Health and Environmental Impacts of NO\textsubscript{x}: An Ultra-Low Level of NO\textsubscript{x} (Oxides of Nitrogen) Achievable with A New Technology

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Abstract

The damages to human health and environment result because of various compounds and derivatives in the family of nitrogen oxides, including nitrogen dioxide, nitric acid, nitrous oxide, nitrates, and nitric oxide. Nitrogen oxides in the atmosphere contribute to photochemical smog, to the formation of acid rain precursors, to the destruction of ozone in the stratosphere and to global warming. On the contrary, an increase in Ozone (O\textsubscript{3}) concentration related to NO\textsubscript{x} emissions has been observed analyzing chemical and transport processes in the troposphere. Ozone can be transported by wind currents and can cause health impacts far from original sources. Ground-level Ozone (Smog) is formed when NO\textsubscript{x} and volatile organic compounds (VOCs) react in the presence of heat and sunlight. Children, people with lung diseases such as asthma, and people who work or exercise outside, are susceptible to adverse effects such as damage to lung tissue and reduction in lung function. Other impacts from ozone include damaged vegetation and reduced crop yields. These O\textsubscript{3} concentration changes, combined with geographically specific demographic data have been used to estimate the increase in mortality and respiratory illness that results from that increase in O\textsubscript{3}. Over the past 150 years, global emissions of nitrogen oxides into the atmosphere have been increasing steadily. A significant amount of the nitrogen oxide emissions is attributed to combustion of biomass and fossil fuels. This paper reviews existing and some emerging technologies for reduction of NO\textsubscript{x} emissions from combustion sources and examines the prospects of these technologies for meeting stricter emissions regulations. Both combustion modification and post-combustion methods for NO\textsubscript{x} reduction are considered. The important role of research on the chemistry of nitrogen oxides in combustion gases in development and optimization of emissions control techniques is described.

Keywords: NO\textsubscript{x}, NO\textsubscript{x} emissions; Health impacts; Mortality; Point sources; Cap-and-trade

Background

Nitrogen oxides, herein referred to as NO\textsubscript{x}, include nitric oxide and nitrogen dioxide. These oxides result primarily from the combustion of fossil fuels by vehicles and various stationary sources, though they are by products of all combustion-based systems and of all high temperature industrial processes. NO is produced by the combination of elemental nitrogen and oxygen in air within the burner/chamber in which combustion is carried out as a result of the high temperature from the highly exothermic combustion reaction. NO\textsubscript{x} is partly produced and emitted with NO, but its origin is mostly due to peroxy radicals and therefore to the complex oxidation chain fueled in the atmosphere after emission.

NO\textsubscript{x} is a deleterious air pollutant which can be poisonous at high concentration levels. Nitrogen oxides (NO\textsubscript{x}) emissions, and in particular NO\textsubscript{2} are a known precursor to the formation of ozone and of secondary aerosol largely contributing to PM\textsubscript{10} and to PM\textsubscript{2.5}. NO\textsubscript{2} therefore is not only criteria pollutant on their own, but they contribute sensibly to other pollutants of major health and environmental concern. In addition, NO\textsubscript{2} can react with volatile organic compounds to form photo-chemical smog, a phenomenon mainly connected with high temperatures and insolation concerning areas and seasons characterized by mild to hot conditions such as for example the Mediterranean region, at least in the summer season.

Power generating stations (Spokoyny, 24 Aug. 1993).

Most recent proposals to achieve further emissions reductions continue to suggest the use of cap-and-trade. Legislative initiatives to tighten the caps have failed primarily because of
debate about whether to include controls on emissions of carbon dioxide (CO₂). In USA, the Bush administration promulgated the Clean Air Interstate Rule (CAIR) in 2005, intending to use cap-and-trade to achieve substantial further reductions for only SO₂ and NOx (and an accompanying rule aimed at mercury). It also introduced an annual NOx cap while preserving as a separate market the five-month seasonal NOx program, but with the latter expanded to a larger region. CAIR aimed to limit emissions in 25 states for SO₂ and annual NOx emissions, with the justification of controlling particulates, and a slightly different 25-state region for controlling summer-season NOx emissions with the intent of controlling ozone. In total, 28 states are affected by CAIR. Implementation of the CAIR rule was tangled up in the courts, but is again proceeding, even as the rule has been remanded to the Environmental Protection Agency (EPA) for revision.

Where Does the NOx Come From?

NOx is produced from the reaction of nitrogen and oxygen gases in the air during combustion, especially at high temperatures. In areas of high motor vehicle traffic, such as in large cities, the amount of nitrogen oxides emitted into the atmosphere as air pollution can be significant. NOx gases are formed whenever combustion occurs in the presence of nitrogen – e.g. in car engines; they are also produced naturally by lightning.

The majority of NOx emissions come from two major areas of human activity [1] (Figure 1):

- Motor vehicles
- Fossil fuel, power plants

Control of NOx must focus on lowering combustion Temperatures through

- Exhaust gas recirculation,
- Increase fuel/air mix (increase hydrocarbons)

Or it may be achieved through catalytic heterogeneous processes promoting reduction of NOx to N₂.

Effect is restricting the growth of industry within their own regions in an attempt to minimize their local NOx problems.

Comparison What Does < 1ppm NOx Mean?

A content of 1ppm of NOx does not really mean anything until it is put into a context. This begins to be understandable when we look at how much the amount of NOx is avoided when the Ener-Core technology is employed rather than traditional combustion technology.

What is the real effect of this capability? How does this translate into impact in the real world?

Let’s begin by looking at the amounts of NOx that are typically emitted by traditional combustion-based technology (assuming it is running 95% of the time at 100% load) [2] (Table 1):

| Source - European Union emission inventory report 1990-2011 under the UNECE Convention on Long-range Trans-boundary Air Pollution (LRTAP) |  |
|---|---|
| Traffic: 40% |  |
| Industrial Energy Use and Energy Production/ | Distribution: 34% |

The move from traditional combustion-based energy generation to wind and solar exerts a positive effect on the total emissions from the Energy Generation Sector, but this still remains a minor generation capacity; therefore, combustion of fuels will remain with us for some time to come.

Traffic remains and will remain the largest single source of NOx pollution until the combustion engine is phased out and electric cars become the norm. The recent scandal concerning emission level cheating by leading car companies has highlighted this issue but the real challenge is the total volume of traffic on the roads and the fact that although the latest emission standards for automobiles might be improving, the NOx situation, it is far from being eliminated, unless using pure oxygen as the oxidizer.

Formation of (thermal) NO proceeds mainly by combination of atmospheric N₂ with dioxygen at high Temperature:

\[ N₂ + O₂ \rightarrow 2 \text{ NO} \]

though the main mechanisms are the following:

\[ N + O₂ \rightarrow NO + O \]
\[ O + N₂ \rightarrow NO₂ + N \]

A small fraction of nitrogen occurring in fuel may yield a correspondingly negligible amount of “fuel” NO.

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| Assumption: Gas Turbine Exhaust: 53600 Nm³/h, Gas Engine Exhaust 13750 Nm³/h, both corrected to dry exhaust at 15% O₂ |  |
|---|---|
| Traffic: 40% |  |
| Industrial Energy Use and Energy Production/ | Distribution: 34% |
Table 1:

| Technology                                      | NO\textsubscript{x} Limit* | kg NO\textsubscript{x} / year |
|------------------------------------------------|-----------------------------|--------------------------------|
| 3.5 MW Turbine [Existing Turbine, Fuel = Biogas, at the limit of allowable NO\textsubscript{x}] | 98 ppm                      | 54,571                         |
| 3.5 MW Turbine [Existing Turbine, Fuel = Natural Gas, at the limit of allowable NO\textsubscript{x}] | 50 ppm                      | 27,842                         |
| 3.5 MW Gas Engine [New Turbine, Fuel = Biogas at the limit of allowable NO\textsubscript{x}] | 15 ppm                      | 8,353                          |
| 3 MW Gas Engine [Existing or New Engine, Fuel = Bio- Gas at the limit of allowable NO\textsubscript{x}] | 87 ppm                      | 34,185                         |
| 3.5 MW Ener-Core System                        | <1ppm**                     | 172                            |

*Limits set by EU for 2017 onwards
** <1ppm NO\textsubscript{x} is not a limit but achievable NO\textsubscript{x} level.

Comparing the annual amounts of NO\textsubscript{x} produced by such systems to the number of Passenger Vehicles producing the same total amounts of NO\textsubscript{x} in the UK makes these numbers a little more understandable (Figure 2):

Assuming that the new EURO 6 limits are in effect on all cars (diesel and gas (petrol) based) then the average passenger vehicle emits 0.344 kg/year of NO\textsubscript{x}, then the equivalent number of passenger vehicles are (Table 2):

Table 2:

| Technology                              | Equivalent Number of Vehicles |
|-----------------------------------------|------------------------------|
| 3.5 MW Turbine 98 ppm NO\textsubscript{x} | 156,785                      |
| 3.5 MW Turbine 50 ppm NO\textsubscript{x} | 98,349                       |
| 3.5 MW Turbine 15 ppm NO\textsubscript{x} | 22,278                       |
| 3 MW Gas Engine 87 ppm NO\textsubscript{x} | 98,349                       |

To put this into even greater perspective these numbers of vehicles can be compared to the estimated number of vehicles in several major cities within Europe [3].

(3) Estimations based on populations of the individual cities and the average number of vehicles per person for the country in question.

Human Harm and the Costs Associated with Nox Pollution

Considering the amount of exhaust gas that a 3.5 MW generation system makes (approximately 50,000 Nm\textsuperscript{3}/h for a gas turbine or 15,000 Nm\textsuperscript{3}/h for a gas engine working at the limit of the proposed legislation, the gas engine would appear to be the better choice in terms of the total amount of NO\textsubscript{x} produced per day (assuming that they were emitting the proposed limits) [4-9] (Table 3).
This does not seem to be a large amount, but we need to consider how this translates to a concentration of NO\textsubscript{x} in the local atmosphere. According to the EPA in the US, there are several important concentrations levels that need to be considered:

- **Warning Level** = 0.6 ppm NO\textsubscript{x} (1.22 mg/m\textsuperscript{3})
- **Emergency Level** = 1.2 ppm NO\textsubscript{x} (2.43 mg/m\textsuperscript{3})

Assuming a day of zero wind (wind-still), so that there is minimal air mixing, that the NO\textsubscript{x} is diluted to a homogeneous level 4, and that there is zero NO\textsubscript{x} in the atmosphere to begin with, then the amounts of NO\textsubscript{x} in the table above are sufficient to generate the following volumes of NO\textsubscript{x}/air mixture (Table 4)(Figure 3):

- **Significant Human Harm** = 2ppm NO\textsubscript{x} (4.05 mg/m\textsuperscript{3})

Assuming a ceiling height of 100 m for this homogenous cloud of NO\textsubscript{x}, and an average population density of 3575 people/sq. km then this NO\textsubscript{x} cloud would potentially affect the following number of people (Table 5) (Figure 4):

| System / Level | Warning | Emergency | Significant Harm |
|----------------|---------|-----------|------------------|
| Existing 3.5 MW Gas Engine* | 4,300 | 2,100 | 1,300 |
| New 3.5 MW Gas Turbine** | 2,100 | 1,000 | 650 |
| 3.5 MW Gas Turbine (15 ppm)*** | 650 | 325 | 195 |
| 3.5 MW Gas Engine (95 mg/m\textsuperscript{3}) † | 1,500 | 770 | 462 |

* system operating at EU allowed limit with natural gas
** system operating at EU allowed limit with natural gas
*** system assumed to have optimal deNox system
† system operating at the EU allowed limit for natural gas

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### Table 5: Total mass of NO\textsubscript{x} emitted per day.

| System / Level | Warning | Emergency | Significant Harm |
|----------------|---------|-----------|------------------|
| Existing 3.5 MW Gas Engine | 105 kg/day | 59 kg/day |  |
| New 3.5 MW Gas Turbine | 40 kg/day |  |

**Potential Number of People Affected [7]**

Given that in London in 2010, short term exposure to the effects of NO\textsubscript{y} was associated with 420 hospital admissions for respiratory disorders the potential cumulative effect of these pollutants - regardless of their source, are clearly having an impact on local populations, and the potential detrimental health effects of individual small and medium scale power [10-13].

4. Population and city surface areas taken for Los Angeles, New York City, Dallas, Paris, Moscow, Rome, London, Berlin, Washington DC, Buenos Aires, Milan.

5. Population and city surface areas taken for Los Angeles, New York City, Dallas, Paris, Moscow, Rome, London, Berlin, Washington DC, Buenos Aires, Milan.
6. Ref.: World Health Organization (2013). Review of evidence on health aspects of air pollution generation systems placed within or near major conurbations could be significant. This is very concerning if these power generation systems are close to hospitals or schools where the effect of the pollution is magnified.

It is therefore hardly surprising that many cities within Europe are limiting the installation of new generation capacity, even though these new systems would conform to the requirements of the EU with regard to NO\textsubscript{x} emission levels [14-18]. In California (USA), the local state regulations have gone further and taken the step of limiting not only the concentration of NO\textsubscript{x} in the exhaust plumes of industrial facilities, but also placing an annual cap for the total mass of NO\textsubscript{x} emitted.

However, the approach to limiting NO\textsubscript{x} in this way is a two-edged sword. Its intention is to reduce or limit pollution effects, but at the same time it makes the growth of businesses more difficult, potentially preventing a company expanding or investing in newer more efficient production processes. As a result, potential jobs are not created, or are created elsewhere, and existing jobs may even be put at danger.

Is there a solution to this challenge for the local governments and the businesses that are located within their communities? Can the requirements of commerce and industry to generate power and heat be fulfilled without generating NO\textsubscript{x}? Thanks to Ener-Core it is now possible.

**Application of the Ener-Core Power Oxidizer Methodology**

The Ener-Core Power Oxidizer replaces traditional combustion chambers within gas turbines and represents a significant new component within the integrated KG2 gas turbine [19,20]. The Dresser-Rand business and Ener-Core engineering teams have worked collaboratively on this effort for 18 months and are nearing completion of an extensive testing regime that covers component-specific testing as well as a full integration test.

The Power Oxidizer and all other system components from the KG2 gas turbine have surpassed some of the most challenging integration hurdles. The test system has performed very close to the required system specifications; the engineering teams from both companies have identified a few additional integration tasks that are expected to further improve the overall system performance [21-30]. These remaining integration tasks are typical within the final testing phase of this sort of technology integration project and the teams expect to implement these remaining improvements before the end of the calendar year.

**Conclusion**

NO\textsubscript{x} has been identified as one of the key pollutants that has been liked to serious health issues and is strongly believed to be a contributing factor in a significant number of premature deaths. As such it has become a major focus of the EU and the USA environmental agencies to reduce these emissions from a perspective of cost reduction in the health sector, as well as (and more importantly) to combat the negative health effects on the population at large. As NO\textsubscript{x} emissions are largely a by-product of combustion, which until recently has been the only way that industry could generate local heat and power, governments are faced with the dilemma that capping the total levels of NO\textsubscript{x} emissions on a tons/year basis means that they are also in danger of limiting the growth potential and competitiveness of that very industry within their region [31-34]. Thankfully that is no longer the case. The Gordian Knot of NO\textsubscript{x} emissions has found its Damocles Sword. The technology from Ener-Core allows distributed power and heat production, often with fuels that other systems could not even use, with near-zero NO\textsubscript{x} emissions.

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None.

**Conflict of Interest**

No conflict of Interest.

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