LAYERED SOLUTIONS APPROACH FOR THE FULFILMENT OF NO$_x$ EMISSIONS LIMITS WHILE INCREASING BOILER OPERATIONAL FLEXIBILITY

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ABSTRACT

The fulfilment of NO\textsubscript{x} emission limits imposed by the European Community Environmental Regulations turns out to be one of the most important medium-term challenges to be faced by the Polish thermal power sector.

This paper presents the fundamentals and outcomes of a novel methodology, named Layered Solutions Approach, which gives response to this objective with maximum reliability and flexibility, overcoming the different operating constraints associated with the typical operation of industrial combustion facilities and with the performance of conventional technologies for NO\textsubscript{x} reduction or abatement.

This methodology, developed by the Spanish engineering company INERCO, along with its Polish associate partner KWANT and the collaboration of the Austrian firm INTEGRAL, is aimed at the abatement of NO\textsubscript{x} emissions below 200 mg/Nm\textsuperscript{3} by means of the staged application of primary and secondary measures under a reliable and cost-effective approach designed on a case-to-case basis.

This paper is focused on the description of Layered Solutions Approach, as well as the technological tools utilised so as to attain the objectives considered within a DeNO\textsubscript{x} project, including not only the achievement of NO\textsubscript{x} emissions targets but also upholding, or even, improving the efficiency and reliability of the process, while minimising capital and operating costs involved.

The technologies entailed in each stage of the Layered Solutions Approach are patented and, due to their demonstrated innovation and effectiveness, have international acknowledgments, such as ABACO technology, which is qualified as Best Available Technique for NO\textsubscript{x} control at the European IPPC Directive. Likewise, these technologies have been successfully applied worldwide with numerous references and noteworthy results concerning the reliable and flexible reduction of NO\textsubscript{x} emissions.
1. **General approach to 200 mg/Nm\(^3\) NO\(_x\) emissions**

The 2001/80/EC Directive for Large Combustion Plants has enforced a demanding 200 mg/Nm\(^3\) (d.b., as NO\(_2\), 6% O\(_2\)) NO\(_x\) emission limit for the thermal power sector, which will came into effect by 1\(^{\text{st}}\) January 2016. This limit might even be stricter in Poland, in accordance with their National Emissions Ceilings.

The implementation of Best Available Techniques for NO\(_x\) emissions abatement requires remarkable investments, whose negative impact over the economical profitability of the corresponding production processes must be necessarily palliated by power utilities.

In this context, some utilities have opted for the installation of high-efficiency NO\(_x\) abatement technologies based on separated SCR reactors, although this solution might not be optimised from an economical viewpoint, as it leads to extremely high investment costs.

Besides this, the application of such catalytic solutions is technically difficult in numerous existing facilities, due to the lack of available space to undertake such a noteworthy retrofitting action. Moreover, this alternative would seriously jeopardise their profitability, entailing serious difficulties to amortise the investment associated, which may even endanger the plant feasibility.

In contrast, other utilities are prone to the application of primary measures so as to achieve a maximum reduction in NO\(_x\) emissions at minimum cost, regardless of the in-furnace combustion conditions promoted, prior to the application of secondary measures (SNCR, SCR, SNCR/SCR hybrid solutions), with the final objective of minimising their scope and the investment involved.

Among the applicable primary measures, it can be mentioned the retrofitting and/or upgrading of the pre-existent burners (implementation of LNB), the retrofitting of the air windbox (OFA nozzles installation), and the implementation of uncontrolled stratified combustion combined with strong reduction of total combustion air.

Nevertheless, when deciding the scope of the DeNO\(_x\) technologies to be implemented in a particular combustion facility, the utilities must take into consideration a number of side effects which can be brought about when trying to attain the environmental targets required. Among these effects, the following can be mentioned:

- Increase in heat rate associated with the impossibility to reach the specified steam parameters, the increment of unburnt carbon-in-ash and the growth of sensible heat losses by the rise of flue gases temperature.
- Increment of maintenance needs due to the uncontrolled performance of combustion process and/or the massive injection of ammonia-based reagents, resulting in diverse phenomena, such as the corrosion, slagging or fouling of the bundle of tubes in the furnace and the air preheaters.
- Logistic problems related to the impossibility to sell the ashes generated to the cement industry because of the increment of carbon-in-ash content and the possible contamination with ammonia-based reagents.
- Environmental limitations associated with the ammonia slip limits, as well as the features of the flue gases plume released through the stack and the odour produced.
- Existence of interferences or incompatibilities in the joint performance of both primary and secondary measures by the uneven operating conditions typically promoted by the former.

Moreover, there are further constraints indissolubly linked to industrial reality: the existence of unavoidable changing operating scenarios that not only intensify the problems mentioned above but also jeopardize a steady fulfilment of the target NOx emissions, because of the lack of flexibility of conventional DeNOx technologies.

Among the factors negatively influencing the correct performance of these technologies it can be highlighted the variation in load profiles, the changes in fuel analyses (fuel substitution, blends variation, biomass co-firing) or the unlike arrangement of active mills due to either scheduled or unscheduled maintenance needs.

This comprehensive assessment has allowed INERCO/KWANT to identify the most challenging limitations to be solved when undertaking a DeNOx project in the current context, namely, the improvement of combustion regulation potential and flexibility, the enhancement of combustion control and the selection of the most adequate and cost-effective abatement technology to comply with NOx emissions targets while assuring plant efficiency and reliability.

The response of INERCO/KWANT to these challenges lies in the Layered Solutions Approach, which assumes the advantages associated with the staged response to the NOx emissions target, but giving priority to the plant safety and flexibility in a cost-effective way. This is achieved by the integration of dissimilar advanced technologies whose scope is to be designed on a case-to-case basis.

This approach firstly pursues the achievement of flexible minimum NOx emissions scenarios compatible with combustion control and operational safety. The distinctive feature of this innovative solution is added by the application of Controlled Furnace (ABACO) technology, which assures the implementation of primary measures with maximum potential.

ABACO technology has been successfully applied for optimising boilers and furnaces of very different design and consuming quite diverse fuels (anthracites, bituminous and sub-bituminous coals, lignites, petcoke, oil, gas, biomass). In this regard, the overall results and cost-effectiveness of ABACO have determined its qualification as Best Available Technique (BAT), for NOx reduction and boiler performance improvement for large coal-fired units, by the Integrated Pollutant Prevention and Control (IPPC) European Directive.

Starting from the safe lowest-NOx operating scenario, the following stage entails the integration of either conventional or tailor-made secondary measures, whose efficiency is
maximised by the advanced technological capabilities involved and its synergic integration within the Controlled Furnace approach.

The individualised techno-economic assessment of alternatives for each combustion facility leads to the reduction of the size and scope of the secondary measures technologies to meet the future NO\textsubscript{x} emissions target, this fact allowing capital and operating costs to be minimised with respect to other conventional NO\textsubscript{x} abatement solutions.

2. Fundamentals of the Layered Solutions Approach

The fundamentals of the Layered Solutions Approach offered by INERCO/KWANT are presented considering the two different stages established above.

2.1 1st Stage: Application of primary measures with maximum regulation potential and advanced combustion control

The approach conceived by INERCO/KWANT combines the achievement of minimum NO\textsubscript{x} emissions for every operating scenario with plant reliability and safety, through the targeted tuning of fuel and combustion air supplies to the boiler under a controlled approach. The actual added value conferred by this approach is the synergic integration of primary measures, either cutting-edge regulation capabilities or conventional NO\textsubscript{x} reduction technologies, with an advanced monitoring and control over combustion performance.

In this sense, the methodology developed is focused on the achievement of the following targets:

- The **enhancement of combustion regulation flexibility**, so as to take full advantage of the available combustion regulation devices, along with additional advanced combustion tuning capabilities.
- The **control over local in-furnace conditions**, as a means to gain maximum profitability from boiler tunings for combustion optimization (NO\textsubscript{x} emissions and heat rate), at the same time that safety limits for boiler regulations can be simultaneously maintained.

A brief description of the individual technologies employed by INERCO to meet the aforementioned objectives is included below.

**Enhancement of combustion regulation flexibility**

The objective of INERCO/KWANT is to maximize combustion tuning capabilities by providing the required technological tools to achieve an optimized combustion performance for any operating condition.

Different solutions can be applied by INERCO/KWANT to reach this objective, although the most innovative approach is the so-called FLEXICOM technology, whose arrangement involves the transfer of coal between different mills, so as to favour the supply of coal in lower boiler levels, regardless of the configuration of mills in service.
In this way, maximum residence time is promoted for a high rate of coal fed to the boiler without penalising its particle size distribution, which results in a reduction of NO\textsubscript{x} emissions without any remarkable effect on carbon-in-ash values.

The flexibility of this approach is absolutely original and guarantees a steadily optimised performance, as the combustion process can be concentrated and maintained in the lower boiler area for whichever mill arrangement, hence avoiding any potential negative influence on NO\textsubscript{x} emissions, heat flux distribution or steam parameters. Additionally, FLEXICOM technology minimise the potential impact of typical maintenance activities or the unavailability of the fuel supply/milling system.

As a complement to this absolutely distinctive approach, other available innovative solutions entail the upgrading of burners or the redesign of the windboxes, so as to intensify fuel and air stratification strategies, on the basis of more flexible supply patterns.

In addition to these actions, it can also be highlighted the improvement or implementation of other complementary boiler tuning capabilities which enhance the performance of the former. These additional boiler capabilities can be conveniently combined and include:

- Automation of existing manual regulations from control room.
- Implementation of regulation wear-proof dampers and valves, for the manual or automated balancing of fuel and air flow rates to each burner (ABACO-Coal and ABACO-Air).
- Improvement of classifier capabilities for optimising pulverised fuel size distribution while maintaining classifier production.

**Control over local in-furnace conditions**

The possibility of carrying out an adequate control over local combustion performance, promoting the so-called “Controlled Furnace” conditions, is intended to be the critical factor to assure maximum benefit of targeted combustion tunings.

These “Controlled Furnace” conditions can be exclusively achieved by the characterisation of in-furnace gas profiles through leading-edge ABACO-Opticom monitoring technology. This technology measures gas concentrations (O\textsubscript{2}, CO, CO\textsubscript{2}, NO\textsubscript{x}) in selected points of the furnace, mainly in a burner per burner basis, by means of water-cooled gas sampling probes withstanding the high temperatures in these areas of the furnace (up to 1.700 °C).

Hence, this innovative approach makes possible a real optimisation of individual burners, which unquestionably results in the overall optimisation of global combustion process, while limiting the appearance of possible combustion malfunctions.

The monitoring approach can be enhanced with other complementary monitoring means, whose scope is to be specifically decided according to plant design, operation characteristics and performance objectives: measurement of fuel and air flow rates (EMIR, APF and ASF
technologies), characterisation of additional fuel properties, determination of furnace temperature distributions, etc...

Among the potential complementary supervisory systems to be used, INERCO/KWANT strongly advocates the automatic monitoring of un-burnt carbon in ash content, due to the operational and logistic importance of this parameter and its intrinsic value as a global threshold to establish a specific operating scenario. To this end, the bran-named ABACO-Loi or AWP4 on-line monitors, successfully implemented by INERCO/KWANT in many facilities, can be applied.

“Controlled Furnace” conditions are established in closed-loop control scenarios by the integration of available monitoring and regulation capabilities with the advanced ABACO combustion control system, which can be configured for each specific application, allowing combustion optimisation strategies to be applied with maximum reliability and profitability.

Main features of these strategies are implemented within an appropriate Expert Combustion Control, which is established in a subordinate manner to the combustion unit Master Control. This Expert System is configured individually for each unit and it is based on modifiable rules established through specific combustion tests. These rules give rise to the definition of different combustion patterns according to the goals to be achieved and the specific boundary conditions of the unit (load, type of fuel, etc.). A comprehensive scheme of ABACO technology application to a pulverised fuel boiler can be observed in Figure 1.

2.2 2nd Stage: Advanced secondary measures

The attainment of the lowest NO\textsubscript{x} operating scenario compatible with operational safety and reliability represents an outstanding starting point to undertake the second stage of the Layered Solutions Approach, which is focused on the smart combination of NO\textsubscript{x} abatement technologies to be assessed on an ad hoc basis. This fact ensures that the secondary measures to be adopted in each individual combustion facility are not oversized, resulting in the optimisation of both the investment and operating costs to be incurred by the utilities.

In this sense, in accordance with the specific characteristics of each combustion unit, it is possible to select a wide range of DeNO\textsubscript{x} technological solutions to be integrated within an optimised approach to be designed by INERCO/KWANT, in collaboration with its partner INTEGRAL, which is a firm with broad expertise regarding catalytic DeNO\textsubscript{x} solutions.

In order to minimise the investments associated with the implementation of NO\textsubscript{x} abatement technologies, the application of pre-catalytic measures, as SNCR technology, turns out to be a highly attractive solution for combustion facilities.

Nevertheless, taking into consideration SNCR technology’s current state of the art, the needs for achieving NO\textsubscript{x} reductions beyond 10-15% can blow up the resulting ammonia slip to values over those recommended to limit the potential appearance of two quite severe operational problems:
- Formation of ammonium salts from the reaction of the ammonia slip and the SO$_3$ generated in the combustion process, which can bring about significant fouling problems in the air preheaters. Typically, a 3 vppm ammonia slip value is considered as a threshold one to cause significant air preheater depositions (result supported by EPRI; see Figure 1).

- A high presence of these ammonium salts can cause the contamination of the ash collected in the ESP, endangering its sale to the cement industry. In this sense, when ammonia slip is kept below 2-3 vppm, ammonia deposition in ash should generally remain below 100 wppm (result supported by EPRI; see Figure 2).

In this context, the Layered Solution Approach proposed by INERCO/KWANT enhances the benefits provided by conventional NO$_x$ abatement technologies, while minimising the impact of ammonia slip.

In the first instance, the distinguishing features of the NO$_x$ abatement technologies offered are directly attached to the synergy and added value provided by ABACO technology. In this manner, the monitoring of local combustion conditions turns out to be a valuable control tool for optimising NO$_x$ abatement technologies.

The establishment of “Controlled Furnace” conditions promotes the implementation of operating scenarios characterised by a balanced temperature and NO$_x$ concentration profiles and by the reduction of O$_2$ excess at boiler exit. As a consequence, this steady performance and the diminution of gas velocities, with the resulting increment of the reaction time between the NO$_x$ and the ammonia reagents, allows maximum efficiency to be achieved through reagents injection.

Moreover, even in case of an unbalanced evolution of combustion performance, the information provided by ABACO monitoring brings about the possibility to establish different reagent injection patterns which can be adjusted on-line on the basis of the gas concentrations locally measured. Consequently, the reaction between NO$_x$ and the ammonia reagent is carried out in a highly efficient way, achieving higher NO$_x$ reductions and lesser reagent consumptions, so that operating costs can therefore be reduced.

Nonetheless, when NO$_x$ emissions have to be reduced over 20% by SNCR technology and ammonia slip has to be kept below 3 vppm, INERCO/KWANT advocates the installation of a slip catalyst in the framework of this Layered Solutions Approach. Apart from assuring the ammonia slip required for any operating conditions, this slip catalyst also provides an additional NO$_x$ reduction to reach and even go beyond the 200 mg/Nm$^3$ NO$_x$ emissions target with a reduced scope, which would generally require minimum boiler retrofitting.

In this sense, it is necessary to underline that the favourable features of the Layered Solution Approach described above are also applicable for any kind of catalytic solution to be employed. Consequently, the catalyst volume can be reduced, with the resulting decrease of investment required to retrofit the plant and, besides, the improved control leads to the reduction of catalyst maintenance and operating costs.
3. Outcomes of the Layered Solutions Approach

The different technologies constituting the Layered Solutions Approach have been implemented and tested worldwide with a significant success in both of the two stages taken into consideration within the present approach.

Particularising to coal-fired boilers, it is necessary to remark that ABACO technology has been extensively applied to numerous power units with dissimilar boiler design and fuel features. In this way, main results achieved by means of the application of ABACO technology on coal-fired power units are summarised in Table 1. This table shows NO\textsubscript{x} reductions mainly ranging from 20 to 30\% with parallel improvements in heat rate around 0.5\%. Nevertheless, it has been possible to achieve 60\% NO\textsubscript{x} reductions with parallel improvements in heat rate up to 2.0\%. These results have been reached for different boiler designs and power outputs from 125 to 560 MWe.

The strict control over combustion performance provided by ABACO and its combination with the novel FLEXICOM technology assures the fulfilment of NO\textsubscript{x} emissions targets for any operating scenario (load profile, fuel analysis, milling system arrangement, etc.).

On the other hand, main available references associated with the application of catalytic secondary measures in coal-fired power plants from Europe and Asia are also detailed in Table 2. It is worthwhile mentioning how the application of advanced catalytic solutions has made possible to achieve over 80\% NO\textsubscript{x} emissions reductions. Likewise, NO\textsubscript{x} emissions have always been no more than 150 mg/Nm\textsuperscript{3}, with minimum NO\textsubscript{x} values below 40 mg/Nm\textsuperscript{3}.

Moreover, the Layered Solution Approach is able to overcome the significant operational constraints linked to the exclusive application of SNCR technology when NO\textsubscript{x} reductions over 20\% are required. Thus, the addition of a tailor-made slip catalyst is able to reduce the ammonia slip up to minimum achievable values, while providing additional NO\textsubscript{x} reductions.

Apart from the significant operating flexibility associated with the Layered Solutions Approach and the individualised integration of advanced primary and secondary measures for NO\textsubscript{x} abatement, it is also necessary to highlight its economical potential, which allows 200 mg/Nm\textsuperscript{3} NO\textsubscript{x} emissions target to be achieved in a reliable and cost-effective way, and even to attain NO\textsubscript{x} values below 150 mg/Nm\textsuperscript{3} with a limited additional cost.

This economical potential turns out to be especially favourable in those cases where the implementation of tailor-made technologies avoids the erection of a catalyst reactor, with capital cost reductions ranging from 20\% to 50\% respecting the application of conventional catalytic solutions. In addition, the high NO\textsubscript{x} abatement efficiency promoted by the application of secondary measures in “Controlled Furnace” conditions results in a remarkable reduction of operating costs as regards to reagent consumption and catalyst maintenance, when applicable.

Finally, it is necessary to emphasise that some of these tailor-made solutions might only be efficiently applicable as a second stage of the referred Layered Solutions Approach, when
appropriate primary measures with a well-defined DeNOx scope are implemented previously. Only in such cases, both DeNOx stages will give rise to the attainment of a global, optimised and economically feasible solution for the abatement of NOx emissions below 200 mg/Nm³.

4. Conclusions

Fulfilment of 200 mg/Nm³ NOx emission target represents quite a significant challenge for the European power sector facing 2016 deadline imposed by the Large Combustion Plants Directive, since it involves the investment of significant expenditures.

In contrast to the conventional strategies followed by many power utilities, the implementation of the Layered Solutions Approach offered by INERCO/KWANT turns out to be a highly reliable and cost-effective method to face up with the 200 mg/Nm³ NOx emissions challenge, while improving boiler operational flexibility.

This approach proposes the application of primary measures with maximum efficiency on the basis of the enhanced combustion control provided by ABACO’s Controlled Furnace technology and the remarkable contribution of the state-of-the-art FLEXICOM technology.

ABACO technology, qualified as Best Available Technique by the European IPPC Directive, has been successfully applied in more than 40 European combustion units and constitutes the keystone to achieve minimum NOx emissions scenarios compatible with plant safety and process efficiency.

Furthermore, the following stage involves the implementation of an optimised approach potentially including a wide range of cost-effective conventional and customised secondary measures for NOx abatement while keeping ammonia slip values below the threshold limits required by combustion facilities.

In addition to the significant expertise provided by the firm INTEGRAL, the added value offered by this approach lies in two different issues: its integration and synergy with the Controlled Furnace technology and its individualised design on the basis of the specific features of each individual combustion facility.

This individualised assessment is critical to minimise the scope of the plant modifications to be undertaken, especially when their design make possible to implement non-conventional tailor-made solutions based on the appropriate installation of catalyst volumes, avoiding the construction of an independent reactor.

In this regard, it is worthwhile reminding that these tailor-made solutions may be necessarily linked to suitable primary measures with combustion control under the Layered Solution Approach.

As a consequence, both capital and operating costs required to reach the 200 mg/Nm³ NOx target are significantly reduced. Thus, aside from the technical reliability provided by the Layered Solutions Approach, the possibility of obtaining cost savings through the application
of tailor-made technologies shows the enormous interest and potential associated with the application of this Layered Approach.

5. Acknowledgements

The authors gratefully acknowledge the collaboration of other personnel involved in activities resulting in this paper. Special thanks are given to the technical staff of INTEGRAL, ENDESA and IBERDROLA. This development has been carried out with partial financial grants from the European Coal and Steel Community, and from the Andalusian Regional Government.

6. Keywords

Layered Solutions, ABACO, FLEXICON, SNCR, SCR, combustion, monitoring, in-furnace, optimisation, NO\textsubscript{x}, corrosion, ammonia slip, levelised costs, emissions, pulverised coal.

7. References


Figure 1: Controlled Furnace ABACO approach for a pulverised coal boiler
Reduction of 15% for ammonia slip < 3 vppm

For slips less than 2-3 vppm, ammonia deposition in ash should generally remain below 100 wppm

Figure 2: Ammonia slip vs. NO\textsubscript{x} reduction achieved by SNCR technology
(EPRI Conference on SCR/SNCR for NO\textsubscript{x} Control)

Figure 3: Ammonia slip vs. Adsorbed ammonia in ashes
(EPRI Technology Review)
### Table 1: References of Controlled Furnace approach for coal-fired units

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**Notes:**
1. ABACO global arrangement in coal-fired power plants is composed of OPTICOM in-furnace monitoring system, ABACO-Coal and ABACO-Air regulation devices and ABACO expert software in both closed and open-loop approaches.
2. In addition, optimisation and/or warranty testing trials have been accomplished at As Pontes 3 & 4 (ENDESA); La Robla 1 & 2, Axaillas (UNION FENOSA); Aboño 2, Soto de Ribera 2 & 3 (HC ENERGÍA); Cercs, Puertollano, Escucha, Puente nuevo (E.ON España); Pego 1 & 2 (PEGOP); Monfalcone 1 (A2A Produzione); Emile Huchet 6, Provence 5 (E.ON France); Bouchain 1 (EDF); and Mohammedia 3 (ONE).
Table 2: References of secondary measures for coal-fired units (extract) \(^1\)

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<td>100</td>
<td>&gt; 77</td>
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<td>Hwa Ya PP 1</td>
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<td>150</td>
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\(^1\) More than 30 additional references for other industrial processes