

The catalytic control of emissions to air from stationary point sources

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access^a

A Catalyst for Clean Air

*Association for Catalytic Control of Emissions from
Stationary Sources, to Air*

CLARIANT^e



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1. Introduction

The growing concern over the impact of air pollution has been compounded by the way the problems are being addressed. Whilst there is general acknowledgment that more needs to be done, there is little agreement on the best course of action and confusion over the technology capabilities, technology trajectories and associated costs. One of the most effective mechanisms of reducing emissions to air from large point sources such as power-plants is Catalytic After-Treatment. Highly efficient, often removing over 90% of targeted pollutants, Catalytic After-Treatment has much to offer in terms of facilitating sustainable economic growth whilst minimising the impact on the environment and in particular on the air we breathe.

“ACCESSA” was established to improve the general level of understanding of the capabilities of catalytic after treatment technology. In the last 50 years there have been significant technical improvements in this field evidenced by the advances made controlling emissions from mobile sources¹. Aided by the adoption of cleaner fuels, the development of advanced materials all coordinated by advances in engineering, the modern automotive engine emits a very small fraction of the emissions its predecessors, in the 1970’s, did. This may be attributed to a coordinated approach across the world to regulate the emission limits from mobile sources. Large and medium sources of air pollution, from combustion and analogous processes continue to make significant contributions to air pollution. The approach to limiting these emissions has been less coordinated and the regionalised or local approach has meant that some power plants have very low emissions whilst others contribute as much pollution today as they did in the 1970s.

ACCESSA’s expertise includes the following emissions to air:

- Oxides of Nitrogen, NO_x
- Carbon Monoxide, CO
- Volatiles and HAPs, VOCs (dioxins, formaldehyde, ‘odour’)
- Methane, CH₄
- Particulate Material PM
- Ammonia, NH₃
- Mercury, Hg

These pollutants may be emitted from a number of industries and processes such as PowerGen (including energy from biomass and waste), chemicals and petrochemicals; minerals (cement, glass, ceramics); surface treatment (printing, coating); iron/steel; pulp/paper/wood; food and drink; machinery and large engines (e.g. mining); agriculture and farming.

The transboundary nature of air pollution, the fact that pollution and their impacts can be felt some considerable distance from its source underlines the requirement for a coordinated approach to what is a growing global environmental and public health issue.

Global agreements and regionalised laws, effectively enforced, can play a major role in improving air quality. For example, the Montreal Protocol has successfully brought 196 countries together to target ozone depletion and the 1996 European Directive on Integrated Pollution Prevention and Control (IPPC) has set a course to limit air and water pollution from industry. However, major disparities between both the ambition and the application of limits and control of pollution from stationary sources, at a national level, means that certain pollutants are growing in prevalence both locally and globally.

Regulatory authorities in the EU, USA and Japan have been under pressure from engine and equipment manufacturers to harmonize worldwide emission standards, in order to streamline engine development and emission type approval/certification for different markets. This facilitates improved air quality whilst driving economies of scale and scope, and lowering the cost of emission control technology. The full impact of air pollution on public health is now well understood. In the UK alone poor air quality causes over 40,000 UK premature deaths per year². In China, 1.6 million people die each year from heart, lung and stroke problems attributable to polluted air³.

2. Regulatory process and standards

There are significant variations in the regulation of air pollution from stationary sources, from region to region and from application to application. This is illustrated in this overview of the regulatory process and standards within the United States, European Union, China and India. The global regulatory framework for air pollution cascades down from World Health Organisation (WHO) Air Quality Guidelines, which offer global guidance on thresholds and limits for key air pollutants that pose health risks (see Table 1 below).

Pollutant	Guideline Values
PM _{2.5}	10 µg/m ³ annual mean 25 µg/m ³ 24-hour mean
PM ₁₀	20 µg/m ³ annual mean 50 µg/m ³ 24-hour mean
O ₃	100 µg/m ³ 8-hour mean
NO ₂	40 µg/m ³ annual mean 200 µg/m ³ 1-hour mean
SO ₂	20 µg/m ³ 24-hour mean 500 µg/m ³ 10-minute mean

Table 1: WHO Air Quality Guidelines 2005

² <http://www.bbc.co.uk/news/health-35629034>

³ <http://www.theguardian.com/world/2015/aug/14/air-pollution-in-china-is-killing-4000-people-every-day-a-new-study-finds>

¹ AECC - the Association for Emissions Control by Catalyst
<http://www.aecc.eu/>

Regional legislation, such as the EU Ambient Air Quality Directive and the US Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS) set legally binding limits for concentrations of major air pollutants that impact public health. Regional and national authorities also set technology based standards for specific sectors. Such limits and standards are transposed into national law. It is the responsibility of national and local authorities to enforce the standards and to manage the emissions from point sources. As such, legislation, for example within the EU or US, is not interpreted or enforced in a uniform manner.

United States

The Clean Air Act (CAA) is the comprehensive federal law that regulates air emissions from stationary sources. It authorizes the EPA to establish NAAQS. NAAQS have been set for six common "criteria pollutants": particulate matter; ozone; sulphur dioxide; nitrogen dioxide; carbon monoxide and lead. Under the CAA States are required to adopt enforceable plans to achieve the air quality standards. State plans must also address control emissions that drift across state lines and harm air quality in downwind states. The law calls for new stationary sources to be built with best technology, and allows less stringent standards for existing stationary sources⁴.

Pollutant	Type	Ave Time	Level	Form
Carbon Monoxide	primary	8-hour	9 ppm	Not to be exceeded more than once pa.
		1-hour	35 ppm	
Lead	primary & secondary	Rolling 3 month average average	0.15 µg/m ³	Not to be exceeded
Nitrogen Dioxide	primary	1-hour	100 pb	98th percentile of 1-hr daily max conc ave over 3 yrs
	primary & secondary	Annual	53 ppb	Annual Mean
Ozone	primary & secondary	8-hour	0.07 ppm	Annual fourth-highest daily ma 8-hr conc. ave over 3 yrs
Particle Pollution	PM _{2.5}	primary	12 µg/m ³	annual mean, averaged over 3 yrs
		secondary	15 µg/m ³	annual mean, averaged over 3 yrs
		primary & secondary	24-hour	35 µg/m ³
	PM ₁₀	primary & secondary	24-hour	150 µg/m ³
Sulphur Dioxide	primary	1-hour	75 ppb ⁽⁴⁾	99th percentile of 1-hr daily max conc ave over 3 years
	secondary	3-hour	0.5 ppm	Not to be exceeded more than once pa.

Table 2: [US National Ambient Air Quality Standards](#)

⁴ <http://www.epa.gov/clean-air-act-overview/clean-air-act-requirements-and-history>

As described by the EPA⁵, Section 112 of the Clean Air Act addresses emissions of hazardous air pollutants. The 1990 Clean Air Act Amendments revised Section 112 to require issuance of technology-based standards for major sources and certain area sources. "Major sources" are defined as a stationary source or group of stationary sources that emit or have the potential to emit 10 tonnes per year or more of a hazardous air pollutant or 25 tonnes per year or more of a combination of hazardous air pollutants⁶. An "area source" is any stationary source that is not a major source. Though emissions from individual area sources are often relatively small, collectively their emissions can be of concern - particularly where large numbers of sources are located in heavily populated areas.

For major sources, Section 112 requires that EPA establish emission standards that require the maximum degree of reduction in emissions. These emission standards are commonly referred to as "maximum achievable control technology" or "MACT" standards. Eight years after the technology-based MACT standards are issued for a source category EPA is required to review those standards to determine whether any residual risk exists for that source category and, if necessary, revise the standards to address such risk.

The Menu of Control Measures (MCM) provides state, local and tribal air agencies with the existing emission reduction measures as well as relevant information concerning the efficiency and cost effectiveness of the measures⁷. Each agency will be able to use this information in developing emission reduction strategies to assure they attain and maintain the National Ambient Air Quality Standards.

European Union

The UNECE Convention on Long Range Transboundary Air Pollution has agreed a number of protocols including the Gothenburg Protocol which sets national emission reduction targets, including for fine particulate matter, to be achieved by 2020. The Convention has been extended to identify specific measures to be taken by Parties to cut their emissions of air pollutants. The Convention has 51 Parties and has eight protocols:

1. The 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol) and its 2012 amended version
2. The 1998 Protocol on Persistent Organic Pollutants (POPs) and its 2009 amended version
3. The 1998 Protocol on Heavy Metals and its 2012 amended version
4. The 1994 Protocol on Further Reduction of Sulphur Emissions

⁵ <http://www.epa.gov/laws-regulations/summary-clean-air-act>

⁶ For the source category list see: <http://www.gpo.gov/fdsys/pkg/FR-2002-11-22/pdf/02-29774.pdf>

⁷ <http://www3.epa.gov/ttn/naaqs/pdfs/MenuOfControlMeasures.pdf>

5. The 1991 Protocol concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes
6. The 1988 Protocol concerning the Control of Nitrogen Oxides or their Transboundary Fluxes
7. The 1985 Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 per cent
8. The 1984 Protocol on Long-term Financing of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP)

Under the Gothenburg Protocol, between 2005 and 2020 the EU member states must jointly cut their emissions of sulphur dioxide by 59%, nitrogen oxides by 42%, ammonia by 6%, volatile organic compounds by 28% and particles by 22%.

The 2001 National Emission Ceilings Directive (NECD)

sets national emission ceilings for all Member States. In December 2013 the Commission published the European Clean Air Package including a revision of the NECD. The proposed revised NECD adopts the targets set out in the newly ratified Gothenburg Protocol for 2020 and contains new proposed emission ceilings for 2030, including new controls on methane and the primary emissions of particulate matter (PM_{2.5}). The proposals will be subject to discussion before any agreement or sign off by Member States.

Pollutant	2020 (relative to 2005)	2030
SO _x	59%	81%
NO _x	42%	69%
VOCs	28%	50%
Ammonia	6%	27%
PM _{2.5}	22%	51%
Methane		33%

Table 3: Proposed emission ceilings within the NECD

The 4th Air Quality Daughter Directive (2004/107/EC) sets targets for levels in outdoor air of certain toxic heavy metals and polycyclic aromatic hydrocarbons. The Ambient Air Quality Directive sets local air quality limits for major air pollutants which may not be exceeded anywhere in the EU. Both are required to be transposed into national law (see Table 4).

Source-specific legislation is designed to limit emissions from specific economic sectors. Two Directives which impact most significantly on stationary installations are the **Industrial Emissions Directive** and the **Medium Sized Combustion Plants Directive**. Smaller combustion plants are regulated under the Ecodesign Directive (2009/125/EC). For specific information on pollution sources, regulated, please see section 4.

Industrial Emissions Directive (IED)

- There are around 52,000 large industrial installations in Europe which fall under the IED (2010).
- The IED applies to combustion plants designed for production of energy with a rated thermal input which is equal to or greater than 50 MW⁸.
- “Best Available Techniques” are defined per sector in reference documents, or “BREFs”, that serve as benchmarks for environmental performance.
- Under the BREFs, the competent authority needs to take BAT conclusions into account in permitting. According to Art. 15.3, the competent authority needs to set Emission Limit Values (ELVs), ensuring that, under normal operating conditions, emissions do not exceed the emission levels associated with the best available techniques (BATAEL), as laid down in the BAT conclusions.
- Installations must comply with new BAT conclusions within four years of publication.

In terms of industrial air pollution, according to the European Environment Agency⁹, half of the €59-189bn air pollution cost burden was caused by just 1% of installations, mostly in Germany and Eastern Europe. Of the 30 biggest facilities it identified as causing the most damage, 26 were power plants, mainly fuelled by coal in Germany and Eastern Europe.

Medium Sized Combustion Plants Directive

- The Commission has proposed that EU air pollution limits should be extended to around 143,000 smaller energy plants and industry installations from 2025.
- The draft directive on medium-sized combustion plants (MCPs) aims to cut SO₂, NO_x and PM from installations with rated thermal inputs of between 1 and 50 MW
- An MCP Directive Impact Assessment document¹⁰ provides the following breakdown of the total number of installations covered: 100,000 combustion plants between 1 and 5 MW; 23,000 plants between 5 and 20 MW 5,000 plants between 20 and 50 MW.
- The NO_x pollution limits have been set at a level that requires only combustion-related modifications, not end-of-pipe abatement.
- There are full exemptions from the SO₂ and NO_x limits for plants that run for less than 500 hours a year.
- It is estimated that 5% of plants in the 1-5 MW class, 10% of plants in the 5-20 MW class and 40% of plants in the 20-50 MW class are part of IED installations and, therefore, subject to the obligation to be covered by a BAT-based permit¹¹

⁸ <http://www.emissions-euets.com/directive-201075eu-on-industrial-emissions-ied>

⁹ <http://www.eea.europa.eu/publications/costs-of-air-pollution-2008-2012>

¹⁰ [http://ec.europa.eu/environment/archives/air/pdf/Impact assessm ent_en.pdf](http://ec.europa.eu/environment/archives/air/pdf/Impact_assessm ent_en.pdf)

¹¹ <http://www.emissions-euets.com/mcp-basics>

Pollutant	Concentration	Averaging period	Permitted exceedances each year
Fine particles (PM _{2.5})	25 µg/m ³	1 year	n/a
Sulphur dioxide (SO ₂)	350 µg/ m ³	1 hour	24
	125 µg/ m ³	24 hours	3
Nitrogen dioxide (NO ₂)	200 µg/ m ³	1 hour	18
	40 µg/ m ³	1 year	n/a
PM ₁₀	50 µg/ m ³	24 hours	35
	40 µg/ m ³	1 year	n/a
Lead (Pb)	0.5 µg/ m ³	1 year	n/a
Carbon monoxide	10 mg/ m ³	Max daily 8 hr mean	n/a
Benzene	5 µg/ m ³	1 year	n/a
Ozone	120 µg/ m ³	Max daily 8 hr mean	25 days averaged over 3 years
Arsenic (As)	6 ng/ m ³	1 year	n/a
Cadmium (Cd)	5 ng/ m ³	1 year	n/a
Nickel (Ni)	20 ng/ m ³	1 year	n/a
PAHs	1 ng/ m ³	1 year	n/a

Table 4: Limits within the 4th Air Quality Daughter Directive and the Ambient Air Quality Directive

Non-road Mobile Machinery (NRMM)

Despite the very broad range of engines used by non-road machinery, only a very small proportion of the engines have a power greater than 560 kW. Taking all of the non-road engines used in construction, mining, agriculture and general industry together, it is estimated that greater than 99.9% of these non-road engines are less than 560 kW. The remaining 0.1% is used predominantly at remote sites in quarry and mining equipment¹².

European Directive 97/68/EC covers diesel fuelled engines for common NRMM. It became effective from 1 January 1999 for certain types of engines. Stage I (1 January 1999) and stage II (1 January 2001), covers diesel fuelled engines between 37 and 560 kW. The second directive, 2002/88/EC, extends the scope of 97/68/EC to cover spark ignited engines (petrol engines) up to 18 kW and held and non-handheld equipment. Stage I (and stage II) became effective in August 2004 with some exemptions for certain applications. A third directive, 2004/26/EC, extends the scope of 97/68/EC to cover diesel fuelled engines from 19 kW to 560kW for common NRMM. The different stages in the 2004/26/EC directive are as follows:

- Stage III A covers engines from 19 to 560 kW including constant speed engines, railcars, locomotives and inland waterway vessels.

¹² Fact sheet - New proposed EU Regulation for nonroad mobile machinery engines – COM(2014) 581 final

- Stage III B covers engines from 37 to 560 kW including, railcars and locomotives.
- Stage IV covers engines between 56 and 560 kW.
- Stage IV was effective from 1 January 2014.

Stage III/IV requirements are harmonized to a large degree with the US Tier 3/4 standards.

Permitting

Each EU country nominates a ‘Competent Authority’ to operate a system of registration and permitting under the various Directives listed above. Using the example of the IED, the general principles governing the basic obligations of the operator, include¹³:

- All the appropriate preventive measures are taken against pollution
- BATs are applied
- No significant pollution is caused

China

China’s State Council released its **Action Plan for Air Pollution Prevention and Control** (Action Plan) on 12 September 2013¹⁴. The Action Plan sets the road map for air pollution control for the five years with a major focus on three key regions (see the below map to identify the key areas):

- Beijing-Tianjin-Hebei area (Jing-Jin-Ji)
- Yangtze River Delta (Shanghai area - YRD)
- Pearl River Delta (Guangdong - PRD)

It has been reported that the Action Plan will be backed by 1,700 trillion yuan (US\$277 billion) in total investments from the central government¹⁵. To put this amount of financial backing in perspective, the 1990 U.S. Clean Air Act Amendments cost US \$85 billion in comparison¹⁶. It is unclear how this planned investment will be spent.

Targets are set for improvement by 2017 (2012 baseline). The plan’s major focus will be on **PM_{2.5}**, setting stricter limits for major urban areas. According to the plan, annual average concentration of PM_{2.5} should be reduced by:

- 25% in Jing-Jin-Ji
- 20% in the Yangtze River Delta
- 15% in the Pearl River Delta

¹³ https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221044/pb13898-epr-guidance-part-a-130222.pdf

¹⁴ Note – the 13th 5-Year Plan (2016-2020) includes greening the economy and abandoning old heavy industry as key areas of focus

¹⁵ http://www.china.org.cn/environment/2013-10/28/content_30425833.htm

¹⁶ <https://www.chinadialogue.net/blog/6255-Will-Beijing-s-277-billion-air-pollution-plan-work/-/en>



The Action Plan sets important mandates and initiatives in the following aspects:

1. By 2017, the proportion of coal in total primary energy consumption in China will be reduced to below 65% (down from 66.8% in 2012) while the proportion of non-fossil energy consumption will be increased to 13%. The three key regions shall make efforts to achieve negative growth of total coal consumption, and replace coal with natural gas for coal-fired boilers, industrial furnaces, and self-sustained coal-fired power stations. According to the Plan, no new coal-fired power plants would be approved in these regions.
2. Use of clean energy such as natural gas and coal-bed methane is to be increased and construction projects that fail to pass environmental evaluations will not be allowed to continue.
3. To further cut pollution, combined heat and power plants will gradually replace decentralized coal-fired boilers in industries such as chemical engineering, papermaking, dyeing and tanning.
4. China will promote the refitting of various industries, and further tighten control over industries that are highly polluting and energy-intensive. The sectors targeted by the latest action plan include iron and steel, cement, electrolytic aluminium and flat glass.

Echoing the national Action Plan, the Beijing Municipal Government unveiled its own five-year plan to improve air quality significantly by 2017. For Beijing, the annual average concentration of PM_{2.5} is targeted to be reduced to 60µg/m³. For all the second and third-tier cities (not covered by the PM_{2.5} target), annual average concentration of PM₁₀ should be reduced by at least 10% compared to 2012 levels and the number of days with clean air should increase over time.

In practice, for major megacities like Beijing, which averaged around 124µg/m³ of PM₁₀ in 2011, cutting 25% of PM_{2.5} to 60µg/m³ will still mean levels significantly higher than the WHO recommended level of 10µg/m³.

Building on the Action Plan for Air Pollution Prevention and Control, Chinese legislators recently passed the first amendments to the country's **Environmental Protection Law (EPL)** in 25 years (since 1989). The amendments give greater powers for environmental authorities and allow harsher punishments for polluters. Unlike previous iterations, the latest EPL establishes the principle that environmental protection comes first. This is a dramatic move away from the conventional one dimensional economic development model of China.

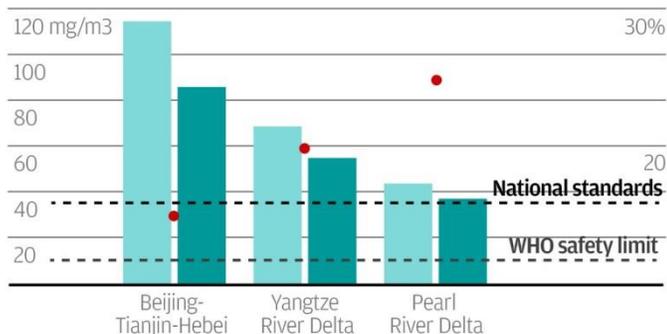
In February 2012, China released a new **ambient air quality standard**, GB 3095-2012, which sets limits for the first time on PM_{2.5}. The new standards take effect nationwide in 2016, but many cities and regions in China are required to implement the standards earlier than the national timeline, as follows¹⁷:

- 2012: Key cities including cities in Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta regions, and provincial capitals
- 2013: Key environmental protection cities
- 2015: All prefecture-level cities
- 2016: Nationwide implementation

Clearing the air

2017 targets to reduce PM_{2.5} pollutants

- Yearly average concentration of PM_{2.5} reduction (%)
- PM_{2.5} existing level of in 2013 (mg/m³)
- PM_{2.5} expected level by 2017 (mg/m³)



Note: calculated based on the targets and existing levels
Sources: National clean air action plan 2013-2017, Ministry of Environmental Protection SCMP

¹⁷http://transportpolicy.net/index.php?title=China:_Air_Quality_Standards

Primary standards				
Pollutant	Averaging time	Limit		Unit
		Class 1	Class 2	
SO ₂	annual	20	60	µg/m ³
	24 hours	50	150	
	hourly	150	500	
NO ₂	annual	40	40	
	24 hours	80	80	
	hourly	200	200	
CO	24 hours	4	4	mg/m ³
	hourly	10	10	
O ₃	daily, 8-hour maximum	100	160	µg/m ³
	hourly	160	200	
PM ₁₀	annual	40	70	
	24 hours	50	150	
PM _{2.5}	annual	15	35	
	24 hours	35	75	

Additional standards				
Pollutant	Averaging time	Limit		Unit
		Class 1	Class 2	
Total Suspended Particles (TSP)	annual	80	200	µg/m ³
	24 hours	120	30	
NO _x	annual	50	50	
	24 hours	100	100	
	hourly	250	250	
Lead (Pb)	annual	0.5	0.5	
	seasonal	1	1	
Benzopyrene (BaP)	annual	0.01	0.01	
	24 hours	0.025	0.025	

Table 5: Chinese ambient air quality standards

China's new national **air pollution standards for thermal power plants** went into effect January 1, 2012, replacing standards that had been in effect since 2003. The standards bring Chinese power plant regulation generally in line with developed world standards for both new and existing power plants¹⁸. There are separate standards for oil and natural gas-fired power plants, with the oil standards being at least as strict as coal and the natural gas standards much stricter. Table 6 compares China's new standards to the US and EU standards for coal-fired power plants.

Pollutant	Plant	China	European Union	United States
NO _x	New Plants	100	500 until 12/31/2015, then 200	117
	Existing Plants (defined in China as built 1/1/04 – 12/3/11) (defined in US as built after 2/28/05)	100	500 until 12/31/2015, then 200	117
	Existing Plants (defined in China as built before 1/1/04) (defined in US as built before 2/28/05)	200	500 until 12/31/2015, then 200	160 (built between 1997-2005) 640 (built between 1978-1996)
SO ₂	New Plants	100	200	160 (built after 2005)
	Existing Plants (28 provinces) (four provinces with high sulphur coal)	200	400	400 160 (built between 1997-2005) 640 (built between 1978-1996)
PM	New and Existing Plants	30	50, with an exception of 100 for low quality coal (lignite)	22.5
Mercury	New and Existing Plants	0.03	0.03 (A German standard only. No EU wide standard)	New: 0.001 (bituminous, gangue), 0.005 (lignite) Existing: 0.002 (bituminous, gangue), 0.006 (lignite)

Table 6: China, EU, and U.S. Coal-fired power plant standards (All units mg/m³)

¹⁸ <http://www.wri.org/our-work/project/chinafaqs>

India

The Air (Prevention and Control of Pollution) Act was passed by Parliament in 1981. The first ambient air quality standards were adopted in 1982 by the Central Pollution Control Board (CPCB) and revised in 1994 and again in 2009. Agencies responsible for air quality standard creation and monitoring include CPCB and several State Pollution Control Boards (SPCBs). All of these entities fall under the control of the Ministry of Environment and Forest (MoEF).

The Air Act mandates the CPCB and SPCBs to¹⁹:

1. Establish national ambient air quality standards for criteria pollutants,
2. Assist government in planning future environmental prevention and control strategies,
3. Carry out research to better understand environmental issues,
4. Undertake nationwide air sampling to ascertain the ambient air quality in India and identification of the problem areas,
5. Conduct air quality inspections in areas of concern.

SPCBs can set more stringent standards than the existing national standards in their respective states (similar to the local divisions used within the US EPA). Proposed phased standards for thermal power plants (after 2017) are intended to decrease emissions of PM by 25%, SO₂ by 90%, NO_x by 70% and mercury by 75% compared with business as usual.

Standards Proposed by Government of India: Mg/Nm ³ (Milligram per Normal Cubic Meter)					
Pollutants	Before December 31, 2003		After 2003 to 2006		From January, 2017
	shall meet limits within 2 years from date of notification		shall meet limits within 2 years from date of notification		
	<500 MW	≥500 MW	<500 MW	≥500 MW	
PM	100		50		30
SO ₂	600	200	-	200	100
NO _x	600		300		100
Hg	-	0.03	0.03		0.03

Table 7: Proposed thermal power plant standards

¹⁹ <http://transportpolicy.net/index.php?title=India: Air Quality Standards>

Latin America

According to a 2012 report by the Clean Air Institute²⁰, approximately two thirds of the Latin American countries have National Ambient Air Quality Standards. In particular, La Paz (Bolivia) is notable for having local standards in line with WHO guidelines. However, according to the CAI, at a national level there is much room for improvement:

- Many Latin American countries do not have national PM^{2.5} standards
- Both the annual and 24-hour PM¹⁰ standards for all countries are higher than the WHO Air Quality Guidelines
- The annual standards for NO₂ for all countries are higher than the WHO guideline but follow the UESPA NAAQS
- The standards for SO₂ 24-hour in all countries are significantly higher than the WHO guidelines.
- Eleven of the sixteen countries with standards have an 8-hour ozone standard in line with the WHO guidelines
- There are currently no identified standards in Honduras, Belize, Haiti, Cuba, Paraguay, Guatemala and Uruguay (although Uruguay has submitted a proposal for approval)

3. Health impact of key pollutants

Pollutant	Impact
Particulate Matter	Major components are sulphate, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water. The most health-damaging particles are those with a diameter of 10 microns or less, (\leq PM ₁₀), which can penetrate and lodge deep inside the lungs. Chronic exposure to particles contributes to the risk of developing cardiovascular and respiratory diseases, as well as lung cancer. WHO Air Quality Guidelines estimate that reducing annual average PM ₁₀ concentrations from levels of 70 μ g/m ³ , common in many developing cities, to the level of 20 μ g/m ³ , could reduce air pollution-related deaths by around 15%. However, even in the EU, where PM concentrations in many cities comply with Guideline levels, it is estimated that average life expectancy is 8.6 months lower than it would be, due to exposures from human sources.
Ozone	Ozone at ground level is one of the major constituents of photochemical smog. It is formed by the reaction with sunlight (photochemical reaction) of pollutants such as nitrogen oxides (NO _x) from vehicle and industry emissions and volatile organic compounds (VOCs) emitted by vehicles, solvents and industry. As a result, the highest levels of ozone pollution occur during periods of sunny weather. Excessive ozone in the air can have a marked effect on human health. It can cause breathing problems, trigger asthma, reduce lung function and cause lung diseases. Several European studies have reported that the daily mortality rises by 0.3% and that for heart diseases by 0.4%, per 10 μ g/m ³ increase in ozone exposure.

²⁰ <http://www.cleanairinstitute.org/calidaddeaireamericalatina/cai-report-english.pdf>

Nitrogen Dioxide	NO ₂ is the main source of nitrate aerosols, which form an important fraction of PM _{2.5} and, in the presence of ultraviolet light, of ozone. The major sources of anthropogenic emissions of NO ₂ are combustion processes (heating, power generation, and engines in vehicles and ships). Epidemiological studies have shown that symptoms of bronchitis in asthmatic children increase in association with long-term exposure to NO ₂ . Reduced lung function growth is also linked to NO ₂ at concentrations currently measured (or observed) in cities of Europe and North America.
Sulphur Dioxide	SO ₂ can affect the respiratory system and the functions of the lungs. Inflammation of the respiratory tract causes coughing, mucus secretion, aggravation of asthma and chronic bronchitis and makes people more prone to infections of the respiratory tract. When SO ₂ combines with water, it forms sulphuric acid; this is the main component of acid rain which is a cause of deforestation. The main anthropogenic source of SO ₂ is the burning of sulphur-containing fossil fuels for domestic heating, power generation and motor vehicles.

Table 8: Health impacts of major air pollutants as defined by the WHO²¹

4. Industries and industrial processes

ACCESSA has an interest in providing technological solutions (which are scalable/not limited by power) to abate pollution from the following industries and processes (all industrial processes regulated under the IED/derived from Annex I of the EU Industrial Emissions Directive²², unless stated otherwise):

Power generation (boilers, engines, turbines, biomass combustion)²³

- Industrial combustion installations using conventional fuel. The criteria for classifying a fuel as a ‘conventional fuel’ is a known composition which remains relatively constant, and indeed is usually standardised. Coal, including lignite, biomass, peat, liquid and gaseous fuels (including hydrogen and biogas) are regarded as conventional fuels.
- Conventional power plants (e.g. utility boiler, combined heat and power plants, district heating plants, etc.) used for mechanical power and heat generation

Chemicals and petrochemicals

- Production of organic chemicals, such as: (a) simple hydrocarbons (linear or cyclic, saturated or unsaturated, aliphatic or aromatic); (b) oxygen-containing hydrocarbons such as alcohols, aldehydes, ketones, carboxylic acids, esters and mixtures of esters, acetates, ethers, peroxides and epoxy

resins; (c) sulphurous hydrocarbons; (d) nitrogenous hydrocarbons such as amines, amides, nitrous compounds, nitro compounds or nitrate compounds, nitriles, cyanates, isocyanates; (e) phosphorus-containing hydrocarbons; (f) halogenic hydrocarbons; (g) organometallic compounds; (h) plastic materials (polymers, synthetic fibres and cellulose-based fibres); (i) synthetic rubbers; (j) dyes and pigments; (k) surface-active agents and surfactants.

- Production of inorganic chemicals, such as: (a) gases, such as ammonia, chlorine or hydrogen chloride, fluorine or hydrogen fluoride, carbon oxides, sulphur compounds, nitrogen oxides, hydrogen, sulphur dioxide, carbonyl chloride; (b) acids, such as chromic acid, hydrofluoric acid, phosphoric acid, nitric acid, hydrochloric acid, sulphuric acid, oleum, sulphurous acids; (c) bases, such as ammonium hydroxide, potassium hydroxide, sodium hydroxide; (d) salts, such as ammonium chloride, potassium chlorate, potassium carbonate, sodium carbonate, perborate, silver nitrate; (e) non-metals, metal oxides or other inorganic compounds such as calcium carbide, silicon, silicon carbide.
- Production of phosphorous, nitrogen or potassium-based fertilisers (simple or compound fertilisers)
- Production of plant protection products or of biocides.
- Production of pharmaceutical products including intermediates.
- Production of explosives.

Mineral industry (cement, glass, ceramics)

- Production of cement, lime and magnesium oxide: (a) production of cement clinker in rotary kilns with a production capacity exceeding 500 tonnes per day or in other kilns with a production capacity exceeding 50 tonnes per day; (b) production of lime in kilns with a production capacity exceeding 50 tonnes per day; (c) production of magnesium oxide in kilns with a production capacity exceeding 50 tonnes per day.
- Production of asbestos or the manufacture of asbestos-based products.
- Manufacture of glass including glass fibre with a melting capacity exceeding 20 tonnes per day.
- Melting mineral substances including the production of mineral fibres with a melting capacity exceeding 20 tonnes per day.
- Manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain with a production capacity exceeding 75 tonnes per day and/or with a kiln capacity exceeding 4 m³ and with a setting density per kiln exceeding 300 kg/m³.

Surface treatment²⁴

- The surface treatment of substances, objects or products using organic solvents, in particular for dressing, printing, coating,

²¹ <http://www.who.int/mediacentre/factsheets/fs313/en/>

²² <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:334:0017:0119:en:PDF>

²³ http://eippcb.jrc.ec.europa.eu/reference/BREF/lcp_bref_0706.pdf

²⁴ http://eippcb.jrc.ec.europa.eu/reference/BREF/sts_bref_0807.pdf

degreasing, waterproofing, sizing, painting, cleaning or impregnating, with a consumption capacity of more than 150 kg per hour or more than 200 tonnes per year.

Waste incineration

- Disposal or recovery of waste in waste incineration plants or in waste co-incineration plants: (a) for non-hazardous waste with a capacity exceeding 3 tonnes per hour; (b) for hazardous waste with a capacity exceeding 10 tonnes per day.

Metal industry

- Metal ore (including sulphide ore) roasting or sintering.
- Production of pig iron or steel (primary or secondary fusion) including continuous casting, with a capacity exceeding 2.5 tonnes per hour.
- Processing of ferrous metals: (a) operation of hot-rolling mills with a capacity exceeding 20 tonnes of crude steel per hour; (b) operation of smitheries with hammers the energy of which exceeds 50 kilojoule per hammer; (c) application of protective fused metal coats with an input exceeding two tonnes of crude steel per hour.
- Operation of ferrous metal foundries with a production capacity exceeding 20 tonnes per day.
- Processing of non-ferrous metals: (a) production of non-ferrous crude metals from ore, concentrates or secondary raw materials by metallurgical, chemical or electrolytic processes; (b) melting, including the alloying of non-ferrous metals, including recovered products and operation of nonferrous metal foundries, with a melting capacity exceeding four tonnes per day for lead and cadmium or 20 tonnes per day for all other metals.
- Surface treatment of metals or plastic materials using an electrolytic or chemical process where the volume of the treatment vats exceeds 30 m³.

Pulp/paper/wood

- Production in industrial installations of: (a) pulp from timber or other fibrous materials; (b) paper or card board with a production capacity exceeding 20 tonnes per day; (c) one or more of the following wood-based panels: oriented strand board, particleboard or fibreboard with a production capacity exceeding 600 m³ per day

Food and drink²⁵

- Treatment and processing intended for the production of food products from: - animal raw materials (other than milk) with a finished product production capacity greater than 75 tonnes per day - vegetable raw materials with a finished product

production capacity greater than 300 tonnes per day (average value on a quarterly basis)

- Treatment and processing of milk, the quantity of milk received being greater than 200 tonnes per day (average value on an annual basis)

Agriculture, farming and mining²⁶

- Land-based compression ignited engines: Non-road diesel engines are used in a variety of machines including excavators, other construction equipment, farm tractors and other agricultural equipment, heavy forklifts, airport ground service equipment, snow groomers, and utility equipment (generators, pumps, compressors). Small diesel engines < 19 kW are mostly used for small agricultural or industrial machines used in private households or farms. Diesel engines > 560 kW are heavy construction equipment and heavy mining equipment.

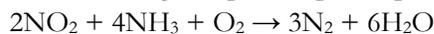
5. Technological solutions

For a summary of Pollutants which can be treated catalytically from specific industrial applications and the technology options which can be applied see table 9.

Selective Catalytic Reduction

Selective catalytic reduction (SCR) of NO_x by nitrogen compounds, such as *ammonia* or *urea* is well proven in industrial stationary applications. The technology has found wide application with hundreds of thousands of systems installed. In addition to common applications, coal-fired cogeneration plants and gas turbines, SCR applications also include plant and refinery heaters and boilers in the chemical processing industry, furnaces, coke ovens, as well as municipal waste plants and incinerators. The list of fuels used in these applications includes industrial gases, natural gas, crude oil, light or heavy oil, and pulverized coal²⁷.

Within the SCR system, the exhaust gas flows through the catalyst, with an injection of ammonia or urea. The chemical reactions proceed rapidly and selectively, i.e. without undesired side reactions, as described by the following reactions:



The SCR process requires precise control of the injection rate of ammonia or urea due to the fact that incorrect dosing may result in unacceptably low NO_x conversions and/or *ammonia slip* to the atmosphere. According to the dominant SCR reaction detailed above, the stoichiometric NH₃/NO_x ratio in the SCR system is

²⁶ <http://biofuelstp.eu/off-road.html>

²⁷ https://www.dieselnet.com/tech/cat_scr.php

²⁵ http://eippcb.jrc.ec.europa.eu/reference/BREF/fdm_bref_0806.pdf

about 1. Ratios higher than 1 significantly increase the ammonia slip. In practice, ratios between 0.9 and 1 are used, which minimize the ammonia slip while still providing satisfactory NO_x conversions. Using urea (or aqueous ammonia), SCR system and catalyst suppliers such as Johnson Matthey and Haldor Topsoe achieve NO_x reductions of 90%+ for diesel or gas engines. Urea is considered the ideal reducing agent as it can be shipped and stored easily and is colourless, odourless, nontoxic and bio-friendly.

The standard SCR System includes SCR catalyst, durable housing, mixing duct, injection system components and control panel or an optional fully integrated skid-mounted package. The skid-mount option includes a converter, injection system components, electronic controls, urea day tank, air compressor and freeze protection²⁸.

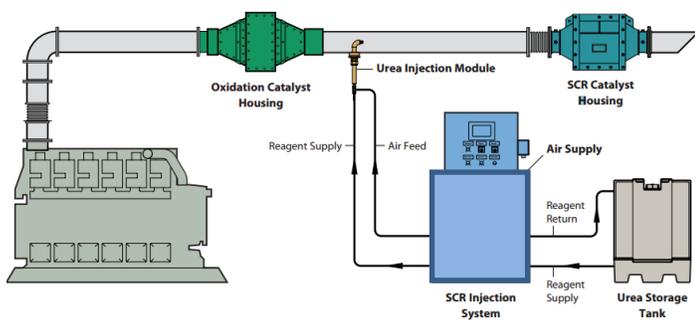


Figure 1: Typical oxidation catalyst and SCR system flow diagram

Oxidation catalysts

Oxidation catalysts owe their name to an ability to promote oxidation of several exhaust gas components by oxygen, which is present in ample quantities in diesel or natural gas exhausts. The catalysts are formulated to achieve maximum conversion of CO, HAPs, VOCs and HCs from stationary gas or diesel engines in power generation, process industries and other applications. Oxidation catalysts for gas turbines were pioneered in the 1970s. Since then, they have been installed in some of the most environmentally challenging applications, consistently providing greater than 90% destruction of CO, VOCs, formaldehyde and other toxic compounds. Today, firms deliver products which can be applied to diesel engines of all sizes and very large gas engines.

Considering gas turbine oxidation catalysts, some company's catalysts are formulated with Platinum Group Metals (PGMs) to achieve maximum conversion of pollutants at turbine temperatures. They have an established durability of 10 or more years of continuous operation, during which catalytic performance can be easily maintained or restored through washing if necessary.

²⁸ <http://www.jmsec.com/cm/products/scr-systems.html>

Formaldehyde

While regulations for formaldehyde emissions vary around the world, it is one of the more regulated compounds due to its toxicity and odour. It can be effectively oxidized and removed from exhaust emissions, such as from automotive and industrial sources. Catalytic technology serves as an ideal method of oxidizing formaldehyde. By comparison to state-of-the-art thermal oxidation technologies, the oxidation reaction occurs at much lower temperature in the presence of a catalyst. For example, in a thermal oxidation reaction, temperatures up to 850°C are required to thermally remove exhaust components of the formaldehyde process, while with a catalytic option formaldehyde can be effectively eliminated under 300°C. Depending on how the thermal oxidation unit is heated (i.e., fuel, electricity, etc.), the catalytic option can equate to lower, long-term running costs.

NO_x, VOC and particulate abatement with catalytic filtration technologies

Catalytically active filters, capable of removing particulates, NO_x, dioxins and volatile organic compounds (VOC's) in one step, is a relatively new technology option. VOC's can be a variety of species such as CO, formaldehyde, toluene, benzene and styrene. Catalytically active filters are relevant when the flue gas contains particulates and the plant is equipped with a bag filter house. Catalyst-coated filters are expected to be widely used in many industries such as power plants, cement plants, glass plants, biomass fired boilers and waste incineration.

The great advantage of the catalytically active filters is that several pollutants can be removed in one single process unit, namely the bag filter house. This eliminates the investment cost of a separate reactor for SCR and oxidation reactions, and will in many cases reduce both CAPEX and OPEX. Catalytic filters can be tailor-made to fit almost any bag house, and can thus be used to replace existing (non-catalytic) filter bags. They can be supplied as both filter bags (length 3-10 m) and ceramic filter elements (length 3 m). The catalytic filter bags can be used in the temperature interval 180°C to 260°C. The ceramic filter elements (sometimes called filter candles) can work in the temperature range from 180°C to 400°C. Removal efficiencies in the catalytic filters can be just as high as for conventional SCR and oxidation catalysts. NO_x removal efficiencies can for example be more than 90% with an ammonia slip lower than 10 mg/Nm³.

In many cases, catalytic filters are an attractive option as ammonia slip catalysts, if the plant applies the SNCR technology and needs to eliminate excess ammonia. In cases where SNCR is no longer sufficient to reach NO_x and ammonia emission limits "SNCR boosters", which increase overall NO_x and ammonia removal efficiency to meet the permissible levels due to stricter legislation, the catalytic filters can also be used as "SNCR boosters", which increase overall NO_x and ammonia removal efficiency to meet the permissible levels.

Pollutant	Power generation – Coal boilers	Power generation – Reciprocating engines	Power generation – gas turbines	Chemical and petrochemical (inc HNO ₃ adipic acid)	Minerals -cement, glass, ceramics	Surface treatment	Waste incineration	Iron and steel	Biomass combustion	Pulp, paper and wood	Food and drink	Machinery and large engines (mining)
NO _x	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓
CO	✗	✓	✓	✗	✓	✗	✗	✓	✓	✗	✗	✓
VOCs	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
PM	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
NH ₃	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
HG	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Other	✗	CH ₄	✗	N ₂ O	✗	✗	✗	✗	✗	✗	✗	✗
Technology Option												
SCR	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓
Oxidation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Catalysed particulate filters	✓	✓	✗	✗	✓	✓	✓	✓	✓	✗	✗	✓

Table 9: Illustration of: A) Pollutants which can be treated catalytically from specific industrial applications; B) Technology options which can be applied to specific industrial applications

6. Case studies

Power generation

The energy mix is evolving towards a lower carbon, more sustainable future. This evolution is slow and is predicted to take many decades – even in the more mature economies in the developed world. In many parts of the developing world the combustion of carbon based fuels is predicted to grow (in some cases rapidly) over the next few decades. There is growing pressure to mitigate the impact this might have on Air Quality

Pollutant Source	NO _x	Particulate Material	CO	Other HC / VOC
Coal/Biomass Boiler	SCR1	Catalytic Filters		
Gas turbine	SCR		OxiCat	OxiCat
Stationary Engine	SCR / TWC		OxiCat TWC	OxiCat 2 TWC
Industrial Processes	SCR	Catalytic Filters	OxiCat	OxiCat
1 – Mercury Hg may also be oxidised in the presence of a halide facilitating the removal of Mercury from the exhaust gas. Under controlled conditions – dioxins and furans may also be destroyed. 2 – Formaldehyde limits are controlled via the oxidation catalyst (oxicat)				

Table 10 – The type of catalytic after-treatment technology available in certain applications.

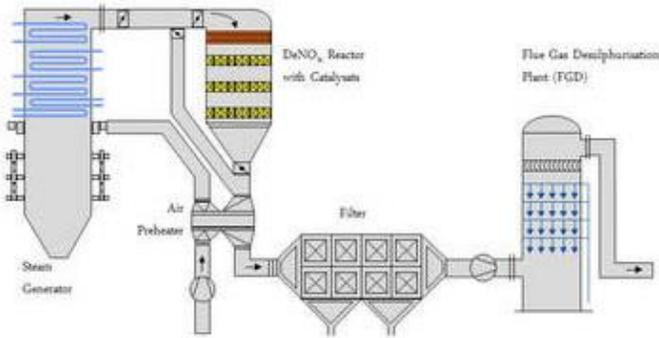
Coal Fired Boilers continue to make a significant contribution to our growing need for power. Often very large (of the order of hundreds of MW installed), their combustion processes also make significant quantities of acidic gasses SO_x and NO_x. SO_x emissions relate directly to the sulphur content in the fuel and can be removed in a scrubber. NO_x is a process pollutant and can be prevented/removed via a number of methods, but the most efficient is SCR. The installation of SCR Reactors on coal fired and co-fired boilers have now become routine in many parts of the world, particularly in North America, Western Europe and China.

Depending on plant requirements (new plant, retrofit or space availability), SCR catalysts have been installed in High-Dust, Low-Dust or Tail end configurations to meet NO_x reduction requirements.

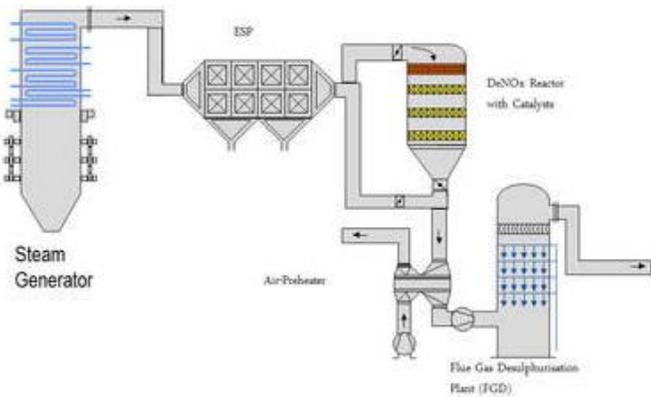
Durable plate type SCR catalysts are ideally suited for high-dust environments in Waste-To-Energy and Biomass-To-Energy power plants.

By changing the pitch of the catalyst low pressure drop and very low dust accumulation is achieved. Soot blowers can be installed, if required, to remove dust from the face of the catalyst and maintain maximum catalyst activity.

1. High dust SCR



2. Low dust SCR downstream Hot ESP



3. Low dust SCR (tail end)

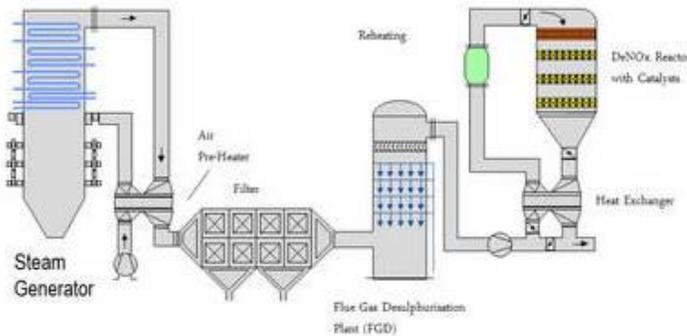


Figure 2: The different configuration options for SCR on a coal fired boiler.

A key concern of operators is ensuring that the emissions from their power plant are compliant with the requirements of their licence to operate. Catalysts are installed in layers and each has a definitive lifetime of compliant operation – determined by their design and the conditions they face during installation and operation.

The decay in performance can be modelled and used to predict when a catalyst layer should be replaced with new or regenerated catalyst.

Predictive NO_xout - Reactor 1 & 2

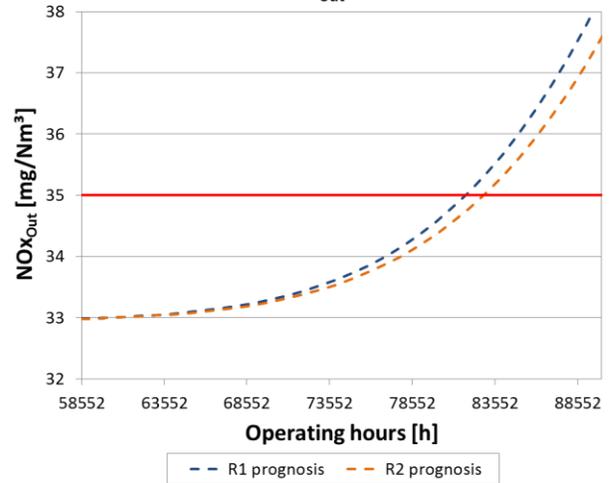


Figure 3: The drop off in SCR performance in the Hemweg 8 reactors due to catalyst aging

After replacement activity can be monitored and modelled to appreciate the next timeframe for catalyst recharge / replacement. All this allows the operator to manage the maintenance cycle of the SCR reactor with that of the rest of the Power plant.

Predictive NO_xout - Reactor 1 & 2

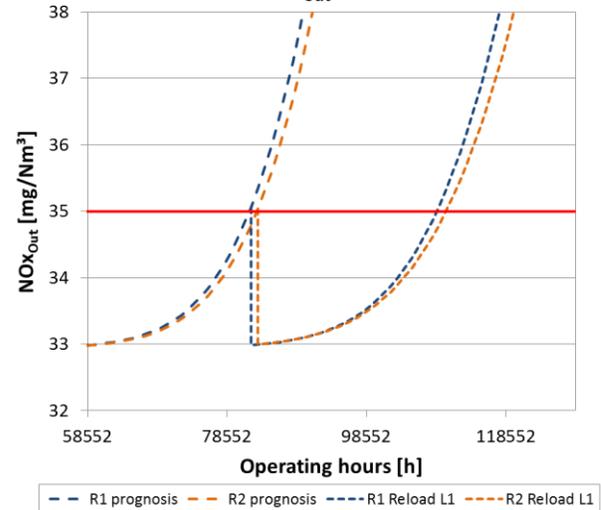


Figure 4: Impact of a catalyst recharge (reload of one of the catalyst layers in each of the Henweg 8 reactors

Mercury emissions

Growing concern over mercury emissions to air from power generation e.g. from coal and biomass has led to some local and national limits being imposed. One of the co benefits of SCR is

that the mercury can be oxidised in the presence of a halide such as chlorine or bromine. The reaction mechanism is thought to follow an Eley Rideal type where:

- The mercury (Hg) adsorbs at the Vanadium (V) Oxide (O) active site creating a V-Hg-O site.
- Hydrogen Chloride (HCl) reacts with the adsorbed Hg generating the oxidised Hg which diffuses into the gas

The mercury chloride is then removed downstream in the scrubber.

Emissions to air from Gas Turbines

In developed and developing economies there is an increased interest in gas fuelled power e.g. Gas Turbines. Gas power is generally cleaner than coal. With relatively little sulphur the main pollutants of concern are NO_x and CO both of which can be removed using SCR and oxidation catalysts respectively.

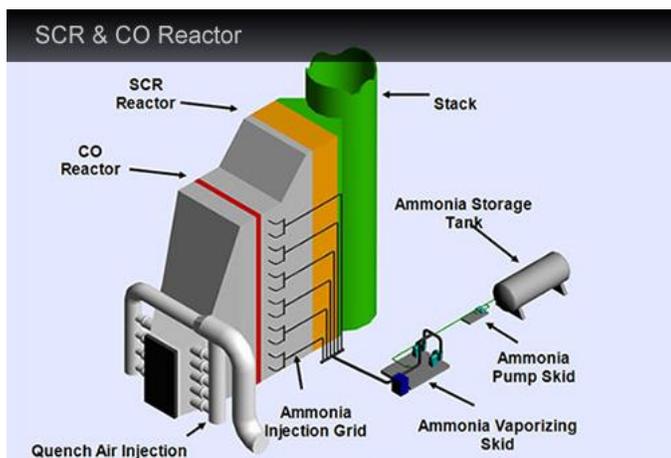


Figure 5: Schematic showing a DeNO_x SCR and Oxidation Catalyst for a combined cycle gas turbine

Very low NO_x emissions can be achieved in well-designed SCR reactors and with optimised ammonia dosing and mixing (see equation on page 11). Some tolerance can be designed into the system by installing ammonia slip catalysts. Recently systems have been designed that combine the oxidation and ammonia destruction function – leading to greater efficiencies.

The movement of gas from its point of extraction to its point of use requires a significant infrastructure including an extensive pipeline network. At various locations in the network the gas is compressed to keep in under pressure and moving to where it is required. These compressor stations are either gas turbines or internal combustion (IC) engines.

Stationary IC Engines

Large IC engines are used for power generation as well as in gas compression and in the oil and gas sector. They are also used in shipping. Typical emissions to air that can be controlled are NO_x, CO, unburned Hydrocarbon (fuel) referred to as Volatile Organic compounds and particulate material. Three-way catalysts can remove NO_x, CO and VOC from a gasoline engine exhaust. Here the exhaust gas chemistry is controlled to ensure a balance of oxidation with reduction.

Diesel engines, using lean burn combustion so there is a surplus of oxygen in the exhaust gas, require separate SCR and oxidation processes to reduce the NO_x and oxidise the CO and VOCs. In clean exhaust gas particulate matter can be oxidised in a wall flow filter. For other cases e.g. exhaust gas from sulphur containing fuel such as HFO, other filtration methods such as applications of filter candles have been developed.

IC engine Gas compressors such as the Loudon compressor station in Clarksburg, and that in Sacramento have been running with catalytic after treatment since 2004. The emissions for four of these engines are reported in the table below. The emissions of NO_x and CO meet with local permitting requirements.

Power kW	NO _x g/kWhr	CO g/kWhr	NO _x Reduction	CO Reduction
999	1.12	1.12	90%	90%
1767	0.52	1.86	90%	90%
2647	0.52	1.86	90%	90%
3531	0.52	1.86	80%	90%

With advanced catalyst design and cleaner exhaust gas, catalysts age and decay less rapidly and recharge periods extended lowering the total cost of operation

Design and evaluation of a catalytic off-gas solution for a European Portland Cement plant

With more than 200 plants and 160 million tons of cement produced in 2014, the Portland cement industry in Europe continues to represent a significant portion of the global cement market. In fact, 4 of the top 10 global cement producers are based in Europe with more than 500-million-tonnes of collective, annual capacity.

Europe has maintained a strong manufacturing base in this area due to the economics of cement distribution and its technology leadership in the field. Furthermore, because up to 35% of the cost of cement is attributable to transportation costs, it is advantageous to have localized production and distribution.

Although European manufacturers are bound by EU-wide legislation, country-specific and region-specific administration and regulations can vary. Emissions limits for toxic pollutants in

the case of cement production differ and, in some cases, are significantly more stringent than the overall EU limits. Furthermore, cement producers in particular regions or states within a country may be subject to additional local pressure to operate with the maximum available technologies, such as sites in the vicinity of outdoor recreation areas or local populations.

In Germany, for example, the Federal Ministry for Environment, Nature Conservation and Nuclear Safety has been a driver for emissions reduction in Europe through the enactment of the “Federal Pollution Control Act”. Recently this legislation was revised with respect to the combustion of waste materials to include Portland cement plants. Being designated as “co-incinerators” of waste materials, these plants are subject to the emissions restrictions created for combustion plants, including restrictions for the emission of carbon monoxide.

In most cases, these regulations are applied with specific exceptions for the operation of cement plants given unavoidable emissions due to the carbon-bearing nature of the raw materials. However, this revised regulation presents a difficult problem for German cement manufacturers. There are few, if any, demonstrated technologies to deal with these emissions, and the technologies that are commercially available, such as thermal oxidation, are often not practical due to energy costs.

One cement producer affected by the aforementioned legislation identified the high risk of inaction and engaged in a pilot testing program to identify a combined catalytic solution for the abatement of VOCs, carbon monoxide, nitrogen oxides and particulate matter. The problem of identifying such technology was not trivial; until now no conclusively demonstrated catalytic oxidation technologies have been demonstrated to withstand the process conditions.

In order to test the combined catalytic solution under realistic conditions, a mobile set-up was designed to utilize a slip stream and perform the tests using actual cement off-gas. The test unit was installed in the cement plant for the duration of the screening and continued operation over one year to include long-term testing. Subsequently, the testing was continued at another facility in the region to evaluate the effect of different effluent gases on the catalyst system. The flexible design of the unit allowed for variation of process conditions to test a combination of: dust-removal, selective catalytic removal (SCR) of NO_x, as well as catalytic oxidation of the volatile carbon species and carbon monoxide (see figure 2).

The testing unit was then used to screen a combination of different SCR and oxidation catalysts – from monolith-type vanadium-tungsten-titanium (VWT) catalysts to combination ceramic filter cartridges – for their lifetime performance in NO_x reduction and CO/VOC oxidation. These cartridges were loaded with an active SCR component based on iron zeolite. The oxidation unit was comprised of monolith-type catalysts chosen from a range of commercially available products, as well

as, a new generation of air purification catalysts based on a platinum-loaded zeolite coating.

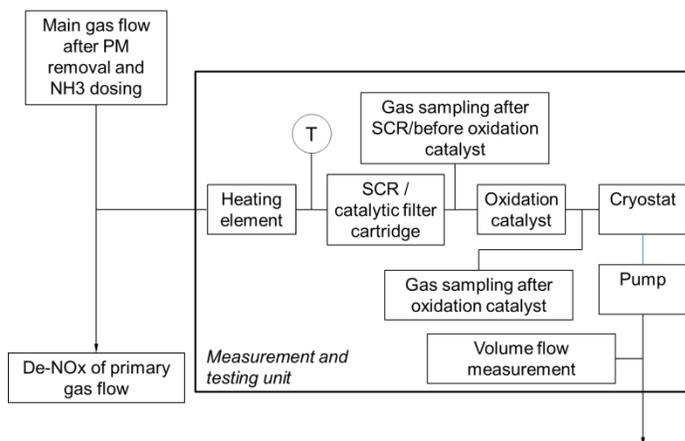


Figure 6: catalytic test set-up installed in slip stream

The results of the slipstream testing showed that, under the specific conditions, it is possible to operate a combination of SCR catalysts and oxidation catalysts together to achieve almost total oxidation of carbon monoxide. These results were obtained in the trial under an ideal temperature range between 350-400°C. In the test, both traditional monolith SCR catalysts and catalytic ceramic filter media were used to maintain low NH₃ slip. Although a number of oxidation catalysts were tested, it was only with the combination of the Pt-modified zeolite catalyst that long term performance was realized.

The duration testing experiments (see figure 3) showed that the performance of the catalyst combination could be maintained over more than 2500h. This was further confirmed by sporadic testing after shutdowns in which the temperature dropped significantly, indicating the performance could be maintained without degradation or deactivation due to sulphate build up.

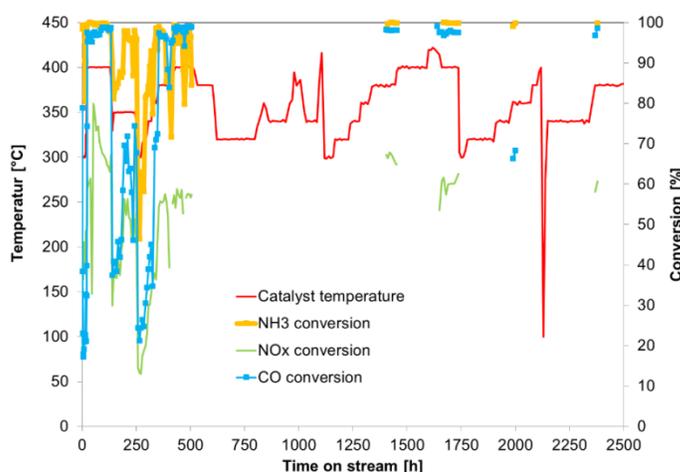


Figure 7: Long term catalytic test under actual cement off-gas conditions

NO_x, VOC and particulate abatement from refineries

Refinery NO_x and VOC emissions primarily originate from combustion processes in heaters, crackers, FCC regenerators, reformers, gas turbines and boilers.

NO_x emissions from refineries can be removed by a variety of methods. The primary methods are combustion modifications, burner operation and maintenance optimization, reburning, flue gas recirculation or use of low-NO_x burners. When the primary methods are not sufficient, the secondary methods Selective Non-Catalytic Reduction (SNCR), or SCR are applied. The SCR method is widely acknowledged as the BAT, making it possible to achieve more than 95% NO_x removal.

At some plants, both secondary methods SNCR and SCR are used. The advantage of this hybrid solution is that a high NO_x removal degree and a low ammonia slip can be achieved, while the needed SCR catalyst volume can be minimized relative to a pure SCR installation.

Implementation of SCR DeNO_x technology on refinery applications has been increasingly applied over the last two decades. Initially, the SCR DeNO_x technology was implemented in the USA, but later refineries in Europe and Asia have also adopted the technology. Often the SCR systems are made as retrofits on existing combustion equipment. For new units however, space is often reserved for the SCR reactor already in the design phase.

The SCR reactor can be placed a variety of places downstream of the combustion unit. The main requirement is a flue gas temperature in the interval 180°C to 500°C, and optimally 350-420°C.

For boilers, the SCR reactor is normally placed immediately after the boiler and economizer sections. For FCC units, heaters, crackers, reformers and gas turbines, the SCR reactor will typically be placed in between the heat exchangers of a waste heat recovery section, where there is sufficient space and a good temperature window.

SCR DeNO_x catalysts installed in refinery applications typically have long lifetimes compared to other industries. Guaranteed lifetimes of 3 to 5 years are standard whereas actual lifetimes may very well be longer than 10 years. These catalysts are designed for a desired end of run activity, meaning that the initial catalyst activity will be higher than the required activity and then slowly decrease to the required activity after several years of operation.

The SCR DeNO_x catalysts will experience a slow decline in performance during their lifetime for one or more of the following reasons: chemical poisoning, thermal sintering, fouling of catalyst surface, erosion or plugging of catalyst channels.

Particularly, SCR catalysts in reformer and ethylene cracker applications experience high deactivation due to chromium poisoning of the SCR catalysts. The catalyst poison chromium arises from the reformer tubes when these are heated to above 700°C.

Table 10 provides several examples of SCR DeNO_x installations in reformers, FCC units, crackers, heaters, gas turbines and boilers at different refineries. NO_x removal efficiencies are typically in the range of 75% to 97%. NO_x and NH₃ emissions are typically 2-100 ppmvd @3% O₂ and 2-15 ppmvd @3% O₂, respectively. An estimate for the total number of SCR installations in refinery applications is more than 1,000 SCR applications globally. The SCR DeNO_x technology is thus a well proven technology for refinery applications.

Removal of Volatile Organic Compounds such as CO, propane, butane, and toluene may be done catalytically. The catalyst is essentially a SCR DeNO_x catalyst with palladium (Pd) added. The removal efficiencies are different from each VOC species. But generally the catalyst can be designed for high removal efficiencies well above 90% of most VOC species. The lower alkanes methane and ethane are exceptions; they cannot be removed catalytically but require elimination by thermal oxidation.

VOC-oxidation catalysts are so far primarily used in gas turbines and a few reformer installations. An example is Celanese Clear Lake methanol plant in USA, see Table 11.

VOC oxidation catalysts may be placed before the injection of ammonia and SCR DeNO_x catalyst. Or the catalysts may be designed as *one* dual functionality catalyst, able to remove both VOC's and NO_x. The dual function catalysts have the obvious advantages of minimal space required, lower pressure drop and reduced SCR catalyst volume.

Country	End user	Plant	Unit size [Nm ³ /hr wet]	Start-up year	DeNO _x , %	NO _x out [ppmvd@3% O ₂]	NH ₃ slip [ppmvd@3%O ₂]
Reformers							
USA	Celanese Clear Lake	Reformer Methanol plant	315,000	2015	97	3	7
Italy	ENI S.p.A. Sannazaro	Reformer	255,000	2012	95	4	5
FCC units							
Thailand	IRPC	FCC	200,000	2014	90	4.7	6.4
China	Petrochina Guangdong	FCC	325,700	2014	75	29	4.7
Russia	Salavat Nefteorgsintez	FCC	78,400	2013	75	102	2
Crackers and heaters							
USA	Tesoro Golden Eagle refinery	Cracker	138,000	2002	92	8	4
USA	ConocoPhillips	Heater	280,000	2014	95	12	5
Taiwan	Taoyuan Refinery CPC Corp.	Heater	250,000	2013	70	36	6
Gas turbines							
Norway	Kaarstoe	Gas turbine	2,055,000	2007	90	6	6
USA	Hess Oil	Gas turbine	1,580,600	2011	81	6	15
Boilers							
USA	Air Products	Aux. Boiler	708,000	2006	90	194	5
USA	Western Refinery Company	Boiler	91,600	2013	86	7	10

Table 11: Examples of SCR DeNO_x installations in refinery combustion units

7. Technology trajectory

Concern over the impact of air pollution drives stricter emission limits. As emission limits are tightened, “in process” modification of the combustion give way to exhaust gas after treatment. Exhaust gas after treatment is more effective and often required where significant emissions reduction is required.

Taking its signal from the market and in particular its regulatory aspect, technology providers invest to develop new and improved technical solutions that are compliant, reliable, durable and cost effective. Technology providers generally follow a trajectory whereby first technology is developed to a stage where it can be demonstrated, and in a “learning / improvement” cycle the technology is fine tuned to the application. When a reliable durable technology is developed significant economies of scale and scope, such as those offered by a wider market, can

dramatically bring costs down. If a technology trajectory is supported in the market place it can bring forward highly efficient and cost effective technical solutions to help solve air pollution problems.

The overarching objective, as ever for the industry, will be to deliver increasingly effective pollution abatement technologies, which require decreasing amounts of catalyst volume at lower cost. Such a trajectory is already in evidence. For example, oxidation catalysts require smaller amount of raw materials than ever before - with improved chemical performance.

8. Emerging applications

Methane emissions from natural gas engines

Engines powered by natural gas fuel (e.g. LNG or CNG) are seen as a preferred option for current and future power generation on land and at sea²⁹. Naturally low in sulphur and a fuel that produces relatively low NO_x during combustion, natural gas also claims significant advantages in efficiency as determined by CO₂ emissions. However the issue of un-combusted hydrocarbon (in this case “methane slip”) needs to be addressed.

Natural Gas is seen as a clean hydrocarbon fuel, being composed chiefly of methane (with some higher hydrocarbons such as ethane and propane). Under normal “lean” operation, natural gas engines suffer a significant problem whereby unburned fuel emerges in the exhaust and enters the atmosphere at the rate of up to ~ 6 g/kWh. Though methane doesn't contribute appreciably to tropospheric ozone, it is a potent greenhouse gas with GHG factor 35 times that of CO₂ at equivalent emission rates. With the advent of shale gas in the US and the growth in natural gas fuelling infrastructure, the Global Warming Potential is slowly being recognised by policy makers. Great strides have been made by the engine OEMs, but it has become clear in recent years that the efficiency benefits of natural gas can only be truly realised with very low emissions of methane, ~ 0.3 g/kWh – and that is likely to require some treatment in the exhaust gas.

A Challenge

Policy makers and influencers have a crucial role to play in the development and deployment of a technical solution to this problem. These include establishing a time table for emissions regulations that set a limit for methane emissions. Were a limit set at 0.5 g/kWh this would create a level of market confidence necessary for the private sector to make timely investment. This endeavour could be supported to facilitate and ensure timely demonstrating and deployment of technical solutions.

9. Outlook

Air pollution in OECD countries has fallen in recent years, and is expected to continue to fall in the coming decades, driven by tighter emission regulations³⁰. However, substantial increases in air pollution are projected to occur in the key emerging economies. Air pollution concentrations in some cities, particularly in Asia, are already far above acceptable health standards (e.g., the World Health Organization's Air Quality Guideline) – leading to severe issues with health and millions of premature deaths.

Technology solutions such as catalytic after treatment can play an important role in limiting the emissions of air pollution often in a cost effective and sustainable manner.

The industry group, ACCESSA represents companies involved in the development and manufacture of technology related to the catalytic after-treatment of exhaust gas. Through its work, with regulators, OEMs, NGOs and other interested parties, it will endeavour to promote a better understanding of the capabilities of Catalytic After-Treatment technology.

²⁹ Natural Gas Engines can meet the IMO III limits for both NO_x and SO_x without the need for an SCR or SO_x scrubber. Further, it offers improvements in fuel efficiency - ~20% (in terms of CO₂ emissions).

³⁰<http://www.oecd.org/environment/indicators-modelling-outlooks/49928853.pdf>