healthy filter emits about 10,000 #/cm³, so rising counts flag service before failure

PN Checks in a Mine Maintenance Program

TEST PROTOCOLS

ALARP: keep cutting exposure unless the cost is grossly disproportionate

1 Test

One-minute tailpipe check at each PM service or weekly

2 Trend

Log every result per machine; watch for rising counts

3 Act

Above target: inspect engine and DPF; above limit: remove from service

4 Verify

Retest after repair before the machine returns to work

1 = 200

one failed filter emits as much as 200 machines with working filters

< 1 min

to find a broken, cracked or tampered filter

Budget

spend maintenance on the machines that cause the exposure — before replacing the fleet

The Metrology Chain

Four layers keep every result traceable

Type approval

National metrology institute (METAS, PTB, NMI) tests each model with soot and salt aerosols

Once per model

Annual calibration

Accredited laboratory (ISO/IEC 17025) or on site against a traceable reference counter

Every 12 months

Functional verification

In-plant check with a portable generator or reference device

Every 3–6 months

Daily checks

Leak test, zero before every test, ambient-air plausibility reading

Every day



Trusted Technical Experts in Legal Metrology

Choosing the Calibration Aerosol

There are no reference particles in a bottle — the test aerosol must be generated

Soot (miniCAST / bigCAST)

- + Closest to real diesel exhaust; preferred for type approval
- Complex, costly, needs controlled conditions and care for operator health

Salt (NaCl)

- + Cheap, stable, reproducible — the standard for on-site calibration in Germany, Belgium and the Netherlands
- Different shape and charge: DC counters need a known salt-to-soot factor

Spark discharge

- + Monodisperse; useful for spot efficiency tests
- Does not represent real emissions

Expert consensus: calibrate in the field with salt (GMD about 70 nm), establish each instrument's salt–soot correlation at type approval, and keep a soot-based reference at the top of the chain.

Calibration in Practice

A field kit: salt aerosol generator plus a traceable reference counter



Calibration case with salt aerosol generator and reference counter

Verify at 4 levels: 50,000 · 250,000 · 500,000 · 1,000,000
#/cm³

Counting efficiency

≥ 50% at 23 nm; check 70–130 nm

Range

5,000 to 2,000,000 #/cm³

Linearity

At least three levels

Zero stability

No significant drift

Response time

95% of final value in ≤ 15 s

Repeatability

Std. deviation < 15%

Protecting Accuracy in Mine Conditions

Dust, humidity, altitude and heavy use — design and routine must compensate

What degrades results

- Temperature, humidity and condensation
- Altitude and ambient pressure at high mines (flow changes)
- Soot contamination of lines and filters
- Vibration and dust
- Probe mis-insertion and leaks
- Long exposure to high concentrations

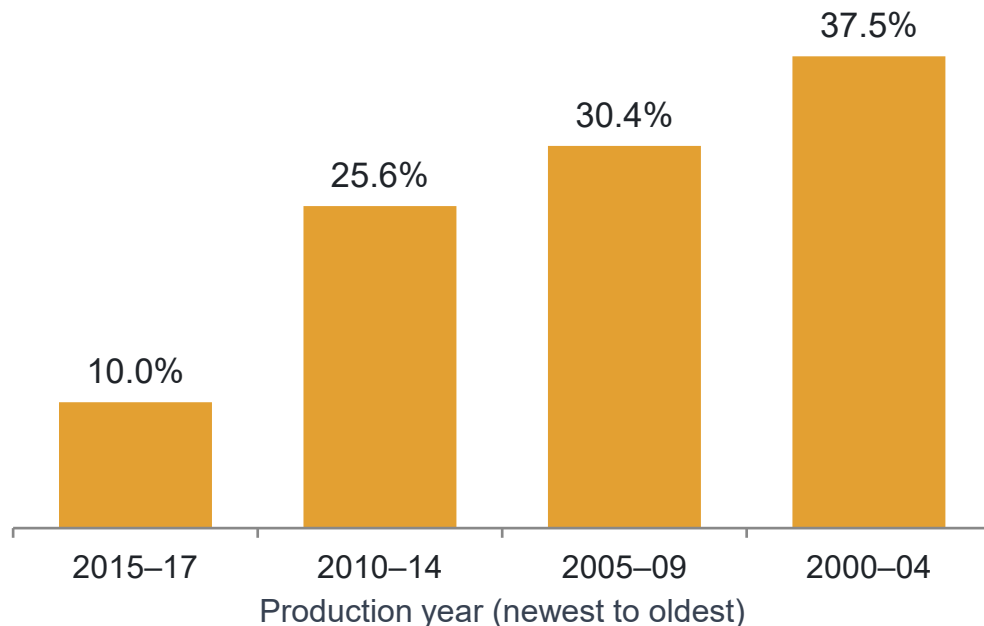
Required safeguards

- Temperature, humidity and pressure compensation
- Active sample-flow control
- Automatic zero check before every test
- Thermally stable, centred probe
- Automatic abort at 2× the limit
- Filter checks and cleaning scaled to test volume

DPF Failures in Construction Machines

RESULTS

PN failure rate ($\geq 250,000 \text{ \#/cm}^3$) by production year — 107 machines, Switzerland



A failed filter = an ENGINE problem

Engine faults

Worn injectors, faulty EGR valves or turbos overload the filter with soot; the next regeneration overheats and cracks it

Lack of maintenance

Ash not cleaned, rising back-pressure and skipped services turn small faults into filter failures

Engine conditions

Long low-load or idle duty keeps the exhaust too cool for the filter to regenerate

The Dirty Tail

A few machines produce most of the particles — find them and the air clears

10% → 80%

just 10% of machines produce 80% of all PN emissions

20% → 95%

20% of machines produce 95% of emissions

20,133 vs 556,224

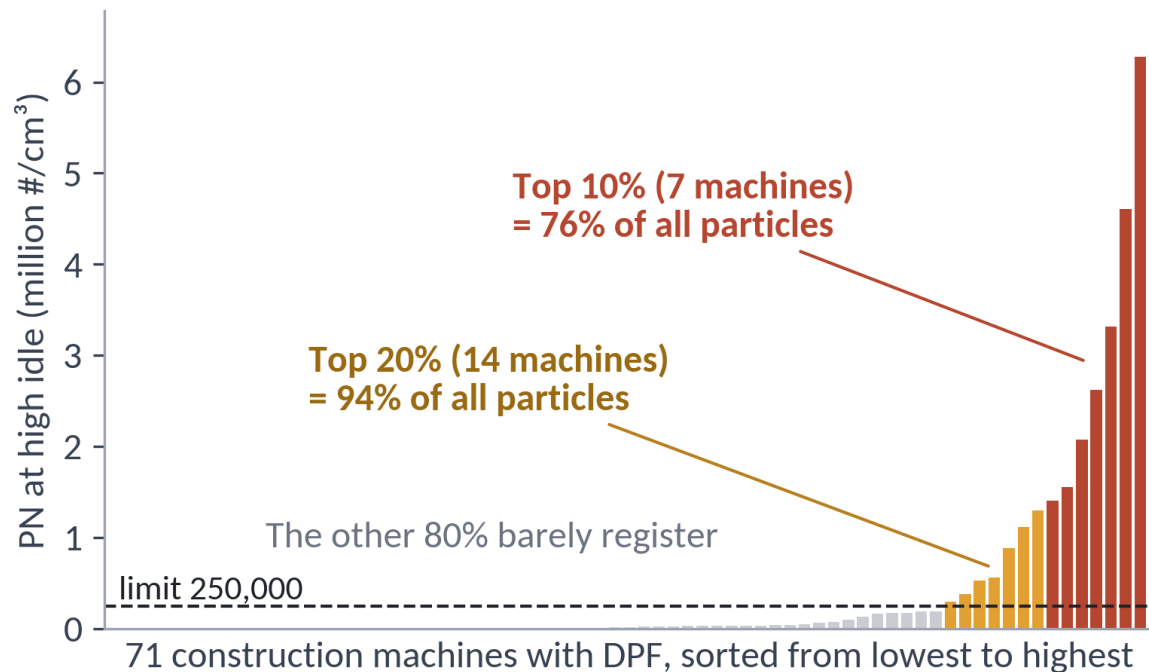
median vs mean PN ($\#/cm^3$) of 107 Swiss machines — a few filters distort the average

What it means underground

- Repairing a small group of gross emitters removes most of the particle load in the drift
- A healthy filter emits around 10,000 $\#/cm^3$; a failed one exceeds 1,000,000 — the tail is easy to separate
- Target maintenance budget at the tail before considering fleet replacement

The Dirty Tail in the Data

PN at high idle of 71 Swiss construction machines with DPF, lowest to highest



The same pattern in cars

Brussels, 2020: 5% of Euro 5b/6 diesel cars emitted more than 90% of the particles

Mayer et al., 2025: 10% of vehicles produce 80% of PN

Each red bar is an engine problem waiting to be found

From Tailpipe to 8-Hour Exposure

PN testing cannot measure the ambient TWA — it removes what drives it

The TWA risk

- One cracked or failed DPF on a loaded machine can flood a drift with enough soot to break the 8-hour limit for every worker in that sector
- Ventilation alone cannot dilute a gross emitter fast enough
- Waiting for end-of-shift sampling finds the problem after the exposure

A preventive compliance tool

- Find the few machines that dominate exposure and fix them first
- Keep mine air below 0.05 mg/m³ EC (EU) by managing emissions at the source
- Lower tailpipe emissions mean ventilation does not have to work as hard
- The same counters can monitor ambient ultrafine particles (non-volatile solid PN)

Recommendations for Mines and Regulators

THE WAY FORWARD

For underground mining operations and authorities worldwide

1

Replace opacity

Make PN the verification test for all DPF-equipped underground machines

2

Specify approved counters

Buy only instruments type-approved by METAS, PTB or NMi and suited to mine conditions

3

Keep them traceable

Annual calibration at an ISO/IEC 17025 laboratory, with regular field checks

4

Cover the whole fleet

Contractors' machines too, with tamper-proof records per machine

5

Link to exposure

Set or enforce a DPM exposure limit and use PN tests as source control

6

Train and share

Train maintenance staff; pool results across mines to refine limits for machinery

Conclusions

- 1 **Opacity is obsolete** — for machines with particle filters — it cannot see a failed DPF
- 2 **PN counting is proven** — over 20 million tests in Europe; the off-road protocol already exists
- 3 **Metrology is the key** — type approval, annual calibration and field checks keep results trustworthy
- 4 **Mines gain most** — finding the dirty tail protects miners' 8-hour exposure at the source
- 5 **Fix the engine** — a failed filter is an indicator of an ENGINE problem

Join VERT



Be part of the network that sets the standard for clean diesel — from filter certification to particle-number inspection

Technology exchange

with filter, engine and instrument makers

Research library

200+ members-only publications

BAT recognition

VERT® trademark and website listing

A voice with regulators

worldwide legislation and retrofit programs

Become a member

office@vert-certification.eu · www.vert-dpf.eu

Robert@purexhaust.com
r.fraser@vert-dpf.eu

SAVE THE DATE

VERT Forum & Focus Day

March 2027

Switzerland

Dates and venue to be announced

Industry, research and regulators meet on emissions control and NPTI