Creating a world
fit for the future

Establishing factors that influence NO_X reduction at Waste incineration plant to levels below the upper end of the BAT-AEL's

Report for Environment Agency

Report for Environment Agency – CAS2020-2(WSIG)

ED 14689| Issue 2 |

Date 14/01/2022

Ricardo Confidential

Customer:

Environment Agency

Customer reference:

CAS2020-2(WISG)

Confidentiality, copyright and reproduction:

Contact:

Rob Davies, Gemini Building, Fermi Avenue, Harwell, Didcot, OX11 0QR, UK

T: +44 (0) 1235 753 126

E: Rob.Davies@ricardo.com

Author:

Alan Leonard, Senior Consultant
Soumya Banerjee, Principal Consultant

Paul James, Consultant Energy & Resources Ltd
Robert Stewart, Principle Consultant

David Woolford, Associate Director

Approved by:

David Woolford, Associate Director

Signed

Date:

31/07/2021

Ref: ED 14689

Ricardo is certified to ISO9001, ISO14001, ISO27001 and ISO45001

Executive summary

In 2019 Best Available Techniques Conclusions (BATC) were published with respect to the operation of incineration plant under the European Industrial Emissions Directive (IED). The BATC provide the legal basis for determining Best Available Techniques (BAT) for an activity including application of emission limits for air pollutants such as Oxides of Nitrogen (NO_x), for both new and existing plant.

The Environment Agency for England (EA) commissioned a review to further develop its understanding of the technical implications and cross-media impacts of requiring new and existing incinerators to meet lower NOx limits. This review has looked at the $DeNO_X$ technologies available and the associated impacts to the environment and the operation of plant.

This review was supported by information from real world plant for normal operation and from trials undertaken to investigate the possibility of achieving the BAT Achievable Emission Levels (BAT AELs) defined in the BATC.

Where plants are currently unable to achieve the BAT AELs there are control techniques and technologies that could be utilised to achieve them. However, on existing plant these may not be present or may involve significant engineering to apply. Consequently, site-specific solutions will be required in order to ensure compliance with the new daily average emissions limit value of 180 mg/Nm^3 from December 2023.

The data provided by operators suggested that for some of the plants that provided data it would be possible to meet a daily average of less than 180 mg/Nm^3 without significant plant modification, although this was not the case for all plant. However, data are limited and show some variability which indicates that the assessment of the potential for further NOx reduction to the BAT AEL and below should be undertaken on a plant-specific site basis. This assessment should be undertaken in a consistent way to ensure that the data produced will be comparable at a plant level and across the sector.

Some of the techniques are associated with an increase in other emission components such as nitrous oxide and ammonia. These have their own environmental impact so should be assessed when implementation of a technology is being considered.

To assess the implications of utilising a technology and complying with the NO_X BAT-AEL's a multi criteria assessment model has been developed. This is designed to enable plant specific assessments to be undertaken.

Table of Contents

List of Figures

List of Tables

Glossary

Abbreviation	Definition
AGAM	Acoustic gas (temperature) measurement
APCr	Air Pollution Control residues
BAT	Best Available Techniques
BATC	Best Available Techniques Conclusions
BAT- AEL	Best Available Techniques -associated emission levels
BREF	EU Best Available Techniques reference documents
CEMS	Continuous Emission Monitoring System
CO	Carbon Monoxide
Defra	Department of Environment, Food and Rural Affairs
EA	Environment Agency
EAR	Excess Air Ratio
EFW	Energy from Waste
ELV	Emission Limit Value
EU	European Union
FGR	Flue Gas Recirculation
HVO	Hydrogenated vegetable oil
IBA	Incinerator Bottom Ash
IED	Industrial Emissions Directive
LNB	Low NOx Burner
LPG	Liquefied Petroleum Gas
MSW	Municipal Solid Waste
MWI	Municipal Waste Incineration
NH_3	Ammonia
N_2O	Nitrous Oxide
NO_X	Oxides of Nitrogen (Nitric oxide + Nitrogen Dioxide)
NSR	normalized stoichiometric ratio
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
WI	Waste Incineration
WtE	Waste to Energy

1. Introduction

On the 3rd December 2019, the European Commission published the revised reference document (BREF) on Best Available Techniques (BAT) and subsequently the Best Available Techniques Conclusions (BATCs) for new and existing waste incinerator plants. The BATCs represents the legal definition of BAT for incineration activities which are within the scope of Annex I of Directive 2010/75/EU on industrial emissions (IED). Permitting of processes under the Environmental Permitting regulation[1] (EPR) enable implementation of the BATCs. The responsibility and mechanism of the implementation of changes is the responsibility of the regulatory authority.

Ricardo has been engaged by the Environment Agency (EA) to help develop its understanding of measures for control of nitrogen oxides (NOx) from waste incineration activities, including:

- Primary controls.
- Technologies currently in use for NO_X abatement.
- Cross-media impacts.
- Barriers to implementation.
- Additional controls.

The objective of the study is to inform the regulatory authority when setting or seeking improvements in NOx emissions performance (below the upper end of new BAT-AELs) from both new and existing plants.

The following tasks were undertaken by Ricardo to establish the factors that influence NOx reduction at existing Waste to Energy (WtE) plants

- Task 1 - Literature search - Technology description (DeNOx technologies).
- Task 2 - Plant Data collection.
- Task 3 - Barriers for retrofit option.
- Task 4 - Impact assessment including cross media impact.

The project output is this report which is based on DeNOx techniques employed at existing municipal waste incineration (MWI) plants in the UK and provides:

- Description of the techniques in use.
- Techniques that might be reasonable to expect within new plants.
- Clear datasets on cross media impacts.
- High-level overall benefit analysis of implementing additional controls.

[1] Environmental Permitting (England and Wales) Regulations 2016 SI 2016/1154

2. Background

2.1 Emission limit values

Existing waste incineration plant operating in the UK are required to meet emission limit values (ELVs) derived from the BAT-AELs in the BATC by December 2023. BAT AELs are specified as a range and operators of incineration plant are expected to be able to comply with the top of that range as a minimum. The Environment Agency is the regulator for IED Annex I incineration plant in England under the Pollution Prevention and Control Act 1999 and the Environmental Permitting (England and Wales) Regulations 2016 as amended (EPR). The EPR transposes the IED requirements into law for England and Wales (other legal instruments transpose IED in Scotland and Northern Ireland). Although the UK has left the EU, the BATCs were published before the leaving date and therefore apply unless changed at a later date by a UK based decision.

The Environment Agency's current policy on setting ELVs in permits in response to BATCs is based on Defra guidance. This guidance requires the upper end of the range to be set, unless the operator proposes a lower limit, or the local environment requires it (for example to meet an air quality standard). However, this approach is expected to change, meaning that lower ELVs could be set for certain pollutants.

BAT 29 of the BATC (2019) prescribes a BAT-AEL range for NOx for existing plants of 50-150 mg/Nm^3 (where the upper end of the range is 180 mg/Nm^3, where SCR is not applicable) and 50-120 mg/Nm^3 for new plants (see Table 1).

Table 1 BAT-AEL for NO_X/CO/ NH_3 for Incineration Plant

Parameter	BAT-AEL (mg/Nm^3)		Averaging period
	New plant	Existing plant	
NO_X	50–120 (^{1})	50–150 (^{1}) (^{2})	Daily average
CO	10–50	10–50	
NH_3	2–10 (^{1})	2–10 (^{1}) (^{3})	

(^{1}) The lower end of the BAT-AEL range can be achieved when using SCR. The lower end of the BAT-AEL range may not be achievable when incinerating waste with a high nitrogen content (e.g. residues from the production of organic nitrogen compounds).
(^{2}) The higher end of the BAT-AEL range is 180 mg/Nm^3 where SCR is not applicable.
(^{3}) For existing plants fitted with SNCR without wet abatement techniques, the higher end of the BAT-AEL range is 15 mg/Nm^3.

DeNOx technologies installed in existing UK WtE plants include Selective Non-Catalytic Reduction (SNCR) and on some plant this is integrated with Flue Gas Recirculation (FGR). The use of this technology is primarily due to the current NOx emission limit of 200 mg/Nm^3 (for a dry gas at 0°C, 101.3 kPa and 11% oxygen). This is derived from the minimum requirements set by Chapter IV of the IED and the previous BREF.

The proposed new upper NOx emission limit for existing WtE plants without a Selective Catalytic Reduction (SCR) system is 180mg/Nm^3 (Table 1). Consequently, it is necessary to consider ways to optimise/enhance SNCR systems to meet this new NOx limit. There are many ways in which this might be achieved, such as injecting more reagent (urea or ammonia).

New plants are required to meet a more stringent NOx emission limit i.e. less than 120 mg Nm^{-3}. This may require introduction of SCR /catalytic bag filter units to meet this new limit including optimisation of ammonia/urea injection system. Achieving lower emission concentrations (below the upper BAT-AEL) may require use of SCR /catalytic bag filter units combined with an optimised of ammonia/urea injection system. It has been reported [footnote] that the combination of SNCR and SCR and catalytic bag filters has achieved 80mg m^{-3}.

However, the implementation of additional NOx controls potentially has cross-media impacts from emissions to land, air, or water.

Examples of these potential cross-media impacts are:

- Higher ammonia (NH_3) release at stack ('ammonia slip').
- Higher nitrous oxide (N_2O) emissions, a greenhouse gas.
- Impact on overall plant efficiency.
- Impact on overall plant availability.
- Increase in plant parasitic load.
- Increased odour and pollution potential from bottom ash.

In addition to any environmental impact there are costs associated with the implementation of any approach to achieve compliance with the BAT-AELs. These include:

- Impact on operating costs.
- Impact on maintenance costs.
- Direct cost-impact due to plant retrofit.

2.2 Formation of Oxides of Nitrogen

There are three mechanisms involved in the formation of Oxides of Nitrogen which are:

- Thermal NO_X.
- Fuel NO_X.
- Prompt NO_X.

An understanding of these mechanism enables control of the reaction pathways associated with each source of NO_X

The flame temperature, fuel air ratio and retention times determine the species and quantities of NO_X resulting from the combustion process.

In the conditions found in MSW WtE plants, fuel and thermal NOx are the greater contributor to NOx emission than prompt NOx[2,3]. Higher temperature combustion (e.g., certain hazardous waste incineration plants are required[4] to operate at high temperatures) usually generates increasing levels of thermal NOx.

Fuel Nitrogen content and variations can have a significant impact on NOx generation and eventual emissions. Higher nitrogen fuels such as sewage sludges will generate more NOx but, MSW is generally considered a medium Nitrogen content fuel, with the main challenge being where variant waste streams are added at significant proportions. In such cases, achieving good fuel mixing in the waste bunker is of increased importance, so that waste fed to the furnace is consistent. With mixing being achieved by grab operators, a smaller-sized waste bunker can be a factor.

2.2.1 Thermal NO_X

Thermal NOx accounts for the largest proportion of NO_X generated in high temperature combustion processes. This mechanism involves the reaction between the nitrogen and oxygen present in the air used for combustion. This occurs in the presence of high temperatures i.e. in the region of 1300ºC producing nitric oxide (NO).

---

[2] Air Pollution Control in Municipal Solid Waste Incinerators, Margarida J. Quina1, João C.M. Bordado and Rosa M. Quinta-Ferreira
[3] Facing New NOx Reduction Challenges in Energy from Waste Systems, Oliver Gohlke, MARTIN GmbH für Umwelt- und Energietechnik
[4] IED 2010/75/EU Chapter IV Article 50

The mechanism is outlined in the following equations :

$$O + N_2 \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

2.2.2 Fuel NO_X

If the flame temperature maximum is below 1000ºC, fuel NOx formation accounts for the majority of the NO_X produced.

Nitrogen that is present in the fuel during combustion produces ammonia (NH_3) or hydrogen cyanide (HCN) that dissociates to NO. Under lean burn conditions nitrogen tends towards the production of NO and N_2 whereas under rich conditions the resulting productions include NH_3 and HCN.

2.2.3 Prompt NO_X

This form of NOx is formed at the flame front and requires high temperature and reaction of hydrocarbon radicals and formation of hydrogen cyanide. Prompt NOx amounts to the smallest share of any oxides of nitrogen formed during combustion in waste incineration.

3. Existing Plant Technology

Prior to publication of the BAT Conclusions in November 2019, there were 48[5] operational WtE plants in the UK, of which 5 were in Scotland and one was in Wales. These are summarised in Table 2. A further five plants were undergoing commissioning in 2019.

Table 2 Summary of existing UK WtE in operations 2019

Date of Commission	Type of Combustion	No. of	Selective non-catalytic reduction (SNCR)	Selective Catalytic Reduction (SCR)	Combined SCR & SNCR	Catalytic Bags
1990 -2000	Grate	19	19	0	0	0
	Fluidised Bed	1	1	0	0	0
	Kiln	0	0	0	0	0
2000-2010	Grate	7	7	0	0	0
	Fluidised Bed	1	1	0	0	0
	Kiln	2	2	0	0	0
2010-2019	Grate	18	18	0	0	0
	Fluidised Bed	0	0	0	0	0
	Kiln	0	0	0	0	0

Table 3 provides a summary of plants listed as being in the process of commissioning at the end of 2019 i.e. the date of publication of the BATC and therefore considered as existing plants.

Table 3 Summary of Plants in commissioning

Date of Commission	Type of Combustion	No. of plant	Selective non-catalytic reduction (SNCR)	Selective Catalytic Reduction (SCR)	Combined SCR & SNCR	Catalytic Bags
2019	Grate	3	3	0	0	0
	Fluidised Bed	2	2	0	0	0
	Rotary	0	0	0	0	0

N.B Two fluidised beds and one of the grate plant utilise gasification rather than mass burn

As can been seen from Table 2 and Table 3, all of the existing plants use SNCR, none has adopted SCR or Catalytic bags for the control of NO_X emissions. Consequently, the SNCR technology will be used as the starting point for assessment to achieve BAT-AELs.

[5] UK Energy from Waste Statistics – 2019 Tolvik Consulting, May 2020 https://www.tolvik.com/wp-content/uploads/2020/05/Tolvik-UK-EfW-Statistics-2019-Report-June-2020.pdf

4. Task 1 Technology description (DeNOx)

4.1 Task 1 Methodology

The study of the available technologies is based on:

- Ricardo's in-house experience and knowledge of NOx abatement technologies; and
- A literature search of technical information and data available in the public domain, including the data held by the EA for WtE plants. The literature search used reliable technical data published in the BREF documents, peer-reviewed scientific journals, and papers available in the public domain including experiences from different industries. This also included information published by public international organisations where appropriate.

This is to ensure that a complete assessment and full understanding of the technical performance including limitations and advantages for various DeNOx technologies currently available in the WtE application.

Ricardo has selected major NOx abatement technologies that are commercially available and currently applied in UK and global WtE plants, that include:

- Primary methods of NO_X reduction.
- Selective Non-Catalytic Reduction (SNCR).
- Selective Catalytic reduction (SCR) /SCR combined with SNCR.
- Catalytic bag filters.

4.2 Primary Methods of NO_X reduction

Primary methods of control involve controlling the parameters that result in the production of the various forms of NO_x formed during the combustion process.

4.2.1 Overview

As outlined in Section 2.2, oxides of nitrogen are mainly formed by two routes in a combustion process:

1. Whenever anything is burnt in air, there is potential for oxides of nitrogen to be formed from the nitrogen present in air – this 'thermal NOx' can be controlled by managing the combustion process to reduce peak temperatures.
2. By the oxidation of nitrogen present in the waste feed – this can be controlled by managing the combustion process to manage availability of air at initial stages of combustion.

Primary control methods are implemented prior to or during the combustion phase targeting the sources and processes involved in the formation of NO_X. Recognised methods include:

- Waste and support fuel selection.
- Auxiliary burner design.
- Combustion Control:
    - Combustion Air control:
        - Low excess air ratios.
        - Air staging.
    - Temperature control.
- Flue Gas recirculation.

Reducing the level of the NOx produced during combustion prior to application of any secondary methods of abatement can reduce the levels of abatement required and consequently reagent consumption and waste streams produced by any secondary technology employed.

4.2.2 Fuel selection

Reducing the nitrogen in the fuel is an approach to reduce the emissions of oxides of nitrogen. However, because of the nature of waste, there may be limited scope to reduce the nitrogen content of wastes presented to the plant. For municipal waste this is not considered a practical methodology Mixing of waste will to some extent homogenise the material and thereby reduce fluctuations in composition which enables better control and hence can assist in maintaining conditions of low NO_X production.

However, management of wastes could be applicable to some commercial or industrial waste feeds, where nitrogen is present in significant quantities and comprises a significant proportion of the fuel e.g. particle board from demolition or furniture manufacture.

For support fuels the nitrogen content of natural gas and LPG are lower than gas oil so there may be some scope for (minor) reduction in NOx emission from use of lower nitrogen support fuels.

4.2.3 Combustion Control

Combustion control systems enable control of the combustion conditions which often vary significantly over time and also across the furnace due to the variability of waste in mass burn incineration. Combustion systems provide an opportunity to manage combustion to reduce the production of NOx. Introduction of dynamic control systems to continually monitor and adjust the combustion conditions provides conditions to:

- Prevent oversupply of air.
- Manage air distribution to encourage homogenous combustion and avoid local temperature hot spots, includes managing the distribution between:
    - Primary air including control of primary air to different areas/zones of the grate.
    - Secondary air.
    - Tertiary air.
- Manage waste feed rates.
- Manage temperatures.

The aim is to optimise operational conditions to maintain the combustion efficiency (to ensure complete combustion of the materials) but to also manage (stage) the supply of oxygen to avoid high temperatures and to maintain ‘fuel rich’ initial combustion conditions to reduce the formation of NOx.

4.2.4 Flue Gas Recirculation (FGR)

FGR is the process of taking a portion of the flue gas from a combustion process and recirculating it back through a boiler or burner. The WI BREF indicates application on incineration plant is to replace 10-20% of the secondary air supply. FGR reduces peak flame temperature by lowering the percentage of oxygen in the combustion air/flue gas mixture, thereby reducing potential for thermal NOx formation.

In addition to the reduction in NO_X emissions heat losses are reduced and process energy efficiency can increase. Heat from FGR could be recuperated via additional low temperature air preheaters, and there may be some small gain in efficiency from a reduction in primary air fan power consumption.

Corrosion issues have been reported occurring in the recirculating duct. These or caused by a number of factors including presence of acid gases, particulate material, poor insulation, and long ducts. However, these issues can be limited by good design and position of the extraction point for the recirculation i.e. positioned downstream of the abatement system. Consequently, as larger volumes of gas are involved there are associated energy losses and the abatement system must be designed to handle these volumes.

If the flue gases are taken upstream of the abatement, this avoids the need to deal with larger volumes in the abatement but the system must be designed to deal with the challenges of higher levels of acid gases and particulate material (and temperature).

On existing plant, FGR requires a redesign of the combustion chamber to ensure that the air distribution remains optimised. In addition, it is reported that FGR does not achieve levels of NO_X reduction sufficient to meet BAT-AELS. Consequently, additional abatement is still required to achieve the required levels of NO_X.

4.2.5 Staged Combustion

Staged combustion describes the process of reducing the air (oxygen) supply in the primary combustion zones and increasing the air supply to secondary combustion areas, This staging of the combustion helps to minimise NOx formation while maintain the effectiveness of the combustion process and for conventional fuels is usually managed within a low NOx burner (LNB) system.

All WtE plant have a high degree of air and combustion management however, air staging of a grate-based municipal waste combustion system is challenging and potential for NOx reductions may be limited by limitations in the air control system.

4.2.6 Auxiliary burners

The use of auxiliary burners is a requirement under the Industrial emission directive (IED). Burners are used to heat the unit prior to the feeding of waste. During this start-up phase the emissions are not currently encompassed in the permit ELV's. Also during plant operation burners are used to ensure :

- Operational temperatures are attained before waste is fed into the unit,
- Temperatures are maintained to ensure the destruction of materials such as dioxins and furans.

The fuel used for the firing of auxiliary burners can reduce the NO_X produce by the system i.e. using natural gas and low nitrogen liquid fuels (HVO) rather than fuel oils.

The design of the burners impact the amount of NO_X produced. Low and ultra-low NO_X burners use some form of staged combustion. However, such burners are more expensive and generally have a larger operating footprint and longer flame path than conventional burners.

4.2.7 Other Approaches

There are other primary approaches to control NO_X that are utilised in combustion processes other than WtE.

4.2.7.1 Oxygen injection

This involves the injection of pure oxygen or air with enhanced oxygen into the combustion chamber. Consequently, reducing the amount of nitrogen introduced by the combustion air and a corresponding reduction in the NO_X produced.

No UK WtE plant uses an oxygen or enhanced oxygen system for NOx control. The approach is very rare on waste incineration plants globally. Plants using such systems are known to have been implemented in Japan, but in Europe the method has not been widely implemented despite its deployment at a fully commercial scale at Arnoldstein in Austria[6] (see Task 3).

4.2.7.2 Natural Gas injection (Reburn)

Reburn is a form of fuel staging and involves the injection of fuel into the combustion zone after primary combustion producing a fuel rich region. This results in the reduction of oxides of nitrogen to N_2. For municipal waste WtE plant this can be achieved using natural gas injection. A project undertaken in the

---

[6] Efstratios N. Kalogirou Waste-to-Energy Technologies and Global Applications Edition1st Edition First Published 2017

earlier 1990's at the Malmo plant[7] demonstrated that typical oxides of NO_X of 350 mg m^{-3} to 175mg m^{-3} were achievable. The WI BREF also references studies by the USEPA. Note that no UK WtE plant uses a reburn system for NOx control.

4.2.7.3 Water injection

Injection of water either into the furnace or directly into the flame can be used to decrease the hot spot temperatures in the primary combustion zone. This drop in peak temperature can reduce the formation of thermal NO_X. A variant used in combustion plant is to use steam injection. This technique is more common in gas turbines for NOx control.

Use of separate water spray lances alongside to reagent spray lances to provide 'selective cooling' has also been reported as a potential way of managing temperature for SNCR in large coal-fired boilers .

This is a proven technology for NO_X control in Gas turbines which have relatively small combustion chambers. However, no WtE plants in the UK are known to use water or steam injection for NOx control This is not working on WtE as the injection would need to cover the whole furnace, which is not practical. Also, the additional water could possibly cause slagging and impact on refractories. Consequently, it is thought unlikely to be workable in practice.

4.3 Secondary methods for NOx reduction

Note that further specific information on secondary methods is given in section 6 to illustrate the barriers and constraints associated with technologies.

4.3.1 Selective Non- Catalytic Reduction (SNCR)

Table 4 SNCR Key Points

- Uses urea or ammonia reagents to reduce NO_X producing N_2, CO_2, N_2O and H_2O.
- Reactions for each reagent are temperature dependant and operate over different temperature ranges
- Reactions are dependent on the mixing/distribution of the reagent with the unit. Modern abatement systems incorporate multiple injection points with the capacity to control reagent distribution both for level and depth within boiler.
- The amount of dilution water used as a carrier medium for urea solution can be optimised to guarantee a high penetration depth (to improve mixing/distribution) and control the flue gas flue gas temperature to the desired range required for SNCR process. Over dosing with too much water may however lead to additional slagging which requires consideration.
- SNCR can achieve BAT-AEL's
- Can result in the emissions of NH_3 - monitoring critical for control of NH_3 slip

4.3.1.1 NOx Reduction chemistry

In the Selective Non-Catalytic Reduction (SNCR) process, reductants in solid form (urea), aqueous solution (ammonia or urea) or in gaseous form (ammonia) are injected into the hot flue gases in the combustion chamber. Typically UK WtE plant use solid urea, aqueous urea, or aqueous ammonia for SNCR.

The urea/ammonia reagent based SNCR process consists of the following four steps:

1. Distribution and mixing of the reagent in the flue gas stream.
2. Evaporation of the water in the reagent solution (if reagent delivered in aqueous solution).
3. Decomposition of the reagent into reactive species (NH_3 and NH_2 radicals).

[7] NOx Reduction using Reburning with Natural Gas Final Report from Fuii-Scale Trial at SYSAV's Waste Incineration Plant in Malmö Jan Bergström Miljökonsulterna September 1993

4. Gas-phase reaction between reactive species and NOx.

The overall reactions for the SNCR process using urea/ammonia with nitrogen oxides are shown below. The reduction of NOx species occurs from contact with radicals including NH_3 and NH_2 to form nitrogen (N_2), water vapour (H_2O). Carbon dioxide (CO_2) is also formed from the breakdown of the urea molecule[8].

Urea Reactions

$$4NO + 2CO(NH_2)_2 + O_2 \rightarrow 4N_2 + 2CO_2 + 4H_2O$$

$$2NO_2 + 2CO(NH_2)_2 + O_2 \rightarrow 3N_2 + 2CO_2 + 4H_2O$$

Equation 1 Overall Urea Reactions

or

Ammonia Reactions

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

Equation 2 Overall ammonia reactions

Both urea and ammonia can be used for SNCR NOx reduction in combustion plants, the WI BREF compares advantages and disadvantages (Table 5) and comments that use of urea may be of benefit where temperature conditions are less stable. This advantage may be reduced due to improved control improving the maintenance of temperature conditions to meet 850°C consistently. However because of its nature waste has significant variability and there will be variations when used as a fuel. Operational practices such as mixing waste and combustion control systems will reduce variations but are unlikely to be eliminated.

Table 5 Summary of advantages and disadvantages (WI BREF)

Reagent	Advantages	Disadvantages
Ammonia	• Higher peak NO_X reduction potential (if well optimised) • Lower N_2O emissions (10–15 mg/Nm^3)	• Narrower effective temperature range (850–950 °C) therefore greater optimisation is required • Handling and storage hazards higher • Higher cost per tonne of waste • Odour of residues if in contact with humidity
Urea	• Wider effective temperature range (750–1 000 °C) makes temperature control less critical • Less storage and handling hazards • Lower cost per tonne of waste	• Lower peak NO_X reduction potential (compared to ammonia when optimised) • Higher N_2O emissions (25–35 mg/Nm^3) and hence GWP

For optimum NOx reduction with minimum NH_3 slip it is necessary to evenly distribute and thoroughly mix the reagent in the flue gases within the appropriate temperature window in which a NOx reduction is possible.

The optimum temperature range to achieve a high NOx reduction together with a minimum consumption of reagent and a low ammonia slip is rather narrow and primarily depends on the flue gas composition.

[8] US EPA Abatement cost manual, SNCR chapter revised April 2019 and available here https://www.epa.gov/sites/production/files/2017-12/documents/sncrcostmanualchapter7thedition20162017revisions.pdf

When dosing is optimised for NO_X control, urea tends to be easier to handle, is effective over a slightly wider temperature window but may have higher associated nitrous oxide (N_2O) emission[9].

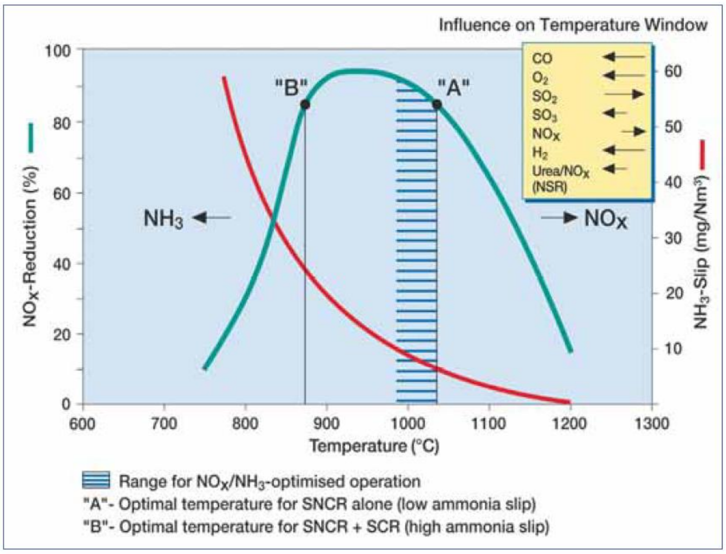


Figure 1 Showing typical SNCR performance and NO_x reduction/ammonia slip with flue gas temperature[10]

The US Environmental Protection Agency (US EPA) abatement cost manual states that "*sources with stable temperatures of 1550°F to 1950°F* {845-1060°C} *, uncontrolled NOx emissions above 200 ppm, and residence times of 1 second are generally well suited to SNCR and attain the highest levels of NOx control"* which is consistent with the range in Figure 1. Above this temperature window, ammonia is oxidised to an increasing extent, i.e. nitrogen oxides are formed.

At lower temperatures the reaction rate is slowed down, causing an increase in ammonia slip which may result in the formation of ammonia salts.

4.3.1.2 Mixing of reagent and flue gas

In general, the flue gas temperatures over the cross-section of a furnace are non-uniform and also variable. Identifying the optimum positions for the injectors to distribute the reagent properly into the flue gas under all operating conditions is a challenge. Homogeneous distribution of reagents can help to achieve mixing with flue gases and the residence time required to complete the chemical reaction. Modern SNCR systems (see Figure 2) can include adjustable injection systems that are designed to deliver reagent to different zones of the furnace to reflect changes in temperature profile.

[9] L. J. Muzio N_2O Formation in Selective Non-Catalytic NOx Reduction Process 1990
[10] SNCR Process – BAT for NOx Reduction in WTE Plants – Bernd von der Heide, Power Gen 2008

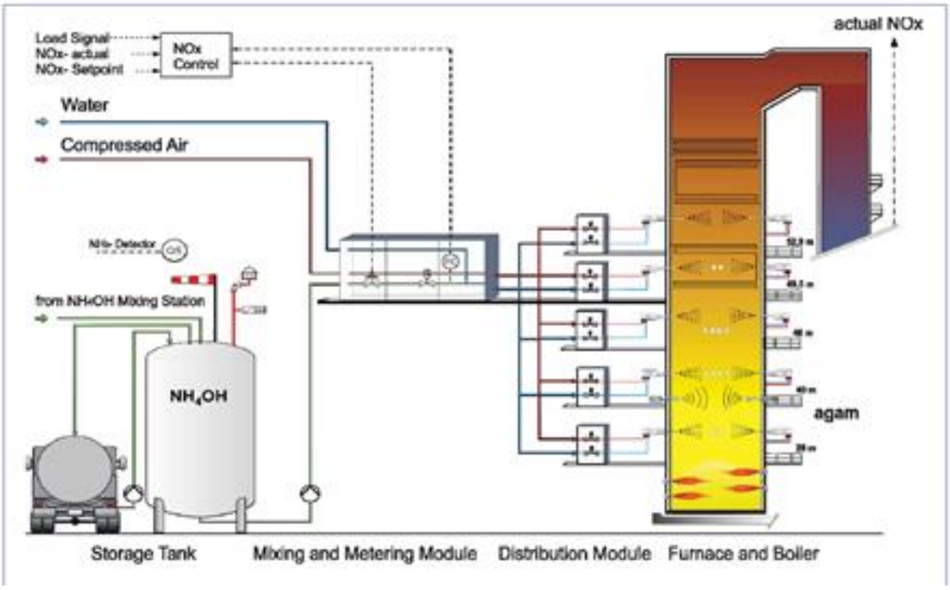


Figure 2 Example SNCR system showing injection control and range of injection levels[11]

The mass of the dilution water used as a carrier medium for urea solution, guarantees a high penetration depth and helps to cool down the flue gas to the desired temperature required for SNCR process.

Rather than controlling the furnace temperature by spray size (see below) this approach involves varying the injection location (and subsequently temperature range) in the boiler where the reagents are added.

The following paragraphs provide an overview of factors reported to influence SNCR effectiveness and choice of reagent.

Reagent spray size - The size of the reagent spray droplets is a very important parameter for the SNCR process and affects the NOx reduction performance.

- Smaller droplets generally evaporate faster and could potentially lead to release of reagent at a temperature which is too high resulting in a reduction in NO_X removal efficiency.
- Larger droplets take longer to evaporate and consequently the reagent may be released outside the ideal temperature window. This would potentially increase the percentage of ammonia slip and reduce the performance of NOx reduction.

However, if the water input and droplet size is big enough, it can be used to moderate the temperature such that injection of urea is possible into a high temperature zone that is too hot for a NOx reduction but the resulting evaporation of the water allows delivery of the reagent into in a cooler zone where NO_X reduction can take place.

For the plants using ammonia, the scope for using spray size to manage delivery of reagent is limited because ammonia is released quickly when the ammonia solution is heated up.

The use of separate water spray to provide ‘selective cooling’ alongside reagent injection sprays has been reported as a potential way of managing temperature for SNCR in large coal-fired boilers[12].

---

[11] NOx Reduction for the Future with the SNCR Technology for Medium and Large Combustion Plants Presented at POWER ENGINEERING AND ENVIRONMENT
VŠB - Technická univerzita Ostrava (Czech Republic) 01. – 03. September 2010 Dipl.-Ing. Bernd von der Heide Mehldau & Steinfath Umwelttechnik GmbH Essen, Germany

[12] Bernd von der Heide, Future-Oriented SNCR Technologies – Application and Advantages of Selective Cooling in Large Coal-Fired Boilers, Mehldau & Steinfath Umwelttechnik GmbH available here https://www.ms-umwelt.de/download/2017-09-pg-asia-bangkok-future-oriented-sncr-technologies-selective-cooling/

Reagent mixing - The mixing between flue gas and reagent is critical to optimise NOx removal performance and to achieve minimum ammonia slip.

Reagent storage - Ammonia is toxic and is a flammable gas, readily soluble in water at ambient temperature. Anhydrous ammonia is an extremely toxic substance, so it is necessary to design a suitable storage/injecting system. Operators consider ammonia solution with a concentration just under 25% to be the optimum fluid for approval reasons. However, if the temperature increases, ammonia will rapidly evolve from solution. At 38 °C the partial pressure of ammonia reaches as much as 1 bar, and storage and delivery systems need to be designed to deal with overpressure and flammability risks. Such safety requirements include explosion-proof equipment in the tank, ammonia sensors, illuminated wind direction indicators, flame arrestors at relief and under pressure valves, gas exchange pipes, emergency showers, eye showers.

In contrast, the decomposition of urea into ammonia and carbon dioxide gas occurs at temperatures in excess of about 130 °C and reaches its maximum at about 380 °C. Such high temperatures are not reached when the chemicals are stored, and therefore safety considerations for storage are lower than for ammonia solution.

4.3.1.3 SNCR enhancement trials

Medium and large combustion plant - A paper presented at the 2010 Power Engineering & Environment conference documents trials of SNCR at various medium and large combustion plant. SNCR development works were conducted by combustion plant operators and equipment suppliers to achieve lower NOx levels (< 200 mg/Nm³). Much of the work in the paper concerns application of SNCR at coal-fired boilers but waste incineration is also considered.

The tests looked at:

- The effect of using Urea or Ammonia.
- Injection Lance location and multiple levels of injection.
- Changing injection location dependant on temperature
- Use of an acoustic gas temperature measurement system (AGAM).

The paper describes a typical SNCR system as achieving NOx emission reduction rates of 50-60%. The (then) generally adopted systems comprise reagent injection at one or two levels in the furnace and such systems are stated to be able to achieve NOx concentrations[13] of 120-150 mg/Nm³ and NH_3 slip of 10-15 mg/Nm³. Achieving this level of emission concentration however depends on the arrangement of the reagent injection lances and the range of temperatures in the furnace. The report comments that with homogeneous fuels and stable output, concentrations of 100 mg/Nm³ can be obtained with moderate NH_3 slip.

Combustion chamber temperature mapping – There are a number of methods utilised in mapping combustion chamber temperature which include

- Suction pyrometer.
- Contact temperature measurement – thermocouples.
- Infrared pyrometry.
- Acoustic pyrometry.

Suction and contact temperature measurements techniques are used in DeNOx systems. However, these have limitations i.e. they are dependent on the number of sensors used which limits the locations within the chamber that can be measured.

The use of conventional thermocouples for measuring flue gas temperatures as part of the NO_X control system has several disadvantages that lead to control and maintenance issues these include:

[13] Note that reference conditions for concentrations are not stated.

- High uncertainty in measuring the flue gas temperatures within the combustion and secondary chamber for example due to radiation from furnace walls.
- A substantial array of sensors is needed to map the temperatures and imbalances that can occur within the flue gas stream.
- Ash deposits on thermocouples can lead to an increasing insulation effect and slow response to changes and consequently require maintenance to maintain response times to provide good control of injection systems.

Consequently, to improve the temperature profiling of the combustion chambers acoustic measurement has been developed enhanced control

Acoustic Gas Measurement[14] is currently being used in more than 90 waste incineration plants (worldwide). SNCR enhancement using acoustic pyrometry allows optimisation of reagent injection to minimise ammonia slip while achieving high NOx removal. One such system is the acoustic gas temperature measurement system (AGAM) which is widely used to assess the furnace exit temperature accurately (up to 2000 ^{o}C) and reliably for conventional boiler and waste to energy incinerator application

Table 6 Acoustic Pyrometry

• The velocity of sound is dependent on the temperature of the flue gases and the AGAM system uses the principal that the sound waves travel faster through hot gases than through cooler gases, thereby enabling temperature profiles to be determined • Sensors and signal generators can be mounted in the same horizontal plane along the flue gas path and can be used to determine an average temperature along the gas path. • Acoustic pyrometers can measure the flue gas temperature quickly and with high precision and this data can be linked to an SNCR control system to modify reagent injection rates and locations to optimise SNCR process

WtE plant equipped with such systems can adjust SNCR reagent injection at individual injection lances. Lances can be switched on and off to make sure the reagent is always injected into locations within the optimum temperature window. With several combined AGAM transmitter/receiver units located on one level, multiple path configurations can provide a rapid two-dimensional temperature distribution.

The injection area is divided into zones (Figure 3) and can be assigned to individual injection lances or groups of lances. The active lances are chosen automatically depending on the flue gas temperature measured at each zone. This ensures most effective use of the reagent even at rapidly varying flue gas temperatures, so that the SNCR plant always operates in the optimum range with regard to NOx reduction, NH_3 slip and reagent consumption.

[14] Waste-to-Energy State-of-the-Art-Report Statistics 6th Edition August, 2012 ISWA

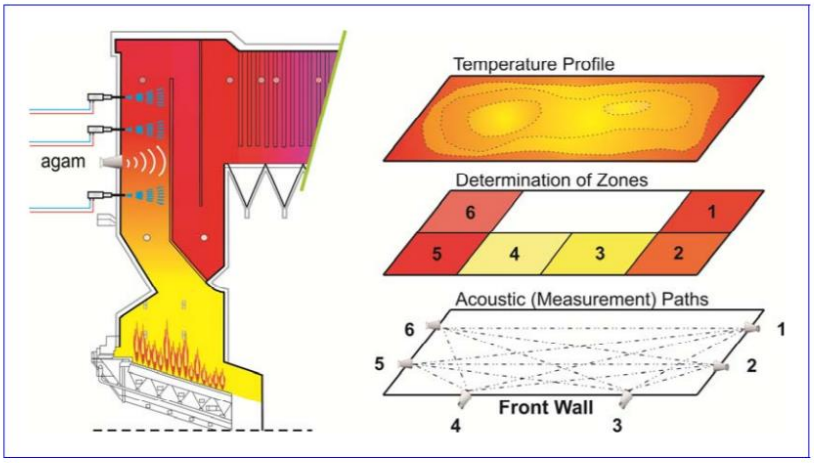


Figure 3 Temperature mapping of the furnace[15]

Other SNCR development work - A paper to the North American Waste-to-Energy Conference[16] in 2010 reported on the Von Roll Inova (now Hitachi Zosen Inova) DyNOR™ SNCR system. In this system infrared pyrometers are used to monitor combustion chamber temperatures and manage the delivery of reagent into the optimal location. The system has a quick response time and was primarily developed to meet a NOx concentration of 110 mg/Nm^3 NOx and 10 mg/Nm^3 NH_3 slip (at 11% oxygen, dry based on ppm data in paper at 7% oxygen). This was achieved in full scale demonstration test unit at a MSWI plant in Trondheim, Norway (Line 3). The same DyNOR^{TM} technology was implemented in other locations within EU (including Pithiviers, France and has also been applied in the UK at Severnside[17]).

4.3.1.4 Availability

All components critical for operation, such as pumps, are duplicated to provide redundancy. The injection lances in contact with the flue gas need to be regularly checked and serviced to ensure free flow of reagent and support/cooling media.

Used lances may be overhauled by cutting or replacing the protection pipes. In some cases, the nozzles also need to be replaced.

Most other operational issues, such as replacement of flow meters and pressure sensors, may be corrected /calibrated during the operation. Control valves are more critical and need programmed maintenance. They are normally provided with a by-pass arrangement such that the reagent can flow under manual control until the relating control valve has been replaced or repaired.

Predictive and regular maintenance during scheduled plant shutdowns normally help to avoid and/or minimise all problems during the operation. However, an unscheduled shutdown of the SNCR plant can typically be corrected within a short period of time such that the daily mean values are not significantly increased in such an event.

Lime deposits in the piping system from the use of hard potable water, including valves and injection lances, need to be avoided. This requires urea solutions to be mixed with a suitable additive (e.g. NOxAMID). If the SNCR plant is operated with ammonia solution as the reagent, demineralised or deionised water is used as the dilution water thereby removing this as an issue.

[15] NOx reduction report by company Mehldau & Steinfath
[16] Sigg, F. et al DyNOR^{TM} DeNOX performance confirmed in further MSW plants. Proceedings of the 18th Annual North American Waste-to-Energy Conference, NAWTEC18, May 11-13, 2010, Orlando, Florida, USA
[17] From https://www.hz-inova.com/projects/severnside-uk/

4.3.2 Selective Catalytic Reduction (SCR)

4.3.2.1 Technology

SCR is a proven DeNOx technique which uses a catalyst to convert NOx into molecular nitrogen gas and water. The reagents used are aqueous ammonia or gaseous ammonia; urea can be applied but it is used as a source of ammonia. The reagent is added to the flue gas and the reaction occurs on catalyst panels located within the exhaust gas system. SCR systems have tended to be applied where lower NOx emission concentrations than can be achieved using SNCR are required and have been shown to reduce NOx by over 90%.

The reactions are as described for SNCR for ammonia (Equation 2) and, as with SNCR, the effectiveness depends on the temperature, effective mixing of reagent and flue gases, stoichiometry, and a range of factors.

The design of the catalyst bed and selection of the catalyst material also impacts the overall efficiency of the denitrification process. The geometry of catalyst is important and must ensure a large surface to volume ratio for better adsorption. Generally, a honeycomb, plate-type or corrugated geometry are commonly used. Smaller diameters of the cells increases the area for adsorption (higher surface to volume ratio) but also increases the risk of cell fouling. Honeycomb catalysts are smaller than plate-type catalysts and less expensive but can cause higher pressure drop and are more vulnerable to plugging (and therefore only suitable for a low-dust environment). The selection of the catalytic bed and catalyst material depends on many other factors such as operating temperatures, catalyst regeneration, composition of flue gas etc.

As with SNCR, an SCR system can be optimised. This will typically involve improved distribution of reagent in the gas stream and duct modifications to develop uniform gas velocity through the catalyst (to avoid channelling of gas flow which will decrease residence time). The system parameters will typically be assessed using a CFD model to fine tune the process design before field trials.

4.3.2.2 Catalyst Selection and Monitoring

Various metals and their combinations have been studied to determine the activity of denitrification for SCR catalyst. SCR catalysts are normally made from various ceramic materials used as a carrier or support for metal oxide such as titanium oxide / aluminium oxide (Al_2O_3). Active catalytic components are usually either oxides of base metals (such as vanadium, molybdenum and tungsten), zeolites, or various precious metals.

Base metal catalysts, such as the vanadium and tungsten, lack high thermal durability. They also have a high catalysing potential to oxidise SO2 into SO3 which can be extremely damaging due to its acidic properties. However, they are less expensive and operate very well at the temperature ranges seen in industrial and utility boiler applications.

Catalyst performance will decline over time and catalyst management is a key part of managing SCR. Plants must consider a comprehensive catalyst management strategy to achieve best catalyst performance. The catalyst management cycle should consider average boiler load demands, boiler/SCR operations assessment, system inspections and field sample data analysis, fuel management and fuel composition, nitrogen oxides (NOx) performance and sulphur dioxide (SO_2) conversion objective including catalyst technology advancements.

Catalyst life management is used to predict catalyst life - when catalyst layers should be replaced or regenerated, or a new layer to be added, based on catalyst deactivation rates, performance requirements and system capabilities .This catalyst life cycle management is normally based on number of layers (2+1 layer and 1+1 layer system) selected for that particular application

Tools and techniques are available to SCR operators for developing an effective catalyst management strategy. They typically include performance audits that analyse the remaining potential of the catalyst with plant operating history, projected use of the SCR, the position of catalyst layers, outage schedules, economic and financial factors, and analysis of recent catalyst technology advancements. In addition, factors such as low-load operation flexibility, mercury (Hg) oxidation and lower sulphur trioxide (SO_3) emissions are also important factors to assess the catalyst life and its performance.

4.3.2.3 SCR Monitoring

SCR systems are extremely sensitive to contamination and plugging resulting from normal operation or abnormal events. Many SCRs are given a finite life due to presence of contaminants in the untreated gas. Most catalyst available on the market is of porous construction This porosity provides high surface area for the catalyst layers which is essential for the NOx reduction. However, the pores can be easily plugged by fine particulates, ammonium sulphate, ammonium bisulphate (ABS), and silicon compounds. Many of these contaminants can be removed while the unit is online by ultrasonic horns or soot blowers. Erosion of the catalyst material can become a serious problem when flue gas has high velocity and high fly ash content.

SCR system inspection is critical and typically includes a physical inspection of the catalyst, reactor and ammonia (NH_3) injection system. During a physical inspection of the catalyst the performance and operational data such as NOx levels, NOx removal efficiencies and NH_3 in ash levels are analysed. Operational load data including fuel and ash data and samples of the catalyst are also analysed to understand the level of degradation of catalyst including SCR performance.

These helps to evaluate the catalytic potential of a SCR catalyst by directly comparing the catalytic potential of the field sample to a fresh catalyst studied in a lab environment. Such pilot sample tests determine the catalyst activity under specific conditions, utilizing representative size catalyst samples for the SO_2/SO_3 conversion rate, pressure drop, initial activity and actual activity. Physical tests evaluate physical properties such as catalyst surface area and porosity. The deactivation rate is determined by comparing the change in catalytic potential versus operating hours of the sample.

One of the key factors while choosing an effective catalyst management strategy is to determine when a catalyst should be replaced, or new catalyst is to be added. Catalyst performance audits are integral to this determination since they provide useful information about the performance potential of the catalyst. In general catalyst layers will deactivate at different rates depending upon the fuel fired. The performance audit should identify which layer needs to be addressed first. In most cases, SCR catalyst reactors are built to accommodate at least one spare layer of catalyst.

4.3.2.4 SCR and Waste to Energy application

SCR is not currently applied on MWI in UK and is not very common for ‘Waste to Energy’ application in other geographies. However it has been proposed at new and plants under construction. There are two potential SCR solutions are generally considered –

- High dust SCR system located in flue gas path before Bag filters.
- ‘Low dust SCR’ (Tail end SCR) after bag filters.

Both options have advantages and disadvantages. High dust SCR systems will present substantial design challenges to integrate into an existing plant and can be susceptible to catalyst poisoning and blockage. Low dust SCR minimises the risk of SCR clogging and catalyst poisoning. However, the disadvantage of this configuration on an existing plant is that the flue gas temperature will be lower than the temperature window required for SCR and reheating is required. This is a consequence of the operating temperatures of the gas clean-up technologies being significantly lower resulting than that required for SCR This will require substantial plant modification to install air/air heat exchangers or may require direct reheat with natural gas burners or similar.

A recent study[18] of environmental impacts by life cycle analysis of different abatement systems for waste to energy plant based on data from plant in France suggests that: *Compared to SNCR, the use of SCR decreases the NOx-related impacts (fine particulate matter formation, terrestrial acidification and photochemical ozone formation) but increases other impacts. For example, the SCR systems have 49–284% greater climate change and 43–150% higher depletion of fossil resources than their SNCR counterparts*.

[18] Dong, J et al The environmental cost of recovering energy from municipal solid waste, Applied Energy 267 (2020) 114792

The analysis was based on the application of SCR after other flue gas treatment and included reheat of flue gases – the most likely scenario for an upgrade for an existing plant. In summary, SCR [19]

- Has a higher NO_X removal efficiency than SNCR.
- Reduces the direct environmental impact of the plant.
- Has higher indirect environmental impacts than SNCR.
- Has increased net environmental impact on global warming due to the need for the use of reheat.
- From an Environmental aspect SNCR should be preferred.

One of the issues with SCR is the life of the Catalyst. In a recent study[20], selective catalytic reduction (SCR) was compared against selective non-catalytic reduction (SNCR) for the reduction of nitrogen oxides (NOx) emitted by municipal waste incineration (MSWI) plants to levels below 100 mg/Nm^3. However, deactivation of the catalyst by compounds in the fly ash can become a serious problem when applied to WtE plant. Fly ash contains many compounds potentially poisonous to the catalysts, of which alkali metals are the main concern.

4.3.2.5 Waste to energy SCR replaced by enhanced SNCR system

The Attero WtE in Netherlands has three lines which were originally equipped with SCR for NOx reduction. The plant was considering replacement catalysts and had high operating costs due to consumption of natural gas for reheating the flue gases. Enhanced SNCR systems were installed on all three lines in 2011/12. The new systems were able to match[21] SCR NOx emission concentrations. Although the consumption of ammonia solution was higher than with SCR, this is more than offset by improved energy efficiency (from removal of natural gas to reheat flue gas and recirculating fans).

Initial test data indicated the possibility of NOx reduction below 100 mg/Nm^3 using SNCR upgrades where modern combustion controls are integrated with smart AGAM sensors.

4.3.3 Hybrid SNCR and SCR

The combined use of SNCR and SCR has been shown in pilot tests to produce greater removal efficiencies than either technology in isolation. A commercially based vanadium and titanium honeycomb catalyst was used for the SCR and urea injection formed the SNCR portion of the system. It was found that the SNCR gave high temperature removal and the SCR provided further removal. The system achieved 85% reductions.

No WtE plant has been found that utilises this approach.

4.3.4 Catalytic Bag filters

Catalytic filters are essentially a dual-purpose filter bag that simultaneously provides particulate filtration and NOx reduction[22]. The technology combines a PTFE membrane for particulate removal with a PTFE-based catalytic felt for simultaneous reduction of NOx and reducing NH_3 slip. The membrane effectively traps dirt and dust and also protects the catalyst and extends its performance-life.

The features of catalytic bag filters:

- The retrofit / conversion is relatively simple – replacement of filter elements.

---

[19] Jo Van Caneghema, Johan De Greef, Chanta Block, Carlo Vandecasteele NOx reduction in waste incinerators by selective catalytic reduction (SCR) instead of selective non catalytic reduction (SNCR) compared from a life cycle perspective: a case study

[20] Agnieszka Szymaszek, Bogdan Samojeden and Monika Motak The Deactivation of Industrial SCR Catalysts—A Short Review

[21] Moorman, F et al Replacement of an SCR DeNOx System by a Highly Efficient SNCR in a Waste-to-Energy Plant in the Netherlands. Presented at VGB Workshop "Flue Gas Cleaning" Rotterdam, 15 – 16 May, 2013 https://www.ms-umwelt.de/wp-content/uploads/2020/08/2013.05-VGB-Flue-Gas-Cleaning__Rotterdam-Replacement-of-an-SCR-by-an-SNCR-Wijster.pdf

[22] https://iopscience.iop.org/article/10.1088/2053-1591/abc71e

- No additional footprint.
- Can provide a polish and NH_3 removal for an existing SNCR system Typically, no new equipment is required, except to replace filter bags.
- Minor operating procedures changes.

Catalytic bags have a quoted maximum operating temperature of 260ºC however no information on the operating temperatures is provided. There may be an activation temperature that the catalyst operates more effectively at which may require additional energy in form of re-heat

Catalytic bag filters are commercially available and have been applied to various WtE incinerator plants in Europe including France (Limoge/Villiefranche sur saone), Italy (Padova)[23]. However, these have typically been integrated with combustion and SNCR enhancements. The bag supplier has published cases studies that show that there is no need for reheat consequently operating energy requirements are unchanged. However, the supplier only reports installation on three plants

Whilst emission reductions claimed by bag manufacturers are impressive e.g. NO_X 176 mg Nm^{-3} with SNCR only to 40mg Nm^3 with SNCR plus DeNOx Filters, it remains unclear what if any reduction in performance occurs over the operational lifetime of the bags. The situations where these have been utilised have formed part of an overall package i.e. primary methods with either SNCR or SCR and then bag filters to provide a final NO_X reduction.

[23] https://www.gore.com/products/nox-and-nh3-filter-bags

5. Task 2- Plant data collection / data generation

5.1 Summary of findings

5.1.1 Normal operation

The main findings from a survey of three UK plant operators for implementation of NOx control during normal operation are provided in Table 7

Table 7 Plant survey information - Key points normal operation

- None of the major 3 UK operators use SCR
- Most WtE plants maintain NOx level below 180 mg/ Nm^3 in normal operation using SNCR
- Automatic SNCR reagent injection is not available at all sites
- Not all sites measure ammonia slip
- Majority of operators are not measuring N_2O emission continuously

5.1.2 NOx Reduction trials

Table 8 provides a summary of key points from the survey of three UK plant operators for information on NOx reduction trials.

Table 8 Plant survey information - Key Points from reduction trials

- Plants historically having low NOx emission concentrations used lower NOx set points during test - typically in the ranges between 135 and 90 mg/Nm^3
- Plants historically having higher NOx emission typically use higher NOx set points during test period - between 195 and 150 mg/Nm^3 .
- For a typical two-line plant it was found that NOx level could reach between 160 and 175 mg/ Nm^3.
- In some cases, NOx reduction below 175 mg/ Nm^3 was extremely difficult or impossible to achieve
- Single line plant with ammonia injection achieved lower NOx level around 120 mg/Nm^3
- In several reduction trials, the ammonia slip increased steadily up to 9 mg/ Nm^3 from an initial level of 2-5 mg/Nm^3
- Reagent injection increased significantly (up to 48%) to achieve NOx reduction beyond an optimum reduction level which varies from plant to plant.
- No major increase in bag filter pressure drop was noticed during the trials.

5.2 Approach

A technical questionnaire was prepared by Ricardo to understand the NOx and NH_3 slip performance from three UK operators to understand the SNCR performance for nine existing plants. As some of this information is commercially sensitive, anonymised data is presented to ensure that no single plant or operator can be identified from the report.

This questionnaire (checklist) prepared for data collection from WtE operators included the following:

Design Characteristics

- WtE plant capacity / number of lines.
- Plant operating life.

- Type of waste and average fuel nitrogen content (as received basis - historical data).
- Furnace thermal capacity.
- Flue gas temperature profile in boiler first pass including furnace exit temperature (design/operational).
- Average/ maximum/ minimum flue gas exit temperature at boiler exit and stack measurements.
- Type of NOx abatement technologies)-FGR with SNCR/SCR (combination)/ catalytic bag filters.
- SNCR –total number of injection points on each grid level.
- Temperature window/ type of temperature sensor installed (at injection level).
- Type of selected SCR (if any) – 'High' dust SCR /'Low' dust SCR system.
- Design capacity (OEM) of selected NOx abatement technology (% of NOx reduction).

Reagent used, NOx data and NH_3 slip

- Type of reagent used (urea/ ammonia).
- Operations and maintenance (O&M) issues including blockage in reagent injection system / frequency of nozzle replacement.
- Average urea/ ammonia consumption per line (daily/monthly basis) / operating cost.
- Average NOx data in last 12 months (maximum / minimum and average data - on monthly basis).
- Ammonia slip data in last 12 months (maximum / minimum and average values - on monthly basis).
- Any measurement of N_2O emission (maximum / minimum and average values - on monthly basis).

General O&M issues

- Any general maintenance issues on SNCR/SCR/catalytic bag filters / additional maintenance costs.
- Any ash blockage issues due to formation of chloride component in ash system including bag filters.
- Any catalyst poisoning issue and 'ammonium bisulphate' formation /blockage for SCR.
- For SCR/catalytic bag filters – ID fan power consumption (w.r.t % of total power generation).
- Frequency of replacement of catalytic bag filters.
- Frequency of catalyst replacement /its cycle.
- Any other technical/operation/maintenance issues (NOx abatement technology as installed).

5.3 Plant operational data from three operators

Operators provided data relating to normal plant operation and, where undertaken, data relating to investigations into reducing NO_X emissions. Some of the plant had undertaken SNCR performance tests, through set point reduction trials, to explore the performance of the systems installed. Where tests had been undertaken each operator provided:

- SNCR/NOx performance data using corrected NOx figures against the standard reference conditions i.e. standardised data as required.
- SNCR performance data covered the following key areas to understand the maximum reduction capacity of the installed SNCR system.
- A basic description of the test procedure.

These data are described in the following sections. The data provided by three WtE operators (UK) is summarised at Table 9, full details are provided in Appendix 1 and Appendix 2.

Table 9 Summary of Provided Plant data

Plant	Type of Combustion System	Type of NO_X Control	Normal Operation				Trial Operation			Comments
			Reagent type	Reagent Consumption monthly avg. tonnes	Typical NO_X mg/Nm3 (Daily average)	Ammonia Slip mg /Nm^3 Daily Average)	Reagent Consumption Monthly Tonnes	Typical NO_X mg/Nm^{3-} Daily average	Ammonia Slip mg /Nm^3 Daily average	
1	Single line Moving grate	SNCR	Ammonia	16.9	116	1.0	No Trials Carried out			
2	Two line Moving grate	SNCR	Urea prill	57.5	146	1.0	ND	130	ND	Using Lowest NO_x achieved
3	Four line Moving Grate	SNCR	Ammonia	91.8	158	0.6	134	149	0.6	Using Lowest NO_x achieved
4	Single line Moving grate	SNCR	Urea prill	14.1	172	6.0	15	140	8.6	Using Lowest NO_x achieved
5	Two line Moving grate	FGR, SNCR	Urea prill	19.8	165	3.5	ND	152	3.2	Using Lowest NO_x achieved
6	Two line Moving grate	SNCR	Ammonia	108	175	1.9	117.5[a]	153	1.5	Using Lowest NO_x achieved
7	Two line Moving grate	FGR, SNCR	Ammonia	47.3	135	0.4	57.9[a,b]	98.9	5.2	Using Lowest

Plant	Type of Combustion System	Type of NO_X Control	Normal Operation				Trial Operation			Comments
										NO_x achieved
8	Single line Moving grate	SNCR	Urea	21.5	188	1.8	42.8[c]	175	2.3	Using Lowest NO_x achieved
9	Two line Moving grate	SNCR	Urea	32.5	178	2.6	41[d] 47[e]	137[d] 174[e]	6.5[d] 8.0[e]	Using Lowest NO_x achieved with Granular Urea- Higher result obtained with prill at same setting

NB Density of 24.5% solution of NH_3 = 0.907 g/cm3

ND – No data

a - test one week in duration assumed 30 days in a month to provide comparable data, b - Test untaken on one line so data multiplied by two, assumed that lines are the same

c - One month test, d – Granular Urea, e – Prill Urea

5.4 SNCR performance - Test data

The current ELV for NOx for WtE plant is generally to maintain daily average NOx concentrations below 200 mg/Nm^3 and maximum half hourly average NOx values should not exceed 400 mg/ Nm^3.

Table 10 Key Points from Plant data collected from UK operators

- Data indicate that plant generally only use SNCR to control NOx emission (a minority of plants for which data was received also incorporate FGR).
- No major issues were highlighted for maintaining current daily average NOx values below 200 mg/Nm^3 or, keeping 'half hourly' NOx average value under 400 mg/Nm^3 during normal operation. Only monthly average NO_X emission data provided.
- Data has indicated that eight of the WtE plants that provided data are able to maintain NOx levels below 180mg/Nm^3 (three below 150mg/Nm^3) during normal operating conditions and therefore may not require any further SNCR optimisation, or limited SNCR optimisation, to meet proposed upper limit from BATC.

5.4.1 Review of test data

Plant data collected from 3 UK operators included test data during NOx set point reduction trials. The trials were undertaken to understand the capability of existing SNCR system and to identify any further modification (including retrofit) if required to meet the new BAT-AEL.

The SNCR performance depends on plant age, SNCR efficiency and the original design intent selected by different original equipment (SNCR system) manufacturers.

All of the tests undertaken to assess SNCR system performance considered NOx emission concentration (as determined by data from the Continuous Emission Monitoring System - CEMS) in conjunction with SNCR reagent consumption rate and measurement of ammonia slip concentrations.

Plant 1 undertook no trials and normally operating with SNCR utilising ammonia. In a configuration with three injection ports at each of three levels. The level of injection is controlled on temperature and the dosing rate on NO_X concentration and reported to be operating at a level significantly lower than the current BAT AEL requirement. However, operational problems were reported during normal operation. These were issues with water softeners which result in reduced reagent flows. Also, probes were regularly replaced due to heat damage which impacted the spray pattern.

During trials undertaken, NOx set points were typically reduced in 3 to 4 steps. This provided information on the SNCR performance across a range of control conditions. Plants with lower initial NOx emission concentrations used lower NOx set points during the test and NOx set points were typically reduced in steps from 135 and 90 mg/Nm^3. Plants with higher initial NOx emission concentration values tended to select higher NOx set points during test period and the set point was reduced typically between 195 and 150 mg/Nm^3.

There were some maintenance changes made prior to trials to prevent possible operational issues such as the need to more regularly clean injection probes and nozzles as these have an impact on the dispersion of the reagent into the chamber. Also Plant 4 reported issues with the differential pressure in the bag filtration system. It was speculated that this was caused by an increase in chloride and ammonia salt formation. Alternatively, this may be a consequence of the additional moisture added with increasing reagent dosing.

One operator reported test data showing differences in results obtained when using granular and prill urea. This raises the question around optimisation of dosing systems and the prospect of using reagent of different physical characteristics to achieve improved results in existing systems

Plant with advanced combustion control integrated with automatic changeover of SNCR reagent lances have shown better NOx result. Both urea and ammonia (chemical reagents) were able to maintain the NOx level below 180 mg/Nm^3 for the test period provided combustion conditions and SNCR control parameters are properly optimised.

The emission data before and during the test periods shows a reduction in the NO_X emissions resulting from increasing dosing. The levels found were significantly below the BATC requirements This was also found in the data provided by the operators.

The period of the tests undertaken ranged from days up to a month. It is not clear if these periods are sufficient to indicate any long-term impact on the plant of maintaining the emission levels achieved.

Note that these findings are unlikely to be identical on all existing plant and should be investigated on a plant-by-plant basis to confirm what is achievable on each system.

5.4.2 Ammonia Slip

Currently some WtE plants do not report ammonia emissions (slip). However this forms part of some of the control systems used so may be available but was not reported Under upcoming BAT a daily average ammonia slip needs to be reported on regular basis. Ammonia slip was found to range between 0.5 mg/ Nm^3 up to 9 mg/ Nm^3 which is within the BAT-AEL range of 2-15 mg/ Nm^3 while NOx set points were reduced during the trials. Seven plant provided ammonia slip concentrations for both normal operation and during the SNCR trials and of these, four reported higher concentrations during the trial periods,

However, three plant reported similar or lower ammonia concentrations during the trial periods as were reported during normal operation. This may indicate potential for further process optimisation.

5.4.3 Test conditions

There are a number of factors that influence any assessment of performance of the NO_X abatement system on a plant. Whilst the operators have provided information on the trials undertaken, it is important to note that there are a number of different variables that can influence the outcome of such tests. The test procedures followed by each operator have not been validated by Ricardo and therefore the results and subsequent conclusions from the data may be limited. However, as they are actual results from operating UK plant, they do offer a valid insight into the scale of reductions in NOx that are achievable.

The information provided by operators suggests that there were some differences in how trials were performed. However, Ricardo has assumed that they provide representative information on SNCR capabilities at the individual plant. For future trials we suggest that operators should use such trials to determine :

- the extent to which existing plant design and operation already delivers the optimal NOx emission.
- the capacity of existing systems to further reduce NOx.

The outcome of such trials should be to identify the design and operational changes required to achieve a lower emission level and, the cost of such changes.

It is suggested that operators should:

1. Operate under each test operating conditions for a minimum 7 days.
2. Ensure that plant/unit should be operating at steady boiler load (ideally at 100% MCR) during test period.
3. Keep the boiler main steam set point unchanged during the test period.
4. Manage waste quality (its composition including waste energy content) within acceptable operating window.
5. Optimise combustion parameters prior to do the test (including combustion air distribution).

6. Optimise waste bed depth (bed height), grate speed and waste throughput before the test.
7. Avoid any abnormal hot spots/sudden furnace temperature spikes for longer duration (say >30 minutes/longer) should be avoided by manual adjustment / corrections (as a rule of thumb).
8. Ensure that sensors for plant operation such as thermocouples measuring furnace temperature (including T2S) are maintained and calibrated as per the standard maintenance /calibration schedule.
9. Ensure that Sensors used for $DeNO_X$ are maintained and calibrates as per the standard maintenance/calibration schedule.
10. Optimise oxygen contents at furnace and boiler exit at close to original design values.
11. Address any abnormal boiler leakage and air ingress before conducting the SNCR test.
12. Ensure boiler cleaning devices (across the furnace vertical pass/ horizontal pass including economiser sections) should be maintained /operated to avoid any abnormal changes in boiler flue gas temperature.
13. Manage the average boiler flue gas exit furnace temperature should between 145 to 155^{0}C
14. Monitor boiler fouling parameters to avoid adjustment for any abnormal rise in furnace exit gas temperature > 160^{0}C.
15. Verify that boiler flue gas flow (along the flue gas path including at the boiler exit) is within the expected design range.
16. Ensure instruments, sensors monitoring combustion parameters (including SNCR process parameters and CEMS) should be maintained and calibrated as per schedule.
17. SNCR -injection nozzle conditions should be maintained before and during the test (standard practice).
18. No abnormal SNCR nozzle blockages should be experienced during the test.
19. No abnormal line blockages for reagents should be experienced during the test.
20. Distribution and mixing of reagent with flue gas are important.
21. Both process conditions should be maintained close to original design intent.
22. Reagent droplet sizes / viscosity/ surface tension of droplets should be as per design intent.
23. No physical properties of droplet including droplet sizes should be altered by varying process conditions and making any hardware changes.
24. All necessary sensors including reagent injection rates need to be calibrated before conducting the test.
25. APCR and IBA ash samples were collected for each test (minimum 3 samples for each test) to check any spikes in chloride content.
26. DP across Bag house filters should be monitored throughout the test.
27. Pulsing devices need to be adjusted to avoid any unnecessary blockage during the test.
28. Selection of SNCR injection level is critical and should be monitored during the test.
29. Automatic lance change-overs (if available) needs to be monitored during the test.
30. Concentration level of reagent should be maintained as per design intent.
31. Average NOx values including Ammonia slip / reagent consumption need to be monitored during the test.
32. Any SNCR control parameters (including control gain functions /similar) should be adjusted prior to do the test.
33. No CFD modelling for SNCR was considered for SNCR optimisation test (first stage test).

Future studies undertaken on a plant-by-plant basis should consider these factors when devising a test protocol to ensure that a representative test program is developed to provide representative data.

A full summary of all of the data provided by the operators that undertook NO_X reduction investigations can be found in Appendix 1 and Appendix 2

6. Task 3 - Barriers for retrofit options

6.1 Summary

The main barriers to each of the approaches considered in this report are summarised in the table below:

- **Primary NOx controls** - plant combustion design constraints and high cost of change. Also high risk and limited reduction potential compared to secondary measures. However, reduced excess air ratio, optimisation of combustion air and enhanced combustion monitoring and control offer potential limited NOx reduction for lower cost and lower risk than other primary interventions.
- **Optimisation of existing SNCR** – the existing SNCR systems were generally not initially set-up to achieve lower levels of NOx reduction. Optimisation will be a lower cost intervention; plant data suggest likely emission reductions in the range 5-40 mg/Nm^3. In addition this will increase overall effectiveness of abatement hence reduce the reagent operating costs.
- **SNCR extension** – challenges around installation on existing plant. Costs may be high compared to emission reduction but potential to achieve reduction of 30-60 mg/Nm^3.
- **SCR** – although a proven DeNOx technology, limited experience in UK and on WtE plant. Integration into existing plant likely to be expensive and likely to need reheat to operate at most effective temperature.
- **Catalytic bag filters** – relatively simple to apply but limited data found suggests these are very effective as part of a combined systems. However the data does not report the need for any additional plant changes such as reheat to operate at most effective temperature.

6.2 Section overview

This section provides a high-level review of the barriers to achieving NOX reduction at existing EfW plant to concentrations below the upper levels of the EU BREF 2019 BAT-AEL ranges.

It considers the technical constraints at existing plants to reducing both:

- NOx production - through primary methods which prevent NOx generation – Section 6.3
- NOx abatement – through the application of certain abatement systems – Section 6.4

Noting that current operational UK MSWIs do not use catalytic bag filters or SCR systems, the focus is mainly on upon barriers to primary NOx reduction and SNCR.

Two main SNCR approaches are considered:

- Optimisation of existing SNCR systems – lower cost approaches – Section 6.4.1
- Extension of SNCR systems – approaches which involve larger CAPEX investments -Section 6.4.2

As an initial high-level report, the issues explored, and conclusion drawn are necessarily general. The report therefore discusses both general and more specific technical constraints as they relate to the NOx reduction approaches at a Sector level. However, it cannot make conclusions at a plant specific level – to do so requires consideration of installation specifics at a level which is beyond the scope of this study.

Plant-specific engineering feasibility studies are required to understand the detail of NOx reduction approaches, allow greater consideration of how the various operational risks and costs relate to the emission reduction achieved. The approach here therefore aims to inform the Environment Agency regulatory approach to NOx reduction at the Sector level, particularly so that it may consider the scope and objectives of any further investigations / Improvement Conditions applicable.

6.3 Barriers to primary NOx Reduction Approaches

6.3.1 Project implementation barriers

Making any change, and particularly larger changes requires careful project planning, development, and implementation. The costs and risks of such change represent a barrier to such changes.

The project development costs include:

- Concept design development
- Trials and testing
- Process integration studies e.g., HAZID/HAZOP, etc
- Detailed design / specification development – including consideration of process interfaces
- Procurement / tendering
- Consideration of Contracts including the impact on supplier guarantees
- Integration to O&M and quality approaches and contracts
- Implementation programming – possible availability losses
- Performance assessment (upside / downside risks)
- Supplier and engineering implementation costs (CAPEX)
- OPEX assessment

The scale of project implementation costs increases with complexity and therefore becomes a larger barrier to change where larger and more complex changes are pursued Changes needed at some older plants are expected to fall within this category. Fundamental NOx generation reduction methods are unlikely to be viable but may be considered when other major works are being undertaken e.g., complete grate replacement or very large-scale boiler cooling surfaces replacements – although these are rare as most installations make such changes gradually during planned outages over the plant lifetime. The risk of outage prolongation is a major factor in such projects and will serve as a barrier to all but the most essential projects of this type.

6.3.2 Basic design and contract constraints

6.3.2.1 Overview

Primary NOx reduction approaches require more significant interventions to address fundamental design aspects that influence NOx generation in the combustion process.

The basic design and operating performance constraints of the facility are set out prior to the plant operation and are influenced by the project contractual specifications, which in turn are influenced by regulatory policy and guidance. These fundamental plant design features have the major influence upon primary NOx production.

During the incineration process primary NOx reduction methods at WtE mainly target reduction of thermal NOx. The reduction of Thermal NOx relates to fundamental plant combustion design attributes that influence the furnace performance as a "reactor". These are:

- Temperature – above certain levels NOx production increases
- Time – evolved (from the solid waste) combustion gas residence time in defined furnace temperature zones
- Turbulence – reactant (Oxygen) gas mixing efficiency
- Reactant concentrations – mainly related to Oxygen excess (above stoichiometric levels)

These interrelated parameters are established via major design decisions around the waste transport into and within the furnace, its scale and layout (e.g. boiler configuration), how it is insulated and cooled (e.g. the location of refractory, water walls, superheaters), and how combustion gases and air supply mix and flow.

These design decisions are based around significant items of plant and equipment that are integral to the operation of the process. As such the **constraints and objectives for the design are established very early on in the project development and then the facility design phases** by furnace, boiler and grate suppliers, who will integrate a wide range of constraints to design systems (e.g. grate bar spacing, air flows, cooling requirements) in order to meet contractual supply and guarantee requirements set out by their Client. Designs have included future regulatory requirements where there was a likelihood of tighter regulation. For example, some plant have included space for additional emission control plant.

It should be noted that boiler and grate suppliers usually supply to an engineering, procurement and construction (EPC) contractor (their Client), who in turn integrates their design into the overall plant design set by a Waste Management Company (Owner), who will often manage the plant operating contract. The Owner will set various performance criteria for the plant to operate within, often set by and reflected in the Owner's contract with the Local Authority for whom the project is intended to serve.

Therefore whilst these systems can be optimised through, for example, the use of enhanced control software (see later sections) the constraints present in the principal components would require significant re-construction of the facility in order to adjust the primary NOx control strategy.

The financing of MWI facilities is usually underpinned by waste supply contracts, in particular longer-term agreements procured by Local Authorities to meet overall waste strategy requirements, and particularly to meet landfill diversion obligations.

The Local Authority Contract specifications therefore influence the fundamental design parameters, which in turn, influence the plant design including the NOx emission level design and operational objectives. Typically, Local Authority requirements will focus upon their key Service requirements, such as waste processing volumes (for landfill diversion) and contract length, but they also include requirements to comply with emissions regulations.

Noting that decisions regarding these matters are taken long before the plant is operational (often at least 5 years before), and that fundamental design changes to the furnace will be highly complex and costly, **reducing "raw" NOx generation in such ways is unlikely to be BAT at existing facilities,** or indeed those which have already passed key design development stages.

6.3.2.2 Conclusion

Fundamental design matters are therefore largely fixed by earlier project decisions (as described above) and establish major constraints, which then become the "set point" for fundamental design decisions. Changes to such fundamental aspects (e.g. redesign and replacement of the furnace with one of a different design) are highly capital intensive and may also require prolonged major outages (several months) to implement. Such changes also come with potential operational risks. As such, reducing NOx emissions at existing[24] plants through primary means is in general not likely to be viable.

Some sub-issues of relevance to this issue and to primary NOx reduction measures are explored in the following sections.

The boxed text section is taken from an earlier consultancy report[25] for EA dated March 2020, and explains this fundamental design issue in the context of "existing and new" facilities, and the opportunity for regulatory guidance:

---

[24] The key opportunity for the Environment Agency to influence NOx emissions (of future facilities) is via regulatory emission BAT guidance, including for example the interpretation of the EU BREF 2019. It is noted that some new facilities are now being developed in the UK with lower NOx AELs e.g. Rivenhall and Edmonton – both large scale facilities with specific project drivers.

[25] EA Research report: An Initial Review Of NOx Control Opportunities at Existing UK EFW Plants, Paul R James, Energy & Resources Ltd, March 2020

Table 11 Existing and New Facilities

• *It is also important to note that, once facilities are developed (even before construction and operational stages), certain constraints are imposed by the adopted design and investment decisions. These constraints, and the normal 25-year plant operational lifetime, mean that it is important for those involved in the development of early conceptual and feasibility studies to take due account of both the current and anticipated regulatory guidance & policy that is specific to the location where the plant will be situated.* • *Published regulatory guidance can greatly assist by adding clarity. It also needs to be updated to consider new developments, at a suitable frequency i.e. without providing a continuously changing landscape that will undermine the clarity sought. Such guidance can help project developers and investors to select those methods that are considered (BAT) for new installations and provide a firm basis to consider how applicability may differ for more constrained existing facilities.*

Influence of plant scale on primary NOx reduction for the reasons set out in Section 6.3.1 above, fundamental design changes (such as combustion chamber physical reconfiguration or grate replacement) are not expected to be viable at any plant scale.

Less drastic, optimisation type interventions (considered in Section 6.4.1 below) to achieve raw NOx reduction through primary combustion improvements may be achievable to some degree at existing facilities and are most likely to be viable at larger throughput facilities as investment costs are then less significant per tonne of waste processed.

6.3.3 Reduction of air supply ratio / stoichiometry (lambda) - for primary NOx reduction

Reduction in the combustion excess air ratio (EAR or Lambda) has been shown to reduce NOx generation[26].

A typical design EAR for a MWI is 1.7 (70% above stoichiometric), with actual plant operation often then optimised to allow operate below this design point. The EAR figure is used by designers to specify plant dimensions and is therefore a **key design parameter** influencing the scaling of all equipment. Elevated EAR levels (within the range 1.6-1.8) increase plant costs, but will reduce throughput capacity risks, which is usually the most critical performance requirement for Owners and Investors.

Operational reduction to figures as low as 1.3 have been found to result in a reduction of NOx generation by up to one half, without significant increase in CO (or other relevant) emissions when combined with combustion air pre-heating (e.g. by recuperation). Improvements in plant energy efficiency are also associated with reductions in EAR.

[26] Advantageous effects of low air ratio combustion in an advanced stoker-type waste incinerator, Y. Miyagoshi, T. Tatefuku, M. Nishino, T. Yokoyama & S. Kadowaki, *Nagaoka University of Technology, Japan, 2004*

However, it should be noted that reducing EAR at existing plants can lead to other challenges, including:

- Combustion instability through gas flow changes
- Potential failure to achieve 850°C and 2 seconds residence due to changes in volumes
- Temperature profile changes in the furnace e.g., inlet to boiler heat exchange elements
- Risk of increased CO and VOC emissions
- Flow and temperature changes resulting in the originally designed air / reagent injection locations being sub-optimal
- Consequent sub-optimal SNCR operation – noting the optimal temperature window for SNCR
- Changes to fouling / corrosion conditions in the furnace and boiler tube bundles – imparting critical performance and availability risks.

Operating at an EAR below the design point can have operational and economic advantages for plant operators, including those derived from:

- Reduced power consumption from fans handling lower air volumes,
- Improved power output from lower combustion air pre-heating demand
- Implications for the flue gas treatment
- Use of less reagent

Noting the potential for such operational advantages, **there are not considered to be significant barriers to Operators of operational plant reporting on their work in this area** (or indeed undertaking studies to assess potential) – with those most suitable then further investigated for implementation feasibility (and BAT).

Combustion modelling (CFD) may be used as a design tool to assess whether overall combustion conditions remain suitable (e.g., when changes are proposed), and so that gas flows and temperature profiles are not altered in ways which may impact on these operational and emission related issues, including the temperature profile dependence of SNCR abatement (see footnote 3).

Although the EAR is a fundamental design point, and therefore complex to re-address after the plant is designed and operational, depending on the EAR the plant is designed to, and operated at, there may be opportunity for some optimisation. **Plant specific assessment of excess air reduction opportunities and threats may reveal some possibility to reduce primary NOx**. This is most likely to be the case at those installations with highest air ratios.

6.3.4 Air supply and distribution - for primary NOx reduction

Achieving good combustion control is an essential component of overall optimisation - **this section focusses purely upon the optimisation of the primary and secondary combustion air i.e. of addition locations, flow volumes / rates & temperature to effectively oxidise products of incomplete combustion while reducing the generation of NOx.**

Key barriers to achieving NOx reduction with this approach are set out in Table 12 and below.

Table 12 Barriers to the use of air supply and distribution for NO_X reduction

• Installation design constraints that set basic limitations on e.g. grate design, firing diagram, air distributions • Competing critical operational priorities e.g., waste burnout, throughput • Challenges accessing optimal air supply locations after the design has been implemented.

The approach includes making changes in overall stoichiometry (EAR is discussed in Section 6.3.3) as well as injection locations, referred to as “zoning” or “staged combustion”, the latter referring to reducing the oxygen supply in the primary reaction zones and then increasing the air (and hence oxygen) supply in later combustion zones to oxidise the gases formed, whilst achieving overall plant operating and emissions performance goals. Such approaches are used (to varying degrees) by technology suppliers to reduce costs as they can result in lower flue gas volumes, which in turn influence equipment sizing and costs.

The need to achieve both solid waste burnout (% carbon in ash), and evolved combustion gas burnout (CO and VOC air emissions), plus reliable flue gas temperature and gas concentrations at the entrance to the boiler tubes are critical design constraints and may be compromised should the air supply and distribution be incorrectly managed.

Within the basic constraints set out by major design decisions taken earlier in the project development stages, the detailed combustion design will determine the precise primary and secondary air distributions and supply requirements and design optimisation tools such as CFD are typically used to determine optimal location of air injection points.

Whilst the main influences in existing plant are set out by the design, there are also potential for some degree of optimisation during the early operational periods. Air supply distribution changes are achievable at most installations to some degree and are quite commonly used to address operational issues such as excessive fouling or fly ash deposition, if this occurs, by modifying the overall flow path dynamics of combustion gases within the combustion chamber.

In general, such approaches are therefore motivated as a response to operational issues, rather than an intentional act of optimisation to control NOx, **with most NOx emission control change (e.g. to ensure compliance) being sought from abatement systems optimisations** – discussed later in Section 6.4.

6.3.5 Enhanced combustion control - for primary NOx reduction

Table 13 Barriers to the use of Primary NO_X reduction Techniques

- System limitations and hence barriers to additional NOx reduction will include:
  - Monitoring system response speed and design
  - Existing control system capability to integrate new signals
  - Cost of implementing an upgraded system (where required)

This approach includes the effective design and deployment of combustion control systems that measure temperature, oxygen, and other parameters to provide signals to inform control system algorithms that then determine interventions, typically air injections, but also other cooling system flow rates. It includes the use of computer-based automatic systems to monitor and control combustion to target operational performance as well as the prevention and/or reduction of emissions.

This includes the use of systems for high-performance *monitoring*, *integration, and reaction to* multiple operating parameters and of emissions. For example, infra-red cameras have been used (with extensive software signal processing to filter soot interference) to monitor flame fronts on grates and trim waste feed and air supply, as well as linking to SNCR reagent dosing as part of an integrated control system.

Whilst there are both technical and cost barriers to the deployment of new and upgraded combustion control systems, there are generally few barriers to the optimised or improved use of existing monitoring and control systems, as this requires the deployment of good O&M practice to extract benefit from existing equipment. **The main barrier to further optimisation may indeed be that good practice is already deployed** (Table 13**)**.

System trials to assess (lower cost / risk) combustion control capacity to deliver primary NOx reductions may be expected to be carried out at relatively low additional cost as part of the normal plant O&M optimisations that are required to effectively maintain WTE installations and

comply with general permit requirements to adopt BAT. The scope of such trials would need to focus upon achieving reductions in raw NOx levels, and overall NOx emissions reductions in a cost-effective way.

6.3.6 Oxygen enhancement - for primary NOx reduction

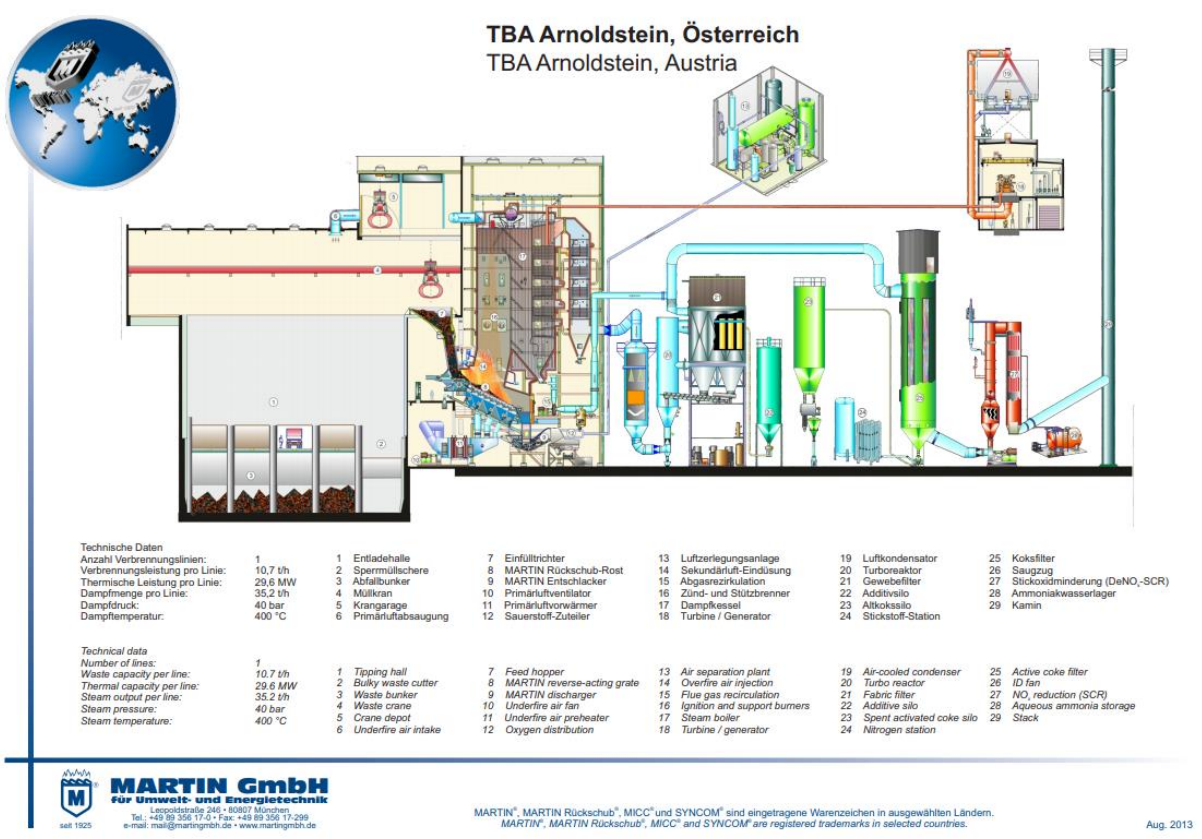
Table 14 Barriers to the use of oxygen enhancement for primary NO_X reduction

- Rare application to EfW
- Increased operational cost and complexity arising from the power consumption (parasitic load) required for the absorbers that generate the Oxygen.
- Other barriers include:
    - Refractory damage at higher temperature gas combustion
    - Risk of increased boiler corrosion
    - Need for additional crushing of sintered ash if metals are present and are to be removed for recycling

Oxygen enrichment of the combustion air reduces combustion gas volumes by displacing nitrogen from the air. This approach to NOx reduction is in many ways similar to the reduction of air supply already described in Section 6.3.4, and therefore exhibits many similar barriers with regard to integration to existing systems that have already passed their “design freeze”. Similar installation operational impacts may be expected through the installation, with the exception of those associated with the addition of the Oxygen generation and supply equipment.

The approach is very rare on MWI plants globally, although examples are known to have integrated oxygen enhancement in order to target certain outcomes e.g., improved leaching characteristics for ash residues from higher temperature ash sintering. Plants using such systems are known to have been implemented in Japan, due to regulation but in Europe the method has not been widely implemented despite its deployment at a fully commercial scale at Arnoldstein in Austria (Figure 4).

Figure 4 TBA Arnoldstein Plant Diagram



With global interest in carbon capture and storage (CCS) for various "essential industries" such as MWI increasing, but as such approaches involve very significant costs (e.g., over £100m CAPEX per installation) there is some interest[27] in the role that Oxygen enhancement may have in improving the economics of CCS. This is because the gas volumes requiring treatment are a key driver for the costs of CCS plant.

The main barriers to the deployment of Oxygen enhancement are increased operational cost and complexity arising from the significant power consumption (parasitic load) required for the absorbers that generate the Oxygen. This relates to both new and existing operational plants, although the fundamental design integration barriers already noted in earlier sections are more relevant to existing operational plants.

Other challenges with this approach are[28]:

- Refractory damage at higher temperature gas combustion
- Risk of increased boiler corrosion
- Need for additional crushing of sintered ash if metals are present and are to be removed for recycling

[27] Paulina Wienchol, Andrzej Szlęk, Mario Ditaranto, Waste-to-energy technology integrated with carbon capture – Challenges and opportunities, Energy, Volume 198, 2020, 117352, ISSN 0360-5442
[28] EU BREF 2019 Section 4.3.7

In the current UK regulatory context[29], due to cost and parasitic load issues **this approach is only likely to be viable as a NOx reduction approach where all other means of achieving compliance with an essential emission level have failed.**

6.3.7 Flue gas recirculation (FGR) - for primary NOx reduction

This approach involves the recirculation of a part (typically 10-20%) of the flue-gas to the furnace to replace the fresh combustion air, with the dual effect of cooling the temperature and limiting the oxygen excess available for nitrogen oxidation, thus limiting the NOx generation. The technique is deployed at some UK installations, including some newer plant e.g. plant 7 operating since 2016.

This technique also reduces the flue-gas energy losses. Barriers for application at existing plant are set out in

Table 15 Barriers to the use of flue gas recirculation

• Integration with existing furnace system • Ensuring gas burnout • Ducting corrosion • Additional cost of ducting

Energy savings are achieved when the recirculated flue-gas is extracted before flue gas cleaning (FGC), by reducing the gas flow though the FGC system and the size[30] of the required FGC system.

The overall principles and barriers are therefore similar to reducing excess air (section 6.3.3) in that there can be impacts due to the challenge such retrofit approaches introduce to an established design.

An additional barrier to FGR is that the ducting required is substantial both in terms of volume and cost and finding suitable ducting pathways through an existing facility can be challenging. Ducting corrosion issues are also widely reported, with substantial insulation being required to reduce this adding further costs. which would be specific to each site.

6.3.8 Performance / availability – fouling / corrosion issues

Plant availability (waste throughput) and performance (energy sales output), as well as OPEX and CAPEX risks are at the heart of plant economics and hence critical to MSWI plant Operators.

The more significant the change approach, and the more it has the potential to introduce challenges with regard to the plant fundamental design and operations, then the greater the risk introduced.

As such fouling and corrosion risks to plant performance and availability are common barriers to change.

[29] CCS with Oxyfuel would require significant subsidy or other incentives to be viable
[30] Reduced flow in the FGC system reduced air handling if fan speeds and loads can be reduced within the fan stalling operational design

6.3.9 Summary of favoured options - for primary NOx reduction

With the integration of fundamental design issues to meet a full range of performance objectives (including NOx emission levels and primary NOx generation levels within that) carried out during the installation development phase, the basic design sets out various constraints which then act as barriers to later change. The exception is where such changes can be integrated into normal plant investment / renovation cycles.

For this reason, **those approaches favoured for primary NOx reduction are those with the lower implementation hurdles (costs and risks).** Actual viability (costs/benefits) will be plant specific, but **the following have the least significant barriers and so may be worthy of such investigations**:

- **Reduced operating EAR** – which has potential to deliver other operating benefits
    - Including potential for FGR retrofit (recognising that there are some barriers)
- opportunities to reduce primary NOx from **combustion air supply and distribution and enhanced combustion monitoring and control -** focussed upon optimal deployment of existing systems, and lower cost / risk additions rather than larger interventions
- It will be appropriate for Operators to explore NOx reduction benefits potential in the context of other operational considerations, including implementation complexity, cost and risk issues[31]

With priority for situations where:

- Larger throughput plant – are most likely to show cost effectiveness per tonne of waste treated
- Higher raw NOx - figures above 400-450 mg/Nm3 may indicate greatest opportunity[32]
- Similarly, those plant with greater reliance upon secondary abatement to comply with final emission levels
- Those with the most significant final NOx emissions – noting mass emissions, plant contribution and background sensitivity

6.4 Barriers to secondary NOx Reduction Approaches

6.4.1 Optimisation of existing SNCR systems

This section focusses upon describing the barriers to the enhanced use of existing SNCR systems to further reduce NOx performance below the top end of the BAT-AEL ranges.

These are **approaches which target the optimal use of existing systems without significant capital investment.** Approaches that involve enhancing SNCR performance through greater intervention (and investment) and considered in Section 6.4.2 below.

The general principle of SNCR systems has already been described in Task 1. Noting the types of systems deployed for SNCR the barriers to their further deployment at existing plants are:

6.4.1.1 Existing installation design

Specifications established during the early project and detailed design phases (pre-operation) define the facility. There will usually be some degree of latitude in such designs to allow for operation optimisation and the potential for changes (e.g., to incoming waste composition) over the plant lifetime, but achieving such flexibility comes at increased cost as additional design capacity may be required to guarantee performance at extremes of operation.

---

[31] in more detail where the case is marginal – very large risk implications might reasonably be discharged with due brevity.
[32] At higher NOx concentrations SNCR reaction rates are improved – so some systems may be specifically designed to relay upon this improved SNCR reduction coupled with marginally higher primary NOx. Furthermore, at lower NOx inlet (to SNCR) levels optimum reaction temperatures are lower, and hence % reduction via SNCR may be lower. Overall this demonstrates the importance of early design decisions and system integration to achieve a specified output.

There are physical barriers related to the injection of SNCR reagent within the dynamic combustion gas flow such that it mixes well, in the right proportions, in the optimal reaction temperature window. The existing reagent dose rates and injection locations are therefore important.

The plant-specific capacity to effectively integrate and then operate at a revised SNCR set point is therefore a potential barrier, although some degree of optimisation is usually possible and may be explored.

6.4.1.2 Guarantee issues

Operation of equipment outside or away from its design set point and envelope can negate guarantees, including product lifetimes, O&M and service repair contracts. In addition, any latent defect liability of the technology provider would need to be considered as it may be affected by any unauthorised update.

6.4.1.3 Reagent type change

Ammonia and Urea are commonly used. Ammonia has a narrower effective temperature range (850-950°C) compared to Urea systems (750-1000°C), and Ammonia has more complex storage hazards. Urea is reported to have higher risk of N_2O emissions. The advantages and disadvantages are summarised in the EU BREF (see Table 5).

With reagent selection specifically part of the design process, there are expected to **be limited opportunities for post operational optimisation via reagent change** unless part of an overall major refurbishment that affords opportunity to consider a revised reagent.

This is supported by EU BREF 2019 noting (page 112) that:

Table 16 BREF Comments on Reagent

- *obtaining a good understanding of temperature profiles in the combustion chamber is fundamental to the selection of the reagent.",* and
- *"In cases where the advantages and disadvantages are finely balanced, storage and handling hazards may have a greater impact on the final reagent selection."*

With the storage of larger quantities of Ammonia specifically regulated under danger substances legislation, this in itself can become a barrier to considering Ammonia use.

UK trials have also assessed using different types of Urea (granular or prilled). The trials were undertaken specifically to demonstrate if the storage, delivery and handling systems could deliver the required urea flow and meet the NOx set point at an acceptable ammonia slip.

The trials with the Prilled Urea were deemed largely unsuccessful due to repeated blockages however there are UK facilities operating with prilled Urea. Trials with the Granular Urea were deemed to be able to achieve the NOx set points, and for the relatively short duration trials <1% of the time was spent at the 70% limit of the screw speed.

The key technical barriers to reagent change are therefore:

- Design optimisation already in place for current reagent e.g. injection locations for required temperature profiles (note – injector locations are considered in section 6.4.1.5 below)
- Poor optimisation will lead to increased risk of reagent consumption, N_2O production, ammonia slip to air and residue contamination
- Different reagent storage and handling requirements, with possible COMAH permitting implications for larger quantity Ammonia storage
- It is not clear whether different reagent preparations (of a reagent type) offer benefits

6.4.1.4 Dose rate increase

The normalized stoichiometric ratio (NSR) defines the amount of reagent needed to achieve the targeted NOx reduction. The factors that influence the value of NSR include the following[33]:

- Percent NOx reduction required
- Uncontrolled NOx concentration in the flue gases
- Temperature and residence time available for the NOx reduction reactions
- Extent of mixing achievable in the boiler
- Allowable ammonia slip
- Rates of competing chemical reactions

Figure 5 below compares increases in the NSR with the achieved % NOx reduction efficiency and demonstrates that (for a defined set of reactor conditions) above a defined level (approx. 1.5- 2.0), increasing the quantity of reagent does not significantly improve the NOx reduction.

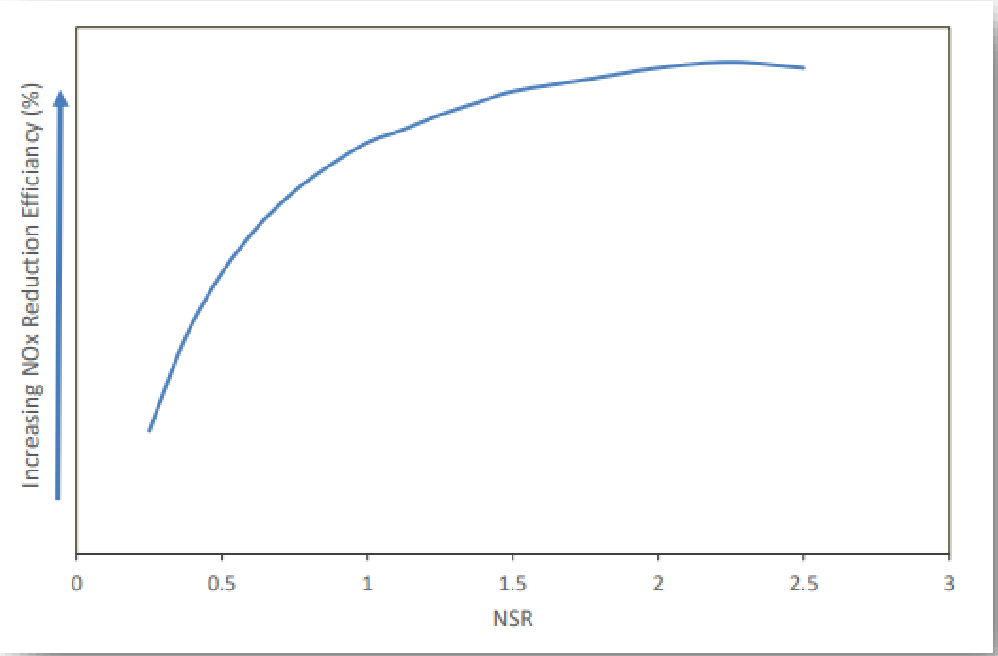


Figure 5 Effect of NSR on NOx reduction (US EPA 2019)

Once injection rates achieve NSR levels above 1.5 – 2.0 the NOx reduction benefits of increased reagent injection slows, and other factors may dominate e.g., Ammonia slip, N_20 production and disproportionate reagent costs. System design factors such as pump, reagent supply and injection nozzle capacities may also provide limitations to increasing injection rates. The "mixing" or the reagent in the combustion chamber will depend on spray nozzle design – with those achieving a finer droplet "mist" generally achieving greater mixing. Nozzle cleaning is important for good operation.

It is also reported[34] that higher stoichiometric ratios of typically 2-3 are required. This is expected to be due to imperfect reactor conditions but suggests that there is scope to optimise reagent dosing at existing plants.

---

[33] US EPA Selective Non-Catalytic Reduction. John L Sorrels, April 2019
[34] EU BREF 2019 p 403

UK operator trials aimed at reducing NOx by adjusting existing SNCR systems have reported:

- Additional residue accumulation on bag filters – requiring adjustments to bag cleaning and APCR recirculation
- Limited impact on bag filter differential pressures
- Some hopper blockages, with a higher differential pressure across the bag filter and an increase in the ID fan levels, potentially due to chloride formation (plant 5) It is not clear the cause of this. Possibilities include chemistry of material resulting in clumping, moisture uptake or cold spots in the hoppers
- Anecdotally reported increased ammonia levels in the IBA (plant 5)
- NOx reductions in the range of 10-20 mg/Nm^3 from an increased reagent dose rate of up to 50%
- Some evidence that above a certain level gains are limited, and instability increases

The key technical barriers to dose rate increases are therefore:

- Operation beyond system design – either physical capacity (e.g., spray nozzle performance) or beyond optimal dose rates i.e. diminishing benefits compared to knock-on impacts
- Adjustments required to bag filter systems
- Potential for increased risk of reagent consumption, N_2O production, ammonia slip to air and residue contamination

Overall investigation of dose rate increases shows promise, but benefits will likely be site-specific.

6.4.1.5 Temperature profile and injection locations in the furnace

As well as at the NOx production stage (noted already in Section 6.3) the NOx reduction efficiency of SNCR systems is critically dependent on the temperature in the location where the reduction reactions will take place (see **Error! Reference source not found.**). The combination of these factors has already been noted above and as well as the temperature includes residence time and mixing, such that reaction kinetics are improved.

The temperature profile in the plant furnace / boiler is therefore a key constraint for SNCR system design. This is a fundamental design issue for MWI plants. At existing plants SNCR injection locations will have already been determined to allow for the plant to meet its emissions targets as set out in the relevant permit.

Combustion units operated at low load or with different fuels may result in changes in the temperature profile in the combustion unit. In some cases, temperatures may be below the optimum required for achieving NOx reductions. To address this concern and permit operational optimisation, SNCR systems are often designed with multi-level reagent injection locations, temperature sensors, and automatic controls to allow switching between injection ports. Using such systems, reagent can be injected at the location with the optimum temperature for NOx reduction.

Review of UK plant data shows that multiple layer and injection location approaches are deployed, with typically 2, 3 or 4 layers being common, and injection numbers per layer varying between 2 and 8. Total injection port numbers reported vary between 4 (a 17MW 2-line plant 5 from 2004) and 32 (a 37.5 MW 2-line plant from 2016.

More layers appear to have been deployed at larger capacity incineration lines, which may be assumed to reflect the challenge of achieving suitable reaction / dose rate levels at larger geometry boilers.

It should also be noted that the change to EAR, through either better combustion control techniques or the installation of FGR, may also create changes in the temperature profile which could benefit from multi-level injection locations.

Although there may be opportunities to reconsider and add new injection locations (and particularly to deploy currently unused locations) during the plant operation there are not expected to be opportunities to alter boiler temperature profiles and hence there is not considered to be a lower cost intervention available to achieve SNCR reduction in this way (effectively the SNCR design must follow the boiler design, and not the reverse).

There is however the potential to assess the deployment of existing and new layers or injection locations – see Section 6.4.2.6 below. Operators have already reported that post commissioning some revised or additional injection locations have been added.

6.4.1.6 SNCR injection system maintenance

Effective maintenance of the SNCR systems are critical to their effective operation. The combustion environment is highly aggressive, equipment materials and maintenance must take this into account. In particular, injection ports, nozzles and monitoring equipment (lenses, suction ports, etc) may be subject to degradation. Without good quality data, control systems will not be able to respond to changing environments and deliver optimised reagent dosing.

UK plant survey data consistently reports challenges from degradation and blockages, and the need for regular cleaning and replacement – notable of injection nozzles.

Review and upgrade of system maintenance affords a generally lower complexity (and lower CAPEX) approach to delivering optimised NOx reduction at existing installations.

6.4.1.7 Ammonia slip constraints

Ammonia slip is the emission of ammonia that results from excess reagent injection to overcome inherent natural system limitations to obtain the desired level of NOx reduction.

Although the level of ammonia slip differs from one unit to the next based on the limitations inherent to each system, for any individual SNCR, the **NOx reduction and ammonia slip levels are determined by the reagent injection rate** – an operational setting that can be adjusted (but only within design limits) based on the target NOx reduction and ammonia slip.

Typically, due to imperfect reaction kinetics (mixing, temperature, etc) significantly more reagent needs to be injected in practice than is required by the theoretical stoichiometric ratio, and as such some slip results.

For a given plant design (with its fixed mixing and temperature characteristics being largely determined by earlier fundamental combustion design decisions), the level of ammonia slip generally increases with increasing reagent injection rates and therefore **the permitted ammonia emission level represents a barrier to further NOx reduction** of SNCR systems at UK MWI plant. The exceptions to this are where wet scrubbing is used[35] as the wet scrubber then provides a means to absorb ammonia. Such systems are rare in the UK, with dry or semi-dry FGT plant preferred and such systems not having the same ammonia absorption potential.

UK plant trials data broadly supports a conclusion that ammonia slip increases when dose rates are increased, and that for individual plants there are different dose rate points at which slip begins to accelerate. This suggests other design and operational factors combine to define the optimum for a given installation.

6.4.1.8 Residue contamination constraints

Increased SNCR reagent dose rates and resultant slip can contaminate residues, which may increase disposal costs or limit recovery options[36].

In UK plant trials one MWI plant (Plant 5 using Urea prill) reported "anecdotally the site reported increased ammonia levels in the IBA" when testing increased SNCR reagent dosing as a means of reducing NOx emissions.

---

[35] Reference plant Umea Energi AB, Sweden – this plant uses high dose SNCR coupled with a wet scrubber to capture ammonia slip. The ammonia water is then re-used as SNCR reagent.
[36] EU BREF 2019 p 403.

6.4.1.9 Monitoring, Control & Instrumentation issues

Most "advanced" SNCR system integrate additional attention to these aspects, although they will usually also involve investment in additional equipment, such as revised injection equipment and locations – as such these are considered in the "extension to SNCR systems" section 6.4.2 below.

At existing installations, the optimisation of SNCR system monitoring, control and instrumentation is expected to generally have the potential for lower cost interventions and some degree of improved NOx emission abatement. Such approaches are therefore worthy of investigation to establish whether there are site specific opportunities, and the degree of abatement that may be so achieved.

Whether there are cost-effective (BAT) opportunities using the current equipment at a specific MWI site will largely depend on the degree of optimisation and design capacity of the current SNCR system. In general, with lower NOx emission levels having been debated for MWIs for at least two decades, newer installations (perhaps less than 10 years of operation) may be expected to have already integrated higher capacity / flexibility systems, with the more accurate and faster monitoring response times, and automated control systems that will allow adjustments to be made at relatively low cost.

Undertaking system modifications to improve monitoring, control and instrumentation may have site specific technical barriers with regard to the integration of any new equipment / systems required (see Section 6.3.5below) but in general will be appropriate to consider at existing MWI plant.

6.4.1.10 Project evaluation and implementation costs and risks

As well as the CAPEX and OPEX cost barriers to any given intervention, there are also cost and risk barriers arising from the need to appropriately consider and implement change that need to be considered.

The project development and execution stages required at an existing plant may be broadly characterised as:

- Assessment of opportunity – examination of the present operation, design, and emission performance to establish whether there is a *prime-face* case for change
- Options assessment – initial identification of technical options suitable for the specific plant
- Pre-feasibility – examination of few favoured options to identify risks, design and outline costs (CAPEX/OPEX), with initial HAZID
- Feasibility – design development and costing update
- Pre/FEED – a more detailed design stage that considers specifications, including interfaces
- Tendering – approach to OEM market for contract
- Project investment decision – project costs, performance and risks consideration
- Implementation – installation of solution, including programming (outage plan integration)
- Testing, commissioning, full operation
- Training and O&M integration

The earlier stages of these assessments are lower cost than the later more detailed stages. Indeed, routine plant O&M good practice, continuous improvement requirements in Quality Management systems, and the requirement to use BAT in permits, may be expected to already include the initial bullet point i.e., Operators may be considered to already have a duty to continually assess the potential for cost effective optimisation opportunities to minimise NOx emissions, rather than simply target compliance with a permit ELV.

These stages are broadly applicable to the consideration and implementation of installation design changes, not just the lower intervention SCNR optimisations considered in this section.

6.4.2 Extension of SNCR systems

This section considers the barriers to approaches which involve capital investment to implement upgraded SNCR systems to further reduce NOx performance below the top end of the BAT-AEL ranges. SNCR systems have already been described in Section 4.3.2. Approaches that involve enhancing SNCR performance through optimal use of existing systems without significant capital investment are considered in Section 6.4.1 above.

Whilst compliance with ELVs of below 100 mg/Nm^3 have been reported for new plants that have included temperature (and overall) optimised SNCR systems evidence of such performance levels at retrofitted existing plants has not been located. The degree of NOx reduction that may be achieved is expected to be higher than the potential noted above for low intervention approaches, but site-specific factors are expected to be dominant. Therefore, site specific feasibility assessment is required to determine the balance of costs and benefits.

Many of the barriers to extension of SNCR systems are similar to those already considered in Section 6.4.1 above in relation to optimisation of current systems. The main differences are highlighted below:

6.4.2.1 Existing installation design

Issues are similar to those noted in Section 6.4.1.1.

The plant physical layout sets constraints on where new systems can be added. Access to those locations deemed optimal (e.g. via gas path temperature measurement and modelling to locate optimised reagent injection locations) may be constrained by physical features such as support structures, gantries, boiler cooling systems, etc.

Larger capacity incineration lines have larger cross-sectional geometry. The greater distances mean that it is more difficult to optimise the reagent distribution in the furnace.

6.4.2.2 Guarantee issues

Issues are similar to those noted in Section 6.4.1.2

The greater degree of change when SNCR systems are extended rather than merely optimised means that the issue will be greater in this case.

6.4.2.3 Reagent type change

Issues are similar to those noted in Section 6.4.1.3

A major refit may afford the opportunity re re-consider the reagent as an integrated part of the project. In general, with both Ammonia and Urea offering a balance of advantages and disadvantages, other upgrade project objectives are expected to dominate design decisions and lead the reagent selection.

6.4.2.4 SNCR injection system maintenance

See comments in Section 6.4.1.6

A larger overhaul affords an improved opportunity to also upgrade systems to address maintenance issues.

6.4.2.5 Dose rate increase

On its own, increasing reagent dose rates may result in additional NOx reduction, but also risk increased ammonia slip (see below). The relationship is already explained in Section 6.4.1.4 above, and it is noted that for a given system there are diminishing returns (due to increasing reaction inefficiencies) at increasing rates. Where this level is will be dependent upon interrelated factors that influence reaction kinetics, notably mixing and temperature profiles (see earlier discussions), which are in-turn influenced (constrained) by design specifics – as described earlier in this report.

System design factors such as pump, reagent supply and injection nozzle capacities & performance that provide limitations to increasing injection rates, may be addressed as part of a larger overhaul project. Whether such approaches are BAT will depend on the overall emission reduction required, but even at new installations deploying a range of NOx reduction systems to optimise performance, guaranteeing level below 100 mg/Nm3 would be considered challenging and unusual – for this reason SCR is generally used when ELVs below 80mg/Nm3 are required.

6.4.2.6 Temperature profile in the furnace, injection locations, SNCR system monitoring, control & instrumentation

As already noted in earlier sections (see 6.4.1.5 & 6.4.1.9 above), SNCR system abatement efficiency is strongly related to the ability of the overall system to place reagents in the combustion gas flow at the correct temperatures for that reagent.

It has already been noted (section 6.4.1.5) that UK plants show significant variation in the number of injection ports and number of layers.

This is a main driver for SNCR systems designers, with the location (and rate) of SNCR reagent injection being determined to suit the overall plant thermal design and geometry. SNCR system design therefore follows the plant thermal design, and as such is constrained by it.

Some SNCR systems are designed with multi-level reagent injection locations, temperature sensors, and automatic controls to allow switching between injection ports. Multi-level injection approaches have been successfully retrofitted to some existing operational plants[37], to meet NOx ELVs below 100 mg/Nm^3. Using such systems in combination with suitable (accurate and fast) monitoring, control and instrumentation can allow reagent can be injected at the locations with the optimum temperature for NOx reduction, adjusting in real time to furnace conditions.

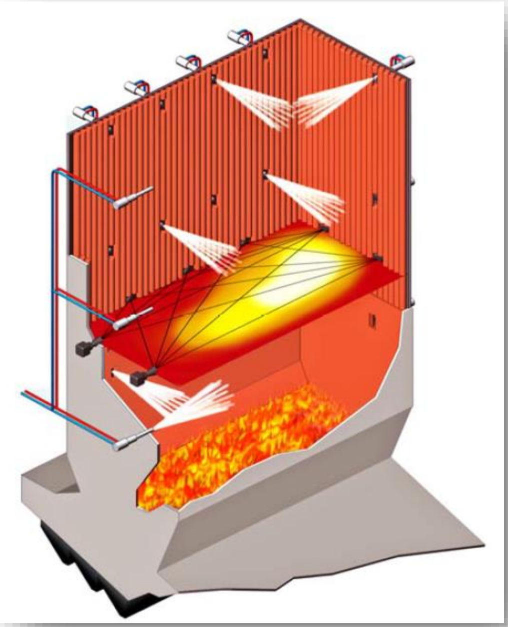


Figure 6 Multi-layer SNCR injection points[38]

Optimizing the location[39] and number of injection lances, with dosing rates optimised to real-time furnace conditions via the support of fast-reacting and accurate temperature measurement systems (e.g. acoustic or infrared)[40] is reported to have achieved emission levels are reported below 100 mg/Nm^3

[37] Filborna, Sweden – ref RWM Conference Feb 2021 Henrik Hofgren BWV
[38] SNCR as Best Available Technology for NOx Reduction in Grate Fired Boilers for Municipal Waste, Biomass, RDF, etc. Bernd von der Heide Claus Stubenhöfer Mehldau & Steinfath Umwelttechnik GmbH Germany PG Europe 2016-Milano-SNCR as BAT for NOx Reduction.docx
[39] Usually at different levels (or "layers") within the furnace to allow optimisation
[40] SNCR Process - Best Available Technology for NOx Reduction in Waste To Energy Plants Bernd von der Heide, Powergen Milan June 2008

(with NH_3 slip below $10mg/Nm^3$) at plants in Germany, Sweden and Netherlands, and is understood to be the basis of design (and EA permit application) for the proposed Indaver installation at Rivenhall in Essex.

The use of acoustic pyrometers within such systems is noted to improve temperature monitoring which then allows optimisation of the SNCR system, but this is not new[41]. Specific benefits from the use of acoustic pyrometers are noted by their suppliers[42] as:

- reduced emissions by managing critical temperature profiles
- reduce slagging by maintaining optimal furnace flue gas temperatures
- avoiding tube damage and leaks by avoiding hot spots and thermal shock
- Improved heat transfer rate by balancing combustion

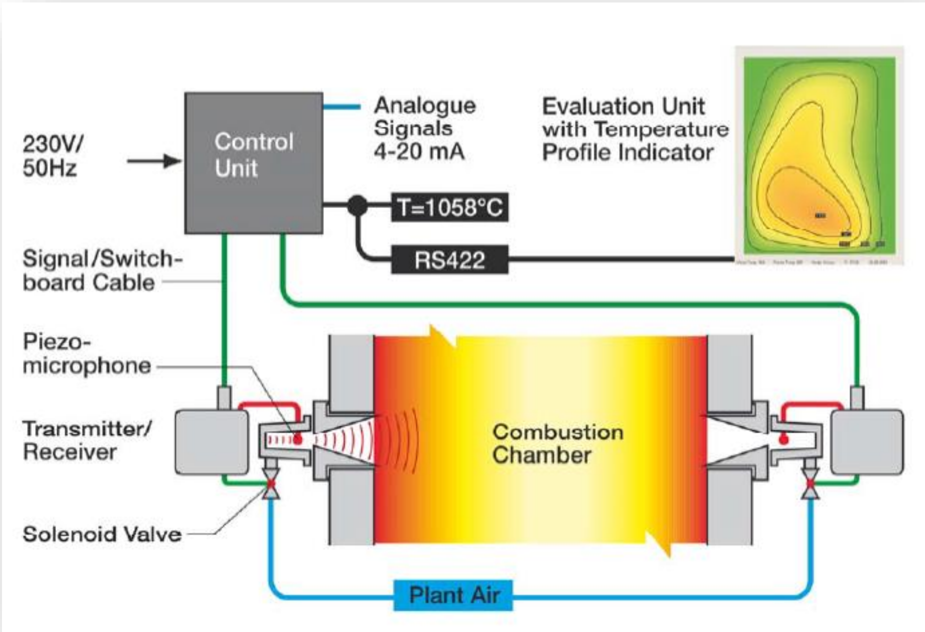


Figure 7 Basic Arrangement of the Acoustic Gas Temperatures Measurement System (AGAM)

Overall, the basic thermal design and layout of the plant acts as a constraint for the addition of newly optimised injection locations and monitoring systems. Whilst there may be opportunity to consider retrofit deployment of upgraded systems during the plant lifetime, the project complexity, risks and costs may be considerable, and has the potential to outweigh the NOx reduction benefits.

Undertaking system upgrades to improve injection locations to suit reaction temperature kinetics, as well as monitoring, control and instrumentation may have site specific technical barriers with regard to the integration of any new equipment / systems required but in general will be appropriate to consider at existing plant, if not always finally considered BAT on a balance of site-specific costs and benefits. Such investments will have the lowest barriers at larger installations with a larger emission footprint in areas where there are specific local NOx concerns.

Installations with fewer injection locations and layers may have opportunity to improve SNCR system performance and achieve NOx reductions from reconsidering the design strategy, including the addition

[41] The use of acoustic pyrometers was noted since the 1980s and considered in Environment Agency commissioned research in 2001 - Review of BAT for New Waste Incineration Issues R&D Technical Report P4-100/TR Part 2 Validation of Combustion Conditions D Scott & A Collings
[42] Example: https://www.valmet.com/automation/boiler-diagnostics/acoustic-pyrometer/?page=1

of more ports and layers. This will need to be done on a site-specific basis as pre-existing design may impart constraints and associated costs, or even compromise the improvement sought.

6.4.2.7 Ammonia slip constraints

Similar comments to Section 6.4.1.7 apply.

If a more significant retrofit or upgrade is undertaken, that also integrates a NOx system upgrade, then there will be opportunity to address overall SNCR system optimisation so that the ammonia slip barrier is adhered to, or so that emissions may even be reduced.

Noting historical and wider UK regulatory policy, it is not anticipated that existing MSWI plants will move to wet scrubbing systems, so ammonia slip will remain a constraint upon SNCR performance.

6.4.2.8 Residue contamination constraints

As noted in Section 6.4.1.8, increased SNCR reagent dose rates and resultant slip can contaminate residues, which may increase disposal costs or limit recovery options.

The opportunity for greater design optimisation when undertaking the larger investments considered here, may afford greater opportunity to reduce such contamination risks.

6.4.2.9 Project evaluation and implementation cost and risks

See Section 6.4.1.10 – issues are similar.

The larger scale of SNCR extension projects (compared to the optimisation of existing systems), means that project development and implementation barriers are greater, due to higher project complexity and hence cost.

6.4.2.10 Additional issues

The main additional barriers to extension / addition to SNCR systems, over and above those which apply to lower intervention optimisation of existing system approaches, are:

- Physical access – to the locations for new equipment e.g., for injection ports / lances
- Reagent supply routing – any new injection locations will require reagent supply piping – this will be especially complicated when different boiler levels are selected
- Cable routing – will also be required for such new equipment for control system integration. Generally, this is a much less significant barrier than reagent supply piping and so is not considered to be a barrier in itself
- Reagent storage – additional capacity may be required. In the case of ammonia this has the potential to also trigger hazardous substances storage regulation.

6.4.3 Addition of SCR

Whilst commonly applied outside the UK, specifically where lower BAT emission limit values are set in permits (invariably an ELV of 80 mg/Nm^3 will result in an SCR system being deployed), SCR is not currently deployed at MWI plant in the UK. This is an unusual approach for the UK but is assumed to reflect local air quality challenges (for NO_2) a desire to develop an “best in class” installation for a large and high-profile project.

Noting that the scope of work for this project was specifically focussed upon other measures, this section only briefly sets out the barriers to SCR.

Barriers to SCR include both technical and cost issues. Table 17 is taken from literature[43] and provides an example of a cost comparison between SCR and SNCR. The key observation is that SCR has significantly higher capital and operating costs than SNCR.

[43] SNCR Process - Best Available Technology for NOx Reduction in Waste To Energy Plants, Mehldau & Steinfath Umwelttechnik GmbH. Presented at POWER-GEN Europe Milan, 3 – 5 June 2008

Table 17 Comparison of costs for SCR and SNCR controls for WtE plant

	Unit	SNCR Urea (45%)	SNCR NH4OH (25%)	SCR NH4OH (25%)
Waste throughput	MT/h	15		
Flue gas volume stream	Nm³/h,dry	80,000		
Operating hours	h/a	7,800		
NOx baseline	mg/Nm³	400		
NOx clean gas concentration	mg/Nm³	200	100	70
Pressure loss	mbar			25
Temperature increase	°C			20
Investment costs	**EUR**	**200.000**	**500.000**	**2.500.000**
Operating time	years	15	15	15
Interest rate		6%	6%	6%
Annuity	**EUR/a**	**20.000**	**50.000**	**250.000**
Ammonia water	EUR/h	-	16,50	6,00
Urea solution	EUR/h	11,30	-	-
Process water	EUR/h	0,58	-	-
Demineralised water	EUR/h		1,20	
Electrical energy	EUR/h	0,15	0,15	6,70
Natural gas	EUR/h	-	-	38,00
Compressed air	EUR/h	2,00	2,00	-
Operating costs per hour	EUR/h	14,03	19,85	50,70
Operating costs per year	**EUR/a**	**109.434**	**154.830**	**395.460**

Cost comparisons are also provided In a major study[44] undertaken for UBA in Germany by the Technical University of Dresden published in 2011 (Table 18).

Table 18 Comparison of SNCR and SCR costs for different final concentrations

NO_x-Konzentration Rohgas: 400 mg/Nm³ tr.

SNCR-Verfahren	NO_x-Reingaskonzentration	mg/Nm³ tr.	200	150	100
	Investitionskosten*	€	265.000	280.000	525.000
SCR-Verfahren	NO_x-Reingaskonzentration	mg/Nm³ tr.	150	100	50
	Investitionskosten*	€	2.280.000	2.308.000	2.365.000

** Anlagenkosten ohne Reduktionsmittellager.*

[44] Beschreibung unterschiedlicher Techniken und deren Entwicklungspotentiale zur Minderung von Stickstoffoxiden im Abgas von Abfallverbrennungsanlagen und Ersatzbrennstoff-Kraftwerken hinsichtlich Leistungsfähigkeit, Kosten und Energieverbrauch von Prof. Dr. Michael Beckmann Technische Universität Dresden (TUD), Dresden

The report also provides detailed breakdowns of component costs for each scenario. The main observations are:

- The investment cost of SNCR is significantly below that of SCR for all three ELV scenarios (200, 150 and 100mg./Nm^3)
- The increase in investment cost for SNCR from 150 to 100 is attributed to the additional gas temperature monitoring required – refer to full report for full assumptions.
- A (reasonable) raw gas (*rohgas*) concentration of 400 mg/Nm^3 is assumed
- Cost of reagent storage is excluded (*Anlagenkosten ohne Reduktionsmittellager)*

Beyond cost issues the following are identified as technical barriers to the addition of SCR at existing MWI installations:

- Site layout – SCR require significant space, although it is noted that many plants have been designed with such space allocated to allow for potential SCR addition in the event it were mandated
- Thermal profile – the SCR unit must be positioned correctly in the plant to avoid thermal losses (minimised by heat recuperation). The catalytic bed usually has an optimum operating temperature that is typically around 200–450 °C for the high-dust type and 170–250 °C for the tail-end type. Figure 5 below shows the temperature profiles.
- Parasitic load - as indicated above the installation can result in heat losses, but it will also require a larger fan due to pressure drop across the catalyst bed. And may also include the need to recirculate exhaust gases for reheat prior to the SCR. Fan load is a major parasitic load.
- Outage availability loss costs for project build – SCR retrofit is a very significant project

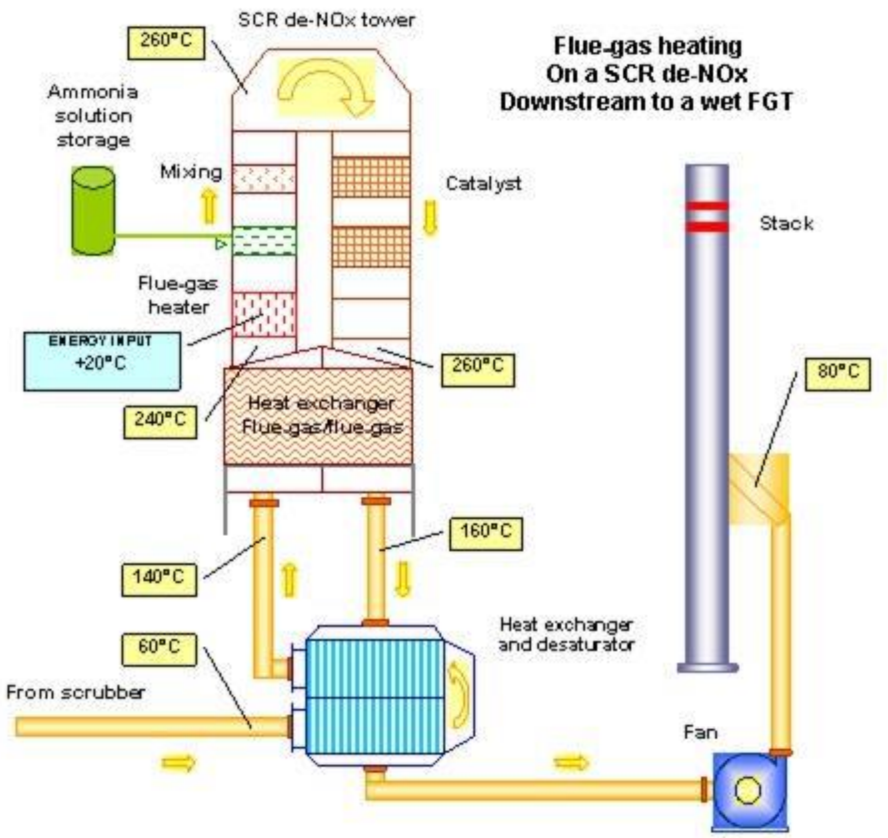


Figure 8 SCR Thermal Profile[45]

6.4.4 Addition of Catalytic Bag Filters

Catalytic filter bags are not widely used in MWI. EU BREF 2019 (p 410) notes that:

"the replacement of filter bags with de-NOX catalytic bags can reduce NOX emissions to those characteristic of SCR at a low investment cost, and with minimal change to the existing plant configuration. NOX emission levels in the 50–75 mg/Nm3 range are reported."

The BREF also reports that plant retrofitted with this technique have achieved NOx and ammonia reductions as shown in Table 19.

Table 19 Emission reductions reported with catalytic filter bags

	Prior to retrofit	With catalytic filter bags
NO_X (daily average, 11 % O_2)	135–200 mg/Nm^3	50–120 mg/Nm^3
NH_3 (daily average, 11 % O_2)	1–10 mg/Nm^3	1–5 mg/Nm^3

Other than increased cost for filter media, no major implementation barriers are noted. However, it is a catalytic reduction process which will have an optimum temperature range and some reheat would normally be required. The potential areas that would require site specific investigation are:

[45] Best Available Techniques (BAT) Reference Document for Waste Incineration, Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)

- Operating temperature compatibility with existing bag filter system
- Pressure drop and associated parasitic load if reheat required / ID fan modifications
- Whether SO_2 levels can be reduced to limit catalyst poisoning
- Additional NOx reduction reagent consumption for the bag filters

6.5 Section summary and recommendations

6.5.1 Key observations summary and discussion

This section has adopted a high-level approach to consider the barriers to the adoption of certain approaches to NOx reduction at UK MWI plants to levels below the BAT-AEL ranges specified in BATC.

A limitation on this work has been that the study scope did not extend to the detailed, plant specific assessments that are required to determine:

- the extent to which existing plant design and operation already delivers the optimal NOx emissions
- the design capacity of existing systems to further reduce NOx
- the design and operational changes “required” to achieve a lower emission level
- the cost of such changes

Noting these constraints, at a high level the main barriers to further NOx reduction at existing MWI are:

- the plants were already designed with the objective of complying with a higher ELV (usually compliance with the WID/IED level of 200 mg/Nm^3)
- the design process involves compromises and optimisations, which set limitations on what can be achieved without significant intervention, or knock-on performance effects
- the fundamental combustion design approaches which establish the baseline constraints for NOx emission control system designs (which then target ELV compliance), are determined by critical business risk factors which are predominantly: installation throughput, availability, and energy recovery performance
- the complexity of more significant changes pressurises these critical business risk factors, meaning larger changes will require more detailed investigations during project feasibility and development – such assessments may on their own impart significant costs, and the operational risks introduced may exceed the value of the reductions achieved
- lower cost interventions based upon optimisation of existing systems, and in some cases their upgrade does appear to have potential, but site-specific assessments are required to evaluate approaches and determine BAT.

6.5.2 What are the main barriers to each approach?

The main barriers to each of the approaches considered in this report are summarised in the table below:

Table 20 Barriers to NOx Reduction approaches

Approach	Main barrier	Comment
Primary NOx reduction	• Basic plant combustion design constraints • High cost of change	• Higher business risks • Reducing final emissions with secondary measures will usually be lower risk / cost • Poorly optimised primary measures may lead to excessive reagent consumption from reliance on secondary measures
Existing SNCR systems optimisation	• Already design optimised at a higher emission level • Slip issues possible	• Generally lower cost interventions • Testing may be used to assess new optimum levels as a part of routine QMS approaches • May deliver emission concentration reductions in the 5-40 mg/Nm^3 range
SNCR extension	• Challenges with the location / installation / maintenance of new equipment at a pre-designed plant	• Costs may be excessive compared to NOx impact reductions gained • Integration of new systems most likely to be viable during other major refit projects in the furnace • Potential to deliver emission concentration reductions in the 30-60 mg/Nm^3 range,
SCR	• Cost – CAPEX & OPEX • Thermal design integration • Energy losses	• Mostly considered BAT at larger installations in higher NOx sensitivity areas • Potential to deliver the largest NOx emission reductions, but at highest costs - unlikely to be BAT in most situations due to barriers noted (see 6.4.3)
Catalytic Bag filters	• System compatibility	• Not widely applied

6.5.3 Which approaches appear most favourable?

Noting that at a specific plant the pre-existing design, degree of optimisation of operations for NOx control, and the currently achieved emission levels will set out the basic constraints and priority for further control, the most favourable approaches (those with the lower barriers) to reducing NOx below BAT-AELs at existing plant are:

Table 21 Approaches to NOx reduction

Approach	Method	Section Ref	Comment
Primary NOx reduction	Explore reduced excess air	4.1	• Operational benefits mean this is likely to already be integrated • Careful consideration of risks also important noting critical risks to plant, performance, and emissions.
Primary NOx reduction	Optimisation of air distribution, flow and control	4.1	• Such approaches are expected to be lower cost as they will already be deployed to achieve the existing ELV • Trials focussed on establishing a new lower ELV are required to understand the site-specific costs and benefits and would typically be combined with existing SNCR system assessments to optimise overall

Approach	Method	Section Ref	Comment
Existing SNCR systems optimisation	Optimisation of existing SNCR systems – using reagent dose rates	6.4.1	• Generally lower cost / risk • Increased O&M attention – injection nozzles, monitoring equipment, etc • The main lower cost opportunity is to vary does rates – location of injections will require greater investment (considered under SNCR extension). • Testing may be used to assess new optimum emission “set point” levels - as a part of routine QMS approaches
SNCR extension	Combination approaches to optimise SNCR reaction kinetics	6.4.2	The approaches would include the integration of a revised SNCR system (where performance merits) including: • Multiple layer reagent injection – more layers and more injection locations • Located to optimise temperature reaction kinetics and gas flow path • Fast acting monitoring and control systems – notably temperature e.g. Acoustic or Infra-Red systems

6.5.4 Consideration of EA regulatory position

With NOx emissions from MWIs having been controlled for over 20 years, plant designers have responded by integrating emission controls into their designs to allow guarantees to be issued to owners and operators for emissions performance levels that comply with regulatory requirements, and do not compromise other plant performance areas.

Whilst achieving regulatory compliance is a critical design constraint, within this constraint plant design (fundamental and detailed) is mainly driven by those elements which dictate performance in areas which have the largest influence on the business model – namely, throughput rate (tonnes/day and per year), availability (operating hours/yr), and energy recovery performance (MW and MWh/year).

Together with historical regulatory policy on NOx, these factors have shaped the design and performance objectives of the existing UK installations. Making changes to NOx emission levels at existing plant, that were designed/optimised for higher emissions levels, to achieve new lower emission levels is generally not a simple matter – especially where larger improvements are sought. Changes will always involve some additional cost but also have the potential to impart excessive costs when considered in the context of the avoided environmental harm so delivered.

The situation is somewhat different at new installations, where designs may be optimised around new emission limit values from the outset, so that reduction may be achieved in a more cost-effective manner from the outset.

As such, **the design and cost barriers to achieving higher NOx reductions (for example to comply with a new ELV of below 100-120 mg/Nm3) at existing MSWI plant are generally expected be excessive. E**xceptions to this are not expected, but may exist in circumstances where:

- There are specific ambient air quality receptor concerns, and
- The installation is larger – makes a higher mass emission concentration contribution, and

  permits abatement cost efficiencies, and
- The existing installation design does not impart specific higher complexity / design cost issues that impart excessive cost, and

- Approaches can be implemented without imparting other significant operational risks, or cross media impacts e.g., Ammonia slip issues, energy efficiency impacts, corrosion / fouling risks, throughout / availability risk more generally

So, it is generally expected that existing installations will be able to make a robust case for 100-120 mg/Nm^3 being "beyond BAT" (costs outweigh benefits).

Achieving lower emission reductions (i.e., in the region of 10-30 mg/Nm^3 and in general an ELV of ~150mg/Nm^3) has rather more potential as it may arise from the implementation of the lower cost / risk optimisation approaches noted in this report i.e., by deploying those approaches with the lowest barriers to implementation noted in Section 6.5.3.

However, this is a general conclusion. Whether an ELV of 150mg/Nm^3 represents BAT for a specific installation, and which techniques, or combination are appropriate, remains a matter that requires plant specific assessment. Requesting such site specific "BAT" assessments via Improvement Conditions would appear to be reasonable. Noting the variations in design, age and performance seen across the fleet, it is not expected that generic studies will deliver a suitably robust assessment.

6.5.5 Regulatory criteria evaluation summary

The table below provides a high-level summary evaluation of each technical approach against key regulatory evaluation criteria including cross media effects.

Table 22 Summary of NOx Reduction approach impacts

Approach / Area	Method/ technique	CAPEX	OPEX	Project risk / integration complexity to plant	NOx Emission reduction potential	NOx ELV compatibility	Expected potential impact on other media (+ = positive from an environmental perspective e.g. air emissions reduction, energy efficiency improvement, residue quality improved)			
							Energy	Slip	Water	Residues
Primary Reduction	Reduce EAR	L	L May enhance	H	M/L	All	+	0	0	0
	Optimise air supply / distribution	L	L	M	M/L		+	0	0	0
	Enhance combustion control	M	M	M	M		0	0	0	+
	Oxygen enrichment	H	H	H	M		-	0	0	+
	Flue Gas recirculation	H/M	H/M	H	M		+	0	0	0
SNCR Optimisation	Reagent change	H/M	H/M	H	L	When targeting lower enhancement and ELVs of ~150-180mg/Nm^3	0	+/-	?	-
	Reagent dose rate increase	L	L	L	L		0	-	?	-
	Optimise SNCR locations to suit temperature profile in the furnace	L	L	M	M/L		0	+	?	+
	Optimise SNCR monitoring, control & instrumentation	L	L	M	M/L		0	+	?	+
SNCR Extension	Reagent change	H/M	H/M	H	L	When targeting greater enhancement to ELVs of ~120-150mg/Nm^3	0	?	?	?
	Reagent dose rate increase	L	L	L	M/L		0	-	?	-
	Optimised SNCR locations to suit the temperature profile in the furnace with monitoring, control & instrumentation	M/L	M/L	M	M		0	+	?	+
SCR	Addition of SCR	H	H	H	H	<80mg/Nm^3	-	+	0	0
Cat. filters	Use of catalytic bag filters	Insufficient information								

7. Task 4 – Multi criteria Analysis Assessment of Impacts

Multi-Criteria Analysis (MCA) can be used to evaluate the ability of an activity to achieve an objective while enabling the consequences of the activity to be reviewed. As such this provides a useful tool to assess the possibilities of achieving further NOx reductions for existing plant.

The principles of the assessment are that a number of weighted criteria are used to determine the key sensitivities that are present for an individual project. Each criterion is individually considered, the input being assessed and multiplied by its weighting. Each of the outputs are then summated to form an output quantum which can be compared to other options to allow ranking of projects or options to be completed.

In this case, the MCA has considered a number of related consequences that might occur through the implementation of a more stringent NOx limit to a facility. These are described in the following section and they, and the initial weightings, were discussed and agreed in a meeting with the Environment Agency to be reasonably representative of the issues that would arise on a development together with the cross medial impacts on a facility.

For example, a site with a sensitive local environment that required the NOx emission levels to be much lower may have an unintended consequence of not being able to recover the bottom ash (some survey respondents indicated ammonia odours from the ash).

It should be noted that the purpose of this report was to propose the use of MCA to assist in the assessment of guidelines into NOx controls. Further selection and consideration of both criteria and weightings to consider related impacts, e.g. carbon impacts of recycling gains or losses as well as environmental would be required to develop the tool for more general issue and use.

The following outlines the tool designed for this project. It is possible to modify the tool to account for the circumstances and consider site-specific parameters at different plants. The model outputs then can be used to develop discussions around focussed areas.

The following sections describe the factors involved in the model

7.1 Criteria

The criteria used for the assessment are derived from consideration of a range of factors and potential impacts that are relevant if a WtE plant is required to achieve more stringent emission limits. These factors include:

- **Site of Special Scientific Interest (SSSI)**- Distance (within km) - These are areas that may be impacted by any changes in the emissions resulting from any changes in plant operations. Information on receptors would be developed as part of the planning and permit application for the site.
- **Air Quality Management area** (AQMA) – This is included as some plants may be contributing to the air quality in an AQMA which are part of a framework to assist in the achievement of national air quality objectives. As such any change in contribution (either positive or negative) to these areas must be considered.
- **Area of population**: Developed site area within 10km of site. An area of population results in the presence of sensitive receptors that can be significantly impacted by air quality.
- **Stack concentration, Ammonia Slip** – An increase in the emissions of ammonia is a possible consequence of using additional reagent to reduce the NO_X. This was not found at all plant data submitted by respondents but can result from a number of factors that reduce the effectiveness of the reagent.
- **Stack concentration, Nitrous Oxide (N_2O)** – It has been reported that under certain conditions the concentration of N_2O emitted increases and as N_2O is a more active greenhouse gas than CO_2 can result in a negative impact hence in its inclusion in the assessment.

- **Stack concentration, NO_X ($NO+NO_2$) –** This is the objective of the project and subject of interest.
- **Stack concentration, CO –** One of the possible impacts is a possible increase in CO emissions resulting from changes in combustion conditions. Any changes should be controlled and reduced by combustion control system.
- **Stack concentration, CO_2** Changes in combustion control and process efficiency could impact the emission of CO_2.
- **IBA – Cost of Disposal/ Treatment** – changes to the composition of the IBA resulting from changes in chemistry may impact on the disposal of the material.
- **IBA – Recoverability** changes to the composition of the IBA resulting from changes in chemistry may restrict the uses of materials.
- **Boiler Ash – Cost of Disposal/ Treatment –** See IBA comments
- **Boiler Ash – Recoverability -** See IBA comments
- **APCr – Cost of Disposal/ Treatment** – See IBA comments
- **APCr – Recoverability** – See IBA comments
- **Plant Efficiency**- Although considering SNCR rather than SCR, there is potential for some controls to have an effect on the plant efficiency.
- **Operating costs -** Operating costs are likely to increase due to factors such as increased reagent requirements
- **Project lifetime –** The remaining plant operating life is considered as this would determine the viability of any investment required to attain the BAT-AELs

Some of the criteria contribute to the overall environmental impact of the process i.e. the recoverability of IBA and boiler ash. There may be a scenario that suggests a negative overall environmental impact when considering all areas of the environment. However, this could be considered in discussions to avoid such an outcome.

7.2 Criteria Weightings

The weightings attributed to each element for the initial discussion of the tool in this application are not derived by detailed analysis and will require further refinement outside of the scope of this preliminary study.

The weighting factor indicates the degree of severity of the criteria against the desired outcome. For example, to carry out a change to a process that results in the change from IBA that can be recovered to aggregate use to one that must be disposed of would be a significant change, both commercially and environmentally. Therefore, the weighting on this element is higher than some of the others.

7.3 MCA tool

The following sections explain how to use the tool.

It is suggested that the data used in the original planning application and reported operating data such as typical reported emissions be used in the tool to provide a baseline assessment, against which subsequent models be compared. These subsequent models should be developed around appropriate approaches for each plant to achieve the BAT-AELS i.e. increased reagent to change of technology.

7.3.1 Criteria Assessed

The criteria assessed tab lists the weighting for each criterion. These have been defined in respect to the environmental impact of the assigned criteria. The weighting tab does allow a user to change criteria weightings. However, to highlight differences between plant this should be kept the same once agreed.

Consequently, the approach is to discuss and agree the weightings prior to using the tool to assess the impacts. The criteria and associated parameters are shown in Figure 9.

Ricardo have assigned assessment criteria and initial weightings on the basis of:

- Information from the paper study describing the different approaches/technologies that meet the BAT AEL's and the possible consequences e.g. increases in ammonia and nitrous oxide emissions.
- Information from the plant real world testing e.g. impact on ash and abatement control unit residues
- Areas that would be sensitive to any changes in the contribution from plants such as SSSI and air quality management zones. However, this would entail more complex considerations as a plant is not the only contribution to impacts in these areas.

The scoring approach has been based on the possible severity of an impact. This has been moderated by using factors such as distance from the source.

Figure 9 - Tool Quantitative Criteria

Instructions

Please allocate weightings against the criteria you deem to be the most important to your authority.
There is 100% to be allocated across the weightings, this can be spread across all criteria or just a few.
Please enter values in the green boxes - Assume criteria and weighting are the same for all countries

Quantitative Criteria

Criteria number	Criteria	Units	Scoring approach	Weighting
1	SSSI- Distance (within km)	Km	Scoring of 1-5 based on ranges, 1:>10, 2:[8-10], 3:[5-8], 4:[2-5], 5:<2	5%
2	Air Quality Management Zone	Km	Scoring of 1-5 based on ranges, 1:>10, 2:[8-10], 3:[5-8], 4:[2-5], 5:<2	5%
3	Area of population: Developed site area within 10km of site	Hectares	Scoring of 1-5 based on ranges, 1:[0-7,500], 2:[7,500-15,000], 3:[15,000-22,500], 4:[22,500-31,400], 5:>31,400	5%
4	Stack concentration, Ammonia Slip	mg/Nm3	Scoring of 1-5 based on ranges, 1:[0-4], 2:[4-6], 3:[6-8], 4:[8-10], 5:>10	1%
5	Stack concentration, N2O	mg/Nm3	Scoring of 1-5 based on ranges, 1:[0-4], 2:[4-6], 3:[6-8], 4:[8-10], 5:>10	8%
6	Stack concentration, NO_X ($NO+NO_2$)	mg/Nm3	Scoring of 1-5 based on ranges, 1:[100-120], 2:[120-140], 3:[140-160], 4:[160-180], 5:>180	5%
7	Stack concentration, CO	mg/Nm3	Scoring of 1-5 based on ranges, 1:[0-10], 2:[10-20], 3:[20-30], 4:[30-40], 5:>40	1%
8	Stack concentration, CO2	mg/Nm3	Scoring of 1-5 based on ranges, 1:[0-4], 2:[4-6], 3:[6-8], 4:[8-10], 5:>10	5%
9	IBA - Cost of Disposal/ Treatment	%	Percentage of existing costs. Scoring of 1-5 based on ranges, 1: [0-600], 2: [600-1,200], 3:[1,200-1,800], 4:[1,800-2,400], 5:>2,400	10%
10	IBA - Recoverability	%	Percentage of recovery achieved following upgrade. Scoring of 1-5 based on ranges, 1:[98-100], 2:[96-98], 3:[94-96], 4:[92-94], 5:[90-92]	20%
11	Boiler Ash - Cost of Disposal/ Treatment	%	Percentage of existing costs. Scoring of 1-5 based on ranges, 1: [0-600], 2: [600-1,200], 3:[1,200-1,800], 4:[1,800-2,400], 5:>2,400	5%
12	Boiler Ash - Recoverability	%	Percentage of recovery achieved following upgrade. Scoring of 1-5 based on ranges, 1:[80-100], 2:[60-80], 3:[40-60], 4:[20-40], 5:[0-20]	5%
13	APCr - Cost of Disposal/ Treatment	%	Percentage of existing costs. Scoring of 1-5 based on ranges, 1: [0-600], 2: [600-1,200], 3:[1,200-1,800], 4:[1,800-2,400], 5:>2,400	5%
14	APCr - Recoverability	%	Percentage of recovery achieved following upgrade. Scoring of 1-5 based on ranges, 1:[80-100], 2:[60-80], 3:[40-60], 4:[20-40], 5:[0-20]	5%
15	Plant Efficiency	%	Percentage improvement on R1 efficiency. Scoring of 1-5 based on ranges, 1: [0-2], 2:[2-4], 3:[4-6], 4:[6-8], 5:>8	3%
16	Operating costs	%	Percentage increase on annual operational costs, averaged over 3 years. Scoring of 1-5 based on ranges, 1:[0-4], 2:[4-8], 3:[8-12], 4:[12-16], 5:>16	3%
17	Project lifetime	years	Expected operating lifetime of the facility post gaining of any necessary approvals. Scoring of 1-5 based on ranges, 1:>20, 2:[15-20], 3:[10-15], 4:[5-10], 5:[0-5]	10%

Weighting Check OK 100.00%

7.3.2 Entries

The finalised tool i.e. with weightings and scoring approaches agreed can be used by plant specific values e.g. Distance from SSSI etc. Values are inputted in the value column in the units defined in the units column of the data entry tab. Figure 10 shows the value input table. An example of inputs is shown in Figure 11

Figure 10 - Value input table

Instructions
Please enter the values for each criterion.

Criterion	Value	Units	Entry Check
SSSI- Distance (within km)		Km	Please enter value
Air Quality Management Zone		Km	Please enter value
Area of population: Developed site area within 10km of site		Hectares	Please enter value
Stack concentration, Ammonia Slip		mg/Nm3	Please enter value
Stack concentration, N2O		mg/Nm3	Please enter value
Stack concentration, NOX (NO+NO2)		mg/Nm3	Please enter value
Stack concentration, CO		mg/Nm3	Please enter value
Stack concentration, CO2		mg/Nm3	Please enter value
IBA - Cost of Disposal/ Treatment		%	Please enter value
IBA - Recoverability		%	Please enter value
Boiler Ash - Cost of Disposal/ Treatment		%	Please enter value
Boiler Ash - Recoverability		%	Please enter value
APCr - Cost of Disposal/ Treatment		%	Please enter value
APCr - Recoverability		%	Please enter value
Plant Efficiency		%	Please enter value
Operating costs		%	Please enter value
Project lifetime		years	Please enter value

Figure 11- Example data entry

Entries

Instructions
Please enter the values for each criterion.

Criterion	Value	Units	Entry Check
SSSI- Distance (within km)	3.50	Km	
Air Quality Management Zone	3.50	Km	
Area of population: Developed site area within 10km of site	6,612.00	Hectares	
Stack concentration, Ammonia Slip	0.10	mg/Nm3	
Stack concentration, N2O	25.00	mg/Nm3	
Stack concentration, NOX (NO+NO2)	170.00	mg/Nm3	
Stack concentration, CO	10.00	mg/Nm3	
Stack concentration, CO2	9.00	mg/Nm3	
IBA - Cost of Disposal/ Treatment	50%	%	
IBA - Recoverability	90%	%	
Boiler Ash - Cost of Disposal/ Treatment	100%	%	
Boiler Ash - Recoverability	95%	%	
APCr - Cost of Disposal/ Treatment	100%	%	
APCr - Recoverability	5%	%	
Plant Efficiency	95%	%	
Operating costs	6%	%	
Project lifetime	20.00	years	

7.3.3 Scoring

The scoring is determined by the model and the weightings associated with each of the criteria to provide an associated score for each relating to the impact. This scoring is used to devise the final scoring to rank the criteria in respect to impact i.e. highest to lowest as listed in the Final score

The scoring using example data can be seen in Figure 12.

Figure 12 Scoring output

Scoring

The table below assigns scores to the entries of each criterion, based on the scoring approach.
The colours correspond to different levels of impact:

Less Impact	1
	2
	3
	4
Greatest Impact	5

Criterion	Value	Scoring	Weighting
SSSI- Distance (within km)	3.50	4	5%
Air Quality Management Zone	3.50	4	5%
Area of population: Developed site area within 10km of site	6,612.00	1	5%
Stack concentration, Ammonia Slip	0.10	1	1%
Stack concentration, N2O	25.00	5	8%
Stack concentration, NOX (NO+NO2)	170.00	4	5%
Stack concentration, CO	10.00	1	1%
Stack concentration, CO2	9.00	4	5%
IBA - Cost of Disposal/ Treatment	50%	1	10%
IBA - Recoverability	90%	5	20%
Boiler Ash - Cost of Disposal/ Treatment	100%	1	5%
Boiler Ash - Recoverability	95%	1	5%
APCr - Cost of Disposal/ Treatment	100%	1	5%
APCr - Recoverability	5%	5	5%
Plant Efficiency	95%	5	3%
Operating costs	6%	2	3%
Project lifetime	20.00	2	10%

7.3.4 Final scoring

The assessment tool produces a final scoring table that ranks the scores highlighting the criteria with the greatest impact. The final scoring produced using the example data can be seen in Figure 13

Figure 13 - Final Scoring and ranking

Final Scoring

The table below calculates the final weighted score for each criterion, according to the scores assigned and its corresponding weighting. It also provides a ranking of the criteria. In order to see the top ranking criterion on the top of the table, select the filter button on the "Rank" column and press "Sort Smallest to Largest".

Less Impact

Greatest Impact

Criteria number	Criteria	Weighted Score	Commentary	Rank
1	SSSI- Distance (within km)	0.2		4
2	Air Quality Management Zone	0.2		5
3	Area of population: Developed site area within 10km of site	0.1		11
4	Stack concentration, Ammonia Slip	0.0		16
5	Stack concentration, N2O	0.4		2
6	Stack concentration, NOX (NO+NO2)	0.2		6
7	Stack concentration, CO	0.0		17
8	Stack concentration, CO2	0.2		7
9	IBA - Cost of Disposal/ Treatment	0.1		10
10	IBA - Recoverability	1.0		1
11	Boiler Ash - Cost of Disposal/ Treatment	0.1		12
12	Boiler Ash - Recoverability	0.1		13
13	APCr - Cost of Disposal/ Treatment	0.1		14
14	APCr - Recoverability	0.3		3
15	Plant Efficiency	0.1		9
16	Operating costs	0.1		15
17	Project lifetime	0.2		8

Total Score:	3.1

8. Conclusions and recommendations

It was found that SNCR is the only technology currently being utilised for NOx reduction in existing municipal waste UK WtE plant.

Data provided by WtE operators suggests that a number of plants could potentially achieve NOx emission concentrations that are less than the upper BAT AEL range following adjustment of the installed existing technologies without the need for significant changes to plant or the change to a different technology. However, this is unlikely to be the situation for all plant.

Plants providing data generally used increasing set points i.e. dosing rates on the SNCR systems to investigate the possibilities of reducing and controlling NO_X emissions. Evidence provided showed that this approach is capable of reaching the required levels. Whilst some plant may be able to achieve the BAT-AELs by increasing reagent dosing rates, this may not be the same for all plants. The optimisation of dosing would need to be undertaken.

Increasing rates of dosing would result in a corresponding increase in operating costs. The project does not have information to be able to quantify this cost.

The newest plant from the which the project received data was operating at permitted levels of NO_X levels below the upper BAT AELs range using SNCR. This is confirmation that the SNCR is capable of operating at the required levels.

The data supplied does not provide evidence on the long-term impact on the operation and of existing plant when adjustments have been made to achieve the required emission concentrations

For individual plants a site-specific assessment will be needed to determine the NOx reduction possible and any engineering needed to attain the BAT-AELs.

Assessments and trials should be undertaken to ensure that the BAT-AELs can be achieved and possibly exceeded consistently without significant impact on plant or that further intervention is required. The same approach will be needed to determine what further NOx reductions may be possible below the top-end of the BAT-AEL range. These trials should be undertaken in accordance with defined criteria to ensure the data produced is comparable.

Fundamental design matters are largely fixed by project decisions early in the development of a WtE plant and establish major constraints, which then become the “set point” for fundamental design decisions. Changes to such fundamental aspects (e.g. redesign and replacement of the furnace with one of a different design) are highly capital intensive and may also require prolonged major outages (several months) to implement. Such changes also come with potential operational risks. As such, reducing NOx emissions at existing plants through primary means is in general not likely to be viable

It was not possible to provide quantitative data on applicability of NOx reduction techniques at a WtE plant.

An assessment tool was developed to allow consideration of environmental impacts of NOx reduction improvements. This can be used to undertake site and plant comparisons

9. References

Frans Moorman, Bernd von der Heide, Claus Stubenhöfer *Replacement of an SCR DeNOx System by a Highly Efficient SNCR in a Waste-to-Energy Plant in the Netherlands, Presented at VGB Workshop "Flue Gas Cleaning", Rotterdam, 15 – 16 May 2013*,

Bernd von der Heide, (2017) *Future-Oriented SNCR Technologies – Application and Advantages of Selective Cooling in Large Coal-Fired Boilers*

Dipl.-Ing. Bernd von der Heide (2010) *NOx Reduction for the Future with the SNCR Technology for Medium and Large Combustion Plants*

Fred Sigg, Roland Halter, Peter Chromec. (2010) *DyNORTM DENOX PERFORMANCE CONFIRMED IN FURTHER MSW PLANTS.*

International Solid Waste Association *Waste to Energy State of the Art Report Statistics*

Mario Grosso, Lucia Rigamonti *Experimental assessment of N2O emissions from waste incineration: the role of NOx control technology*

Crisanto Mendoza-Covarrubias, Carlos E. Romero, Fernando Hernandez-Rosales, Hans Agarwal *N_2O Formation in Selective Non-Catalytic NOx Reduction Processes*

L J Muzio, T D Martz, T A Montgomery, G.C Quartucy, J A Cole, J.C Kramlich *N_2O Formation in Selective Non-Catalytic NO_X reduction process*

Oliver Gohlke, *Facing New NOx Reduction Challenges in Energy from Waste Systems*

N. Verdone, G. Liuzzo, P. De Filippis & F. Mazzoni *Oxygen-enhanced combustion in waste incineration:economic and environmental considerations*

DEFRA (2013) *Incineration of Municipal Solid Waste*

Jo Van Caneghem,*, Johan De Greef, Chantal Block, Carlo Vandecasteele *NOx reduction in waste incinerators by SCR instead of SNCR compared from a life cycle perspective: a case study*

John L. Sorrels, David D. Randall, Karen S. Schaffner, Carrie Richardson Fry.(2019) *Selective Catalytic Reduction*

Tomáš Blejchař,*, Jaroslav Konvička, Bernd von der Heide, Rostislav Malý, and Miloš Maier. *High Temperature Modification of SNCR Technology and its Impact on NOx Removal Process*

Matthias Schneider Kolkata, Raipur,(2016) *Combustion Optimization & SNCR Technology for coal*

fired power stations and retrofit experience

Piotr Krawczyk *Experimental investigation of N2O formation in selective non-catalytic NOx*

reduction processes performed in stoker boiler

Seongmin Kang , Joonyoung Roh and Eui-chan Jeon , *Major Elements to Consider in Developing Ammonia Emission Factor at Municipal Solid Waste (MSW) Incinerators*

Giuseppe Liuzzo, Nicola Verdone *, Marco Bravi (2006*) The benefits of flue gas recirculation in waste incineration*

Tolvik Consulting 2020 UK Energy from Waste Statistics - 2019

Jun Donga,b,c,∗, Harish Kumar Jeswanic, Ange Nzihoub, Adisa *Azapagicc The environmental cost of recovering energy from municipal solid waste*

Appendices

A1 Provided Plant Data – Reduction trials

O&M issues - Trial Period	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
Date of trial	No trials carried out to reduce NO_X from permitted 150 mg/Nm^3	July 2019			
Any general maintenance issues on SNCR/Catalytic bag filters / additional maintenance costs	Not applicable	APCR recirculation reduced.	Bag filters tend to blind quicker as the set point of NOx emissions is reduced. Pulse and frequency of the reverse air required adjustment to avoid bag blockages	None over ordinary operation	Nil
O&M issues including Blockage in Reagent Injection System /frequency of nozzle replacement	Not applicable	Nozzles cleaned IR camera serviced & cleaned in readiness for trial - no problems during trial.	Ammonia injection is affected mostly by the atomising air. Once set to optimise ammonia slip the system will run reliably.	None over ordinary operation	Nil
Any Ash Blockage issues due to formation of chloride component in ash system including bag filters	Not applicable	None, reverse pulse cleaning program remained unchanged.	Not Known Unlikely	High bag filter pressure drop, this could be due to high levels of ammonia salt formation and could be burnt off at 160C+. This process of increasing flue gas temp to achieve 160C has been carried out for periods of 1 hour at a time. Increased NH3 could be noticed but with little impact on bag filter DP.	Some hopper blockages, with a higher differential pressure across the bag filter and an increase in the ID fan levels, potentially due to chloride formation.
Any catalyst poisoning issue and 'ammonium bisulphate' formation /blockage for SCR	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
For catalytic bag filters – ID fan power consumption (w.r.t % of Total Gross Power Generation)	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Frequency of replacement of catalytic bag filters	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Any other technical/operation/maintenance issues (NOx abatement technology as installed)	Not applicable		With the existing equipment, practical reduction from 200mg/Nm^3 to 170mg/Nm^3 could be achieved. If the set point was reduced further, the system became		Anecdotally the site reported increased ammonia levels in the IBA

O&M issues - Trial Period	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
			unreliable and the quantity of ammonia increase with no real gain on emissions.		
Reagent used- Trial Period / NOx Performance					
Type	Not applicable	Urea Pril	Ammonia Concentration 25%	Ammonia 46% Nitrogen	
Test Procedures / Duration for Each Test Period 1/2/3/4/5	Not applicable	Prepared plant by cleaning injection lances, IR camera, Reduce NOx set point Two trials carried out at 180 (Period 1) and 160mg/Nm3 (Period 2)	7 days and 5 test runs carried out	Weekly test in a total period of three weeks	Weekly tests conducted in boiler 2. Total duration was four weeks. As the test was only conducted on one-line, accurate reagent consumption wasn't available.
Test description(Process "Boundary Conditions") for Each Test Period 1/2/3/4/5	Not applicable	Set points reduced in a controlled and stipulated time frame.	Set point changed in the following order For 1st tests SP = 180mg/Nm^3, for 2nd test SP = 185mg/Nm^3, for 3rd test SP = 180mg/Nm^3 for fourth test SP = 175mg/Nm^3, for 5th test SP = 170mg/Nm^3	We decreased the emission level progressively to understand the effects on ammonia slip and reagent consumption, see results below.	We decreased the emission level progressively to understand the effects on ammonia slip and reagent consumption, see results below.
Average reagent consumption per month (Trial period) or Each Test Period 1/2/3/4/5	Not applicable	Period 1 5% to 8% Period 2 30%	Period 1 = 2.5 Period 2 = 2.2 Period 3 = 3.2 Period 4 = 3.8 Period 5 = 3.7	Period 1 = 484 kg/day Period 2 = 567 kg/day Period 3 = 617 kg/day	
Average NOx per month(Trial Period) - litres/tonne of waste month(Trial Period) mg/Nm3	Not applicable	Period 1 150 Period 2 130	Period 1 = 158 Period 2 = 160 Period 3 = 155 Period 4 = 152 Period 5= 149	Period 1 = 161 Period 2 = 148 Period 3 = 141	Period 1 = 169 Period 2 = 174 Period 3 = 163 Period 4 = 151
Average ammonia slip per month(Trial Period) mg/Nm3	Not applicable	No Data	Period 1 = 0.45 Period 2 = 0.25	Period 1 = 2.6 Period 2 = 3.4	Period 1 = 2.6 Period 2 = 1.6

O&M issues - Trial Period	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
			Period 3 = 0.28 Period 4 = 0.4 Period 5= 0.55	Period 3 = 8.6	Period 3 = 1.7 Period 4 = 3.2
Any N_2O measurement(Trial period)	Not applicable	No Data		Period 1 = 4.4 Period 2 = 4.0 Period 3 = 4.4	

O&M issues - Trial Period	Plant 6	Plant 7	Plant 8	Plant 9
Any general maintenance issues on SNCR/Catalytic bag filters / additional maintenance costs			No	No significant additional maintenance required during the trials as they were relatively short term.
O&M issues including Blockage in Reagent Injection System /frequency of nozzle replacement	Nozzle system blockages very rare. Weekly flush is undertaken.		Preventative maintenance required to clean the injection lances on a weekly basis.	The trials were undertaken specifically to demonstrate if the storage delivery and handling systems could deliver the required urea flow and meet the NOx set point at an acceptable ammonia slip. The trials with the Prilled Urea were deemed largely unsuccessful due to repeated blockages. The trials with the Granular Urea were deemed to be able to achieve the NOx set points, and for the relatively short duration trials <1% of the time was spent at the 70% limit of the screw speed.
Any Ash Blockage issues due to formation of chloride component in ash system including bag filters	No salt build up on bag filters. Differential pressure readings taken across the bag house to monitor for this issue.		No	Not applicable
Any catalyst poisoning issue and 'ammonium bisulphate' formation /blockage for SCR	Not applicable		No	Not applicable
For catalytic bag filters – ID fan power consumption (w.r.t % of Total Gross Power Generation)	Not applicable		No	Not applicable
Frequency of replacement of catalytic bag filters	Not applicable		No	
Any other technical/operation/maintenance issues (NOx abatement technology as installed)		Potential limitations with the control loop were highlighted, where a slow response at lower NOx setpoints led to sudden drops in the NOx concentration and increases in the NH3 slip. The system was also observed to be continuously dosing at the highest level 4, suggesting that a level above this may be required for optimal operation. Availability of	Stability of the combustion (secondary air) impacts on the NOx levels directly. Optimisation required in this area to reduce the variability in the process.	Ammonia in ash results were also analysed during the trials and were increased at the reduced set points and increased from 168 mg/kg for the 'baseline' to 778 mg/kg for the 180 mg/Nm3 NOx set point, which would go some way to explaining the only modest increases in ammonia slip measured at the stack. The data presented shows longer term averages are achievable, but reductions of

O&M issues - Trial Period	Plant 6	Plant 7	Plant 8	Plant 9
		space for an additional injection level would have to be evaluated.		short term ELVs would pose some operational risk.
Reagent used- Trial Period / NOx Performance				
Type	Ammonia (33%)	Ammonia (24.5%)	Urea (25%)	Urea (Solid)
Test Procedures / Duration for Each Test Period 1/2/3/4/5	A series of 1 week tests were conducted, during each test the following ammonia dosing rates were maintained. Test Period 1. Operation at reference conditions Ammonia 80 l/hr Test Period 2. Operation at Ammonia 85 l/hr Test Period 3. Operational at Ammonia 90 l/hr	Test involved reducing the SNCR NOx setpoint to investigate proposed BAT-AEL limits. Three setpoints (135, 110 and 90 mg/Nm3) were trialled on L1, between 17/07/19 - 01/09/19. 135 mg/Nm3 held for 459 hrs, 110 mg/Nm3 held for 233.5 hrs and 90 mg/Nm3 held for 159 hrs	Durations below. Steam setpoint kept constant at 52 t/hr and setpoint for NOx altered on control panel for urea to furnace.	Trials performed at varying set points with both prilled and granular urea. 160 & 136 mg/Nm3 NOx set point (to meet 180 & 150 mg/Nm3 BREF with some operational margin) trial repeated in 2020 following an operational increase in boiler load from 55 to 57 t/hr
Test description(Process "Boundary Conditions") for Each Test Period 1/2/3/4/5	1. large array of plant performance parameters monitored 2. large array of plant performance parameters monitored 3. Array of emission parameters monitored (NOx, NH_3, N_2O)	Steam production setpoint maintained as constant as possible during the period, to ensure that all systems experienced the same thermal demand during each of the test periods.	1) NOx SP 195 2) NOx SP 180 3) NOx SP 150	1. NOx set point of 180 mg/Nm^3 @ 11% O2 with priled urea (c.f 'normal' operation at current set point with Granular urea) 2. NOx set point of 160 mg/Nm3 @ 11% O2 with granular urea (to meet 180mg/Nm^3 BREF with some operational margin) 3. NOx set point of 160 mg/Nm^3 @ 11% O2 with prilled urea (to meet 180mg/Nm3 BREF with some operational margin) 4. NOx set point of 136 mg/Nm^3 @ 11% O2 with granular urea (to meet 150mg/Nm3 BREF with some operational margin) 5. NOx set point of 136 mg/Nm^3 @ 11% O2 with prilled urea (to meet 150mg/Nm^3 BREF with some operational margin) 6. Repeat Test 2 at slightly increased boiler load .
Average reagent consumption per month (Trial period) or Each Test Period 1/2/3/4/5	Period 1 = 79 Period 2 = 85	Period 1 = 35.4 Period 2 = 46.5	Period 1 = 13 t (1.65kg/t) Period 2 = 43.21t (1.72 kg/t)	Period 1 = 42.1kg/hr Period 2 = 57.2g/hr

O&M issues - Trial Period	Plant 6	Plant 7	Plant 8	Plant 9
	Period 3 = 90	Period 3 = 44.4 Reaction efficiency seen to decrease for the lowest NOx setpoints (observed by an increase in NH3 slip and presence of ammonia in air pollution control residue (APCR)).	Period 3 = 42.84t (3.81 kg/t) Significant increase in reagent consumption when the 150 set-point was trialled, see NOx comment below.	Period 3 = 45.4 kg/hr Period 4 = 56.7 kg/hr Period 5 = 64.3 kg/hr Current maximum urea delivery capacity (approx. 75 kg/hr) for circa 18% of the time on the lowest set point and granular urea.
Average NOx per month(Trial Period) - litres/tonne of waste/month(Trial Period) mg/Nm3	Period 1 = 175 Period 2 = 146 Period 3 = 153	Period 1 = 135 Period 2 = 112 Period 3 = 99 Difficulty maintaining SP at the lower NOx levels, variability increased	Period 1 = 192 Period 2 = 178 Period 3 = 175 System unable to deliver NOx below 175 consistently during trial period. Unable to achieve the 150 set-point on average.	Period 1 = 42.1kg/hr Period 2 = 57.2g/hr Period 3 = 45.4 kg/hr Period 4 = 56.7 kg/hr Period 5 = 64.3 kg/hr
Average ammonia slip per month(Trial Period) mg/Nm3	Period 1 = 1.3 Period 2 = 0.9 Period 3 = 1.1	Period 1 = 1.3 Period 2 = 3.8 Period 3 = 5.2 Significant increase in NH3 slip at the lower NOx levels	Period 1 = 1.3 Period 2 = 2.2 Period 3 = 2.3 Increased ammonia slip in the flue gas. The ammonia concentration was not analysed in the APCR but based on other site data this is likely to have increased significantly as the concentration in the flue gas did not increase relative to the reagent consumption.	Period 1 = 180 Period 2 = 160 Period 3 = 160 Period 4 = 137 Period 5 = 174
Average APCR NH3 content over Test Period (Line 1)		Period 1 = 29 Period 2 = 35 Period 3 = 108		Period 1 = 3 Period 2 = 4 Period 3 = 5 Period 4 = 6 Period 5 = 8

O&M issues - Trial Period	Plant 6	Plant 7	Plant 8	Plant 9
Any N2O measurement(Trial period)			Period 1 = 1.6 Period 2 = 3.1 Period 3 = 2.6	

A2 Provided Plant Data – Normal operation

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
Plant Capacity	85,000 t/a MSW Gen 7.25MW	300,000tpa - Gen 26MW	80 MW + 57 MWth CHP	10.1MVA (rated)	17 MW
Number of lines	1	2	4	1	2
Type of waste	MSW Commercial & Industrial 200301 and 191212 small quantities 18 01 04 non-haz offensive waste	200,000 tonnes MSW 100000 tonnes Commercial	Mostly RDF. Medical only under RPS23 - negligible amounts.	MSW	MSW
Average Fuel Nitrogen in last 12 months	No Data	No Data	0.71	No data	No data
Flue gas temp (°C) 1st pass 100% MCR	Design = 975 Average = 1010 Max = 1050 Min = 910	Design = 1184 Average = 1184 Max = 1265 Min = 1138	Design = 1000 Average = 950 Max = 1250 Min = 900	Design = 890 Average = 792 Max = 1050 Min = 745	Design = Average = 930 Max = 980 Min = 850
NO_X Abatement Technology	Ammonia SNCR	SNCR Urea Pril Injection	SNCR	SNCR	FGR. SNCR,
NOx Abatement - Name of Technology Provider	Yara NOxCare	SAMAT	Keppel Seghers	Santenini	CNIM-LAB
Description	3 injectors per level 3 levels of ports. In normal running the higher one or two levels operate. During start-up and shutdown the system automatically moves the levels up and down as the temperatures change to optimise reaction Max design ammonia consumption 40kg/h	3 levels for injection points of which only the 2 lower levels used 3 injection points each level Temperature measurement on each level Flue gas temperature sensor/Acoustic pyrometer. Temp window SNCR grid 850°C to 900°C Best operation found at 900°C	There are 12 injection lances in use during normal running and 4 levels in which they can be placed with 20 possible injection points. During normal running six lances are in the lowest level and 6 in the highest level Only at start-up after a shutdown is the second level used for the first few weeks of operation. Flue gas temperature sensor/Acoustic	4x ports/nozzles per level, 2x levels 2x Raytek Pyrometers (120C to 1650C instrument range) K-type thermocouples and IR temperature probe. Temperature window 800 – 1050°C Urea prill from a silo, blown through. Qty delivered to furnace measured against stack NOx and NH3 Cooled jacket. System alternates between levels depending on temperature,	2x ports/nozzles per level, 2x levels Thermocouple on roof and IR thermometer on injection point System alternates between levels depending on temperature, cannot dose from both levels simultaneously. Upper level predominates at full load.

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
			pyrometer. Temp window SNCR grid 875ºC to 975ºC Best operation 950ºC	cannot dose from both levels simultaneously. Upper level predominates at full load.	
Operational Comments	Level of injection nozzles moved up one level in Outage 2018 - ammonia use and residue in flyash/IBA had increased - decreased after change.				
O&M Issues					
Any general maintenance issues on SNCR/Catalytic bag filters / additional maintenance costs	None	SNCR Urea prill injection Big Bag system loading hoppers. Mouth of hopper to feed screw prone to blocking due to symmetrical hopper & bridging taking place. Conveying system modified by replacing original shorter 90º bends with longer radius 90º bends with inspection/rodding ports. Blockages of distributors between conveying system and multiple injection lances, occasional.	No trouble-free system	Operationally, daily inspection of nozzles for missing distribution pins, heat corrosion on tips, cooling air flow. Distribution pot for injection points can block. Silo to injection screw can become clogged with clumpy urea. Maintenance PPM includes inspection of blower unit.	Weekly routines checking the nozzles for blockages, nozzles are replaced every 2-3months, maintenance on the compressors with filter cleans monthly, daily check of the Infrared temperature lens, approximately annual replacement of reagent delivery hoses, general maintenance on hopper system and screws, venturi cleaning every week
blockage in reagent injection system / frequency of nozzle replacement	Fairly frequent nozzle replacement, they burn away losing the optimised spray pattern. If there are problems with the water softeners this has a knock-on effect on	Frequency of blockages in reagent injection system roughly 1 each month. Nozzles cleaned at every opportunity whenever the first pass is out of service and cooled. Build-up accumulation quickly forms	None	See above for operational issues. Nozzle replacement as and when required, can generally be 2 months. Site run a routine a monthly basis to burn off chloride in bag filter. No ash blockages	Blockages occur on around a monthly basis in change over valve between top and bottom levels

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
	the SNCR and can result in limescale reducing flows.	and can grow up to 500mm into the first pass around some nozzles.		due to chloride have been identified.	
Any ash blockage issues due to formation of chloride component in ash system including bag filters				Site run a routine a monthly basis to burn off chloride in bag filter. No ash blockages due to chloride have been identified.	Not that has been confirmed as caused by chloride accumulation
Any catalyst poisoning issue and 'ammonium bisulphate' formation /blockage for SCR	Not applicable	Not applicable	Not applicable	Not applicable	
For catalytic bag filters – ID fan power consumption (w.r.t % of total power generation)	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Frequency of replacement of catalytic bag filters	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Frequency of catalyst replacement /its cycle	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Any other technical/operation/maintenance issues (NOx abatement technology as installed)	None	None	None	Urea hang up in silos. Silo humidity control.	
Reagent used/Performance					
Type	Ammonia Growhow Ammonia 24.5%	Urea Technical Grade	Urea Type Ammonia	Urea - Yara ctech	Urea - Dry prill Type
Concentration	24.5% diluted as per control system receipt depending on NOx levels (NOTE DAILY ELV = 150mg/Nm3 not the usual 200mg//Nm3) Note outage in May for the below figures for ammonia use		25%	46% nitrogen	

<table>
<tr><th></th><th>Plant 1</th><th>Plant 2</th><th>Plant 3</th><th>Plant 4</th><th colspan="2">Plant 5</th></tr>
<tr><td>Average consumption (total litres used in 12 months)</td><td>Ave.= 18667
Max =46766
Min = 7765
Stdev. =10574</td><td>Ave.= 57.8 tonnes
Max= 62 tonnes
Min =40 tonnes
Stdev. = 8 tonnes</td><td>Ave.= 2.6 kg/t
Max= 3.0kg/t
Min = 2.1 kg/.t
Stdev. = 0.3kg/t</td><td>Ave.= 456
Max= 530
Min = 360
Stdev. = 53</td><td colspan="2">Ave.= 19.8
Max= 23.0
Min = 13.0
Stdev. = 2.9</td></tr>
<tr><td>Average NO_X mg/Nm3-</td><td>Ave= 116
Max= 141
Min = 111
Stdev. 8</td><td>Ave= 146
Max= 157
Min = 138
Stdev. 8</td><td>Ave= 158
Max= 160
Min = 156
Stdev.= 1.3</td><td>Ave= 172
Max= 178
Min = 167
Stdev.= 3.1</td><td>Line 1
Ave =162
Max= 182
Min = 135
Stdev= 17</td><td>Line 2
Ave = 169
Max= 176
Min =160
Stdev=5</td></tr>
<tr><td>Average NH_3 mg/Nm3.</td><td>Ave.= 0.9
Max = 2.7
Min = 0.4
Stdev. = 0.7</td><td>Ave.= 1.0
Max = 2.0
Min = 0.3
Stdev. = 0.5</td><td>Ave.= 0.4
Max = 0.6
Min = 0.3
Stdev. = 0.1</td><td>Ave.= 5.8
Max = 11.0
Min = 2.0
Stdev. =3.2</td><td>Line 1
Ave =4
Max= 10
Min = 1
Stdev= 3</td><td>Line 2
Ave = 3
Max= 4
Min =2
Stdev=1</td></tr>
<tr><td>N_2O measurement mg/Nm3</td><td>< 1</td><td>Ave.= 9.1
Max = 15.2
Min = 4.5
Stdev. = 3.4</td><td>Ave.= 3.2
Max = 5.5
Min = 2.2
Stdev. = 1.1</td><td>7.11
9.84</td><td colspan="2"></td></tr>
</table>

	Plant 6	Plant 7	Plant 8	Plant 9
Plant Capacity	35MW	Design - 37.5 MW Max - 40.8 MW	10.84	26
Number of lines	2	2 - identical process lines, 5-pass boilers with separate flue gas treatment systems.	1	2
Type of waste	MSW	MSW	MSW	MSW
Average Fuel Nitrogen in last 12 months		0.57	0.44	0.6
Flue gas temp °C) 1st pass 100% MCR	Design = 884 Average = 814 Max = 845 Min = 747	Design = 1220 Average = 982 Max = 1018 Min = 886	Design = 1027 Average = 1100 Max = 1200 Min = 950	Design = 841-892 Average = 904 Max = 917 Min = 850
NO_X Abatement Technology	SNCR Ammonia	FGR, SCNR	SNCR	SNCR
NOx Abatement – Name of Technology Provider	Martin	Hitachi Zosen Inova (HZI) DyNOR system	ERC	CNIM / ECM
Description	9x ports/nozzles per level, 2x levels K-type thermocouples and IR temperature probe. 800 – 1050°C	4 distribution modules with 4 injection levels – each featuring a Y-Splitter into a 10° and 30° nozzle (4 levels and 32 nozzles in total) 4 temperature sensors sending control signals to the 4 distribution modules 850±75°C, allowable temperature deviation on the DCS NH4OH injection of 8-125 kg/hr @ 5.9 bar(g)	2 levels, 6 on each (see comments below) Thermocouple 870-1000°C	2 levels / 6 per level Pyrometer Upper level not currently used
Operational Comments			Additional 6 injection ports installed +7m above original installation location after thermal survey revealed injection point was too hot. The previous 6 set on the lower level have been left piped in but isolated.	No significant upgrades. Liners upgraded in urea screws and some pipework replaced.

O&M Issues				
Any general maintenance issues on SNCR/Catalytic bag filters / additional maintenance costs	Nozzle system blockages very rare. Weekly flush is undertaken.	Bespoke instrumentation for SNCR distributors and thermocouples often means that replacement parts have a long lead time.	Fouling of injection lances over time due to urea solution and furnace conditions. Cleaned once per week.	Requires general maintenance.
blockage in reagent injection system / frequency of nozzle replacement	Nozzle system blockages very rare. Weekly flush is undertaken.	Thermocouples are somewhat susceptible to being obscured, although this is generally easy to rectify.	Lance blockages if maintenance is not completed as above. Nozzles inspected when cleaning is undertaken, replaced as required. Additive dosed to the urea by the supplier to help minimise blockages in the system.	As the system is a solid urea-based system it has been prone to blockages in the dry urea storage silo, and in the delivery system to the injectors. The silo was not used for circa a year due to repeated blockages but is now in service with reasonably successful operation. There are still occasional blockages in the delivery systems to the injectors and would likely increase with an increase in urea mass flow longer term. Due to blockages in the delivery systems, the conveying screws were limited during the initial commissioning to 70% and have not been changed during operation.
Any ash blockage issues due to formation of chloride component in ash system including bag filters	No salt build up on bag filters. Differential pressure readings taken across the bag house to monitor for this issue.	Not applicable	Not applicable	
Any catalyst poisoning issue and 'ammonium bisulphate' formation /blockage for SCR	Not Applicable	Not Applicable	Not Applicable	
For catalytic bag filters – ID fan power consumption (w.r.t % of total power generation)	Not Applicable	Not Applicable	Not Applicable	Not Applicable
Frequency of replacement of catalytic bag filters	Not Applicable	Not Applicable	Not Applicable	Not Applicable
Frequency of catalyst replacement /its cycle	Not Applicable	Not Applicable	Not Applicable	Not Applicable
Any other technical/operation/maintenance			Stability of the combustion (secondary air) impacts on the NOx	

issues (NOx abatement technology as installed)			levels directly. Optimisation required in this area to reduce the variability in the process.	
Reagent used/Performance				
Type	Ammonia	Ammonia	Urea – Type solution with additive	Urea - Solid (Granular)
Concentration	33%	24.5%	25 %	N/A - Solid urea directly injected with Air as ballast medium.
Average consumption (12 months)	Ave.=108 Max = 133 Min = 39 Stdev. = 28	Sum for both lines Ave.= 52137 Max = 63166 Min = 41212 Stdev. = 6484	Ave.= 2.1 kg/t Max = 4.4 kg/t Min = 1.3 kg/t Stdev. = 0.9kg/t	Ave.= 45kg/hr Max = 57 kg/hr Min = 35 kg/hr Stdev. = 6.0 kg/hr
Average NO_X mg/Nm3-	Ave= 175 Max= 182 Min = 167 Stdev. 5	Ave= 135 Max= 136 Min = 135 Stdev. 0.3	Ave= 188 Max= 195 Min = 182 Stdev.= 4.0	Ave= 179 Max= 181 Min = 165 Stdev.=4.2
Average NH_3 mg/Nm3.	Ave.= 1.9 Max = 3.3 Min = 0.9 Stdev. = 0.8	Ave.= 0.4 Max = 0.5 Min = 0.3 Stdev. = 0.1	Ave.= 1.8 Max = 3.0 Min = 1.2 Stdev. = 0.5	Ave.= 2.6 Max = 3.4 Min = 1.9 Stdev. = 0.5
N_2O measurement mg/Nm3		9.6 38.45	Ave.= 2.4 Max = 3.0 Min = 1.4 Stdev. = 0.5	5.4 35.2

T: +44 (0) 1235 753000

E: enquiry@ricardo.com

W: ee.ricardo.com