

4.1.1.1 Site Specific Application of SCR to Ellis County Cement Kilns

SCR offers the possibility of significant NO_x reduction the plants in Ellis County. As an “ add on” technology, which can achieve 90% or greater NO_x reduction, with demonstrated performance at hundreds of coal fired power plants, SCR is a viable technology that is available to both for dry and wet kilns. The economics of SCR are greatly influenced by the temperature of the flue gas at the point of installation. For the three dry precalciner kilns in Ellis County, a location in process with suitable temperatures is assumed and this leads to lower overall costs and cost effectiveness. For the wet kilns, a location downstream from the electrostatic precipitators (ESPs) is selected for installation and reheat of the process gas is required. This substantially increases the overall cost and decreases the cost effectiveness of SCR in comparison to the dry kiln applications.

The technology has been available at only one cement plant, the Solnhofer Portland – Zemetwerke AG dry kiln plant in Southern Germany, now in its fourth year of operation with SCR. While there are, at this time, no operating units in the U.S., the German experience leads one to assess the possibility that SCR can make a significant impact on NO_x reduction in Ellis County. In fact, the Midwest Regional Planning Organization has recently concluded that SCR is a reasonably available technology for controlling NO_x at cement plants (1), and the possibility exists, with reheat, to utilize SCR at wet, as well as dry, kilns.

4.1.1.2 Applicability of SCR to Cement Kilns and Areas of Concern

Before examining site-specific data, it is important to first examine the areas of concern with respect to SCR, many of which have been raised in the literature (see, for example, 2,3,4,5). This is necessary to see whether the data from the coal fired plants and from the one cement plant, is sufficient to attempt to make even qualified statements with respect to existing facilities, even though some analyses now suggest that the German data indicates that these problems will not exist for the cement industry in the U.S. (see, for example, reference 6). These concerns are delineated and discussed here. They include: catalyst deactivation due to catalyst poisoning; catalyst plugging and fouling due to high dust loading and deposits; reduction in NO_x control efficiency due to high sulfur levels; temperature related factors leading to lower NO_x removal

flue gases have significant levels of both calcium oxide (CaO) and sulfur dioxide (SO₂), the condition can be handled in SCR systems without the occurrence of pore masking from calcium sulfate (CaSO₄) formation. Third, the power plant experience shows that SCR systems can be designed to achieve at least 85% NO_x reduction despite extremely large gas flow rates with significant NO_x variability and relatively high particulate loadings. Last, the power plant experience shows that equipment can be designed and operated such that the flue gas entering the SCR catalyst will always be in the proper temperature range. For wet kiln applications, this can lead to a requirement for significant gas re-heat.

4.1.1.4 Site-Specific Analyses

The follow sub-sections are specific to TXI, Holcim, and Ash Grove. In what follows, the additional NO_x associated with gas re-heat, if required, has not been added, as the level of additional NO_x would be below 10 tons per year and 85% of that would be removed.

4.1.1.4.1 SCR at the TXI Kilns

To consider SCR at the TXI facilities, one must perform separate analyses for Kiln 5 (the dry kiln with pre-heater/pre-calciner, as found at the Solnhofer plant) and Kilns 1-4 (the long wet kilns, which usually operate as kilns 1 and 4 in tandem, or 2 and 3 in tandem). Neither the alkali percentages, the sulfur fuel percentages nor the stack concentrations (extrapolated to uncontrolled for TXI #5) would be considered high for SCR utilization in coal-fired power plants (see Confidential Attachment – TXI).

With respect to the dry kiln (TXI 5), it would be expected that an SCR system would be installed downstream of the pre-heater, where the temperature would be in the range required. With respect to process economics, this temperature is assumed to be 700 F (the temperature utilized in all the cases at all the plants studied). With respect to this particular kiln, the present data indicates a low NO_x level in the 150-ppm range. For conservatism, it is therefore assumed that an SCR system for this kiln would operate at an 80% reduction efficiency, as opposed to a significantly higher level (85%) to be expected at the other kilns at TXI and at the other facilities in Ellis County.

The economic analysis for this case is found in the Appendix. It is found that the cost effectiveness, based on NO_x removed (\$/ton NO_x removed) is in the \$2300/ton to \$2600/ton range. With respect to cost effectiveness based on metric tonnes of clinker produced (\$/tonne clinker), the range is \$0.86/ton to \$0.93/ton.

The wet kilns have been economically modeled based on a number of possible scenarios. The reported stack gas temperature 160 C (320 F) was utilized in the reheat calculations (to 700 F at the SCR inlet) in all cases, and natural gas, at \$12.00/ dtherm is utilized. Three different scenarios were studied. In the first scenario, one SCR system serves kilns 1 and 4 consistent with TXI's operation (85% of the time). In the second scenario, one SCR system serves kilns 2 and 3 again consistent with TXI's operation (15% of the time). In the third scenario, one SCR system serves all four wet kilns with piping and controls to match the normal operating scenarios. These three scenarios were again modeled based on the possibility that TXI might introduce mid-kiln firing as a method of NO_x control in its four wet kilns. Therefore, a total of six economic analyses for the TXI wet kilns are found in the Appendix.

For the scenario without mid-kiln firing in kilns 1 and 4, the cost effectiveness based on NO_x removal (\$/ton NO_x removed) is in the \$4400/ton to \$4600/ton range. The cost effectiveness based on metric tonnes of clinker produced (\$/tonne of clinker) is in the \$8.80 to \$9.20/tonne range. With mid-kiln firing the cost effectiveness for NO_x removal increases to the \$6300/ton to \$6500/ton range (less NO_x removed), while the cost effectiveness based on tonnes of clinker remains unchanged.

The scenarios involved with kilns 2 and 3 with SCR lead to what must be considered unacceptable economics, since capital cost is essentially equal to that for kilns 1 and 4, but operation (both from the standpoints of NO_x removed and clinker produced are only 15% of the total). Therefore, without mid-kiln firing, the economics yields a cost effectiveness based on NO_x removal in the range of \$86,000/ton to \$93,000/ton, while the cost effectiveness based on clinker produced is in the \$18.50/tonne to \$19.90/tonne range. With mid-kiln firing, the cost effectiveness based on NO_x control is in the range of \$62,000/ton to \$71,000/ton while the cost effectiveness based on clinker produced is in the \$8.90/tonne to \$10.10/tonne range.

Based on economics of scale, utilizing one SCR unit to service all four kilns (only 2 are used at any time) should lead to the most cost effective manner of control. The economic analysis indicates that without mid-kiln firing, the cost effectiveness based on NO_x removal is in the \$4600/ton to \$4700/ton range, while the cost effectiveness based on clinker produced is in the

\$6.60/tonne to \$6.70/tonne range. With mid-kiln firing, the cost effectiveness based on NOx removal uses the range of \$5900/ton to \$6000/ton, while the cost effectiveness based on clinker produced decreases to the \$5.90/tonne to \$6.00/tonne range.

It is clear that while the reheat required in the wet kilns significantly increases the costs associated with NOx control with the utilization of SCR, the cost effectiveness is best when one SCR unit is installed for all four wet kilns. For the dry kiln, the economics is, of course, significantly better and assuming space for the catalyst beds and ancillary equipment is available, SCR must be seriously considered, at least at TXI 5.

4.1.1.4.2 SCR at the Holcim Kilns

To consider SCR at the Holcim facilities, separate analyses are performed for each of the two dry units. Each is equipped with precalciners and preheaters, but Holcim 2, is a newer, more efficient unit, emitting 26% less NOx (in mg/m³). The temperature after the preheater for both Holcim 1 and 2 is expected to be adequate (i.e. 700 F), so no reheat would be required, and 85% NOx removal is assumed. Neither the alkali percentages, the sulfur fuel percentages nor the stack concentrations extrapolated to uncontrolled would be considered high for SCR utilization in coal-fired power plants (see Confidential Attachment – Holcim). The utilization of SCR is, therefore, not precluded.

The annual cost spreadsheets are found in the confidential attachments for each cement plant. The cost effectiveness based on NOx removal (\$/ton NOx removed) for Holcim 1 and is in the \$1900/ton to \$2100/ton range. The cost effectiveness based on metric tonnes of clinker produced (\$/tonne clinker) is in the \$2.00/tonne to \$2.20/tonne range.

For Holcim 2, which is more efficient, the NOx removed is less (since less NOx is produced) and the clinker production is greater. Therefore, the cost efficiency based on NOx removal is greater for Holcim 2, in the \$2000/ton to \$2200/ton range, and the cost effectiveness based on tonnes of clinker produced is in the \$1.70/tonne to \$1.80/tonne range.

4.1.1.4.3 SCR at the Ash Grove Kilns

Ash Grove has three wet kilns, with mid-kiln firing Ash Grove 1, Ash Grove 2 and Ash Grove 3. Data indicates nearly identical operating conditions and NOx emission levels (in the 350 ppm to 400 ppm range). Neither the alkali percentages, the sulfur fuel percentages nor the

stack concentrations would be considered high for SCR utilization in coal-fired power plants (see Confidential Attachment -- Ash Grove). In addition, Ash Grove reports temperatures at the air pollution control device (APCD's) inlets of 330F to 370F. Assuming the installations of SCR between the APCD's and the stacks, these temperatures indicate that Ash Grove can install SCR at each of their kilns with reheat required, and 85% NO_x removal can be expected.

Four scenarios are presented, that of the installation of an SCR at each of the three wet kilns, the fourth being the installation of one SCR for all three units. For Ash Grove 1, the cost effectiveness based on NO_x removal (\$/ton NO_x removed) varies from \$6400/ton to \$6600/ton (all reheat at \$12/dtherm). The cost effectiveness based on clinker produced (\$/tonne clinker) varies from \$9.10/tonne to \$9.40/tonne.

For Ash Grove 2, the cost effectiveness based on NO_x removal varies from \$6400/ton to \$6600/ton. The cost effectiveness based on clinker produced varies from \$9.80/tonne to \$10.10/tonne.

For Ash Grove 3, the cost effectiveness based on NO_x removal varies from \$6700/ton to \$6900/ton. The cost effectiveness based on clinker produced varies from \$10.50/tonne to \$10.80/tonne.

If space is available and operation is not impeded, one SCR unit can be installed to service all three kilns. In this case, the cost effectiveness based on NO_x removal varies from \$5100/ton to \$5200/ton. The cost effectiveness based on clinker production varies from \$7.60/tonne to \$7.80/tonne.

It is clear that if space is available for one SCR unit and its ancillary equipment, in order to serve all three kilns, the economics is far more favorable than if three SCRs are installed. SCR, therefore, for these wet kilns is an available technology at 85% NO_x control, albeit at a high cost/ton of clinker removed.

Table 4-1.2 Summary of Modeling Results for SCR on Ellis County Kilns – Performance Results

Existing Unit	Control Technology	Emissions Rate tpy before	Emissions Rate tpy after (a)	Controlled Emissions Rate ppm	Controlled Emission Rate lb/tonne clinker	Control Efficiency %	Reduction tpy
Ash Grove #1- wet	SCR	702	301.6	60	0.84	85%	400.4
Ash Grove #2- wet	SCR	750	322.2	58	0.89	85%	427.8
Ash Grove #3- wet	SCR	764	328.3	53	0.91	85%	435.7
Ash Grove #1,2,&3 (c)	SCR	2205	947.4	57	0.88	85%	1,257.6
TXI #1 and #4-wet (b)	SCR	838	155.3	109	1.21	85%	478.0
TXI #2 and #3-wet (b)	SCR	121	52	109	0.49	85%	69.0
TXI #1,2,3,4 –wet (c)	SCR	1802	774.2	109	0.84	85%	1,027.8
TXI#5 – dry	SCR	1710	734.7	29	0.30	80%	975.3
Holcim #1 – dry	SCR	2222	954.7	73	0.38	85%	1,267.3
Holcim #2 – dry	SCR	1778	763.9	53	0.30	85%	1,014.1

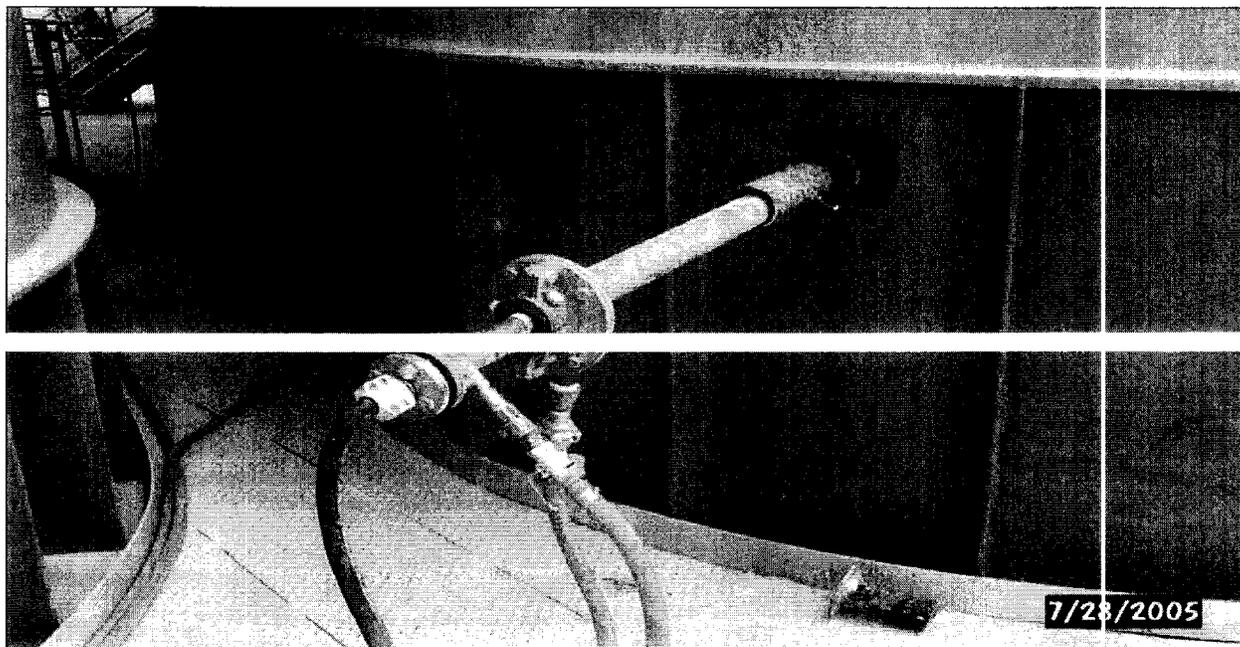
- a) NOx emission rate after SCR does not reflect SCR efficiency reduction due to adjustment by the ozone season factor of 0.671 (NOx reduction is modeled to occur only during the ozone season).
- b) The results for TXI 1 & 4 and #2 & #3 are average per kiln – for example, total emissions reductions for controlling both TXI #1 & #4 are double the value listed in the table.
- c) A large single SCR was modeled for the Ash Grove and TXI wet kilns with the capacity of 3 wet kilns.
- d) Models assume mid-kiln firing installed at TXI as required under current SIP.

Table 4-1.2 Summary of Modeling Results for SCR on Ellis County Kilns – Economic Results

Existing Unit	Control Technology	Capital Cost	Annual Cost	Cost Effectiveness \$/ton NOx	Energy Penalty or Benefit	Emissions Penalty or Benefit	Eurden Cost \$/tonne clinker
Ash Grove #1- wet	SCR	\$4.5MM	\$2.3 MM	\$6,390	a)	b)	\$9.10
Ash Grove #2- wet	SCR	\$4.7MM	\$2.5MM	\$6,400	a)	b)	\$9.80
Ash Grove #3- wet	SCR	\$4.8MM	\$2.6MM	\$6,740	a)	b)	\$10.50
Ash Grove #1,2,&3(d)	SCR	\$12.0MM	\$5.8 MM	\$5,100	a)	b)	\$7.60
TXI #1 and #4-wet (c)	SCR	\$5.6MM	\$2.6MM	\$6,310	a)	b)	\$8.90
TXI #2 and #3-wet (c)	SCR	\$5.6MM	\$0.6MM	\$85,700	a)	b)	\$12.16
TXI #1,2,3,4 –wet (d)	SCR	\$11.4MM	\$5.4MM	\$5,900	a)	b)	\$5.90
TXI#5 – dry	SCR	\$7.8MM	\$2.0MM	\$2,400	a)		\$0.90
Holcim #1 – dry	SCR	\$6.8MM	\$2.4MM	\$2,070	a)		\$2.00
Holcim #2 – dry	SCR	\$6.0MM	\$2.0MM	\$2,100	a)		\$1.70

- a) increased fan power due to pressure drop across catalyst bed included in the models
- b) increase in NOx from gas reheat occurs, but is controlled by the SCR
- c) The results for TXI 1 & 4 and #2 & #3 are average per kiln – for example, total capital costs for controlling both TXI #1 & #4 are double the value listed in the table.
- e) A large single SCR was modeled for the Ash Grove and TXI wet kilns with the capacity of 3 wet kilns.
- f) Costs for wet kilns include cost of RTO to reheat flue gas.

Figure 4-1.2. Application of SNCR at Holcim.



Albert Scheuer, of the Research Institute of the Cement Industry in Düsseldorf, Germany, reported on 148 SNCR trials carried out on five different kilns. Three kiln systems had cyclone preheaters and two had grate preheaters. A 25% molar concentration of NH_3 in water was the main reagent tested, with some additional testing done with ammonium sulfate solutions and with urea solutions. Scheuer reported that NO reductions with the NH_3 /water solution ranged from 15% to 75% and that temperature appeared to be one of the main determinants of the effectiveness of the reagent. Maximum NO reduction occurred at 980°C (1796°F). NH_3 escape occurred when temperatures were less than 900°C (1652°F) and when the NO concentration fluctuated. NH_3 utilization decreased significantly with increasing NH_3 :NO molar ratio and with decreasing NO concentration in the exhaust gases, indicating that SNCR appears to be a less promising methodology at low NO emissions rates.^{13,56}

SNCR is presently being used in 18 cement kilns in Europe. Fifteen kilns are in Germany, two are in Sweden, and one is in Switzerland. These kilns are either suspension preheater kilns or precalciner kilns. The most common reagent used is 25% ammonia water.¹ NOx reduction rates vary from 10 to 50 percent with NH_3 :NO₂ molar ratio of 0.5 to 0.9, NOx emissions at these reductions are 2.4 to 3.8 lb/ton of clinker. Two dry process cyclone preheater/precalciner kilns in Sweden achieve 80 to 85 percent reduction (1.0 lb/ton of clinker) at

reduction at NSR=1.6; 50% reduction at NSR=1.0, etc. Performance improves with increased turbulence or mixing, residence time, and more favorable temperature conditions. A higher NOx baseline generally leads to a higher percentage of NOx reduction.⁵²

Urea is safer to handle than anhydrous ammonia. Both ammonia and urea need to be injected in a similar temperature window which is 870 to 1090°C (1600 to 2000°F). The Polysius results earlier noted, however, appear to suggest that the ammonia optimum may be lower than the urea optimum. Proprietary additives have been developed by Nalco to widen the temperature window.⁶³ One modification of the urea-based SNCR system is the addition of methanol injection downstream of the urea injection point to improve overall NOx removal. Nalco also introduced an improved NOxOUT[®] PLUS, which is said to further broaden the operating temperature window and to reduce ammonia slip and CO and NO₂ formation.

The Ash Grove plant in Seattle is a preheater/precalciner kiln with average processing rates of 160 tons dry feed/hour producing approximately 100 tons clinker/hour. NOxOUT[®] was tested on this kiln under varying conditions, including the use of different fuel types (natural gas and coal), heat input to the calciner (5 to 9 percent), and preheater O₂ (1.8 to 2.9 percent). (It is probably necessary to point out that this calciner is an example of the so-called “air through” unit which employs no tertiary air duct; all air for combustion in the calciner must be furnished through the kiln. As of the present time, this heat input is in the range of 20-30% of the total^{ref}) The baseline NOx levels varied from 350 to 550 lbs NOx/hour. When NOxOUT[®] was used, NOx emission reductions varied significantly depending on the conditions, with a maximum reduction of 90 percent (less than 100 lbs NOx/hour). Typical reductions were greater than 50%.⁵⁸

NOxOUT[®] was tested for one week in October of 1998 on the preheater/precalciner kiln at the Lafarge-Davenport Plant. Operating conditions were unstable most of that week and only five hours of testing produced results that could provide a reasonable indication of what may be achievable with NOxOUT[®]. The baseline NOx rate was approximately 350 lbs NOx/hour. Using NOxOUT[®], emission reductions of 10 to 20 percent were achieved.⁵⁹ Operating conditions such as residence time, temperature, and the use of coal at this kiln were contrasted to conditions at the Ash Grove kiln that achieved greater reductions to explain why NOxOUT[®] may achieve better results on some kilns than others.

Nalco also has conducted a number of demonstrations and commercial projects in preheater/precalciner cement kilns. The fuels have included coal, and coal in combination with No. 6 heavy fuel oil, waste oil, and/or tire chips. The clinker capacity on these kilns ranged from

4.1.2.3 Site-Specific Analyses

4.1.2.3.1 SNCR at Holcim

Holcim Kiln #1

Holcim carried out trial SNCR tests on both of their precalciner kilns in Midlothian, TX. For the injection in line 1, (the older unit) the optimum location was identified to be on the riser duct, after the precalciner and before the bottom stage cyclone. This location would address NO_x formed both in the kiln (principally presumably thermal NO_x) and in the calciner (principally presumably fuel NO_x). The reports do not indicate the temperature, oxygen, or carbon monoxide concentrations of the flue gas, considered very important for optimum efficiency. There is therefore no basis for concluding that conditions had been optimized. With this condition, it proved possible to obtain about 50% removal of NO_x at a molar ratio of ammonia to NO_x of 0.75. This is not considered to be as good as obtained in the Florida kiln indicated earlier, nor for some of the Northern European kilns. However, the removal efficiency appears to be in good agreement with the data cited earlier, where a molar ratio of 0.5 is cited as achieving 40% removal, while a molar ratio of 1.0 is said to achieve 60% removal. While the conditions may not have been optimized, the results are considered acceptable compared to performance at other similar kilns. Experience at other kilns indicates further optimization may result in better performance at Holcim #1 than was achieved during the initial trial period.

Holcim Kiln #2

For the Kiln #2 system, the injection point was on the riser duct after tertiary air input and before the Pyroclon (calciner). This differs from the location for the Kiln #1 system, where the injection point is post-calciner. This difference implies that the gases from the calciner were treated in the Kiln #1 system, but no SNCR was applied to calciner exhaust gases in the Kiln #2 system. Experience to date suggests that with normal bituminous coal fuel, roughly 70% of the system NO_x may be generated in the kiln, and 30% in the calciner as a general rule of thumb. To the extent that this supposition is justified, it appears as though an SNCR injection location that does not treat gases from the calciner may be omitting treatment of about 30% of the NO_x. In addition, the injection location for this kiln system may be experiencing a temperature decrease from the cooler tertiary air. Any residual carbon monoxide from the kiln exit gases was probably

oxidized by the high O₂ content at this location, further compromising the results. If this is the case, further erosion of the efficiency of the SNCR system may be occurring.

As a result, with a molar ratio of 0.75, the efficiency of removal of NO_x was only 35%. This cannot be considered satisfactory. It proved possible to increase the NO_x removal to as high as 80%, but this was with a molar ratio of about 2.0. At this molar ratio, ammonia slip and detached plumes were severe. In addition, the plant reported a buildup of ammonium sulfate/ammonium bisulfate in the top preheater stage forming under conditions of high ammonia injection. They claim that this buildup had the potential to assume catastrophic dimensions, but was removed before this occurred.

It does not appear likely that the location for NO_x removal on Kiln #2 was optimized. The lack of any data on temperature, oxygen, and/or carbon monoxide suggests that these data were not collected. It was discovered during the Florida test that optimization of these parameters was important to the success of the experiment. We believe that if the conditions are properly optimized using the necessary temperature, oxygen, and CO data, that better results are achievable at Holcim#2.

4.1.2.3.2 SNCR at TXI

TXI Kiln #5

This kiln is already achieving very good NO_x control without employing any end of pipe technologies. It appears that the kiln is running at about 1.9 lb NO₂/ton clinker at present – this may be the lowest value for any portland cement kiln in the country. The application of SNCR may be worth consideration for further reduction of NO_x. It should be recognized, however, that 35% removal may be the best achievable, and even this level may not be achievable without optimization of the location in the preheater tower for temperature, oxygen, and CO. SNCR becomes less effective at lower NO_x concentration and European experience indicates that 200mg/m³ or approximately 100 ppm may be a lower limit for efficient application of SNCR at cement kilns. As earlier indicated, TXI has a high level of relatively nonvolatile organic carbon, a high level of total Kjeldahl nitrogen (unfortunately, the temperature profile of nitrogen release from the feed at TXI is not known), and an apparently relatively easy burning mix. All these factors mitigate in the direction of lower uncontrolled NO_x numbers.

TXI Wet Kilns

The ERG Team has estimated that the TXI wet kilns are currently operating at over 8 lbNO₂/tonne of clinker. The Texas Code (Chapter 117) requires mid-kiln injection or meeting an emissions limitation of 4.0 lbs/ton of clinker. For the purposes of modeling SNCR and other control techniques on the TXI wet kilns, a 30% reduction in NO_x emissions is assumed to result in emissions similar to the Ash Grove wet kilns when the mid-kiln firing is installed. The ERG Team understands that TXI is waiting for permit approval to convert the wet kilns to mid-kiln firing with tire injection. As discussed above, the lack of available alternative NO_x controls for wet kilns leads the ERG Team to a recommendation of trying innovative or experimental techniques involving some SNCR injection involving urea or another reagent in tires. This experimentation would determine if mixing and the proper form of ammonia might travel into the proper temperature range of the kiln to be effective. These ideas will have to be verified or disproved with experimentation. For the purposes of cost modeling, a 35% efficiency is assumed to be achievable through a mid-kiln injection of a SNCR reagent.

4.1.2.3.3 SNCR at Ash Grove

Ash Grove Wet Kilns

The Ash Grove wet kilns are already using mid-kiln firing and are emitting approximately 5.0 lbs/ton of clinker. Mid-kiln firing is traditionally regarded as the most effective wet kiln method for controlling NO_x. As discussed above, it may be worthwhile considering a modification of traditional SNCR here, in which the urea is introduced inside whole tires, and mixing air is used to promote reaction with NO_x before the urea is decomposed. This is innovative and speculative, and requires testing to verify, but it should be quite inexpensive and cost effective for a plant already employing mid-kiln firing. Attempting an innovative control method for wet kilns based on SNCR seems to be a worthwhile option since other control options have not been applied to wet kilns. SCR and LoTO_x appear to be transferable from other applications but have high costs associated with reheating the flue gas in the case of SCR and installing a spray tower in the case of LoTO_x. As mentioned in evaluating TXI #5, there appears to be the potential for some NO_x reduction to be occurring from the materials already being fed to this kiln. With other mid-kiln injection in long kilns, NO_x reduction has occurred through feeding nitrogen containing sands at mid-kiln. It might be

possible to introduce another material high in non-volatile carbon and/or TKN nitrogen at mid-kiln to see whether the foregoing explanation for the low NOx from the TXI kilns is valid. Again, this would not be expensive as an experimental investigation. Similar to the TXI wet kilns, for the cost models, it was assumed that one of these experimental techniques could result in 35% NOx reduction and that the costs would be similar to the costs of installing SNCR on a utility boiler.

Table 4-1.5. Summary of Modeling Results for SNCR on Ellis County Kilns – Performance Results

Existing Unit	Control Technology	Emissions Rate tpy before	Emissions Rate tpy after (a)	Controlled Emissions Rate ppm	Controlled Emission Rate lb/tonne clinker	Control Efficiency %	Reduction tpy
Ash Grove #1- wet	SNCR	702	537.1	200	3.6	35%	164.9
Ash Grove #2- wet	SNCR	750	573.9	200	3.9	35%	176.1
Ash Grove #3- wet	SNCR	764	584.6	200	3.9	35%	179.4
TXI #1 and #4-wet (b)	SNCR	838	641.2	250	3.7	35%	196.8
TXI #2 and #3-wet (b)	SNCR	121	92.6	250	3.7	35%	28.4
TXI#5 – dry	SNCR	1710	1,308.4	100	1.0	35%	401.6
Holcim #1 – dry	SNCR	2222	1,476.5	190	1.9	50%	745.5
Holcim #2 – dry	SNCR	1778	1,181.5	150	1.5	50%	596.5

g) NOx emission rate after SNCR does not reflect SNCR efficiency reduction due to adjustment by the ozone season factor of 0.671 (NOx reduction is modeled to occur only during the ozone season).

b) The results for TXI 1 & 4 and #2 & #3 are average per kiln – for example, total emissions reductions for controlling both TXI #1 & #4 are double the value listed in the table.

Models assume mid-kiln firing installed at TXI as required under current SIP.

Table 4-1.6. Summary of Modeling Results for SNCR on Ellis County Kilns – Economic Results

Existing Unit	Control Technology	Capital Cost	Annual Cost	Cost Effectiveness \$/ton NOx	Energy Penalty or Benefit	Emissions Penalty or Benefit	Eurden Cost \$/tonne clinker
Ash Grove #1- wet	SNCR	\$1.2 MM	\$0.4MM	\$2,500	a)	b)	\$1.70
Ash Grove #2- wet	SNCR	\$1.3MM	\$0.4MM	\$2,400	a)	b)	\$1.70
Ash Grove #3- wet	SNCR	\$1.4MM	\$0.4MM	\$2,400	a)	b)	\$1.70
TXI #1 and #4-wet (c)	SNCR	\$1.4MM	\$0.5MM	\$2,400	a)	b)	\$1.60
TXI #2 and #3-wet (c)	SNCR	\$1.4MM	\$0.3MM	\$13,000	a)	b)	\$5.00
TXI#5 – dry	SNCR	\$2.3MM	\$1.0MM	\$2,900	a)		\$0.45
Holcim #1 – dry	SNCR	\$2.3MM	\$1.1MM	\$1,500	a)		\$1.00
Holcim #2 – dry	SNCR	\$2.3MM	\$1.0MM	\$1,700	a)		\$0.90

a) SNCR should not have energy impacts.

b) Ammonia slip can be significant for SNCR when not properly optimized.

c) The results for TXI 1 & 4 and #2 & #3 are average per kiln – for example, total capital costs for controlling both TXI #1 & #4 are double the value listed in the table.

"Oxone" Monopersulfate Compound	70693-62-8	
Potassium Peroxymonosulphate	10058-23-8	34-43
Potassium Bisulfate	7646-93-7	18-23
Potassium Sulfate	7778-80-5	23-29
Potassium Peroxydisulfate	7727-21-1	2-3
Sodium Carbonate	497-19-8	0-20
Magnesium Carbonate	546-93-0	1-2

Potential applicability. Applicability is similar to the wet low temperature hydrogen peroxide option.

Advantages. Advantages are similar to the hydrogen peroxide option. Costs may be lower.

Disadvantages. This is an experimental technology. Additional nitrate captured in the existing sulfate scrubber could impact the quality of the plant's artificial gypsum although with a typical dewatering system this should not be a problem because of the much higher solubility of the nitrates relative to sulfates. High nitrate wastewater could be used by local farmers as fertilizer or could be used at the plant to fertilize grass areas as well as water/fertilizer in quarry reclamation areas.

Emissions performance. As an experimental technology performance is not clear but is likely to be similar to the hydrogen peroxide technology. This technology should be considered investigative in nature.

Cost. Oxone is a commercial product manufactured by Dupont. Inquiries to Dupont about cost have not been responded to at this time.

4.3.5 Sodium Acetate Process

General description. The wet processes involve absorption and subsequent reaction of NO_x in the aqueous phase. Direct absorption involves a reaction chain that achieves both SO_x

and NO_x removal. One form involves an SO₂ reaction step, a subsequent NO reaction, and a termination step that produces gypsum. Table 4-3.3. shows the different steps involved in the process.

Table 4-3.3. Reaction Steps and Pathway Equations for the Sodium Acetate Direct Absorption Process For Simultaneous NO_x And SO_x Removal (OECD, 1983).

Absorption and gypsum formation
Absorption $SO_2 + 2CH_3COONa + H_2O \rightarrow Na_2SO_3 + 2CH_3COOH$ $2NO + 5Na_2SO_3 + 4CH_3COOH \rightarrow 2NH(NaSO_3)_2 + Na_2SO_4 + 4CH_3COONa + H_2O$
Gypsum formation $Na_2SO_4 + Ca(OH)_2 + 2CH_3COOH \rightarrow CaSO_4 \cdot 2H_2O + 2CH_3COONa$
Imide treatment step
Hydrolysis $NH(NaSO_3)_2 + 2H_2O \rightarrow NH_4HSO_4 + Na_2SO_4$ Release of NH ₃ $NH_4HSO_4 + Ca(OH)_2 \rightarrow NH_3 + CaSO_4 \cdot 2H_2O$ Nitrogen gas formation $4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$

Potential applicability. Applicability is likely to be similar to the wet low temperature hydrogen peroxide process.

Advantages. The advantage of this process is its ability to eliminate gaseous NO_x and SO_x simultaneously. For plants with existing SO_x scrubbers the application may be as simple as adding selected reagents to the recirculating scrubber solution and subsequent scrubber treatment tanks. For plants with cooling towers the option of adding the reagents to the cooling tower water feed may be functional.

Disadvantages. SO_x is required in adequate quantities to maintain the chain-reaction mechanism. Also, this process turns an air-pollution problem into a wastewater problem. Additional nitrate captured in the existing sulfate scrubber could impact the quality of the plant's artificial gypsum although with a typical dewatering system this should not be a problem because of the much higher solubility of the nitrates relative to sulfates. High nitrate wastewater could be

used by local farmers as fertilizer or could be used at the plant to fertilize grass areas as well as water/fertilizer in quarry reclamation areas.

Emissions performance. Unknown. Data for application of this technology to cement kilns and similar emission sources was not found in the literature. This technology should be considered investigative in nature.

Cost. Costs are not clear at this time but may be lower than the hydrogen peroxide option.

4.3.6 Potential Applicability of Oxidation Technology to Ash Grove Plant

General Discussion. The Ash Grove plant has three wet process kilns without any existing wet scrubber system. That would require them to place a complete oxidation system in place as an add-on technology including the scrubber or alternatively just a spray tower after the existing ESPs. Assuming that all of the available options would have a similar capital cost for a spray tower/scrubber system careful evaluation of the alternative reagent systems is warranted.

A trial system for evaluating the reagent systems may be warranted. As an example, three one-month trials using alternative reagents in a skid-mounted scrubber could be performed prior to scaling up to a full system. It may be possible to combine the gas flows from the three kiln systems into a single flow to minimize the cost of the scrubber system.

Because of the high moisture levels in the gasses from wet kilns it may be necessary to bypass a portion of the stack gasses around the spray tower/scrubber for use as reheat gas after the spray tower/scrubber to prevent condensation problems in the stack. To the extent that such a strategy is required the efficiency of the NO_x removal would be proportionately impacted.

Conclusions. SCR at the Ellis County wet kilns would require reheat of the exhaust gas and no other technology is commercially available for wet kilns. This suggests that further investigation of the oxidation technologies is likely to be a cost effective option. As these technologies would require a scrubber, consideration of the benefits of control of sulfur oxides should also be considered in evaluating scrubber options. The cost modeling for oxidation technologies is based on a simple spray tower that does not control sulfur oxides. However,

saleable emissions reduction credits might be obtainable to a source that chose to install flue gas desulfurization. A combination of midkiln combustion, midkiln SNCR and a low temperature oxidation technology may provide exceptional NO_x control at the most effective aggregate cost per ton of NO_x controlled for wet kilns.

4.3.7 Potential Applicability of Oxidation Technology to Holcim Plant

General Discussion. The Holcim Plant has two large precalciner kiln systems with existing scrubbers. An oxidative control technology for these kiln lines has significant potential to provide NO_x control using the existing scrubber system.

A variety of low temperature oxidation reagent systems could be tested for efficiency in the existing wet scrubber system. It should also be relatively simple to set up a temporary system to test the high temperature hydrogen peroxide control option in a manner similar to the set up that was used to test SNCR. The critical factor in the successful use of the high temperature hydrogen peroxide control technology will be determining the best location for injection. Careful gas phase temperature measurements and modeling should help determine the optimum location.

Conclusions. It may be possible to add a hydrogen peroxide injection system to the preheater tower at the correct location with a relatively low capital expenditure. By combining SNCR and the high temperature hydrogen peroxide system an effective control system could be put in place at a minimal capital expenditure that would then allow the plant to use more or less of the hydrogen peroxide and ammonia reagents based on their current costs – thus optimizing the long term cost per ton of NO_x control.

4.3.8 Potential Applicability of Oxidation Technology to TXI Plant

General Discussion. The TXI plant has 4 wet process kilns without any existing wet scrubber system. That would require them to place a complete oxidation system in place as an add-on technology including the scrubber for these systems. Assuming that all of the available options would have a similar capital cost for a spray tower/scrubber system careful evaluation of the alternative reagent systems is warranted.

A trial system for evaluating the reagent systems may be warranted. As an example, three one-month trials using alternative reagents in a skid-mounted scrubber could be performed prior

to scaling up to a full system. It may be possible to combine the gas flows from the kiln systems into a single flow to minimize the cost of the scrubber system.

Because of the high moisture levels in the gasses from wet kilns it may be necessary to bypass a portion of the stack gasses around the spray tower/scrubber for use as reheat gas after the spray tower/scrubber to prevent condensation problems in the stack. To the extent that such a strategy is required the efficiency of the NO_x removal would be proportionately impacted.

TXI also has a large modern precalciner kiln with a scrubber system on-site. An oxidative control technology for the precalciner kiln has significant potential to provide NO_x control using the existing scrubber system. A variety of low temperature oxidation reagent systems could be tested for efficiency in the existing wet scrubber system. It should also be relatively simple to set up a temporary system to test the high temperature hydrogen peroxide control option. The critical factor in the successful use of the high temperature hydrogen peroxide control technology will be determining the best location for injection. Careful gas phase temperature measurements and modeling should help determine the optimum location.

For TXI the added benefit of the high temperature hydrogen peroxide control technology might be the added control of hydrocarbons. There is the real potential that at the temperatures, which the hydrogen peroxide system operates at, those hydrocarbons will also be oxidized. Because these hydrocarbons may be evolved from the raw feed at a lower temperature this is not a sure thing but if it were to occur the potential does exist for such a system to replace the existing catalytic control system. In that even the savings on natural gas costs would be substantial.

Conclusions. For the precalciner the addition of the high temperature hydrogen peroxide oxidation control technology to the preheater tower has significant potential. In addition to controlling NO_x emissions this oxidation technology has the potential to control hydrocarbon emissions and eliminate the need for the existing catalytic control system and the associated operating costs. These potential cost savings could more than offset the cost of the hydrogen peroxide and capital investment for this kiln line to achieve even greater NO_x control than its already relatively low levels. Tests of this technology should be able to be conducted with minimal investment. Alternatively tests of various wet scrubber reagent systems could also be conducted in the existing SO_x scrubber system.

In the wet kilns, because of the reheat costs, further investigation of the low temperature oxidation technologies is likely to be the most cost effective and is therefore recommended for further investigation. Combination of midkiln combustion, midkiln SNCR and a low temperature oxidation technology may provide exceptional NO_x control at the most effective aggregate cost per ton of NO_x controlled for these kilns.

Table 4-3.4. Summary of Modeling Results for LoTOx on Ellis County Kilns – Performance Results

Existing Unit	Control Technology	Emissions Rate tpy before	Emissions Rate tpy after (a)	Controlled Emissions Rate ppm	Controlled Emission Rate lb/tonne clinker	Control Efficiency %	Reduction tpy
Ash Grove #1- wet	LoTOx	702	301.6	60	0.84	85%	400.4
Ash Grove #2- wet	LoTOx	750	322.2	58	0.89	85%	427.8
Ash Grove #3- wet	LoTOx	764	328.3	53	0.91	85%	435.7
TXI #1 and #4–wet (b)	LoTOx	1197	514.3	109	1.21	85%	682.7
TXI #2 and #3–wet (b)	LoTOx	121	52	109	0.49	85%	69.0
TXI#5 – dry	LoTOx	1710	734.7	29	0.30	80%	975.3
Holcim #1 – dry	LoTOx	2222	954.7	73	0.38	85%	1,267.3
Holcim #2 – dry	LoTOx	1778	763.9	53	0.30	85%	1,014.1

- h) NO_x emission rate after SCR does not reflect SCR efficiency reduction due to adjustment by the ozone season factor of 0.671 (NO_x reduction is modeled to occur only during the ozone season).
- i) The results for TXI 1 & 4 and #2 & #3 are average per kiln – for example, total emissions reductions for controlling both TXI #1 & #4 are double the value listed in the table.
- j) Models assume mid-kiln firing installed at TXI as required under current SIP.

Table 4-3.5. Summary of Modeling Results for LoTOx on Ellis County Kilns – Economic Results

Existing Unit	Control Technology	Capital Cost	Annual Cost	Cost Effectiveness \$/ton NO _x	Energy Penalty or Benefit	Emissions Penalty or Benefit	Burden Cost \$/tonne clinker
Ash Grove #1- wet	LoTOx	\$4.8 MM	\$1.4 MM	\$3,400	a)		\$5.00
Ash Grove #2- wet	LoTOx	\$5.2MM	\$1.5MM	\$3,500	a)		\$5.40
Ash Grove #3- wet	LoTOx	\$5.8MM	\$1.6MM	\$3,700	a)		\$5.70
TXI #1 and #4–wet (b)	LoTOx	\$5.4MM	\$1.6MM	\$3,300	a)		\$4.70
TXI #2 and #3–wet (b)	LoTOx	\$2.8MM	\$0.5MM	\$11,000	a)		\$10.50
TXI#5 – dry	LoTOx	\$5.2MM	\$2.4MM	\$2,600	a)		\$0.90
Holcim #1 – dry	LoTOx	\$6.7MM	\$3.1MM	\$2,400	a)		\$2.35
Holcim #2 – dry	LoTOx	\$5.4MM	\$2.5MM	\$2,300	a)		\$1.90

- a) Increased fan power due to pressure drop across scrubber included in the models
- b) The results for TXI 1 & 4 and #2 & #3 are average per kiln – for example, total capital costs for controlling both TXI #1 & #4 are double the value listed in the table.
- c) Costs for wet kilns include addition of spray tower to scrub oxidation products.

reducing excess air from 10 to 5 percent (i.e., reducing exhaust oxygen levels from 2 to 1 percent) NO_x emissions per unit time can be reduced by approximately 15 percent.^{4,5}

With state-of-the-art continuous emissions monitoring systems (CEMS) and feedback control, excess air can be accurately controlled to maintain a level that promotes optimum combustion and burning conditions in addition to lowering NO_x emissions. Reducing excess air level also results in increased productivity per unit amount of energy consumed and thus results in an indirect reduction of NO_x emissions per unit amount of clinker product.

4.4.2 Feed Mix Composition

Heat requirements for producing clinker are dependent on the composition of the raw feed which varies among cement plants. Experiments have demonstrated that by improving the burnability of the raw feed, the heat requirement of clinker can be reduced by 15 percent⁶ If the raw feed composition can be formulated to require less heat input per ton of clinker, less fuel is burned and less NO_x per unit product is produced. This approach of changing the feed composition may, however, be highly site specific and may not be applicable at all locations.

Reduction of Alkali Content of Raw Feed. The alkali content of finished cement generally needs to be below a certain acceptable level. Low alkali requirements need higher kiln temperatures and longer residence times at high temperatures to volatilize the alkali present in the semi-molten clinker. Raw materials with greater alkali content need to be burned longer at higher temperatures to meet alkali requirements and thus may produce greater NO_x emissions. Increased volatilization of alkali also results in increased alkali emissions in kiln exhaust gases. To control alkali emissions, a part of the kiln exhaust gases may be bypassed around a downstream unit, e.g., a precalciner. The bypassed gases are quenched to remove alkali and sent through a particulate collector. The bypass of kiln exhaust gases typically involves a fuel penalty, e.g., about 20,000 Btu/ton of clinker for every 1 percent gas bypass. The additional heat requirement may also contribute to increased NO_x emissions; thus, reducing the alkali content of the raw feed mix may contribute to a reduction in the NO_x emissions.

4.4.3 CemStar Process

Another feed modification that can reduce NO_x emissions is the addition of a small amount of steel slag to the raw kiln feed. This patented technique is known as the CemStar

Process and was developed by TXI Industries. Steel slag has a low melting temperature and is chemically very similar to clinker. Since many of the chemical reactions required to convert steel slag to clinker have already taken place in a steel furnace, the fuel needed to convert steel slag into clinker is low. The decreased need for limestone calcination per unit product and improved thermal efficiency of the process both contribute to reduced thermal NOx and CO2 emissions.⁷

Eleven facilities are using or in the process of incorporating CemStar⁸ CemStar requires little extra equipment and the addition of steel slag to the feed mix can result in a reduction or elimination of the need for some mineral sources, such as shale or clay. This process can also increase production by 15 percent.⁷

According to the Entellect Environmental Services “Evaluation of the Effects of the CemStar Process on a Wet Process Cement Kiln” report, the CemStar process reduces the kiln material temperature in the region of the flame by an average of 200°F (from 2610°F to 2405°F); the lower gas temperature of the flame results in lower NOx emissions.⁹ Another test of CemStar technology found an average reduction in burn zone temperature of 160E F, a six percent reduction.⁹ The amount of NOx emissions reductions achievable with CemStar varies by kiln type but ranges from over 20 to 60 percent.⁷ Short- and long-term tests of CemStar were conducted at two different types of TXI cement kilns in 1999. Short-term tests (two days) on a preheater/precalciner kiln found NOx emissions reductions in lbs NOx /ton of clinker of 44 percent when operated at maximum capacity, and between 9 and 30 percent when operated at normal capacity, depending on the quality of the raw feed mix (see Table 4-4.1.).

Table 4-4.1. Results Of Short-Term Cemstar Tests On A Preheater/Precalciner Kiln

	Poor Quality Feed Mix (lb NOx/ton of clinker)	Percent Reduction ^a (%)	Ideal Quality Feed Mix (lb NOx/ton of clinker)	Percent Reduction ^a (%)
Without CemStar	4.98	-	5.59	
With CemStar at normal feed rate ^b	4.51	9	3.89	30
With CemStar at maximum feed rate ^c	(no test)	-	3.15	44

^a Percent reductions are relative to the emission rate without CemStar.

^b The normal feed rate is 170 - 180 tons per hour of dry feed.

^c The maximum feed rate is 195 tons per hour of dry feed.

Andover Technologies also reported on short-term and long-term tests of a wet kiln using CemStar Technology. The short-term tests (one day) found emission reductions of 36 to 55 percent in lbs NOx/ton of clinker, and the long-term tests (approximately two and a half months) found reductions of 24 percent (see Table 4-4.2).⁷

Kilns with lower initial baseline NOx emissions would have less NOx reductions with CemStar than those with higher baseline emissions. Wet and long-dry kilns would have greater NOx reductions with CemStar because more energy is used per ton of clinker produced than preheater/precalciner kilns. Wet kilns may achieve the greatest NOx reductions with CemStar because the addition of steel slag would reduce the amount of water needed to create the slurry and consequently decrease the amount of heat needed to dry it.⁷

Table 4-4.2. Results of Cemstar Tests on a Wet Kiln

	Test 1 (lb NOx/ton of clinker)	Test 2 (lb NOx/ton of clinker)	Percent Reduction ^a (%)
<i>Short-Term Test</i>			
Without CemStar	17.53	24.7	-
With CemStar	11.24	no 2 nd test	Test 1 = 36 Test 2 = 55
<i>Long-Term Test</i>			
Without CemStar	5.23	no 2 nd test	-
With CemStar		no 2 nd test	24

^a Percent reductions are relative to the emission rate without CemStar.

4.4.4 Kiln Fuel

Changing the primary kiln fuel from natural gas to coal can reduce the flame temperatures significantly, resulting in lower thermal NOx emissions.^{10,11} Although nitrogen present in coal may provide greater fuel NOx contribution, switching the fuel burned in kilns from natural gas to coal has been shown to provide substantial reduction in the total NOx emissions in one experimental study.¹⁰ In the dry process kilns tested in this study the average NOx emissions decreased from 20.4 lb/ton of clinker to 6.2 lb/ton of clinker when the fuel was changed from natural gas to coal. A number of cement kilns have already made the switch from natural gas to coal and currently 87 percent of cement kilns in the United States use coal as the primary fuel.¹²

When natural gas (with no nitrogen in the fuel) is used in the burning zone of a cement kiln, the NOx emissions are significantly higher than when coal is used. There may be additional environmental impacts when coal is burned as opposed to natural gas (e.g., sulfur dioxide and

sulphate emissions may increase). Although switching to a lower nitrogen fuel in a precalciner may reduce NO_x, the fuel nitrogen content in the burning zone has little or no effect on NO_x generation. Some researchers have found no relationship between fuel nitrogen content and the NO_x emissions from a cement kiln.¹³

Switching to a fuel with a higher heating value and lower nitrogen content may reduce NO_x emissions in a cement kiln, e.g., petroleum coke has a lower nitrogen content per million Btu than coal. Petroleum coke is also more uniform in terms of heat value, lower in volatile matter content and burns with a lower flame temperature. However, petroleum coke cannot be burned alone because it does not provide enough volatile matter.¹⁴

4.4.5 Increasing Thermal Efficiency

The thermal efficiency of the cement-making process has improved substantially as energy costs have increased and new technology has been developed. Although there are a variety of cement process technologies used in the US, the kilns in this study are all either 1960's wet kiln technologies that are not energy efficient or modern dry process kilns with preheat and precalcination that represent the most energy efficient process for making Portland cement. Both Holcim #2 and TXI #5 are new and energy efficient units. Holcim #1 began operation in 1987 and is slightly less efficient and could potentially be upgraded by options such as calciner modification discussed below. In addition, there are interim steps that improve the efficiency of wet process to semi-wet or semi-dry process. However, the main opportunity for substantial reductions in NO_x emissions in Ellis County from energy improvements comes from closing the wet process units and replacing them with modern, dry-process production.

Calciner Modifications

A study for the Department of Energy (Worrell 2004) reports evaluates use of low pressure drop cyclones for suspension preheaters. Worrell reports: "Cyclones are a basic component of plants with pre-heating systems. The installation of newer cyclones in a plant with lower pressure losses will reduce the power consumption of the kiln exhaust gas fan system. Depending on the efficiency of the fan, 0.6-0.7 kWh/ton clinker can be saved for each 50 mm W.C. (water column) the pressure loss is reduced. For most older kilns this amounts to savings of

0.6-1.0 kWh/ton (Birch, 1990). Fujimoto (1994) discussed a Lehigh Cement plant retrofit in which low-pressure drop cyclones were installed in their Mason City, Iowa plant and saved 4 kWh/ton clinker (Fujimoto, 1994). Installation of the cyclones can be expensive, however, since it may often entail the rebuilding or the modification of the preheater tower, and the costs are very site specific. Also, new cyclone systems may increase overall dust loading and increase dust carryover from the preheater tower. However, if an inline raw mill follows it, the dust carryover problem becomes less of an issue. A cost of \$2.7/annual ton clinker is assumed for a low pressure drop cyclone system.”

The only candidate for a calciner upgrade among the Ellis County kilns is Holcim #1. This process line represents a slightly older version of the technology than Holcim #1 or TXI #5. Low-Nox and low energy consumption performance is largely inherent in the design and Holcim #1 would appear to be the unit that could best benefit from this upgrade. Cost modeling has been provided based on the assumption that this unit could move to a level of performance similar to TXI #5 after the upgrade. These results are provided in Table 4-4.5..

Semi-Wet Upgrades to Wet Kilns

Hendriks and Worrell (Hendriks 1998) report that conversion from a wet to a semi-wet process can save between 0.8 and 1.6 GJ/ton of clinker. There is a penalty of increased electrical energy use associated with this conversion of approximately 3 to 5 kWh.

Worrell (Worrell 2004) also reviews this option and describes it as a filter press system. “In the wet process the slurry typically contains 36% water (range of 24-48%). A filter press can be installed in a wet process kiln in order to reduce the moisture content to about 20% of the slurry and obtain a paste ready for extrusion into pellets (COWIconsult et al., 1993; Venkateswaran and Lowitt, 1988). In the U.S. several plants have tried slurry filters, but have not been very successful. Currently, there seem to be no plants in the U.S. using this technology (Young, 2002). Additional electricity consumption is 3-5 kWh/ton clinker (COWIconsult et al., 1993). In this analysis it is assumed that energy use increases by 4 kWh/ton clinker to reduce the moisture content to 20%. The corresponding fuel savings are 1.0 MBtu/ton (COWIconsult et al., 1993). Jaccard and Willis (1996) estimate the conversion cost to run \$1.6/annual ton clinker capacity with increased operation costs of \$0.1/ton clinker (Jaccard and Willis, 1996).”

Semi-Dry/Semi-Wet Upgrades to Wet Kilns

Hendriks and Worrell (Hendriks 1998) report that conversion from a wet to a semi-dry process can save approximately 2.0 GJ/ton of clinker. They report a “small” increase in electrical energy use associated with this conversion of approximately 3 to 5 kWh.

Buzzi-Unicem operates a semi-dry/semi-wet system in Greencastle, IN, which had been converted from a large wet kiln system. While anticipated increases in production capacity were achieved predicted improvements in thermal efficiency were not fully realized. Actual thermal efficiency improvement was only about 15%. Capital cost for this type of conversion are likely to be in the range of \$75-85/tonne. Significant NO_x improvements have been observed in this conversion although not to the levels predicted by the vendor. Even with a 50% increase in production total NO_x emissions have been significantly reduced.

Because kiln conversion economics are significantly impacted by the size of the exiting kiln the conversion of any of the wet kilns at TXI or Ash Grove is not considered a feasible alternative for further analysis.

Replacement of Wet Kilns with Dry

Worrell evaluates conversion of a wet kiln to a dry preheat/precalciner process (Worrell 2004). This conversion is essentially a reconstruction of the main kiln and processing areas with a new, modern dry plant. Worrell reports “If economically feasible a wet process kiln can be converted to a state-of-the art dry process production facility that includes either a multi-stage preheater, or a pre-heater/pre-calciner. Average specific fuel consumption in U.S. wet kilns is estimated at 6.0 MBtu/ton clinker. Studies of several kiln conversions in the U.S. in the 1980s found fuel savings of 2.9 MBtu/ton or less (Venkateswaran and Lowitt, 1988). In Hranice (Czech Republic) a 1,050 tonne per day wet process plant was converted to a dry kiln plant with a new kiln specific fuel consumption of 2.7 MBtu/ton clinker (Anon., 1994b). Fuel savings of 2.7 MBtu/ton clinker and an increase in power use of about 9 kWh/ton clinker (Vleuten, 1994) are assumed. The cost of converting a wet plant to a dry process plant may be high, as it involves the full reconstruction of an existing facility. Costs may vary between \$50/annual ton clinker capacity and \$100/annual ton clinker capacity (van Oss, 1999; Nisbet, 1996).”

This options is also discussed by Hendriks (Hendriks 1998). Hedriks gives a cost of approximately \$133/ton of annual capacity as the cost of building the new dry process plant. Hedriks estimates that about 2.2 GJ/ton of energy can be saved. Increased energy use of about 10kWh/ton is required for operation of the preheat/precalcination tower.

Wet to Dry Conversion of Ellis County Kilns

On average, dry preheat/precalciner kilns emit substantially less NO_x per tonne of cement produced and require about less energy per tonne of cement produced. Both in terms of energy use and NO_x emissions rates, the wet process units are often nearly double the modern dry process units. The cost modeling presumed that the wet kilns could obtain a value approximately that of high performing modern kilns and that would result in an approximate 65% decrease in NO_x emissions. A substantial energy savings was predicted to result in fuel savings in the cost models (see Confidential Attachment Wet to Dry Conversions).

The economics of wet kilns compared to dry kilns are very complex and involve issues such as lower production capacity of wet kilns, use of waste fuels and quality of cement products. However, as the energy costs of wet production are higher than for modern dry process units, there is a point at which the higher costs of pollution controls that may result from the final determinations of this study would trigger a decision to close the wet kilns and replace them with dry. Stating this another way, it is likely that at a certain cost of pollution controls in terms of dollars per tonne of clinker produced, the economics of the wet process including higher fuel costs and higher pollution control costs would reach a point where replacement of the wet units with larger dry process units would be the reasonable alternative for a cement plant to continue operations at that site.

It is likely that any new kilns built to replace the wet kilns in Ellis County would include increased production capacity in the economic justification. However, for the purposes of control cost modeling, the units need to replace the existing capacity for the evaluations to make sense in the context of our control option evaluations. For this reason, two dry process kiln replacement scenarios were modeled. One involved replacing the three wet kilns at Ash Grove with one new dry process unit and the second involved replacing the four wet kilns at TXI with one new dry process unit. The capacity of the new units was modeled as essentially equal to the capacity of the exiting wet units combined. It is likely that Ash Grove and perhaps TXI would

replace the existing kilns with a new dry preheat/precalcination process typical of current generation dry process plants with approximately twice (over 2 million tons per year of clinker) the capacity of the existing wet kilns (under one million tons per year of clinker) and the added production capacity would be an important part in cost justification of the expense of the new dry process unit.

The modeling, summarized in Table 4-15, shows an annualized cost of approximately \$11 per tonne of clinker for the replacement dry process units. This cost includes an annual benefit of approximately \$4.0 to \$4.5 million in reduced fuel costs used as the fuel. An increased annual cost of electricity of approximately \$0.5 million results from the additional fan power required to move air through the preheat and precalcination tower. This information indicates that energy savings are very significant, but are not sufficient for a company to justify replacement of the wet kilns. Annual operating costs (capitalization of the new equipment) are reduced by nearly one third to approximately \$9 million dollars by energy savings; however, even with the current high costs of energy this would not by itself justify replacement of the wet kilns.

The current use of alternative fuels complicates this analysis. The fuel savings are based on an assumption that the energy for the current wet kilns is all based on coal. Lower cost alternative fuels lessen the economic benefit of the increased energy efficiency. Preserving these alternative fuel programs may be important economic considerations in company analyses of wet to dry conversions and the overall economics of cement production on a dollars per tonne of clinker basis. The realistic assumption that larger modern units of a size similar to TXI #5 would be needed to achieve the energy efficiency desired and to use increased production to offset the high cost of these projects also impacts the fuel economics. If we assume that the current amount of alternative fuels are permitted to be used in a new larger kiln, the amount of coal predicted to be reduced would still be reflected in the overall reduction in fuel use.

Conversion of the Ellis County wet kilns to dry process would result in year-round emissions reductions for NO_x, SO₂, particulate matter and hazardous air pollutants. The modern dry process unit would have updated controls that would result in a potentially large emissions reduction credits for SO₂ that could be marketable depending on how this overall project was viewed under Texas regulations. If this emissions reduction was creditable and marketable, this would provide some additional benefit to this approach.

Table 4-4.3. Summary of Modeling Results for Wet to Dry Conversion of Ellis County Kilns – Performance Results

Existing Unit	Replacement Unit	Emissions Rate tpy before	Emissions Rate tpy after	Controlled Emissions Rate ppm	Controlled Emission Rate lb/tonne clinker 2.0 lbs/ton clinker	Control Efficiency %	Reduction tpy
Ash Grove #1- wet Ash Grove #2- wet Ash Grove #3- wet	Ash Grove #4 - dry	2,200	772	180	1.99	65%	1,428
TXI #1 -wet TXI #2 -wet TXI #3 -wet TXI #4 -wet	TXI #6 - dry	1,800	630	180	1.94	65%	1170

Table 4-4.4. Summary of Modeling Results for Wet to Dry Conversion of Ellis County Kilns – Economic Results

Existing Unit	Replacement Unit	Capital Cost	Annual Cost	Cost Effectiveness \$/ton NOx	Energy Penalty or Benefit*	Emissions Penalty or Benefit**	Burden Cost \$/tonne clinker
Ash Grove #1- wet Ash Grove #2- wet Ash Grove #3- wet	Ash Grove #4 - dry	\$169 million	\$9.3 million	\$6,500	-\$4.4 million	-1,428 tpy	\$10.94
TXI #1 -wet TXI #2 -wet TXI #3 -wet TXI #4 -wet	TXI #6 - dry	\$143 million	\$7.9 million	\$6,700	-\$3.7 million	-1,170 tpy	\$10.94

* large benefit in fuel efficiency partly offset by increased electrical use in tower

** large benefit in reduced fuel – does not account for increased emissions at power plant for power used in tower.

Table 4-4.5 Summary of Modeling Results for Calciner Upgrade for Ellis County Kilns – Economic Results

Control Technology	Control Technology Status	Emissions Rate before control tpy	Emissions Rate before control lbsNOx//tonne	Percent Control	Emissions Reduction from Control tpy	Controlled Emission Rate lbNOx/tonne	Cost Effectiveness \$/ton NOx	Burden Cost \$/tonne clinker
Holcim #1	Available	2,222	3.76	40%	888.8	2.2	\$2,795	\$2.70

40% for new low-NOx calciner based on TXI #5 performance.

Cost effectiveness for calciner upgrade calculated by ratio of burden costs using SCR data.

Calciner upgrade is not a seasonal ozone measure – emissions benefit is for full year.

References:

Worrell, Ernst and Galitsky, Christina, “Energy Efficiency Improvement Opportunities for Cement Making An ENERGY STAR Guide for Energy and Plant Managers”, Energy Analysis Department, Environmental Energy Technologies Division., Ernest Orlando Lawrence Berkeley National Laboratory, University of California, January 2004

Hendriks, C.A., E. Worrell, D. de Jager, K. Blok, and P. Riemer. 1998. Emission Reduction of Greenhouse Gases from the Cement Industry Lawrence Berkeley National Laboratory, Berkeley, California. IEA Website <http://www.ieagreen.org.uk/jan46.htm>

ATTACHMENT A

ERG Summary of EPA 2000 NO_x Controls for Cement Kilns

Table 1-1. Summary of EPA Reported NO_x Control Technologies for Cement Kilns – EPA 2000

NO _x Control Strategies	Applicability	NO _x Reduction Efficiency (%)	Estimated Costs	Number of Installations
Process modifications	Excess air and temperature optimization (using CO and O ₂ CEMS and feedback control)	15 ^a	Capital cost = ~\$750,000 ^s	Unknown
	Reduce alkali content of feed where feasible	Not available	Not available	Unknown
	CemStar (addition of steel slag)	All kiln types although higher NO _x reductions expected from wet and long-dry kilns due to greater heat input offsets	9 - 60 ^b	Capital cost = \$200,000 - \$500,000 ^t Annual costs are highly site-specific (e.g., slag injection rate, potential cost savings due to increased production)
Combustion modification	Fuel switching (natural gas to coal)	All kiln types	Not available	~ 87% of existing kilns use coal
	Improving thermal efficiency	All kiln types	Not available	Unknown
	Staged air combustion - staged fuel combustion	All kiln types (most effective with indirect fired kilns)	Not available	Unknown
	Staged air combustion - flue gas recirculation	May not be suitable for cement kilns. Incorporation of FGR in a cement kiln also results in somewhat increased power consumption and reduced kiln output.	Not available	Unknown
	Staged air combustion - flue gas recirculation w/low-NO _x burner		15 - 38 ^d	Not available

Table 1-1. Summary of EPA Reported NO_x Control Technologies for Cement Kilns – EPA 2000

NO _x Control Strategies	Applicability	NO _x Reduction Efficiency (%)	Estimated Costs	Number of Installations
Staged air combustion - Low-NO _x burner	All kiln types (burners that use 5-7% excess air are only for indirect-fired kilns)	44 ^e 15 - 33 ^f 23 - 47 ^g 14 ^h	Capital cost = \$511,000 - \$966,000 ^u Annual cost = \$136,000 - \$204,000 ^u	~22 existing kilns use low-NO _x burners
Staged fuel combustion - Tire-derived fuel (TDF)	All kiln types	30 - 40 ⁱ		Unknown. Approximately 53,300,000 tires are burned in cement kilns annually http://www.epa.gov/epaoswer/non-hw/municipl/tires/tdf.htm#cement
Staged fuel combustion - Low-NO _x precalciner	Not applicable to preheater kilns that fire fuel in the riser	<46 ^j	Not available	Unknown
Staged fuel combustion - Mid-kiln firing	Wet and long-dry kilns	38 ^k 11 - 55 ^l 28 - 59 ^m	Capital cost = ~\$3,000,000 ^v Annual cost = (\$370,000) - \$189,000 ^v	21 long kilns (US), 40 kilns (worldwide)
Selective catalytic reduction (SCR)	No cement kilns had SCR at the time of the EPA Study prior to 2000.		Not available in 2000.	No installations were reported on cement kilns in EPA 2000.
Selective non-catalytic reduction (SNCR)	Best application is for preheater/precalciner kilns. Generally not applicable to long-dry or wet kilns	71 -98 ⁿ 10-20 ^o	Not available	2 kilns (US), 18 in Europe
Biosolids (SNCR)	Preheater/precalciner kilns	Not available	Capital cost = \$240,000 ^w Annual cost = (\$22,000) ^w	Unknown

Table 1-1. Summary of EPA Reported NO_x Control Technologies for Cement Kilns – EPA 2000

NO _x Control Strategies	Applicability	NO _x Reduction Efficiency (%)	Estimated Costs	Number of Installations
NO _x OUT (SNCR)	Preheater/precalciner kilns	> 50 - 90 ^p 10 - 20 ^q 46 - 53 ^r	Capital cost = ~\$1,200,000 ^x Annual cost = \$560,000 - \$2,000,000 ^x	None
Low Temperature Oxidation (LoTox, Hydrogen Peroxide, OXONE (Dupont) & Sodium Acetate)	Oxidation technologies were not discussed or considered in the EPA 2000 report.	Not considered	Not considered	Oxidation technologies were not discussed or considered in the EPA 2000 report.

^aResults based on experimental test on one kiln.

^bResults derived from short- and long-term tests on two different kiln types.

^cResults based on emission tests of dry kilns.

^dResults based on a single 1988 study. The percent reduction depends on degree of flue gas recirculation.

^eResults based on emission tests of a preheater/precalciner kiln.

^fResults based on emission tests of five kilns.

^gResults based on emission tests of four kilns.

^hEmission test of one kiln.

ⁱResults based on tests conducted at one California facility.

^jResults based on a test conducted by the Portland Cement Association.

^kResults based on one study.

^lResults based on testing of seven dry kilns.

^mResults based on testing of three wet kilns.

ⁿBased on emission tests of a preheater/precalciner kiln at one facility.

^oResults based on emission test at one facility

^pResults based on emission tests of a single kiln.

^qResults based on a emission tests of a single kiln (operating conditions during most of the test were unstable).

^rResults based on emission test of two kilns.

^sEstimate for a commercially available process control system.

^tCost estimates obtained from Texas Industries (TXI).

^uCosts derived for retrofitting low-NO_x burners to eight model kilns with clinker production capacities ranging from 25 to 150 tons of clinker per hour.

^vCosts derived for retrofitting low-NO_x burners to four model kilns with clinker production capacities ranging from 25 to 50 tons of clinker per hour. Annual costs reflect the fuel credit associated with using tire-derived fuel.

^wCosts based on a clinker production rate of 215 tons per hour.

Table 1-1. Summary of EPA Reported NO_x Control Technologies for Cement Kilns – EPA 2000

NO _x Control Strategies	Applicability	NO _x Reduction Efficiency (%)	Estimated Costs	Number of Installations
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^xCosts based on two preheater/precalciner kilns with a clinker production rates of 92 tons per hour and 133 tons per hour.

ATTACHMENT B

ATTACHMENT B

Sample Acquisition and Handling

Clean, clear, pre-labeled, one (1) liter sample bottles were shipped to each Kiln site on Aug __, 2005 via Federal Express. The nine (9) samples returned on August ___ in good condition from Texas Industries Inc. included three wet slurry, three dry powder and three slag samples. The six (6) samples returned from Ash Grove Cement on August ___ included three (3) wet slurry and (3) slag samples. The 6 samples returned from Holcim on August 31 included (3) samples from line 1 and 3 samples from line 2.

All were samples returned to ERG's analytical laboratory with chain of custody and security seals. ERG consulted with three cement kiln experts, F. MacGregor Miller, Gabriel Miller David Gossman on the analyses required to determine key features of the kiln feed chemistry important to NOx emissions and control. Recommendations were sought from the experts' laboratories experienced in each analysis. Three laboratories were ultimately selected on the basis of expertise and price. Table 1 summarizes the analyses requested for each sample.

ERG repackaged samples for distribution to the specialty analysis laboratories scheduled to perform feed material composition analysis. Repackaged samples were given unique identification numbers to keep Kiln identity anonymous to the analysis laboratories.

Table 1. Feed Chemical Composition

Plant Name	Samples Received	Sample Type	Total Sulfur	Sulfate	Sulfite	Pyritic Sulfur	Organic Sulfur	Chloride	Nitrogen (TKN)
Texas Industries Inc (TXI)	3	Wet Slurry	X	X	X	X	X	X	X
Texas Industries Inc (TXI)	3	Dry Powder	X	X	X	X	X	X	X
Texas Industries Inc (TXI)	3	Slag Dry	X	X	X	X	X	X	X
Holcim US Inc	0	Power Line 1 Dry	X	X	X	X	X	X	X
Holcim US		Power							

ATTACHMENT C

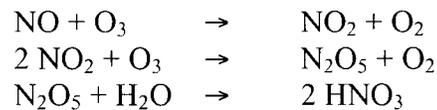
ATTACHMENT C

ERG Report - Refinery Application of Low Temperature Oxidation Emission Controls

LoTOx™

LoTOx™ is a trademark of the BOC Group Inc. for an end-of-pipe process that uses ozone to oxidize insoluble species of NOx, such as NO and NO₂, to highly soluble species, primarily N₂O₅. N₂O₅ then reacts with moisture in the flue gas to form nitric acid (HNO₃) and is removed from the gas in a wet gas scrubber. LoTOx is a developing technology for NOx control, and there are currently only about three commercial applications of LoTOx. Another three installations are planned in the next two years. LoTOx has been demonstrated using slipstream testing at ten types of facilities, including a smelting plant, a glass furnace, a lead furnace, a petroleum coke and high sulfur coal fired boiler, a chemical plant, a steel pickling bath process gas-fired boiler, a composite fuel fired boiler, a petroleum refinery fluid catalytic cracking unit (FCCU), and a lignite-fired boiler. No cement plants have tested LoTOx.

In the LoTOx process, ozone is formed from oxygen using a corona-discharge ozone generator. The resulting concentration of ozone is between 7 and 15 weight percent (Ferrell 2000, p. 1). The ozone/oxygen mixture is injected into the flue gas stream as it enters either a wet gas scrubber or a reaction vessel adjacent to a wet gas scrubber. The ratio of ozone to NOx is 2.8:1, and varies with factors such as flue gas temperature and residence time. The principal reactions for NOx oxidation are:



The maximum temperature for the oxidation reactions is 325 °F (163 °C), while the optimal temperature is generally less than 300 °F (149 °C). The NOx oxidation reactions become unstable over 325 °F. Trials at a coal-fired power plant and a steel pickling process found that optimal temperature was in the range of 160 to 250 °F (Ferrell 2000, p. 10). A trial at a batch lead recovery furnace found the optimal temperature was 175 °F or less, although the temperature could be increased up to 225 °F without sacrificing NOx removal, but at the cost of increased ozone demand (Ferrell 2003, p. 9). A trial at Marathon Ashland Petroleum's (MAPCO) Texas City refinery FCCU found the optimal temperature was 140 to 150 °F (Sexton 2004, p. 23). These temperatures are lower than typical cement kiln flue gas temperatures. In addition,

Relative Solubility of Flue Gas Components

Species	Relative Solubility at 25 °C
NO	1
NO ₂	20
SO ₂	2000
N ₂ O ₅	>>2000
HNO ₃	Mixes with water in all proportions

Ferrell 2003, p. 4

N₂O₅ reacts immediately and irreversibly with water to form nitric acid. The nitric acid is neutralized with caustic or lime in the scrubber liquor to form sodium or calcium nitrates.

Potential Advantages of LoTOx

The potential advantages of LoTOx are as follows.

LoTOx can provide a high degree of NOx removal. Based on slipstream testing, 90 percent NOx removal is typical, with greater than 95 percent NOx removal achievable.

LoTOx can respond quickly to variable NOx emissions. Since ozone is produced on demand, changes in NOx load can be met without loss of NOx removal efficiency. Swings in NOx concentration by 100 percent or more over the course of minutes have been accommodated using combined feed-forward/feed-back control schemes (Ferr 2000, pp. 8-9; Ferrell 2003, pp. 13-14). Although most LoTOx trials have been for combustion processes (90:10 NO to NO₂ ratio), the steel pickling process had variable NO to NO₂ ratios, with NO₂ sometimes higher than NO. Ozone production was decreased since less ozone was required to oxidize NOx to N₂O₅, while NOx removal was maintained above 95 percent (Ferrell 2000, p. 8).

LoTOx does not emit excess reactant. Unlike SCR and SNCR, which can emit excess ammonia, the ozone that does not react with NOx in the LoTOx process is scavenged by sulfite in the scrubber solution. A trial at a lead furnace examined the potential for unreacted ozone to be emitted from the process. It was found that the ozone addition rate had to be increased by a factor of eight over what was required for NOx removal to cause 10 ppm of ozone to be measured in the stack gas (Ferrell 2003, pp. 9-10).

$\text{CO} + \text{O}_3 \rightarrow \text{CO}_2 + \text{O}_2$	1
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Ferrell 2003, p. 3

LoTOx does not interfere with other pollution control technologies. The trial at MAP's Texas City refinery FCCU indicated LoTOx does not have a negative impact on SO₂ scrubbing efficiency. The scrubber maintained SO₂ removal in excess of 99 percent during the LoTOx trial (Sexton 2004, pp. 16, 19).

Areas of Concern

Wet Gas Scrubber Required

A wet gas scrubber is necessary to take advantage of the increased solubility of N₂O over NO and NO₂. For cement plants with an existing wet gas scrubber for SO₂ and particulate matter removal, LoTOx can be installed as an upstream retrofit. For plants that do not require a scrubber for SO₂ or particulate matter removal, installing a scrubber for NOx removal only may not be cost effective.

Gas Temperature

Cement kiln flue gases typically have temperatures greater than the LoTOx maximum temperature of 325 °F. If the flue gas temperature is greater than 325 °F after useful heat has been recovered, quenching with water is required prior to ozone injection. BOC indicates that water quenching can be used on gas streams with temperatures up to 600 °F and moisture contents of 30 to 35 percent.

Nitrates in Wastewater

Sodium nitrate is typically the primary byproduct of the LoTOx process. This may be a concern for treatment and/or discharge of the wastewater. MAP examined the possible problems of increased nitrates in the study at the Texas City refinery (Sexton 2004, 22-23). Regarding sodium toxicity, MAP found that the contribution of sodium nitrate from LoTOx was small compared to sodium sulfate from SO₂ scrubbing. Regarding wastewater treatment impacts, monovalent cations, such as sodium, can have a destabilizing effect on bioflocculation by displacing divalent cations, such as calcium and magnesium. This can lead to decreased biofloc settling and increased suspended solids. This problem does not occur if the monovalent to divalent cation ratio is maintained at 2:1 or less (by addition of divalent cations if necessary). In addition, nitrogen gas

removed. In general, the cost per ton of NO_x removed was lower for units with high NO_x removal (greater than 85 percent), due to economy of scale. Similarly, the annual operating cost was at least 50 percent of the total annualized cost for those units with the lowest cost per ton of NO_x removed. The costs of oxygen and electricity for the ozone generator accounted for 80 to 90 percent of the annual operating costs.

For a 200 MW coal-fired power plant, BOC estimated the cost to be only 1,696 dollars per ton of NO_x removed (Ferrell 2000, pp. 12-13). This application was designed for 95 percent NO_x removal, and the annual mass of NO_x removed was 4 to 46 times larger than the refinery applications.

References Cited

(Ferrell 2000). Ferrell, R., M.H. Anderson, S.C. Hwang, N.J. Suchak, R. Kelton, J.T. Tsen. "Applications and Economics of Low Temperature Oxidation NO_x Control." Paper presented at Power-Gen 2000, November 14, 2000, Orlando, FL.

(Ferrell 2003). Ferrell, R., N. Suchak, R. Kelton, H. Hine, Shyam Nadkarni. "Application of Low Temperature Oxidation for NO_x Emissions Control on a Lead Recovery Furnace." Paper presented at ACE 2003, June 22-26, 2003, San Diego, CA.

(Sexton 2004). Sexton, J., N. Confuorto, M. Barrasso, N. Suchak. "LoTOx™ Technology Demonstration at Marathon Ashland Petroleum LLC's Refinery in Texas City, Texas." Paper presented at NPRA Annual Meeting, March 21-23, 2004, San Antonio, TX.