December 9, 2019

Mr. Bill Lichtenberg, P.E.
Permit Engineer
Air Quality Division
Arizona Department of Environmental Quality

Subject: Drake Cement Four Factor Analysis

Dear Mr. Lichtenberg,

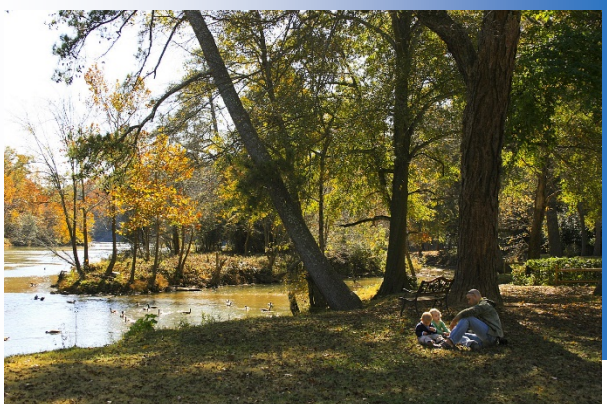
Drake is submitting this Four Factor Analysis under the Regional Haze Program 2nd implementation period for the Drake Cement Plant. This submittal includes the four-factor analysis and cost summary completed. Drake is also including the excel file of the cost summary to aid in your review. Please let us know if you have any questions or concerns regarding this analysis. Drake is available for a meeting to review and discuss this report if deemed necessary.

I certify that based on information and belief formed after reasonable inquiry, the statements and information contained in this submittal are true, accurate, and complete.

Sincerely,

David Chavez
Chief Compliance Officer
Skanon Investments, Inc.

EHS Department
21803 North Scottsdale Road, Suite 220
Scottsdale, Arizona 85255



DRAKE CEMENT
FOUR FACTOR ANALYSIS
REGIONAL HAZE
2ND IMPLEMENTATION PERIOD

Prepared By:

28150 N. Alma School Pkwy.
Suite 103-106
Scottsdale, AZ 85262

1661 E. Camelback Rd. #290
Phoenix, AZ 85016

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1. EXECUTIVE SUMMARY

This report documents the results of a four-factor control analysis of the nitrogen oxide (NO_x) emissions from the preheater/precalciner cement kiln at Drake Cement LLC (Drake). Drake owns and operates a Portland cement manufacturing facility in Paulden, Yavapai County, Arizona (Paulden Facility). The Paulden Facility operates a state-of-the-art rotary kiln (RK 9.1) equipped with a six-stage preheater and in-line calciner. The kiln has many existing voluntary controls installed to reduce NO_x emissions.

The United States Environmental Protection Agency's (U.S. EPA) guidelines in 40 CFR Part 51.308 were used to evaluate control options for the kiln. In establishing a reasonable progress goal for any mandatory Class I Federal area within the State, the State must *consider the costs of compliance, the time necessary for compliance, the energy and non-air quality environmental impacts of compliance, and the remaining useful life of any potentially affected sources, and include a demonstration showing how these factors were taken into consideration in selecting the goal*.

The purpose of this report is to provide information to the Arizona Department of Environmental Quality, (ADEQ) and U.S. EPA Region 9 on available control technologies for NO_x emissions reductions and its applicability to the Paulden Facility. Since control options are only relevant for the Regional Haze Rule (RHR) if they result in a reduction in the existing visibility impairment in a Class I area, Drake assumes that ADEQ will only move forward with requiring emission reductions from the Paulden Facility if the emission reductions can be demonstrated to be needed to show reasonable progress and provide the most cost effective controls among all options available to ADEQ.

The Paulden Facility currently uses low- NO_x burners, preheater riser duct firing, and Selective Non-Catalytic Reduction (SNCR) to reduce and control NO_x emissions. The use of low NO_x burners in conjunction with SNCR is a commonly applied technology in current Best Available Control Technology (BACT) determinations for new rotary preheater/precalciner kilns today. Additionally, the Kiln also uses preheater riser duct firing to reduce NO_x emissions. The only other potential NO_x emission control evaluated for this kiln is Selective Catalytic Reduction (SCR). There is only one instance of SCR installation on a cement kiln in the U.S. This installation was recently implemented on a long, dry cement kiln at the Joppa Cement Plant, which is significantly different from the preheater/precalciner kiln system at the Paulden Facility and was installed as a result of a consent decree. Drake believes that the currently installed control systems provide reliable reductions in NO_x emissions and a SCR installation is currently not commercially available and cost-prohibitive on this type of kiln system. Additionally, Drake reserves the right to supplement this submittal with additional supporting documentation, any vendor specified cost information, and any appropriate modeling (if applicable).

2. REGIONAL HAZE PROGRAM BACKGROUND

In the 1977 amendments to the Clean Air Act (CAA), Congress set a national goal to restore national parks and wilderness areas to natural conditions by preventing any future, and remedying any existing, man-made visibility impairment. On July 1, 1999, the U.S. EPA published the final Regional Haze Rule (RHR). The objective of the RHR is to restore visibility to natural conditions in 156 specific areas across with United States, known as Class I areas. The Clean Air Act defines Class I areas as certain national parks (over 6000 acres), wilderness areas (over 5000 acres), national memorial parks (over 5000 acres), and international parks that were in existence on August 7, 1977.

The RHR requires States to set goals that provide for reasonable progress towards achieving natural visibility conditions for each Class I area in their state. In establishing a reasonable progress goal for a Class I area, the state must:

> *(A) consider the costs of compliance, the time necessary for compliance, the energy and non-air quality environmental impacts of compliance, and the remaining useful life of any potentially affected sources, and include a demonstration showing how these factors were taken into consideration in selecting the goal. 40 CFR 51. 308(d)(1)(i)(A).*
>
> *(B) Analyze and determine the rate of progress needed to attain natural visibility conditions by the year 2064. To calculate this rate of progress, the State must compare baseline visibility conditions to natural visibility conditions in the mandatory Federal Class I area and determine the uniform rate of visibility improvement (measured in deciviews) that would need to be maintained during each implementation period in order to attain natural visibility conditions by 2064. In establishing the reasonable progress goal, the State must consider the uniform rate of improvement in visibility and the emission reduction. 40 CFR 51. 308(d)(1)(i)(B).*

On July 10, 2019, ADEQ sent a letter notifying Drake that they had been selected to conduct "a four-factor analysis under the regional haze program" for the Paulden Facility. ADEQ followed this letter notification on July 10, 2019 with an email on September 13, 2019 outlining the ADEQ screening analysis methodology used to determine which process sources would be required to be analyzed, along with the results of this screening analysis which determined that only NO_x emissions from the kiln process would be subject to the four-factor analysis under this regional haze implementation period. Drake understands that the information provided in a four-factor review of control options will be used by ADEQ in their evaluation of reasonable progress goals for Arizona. Since emission reductions are only relevant if they result in a reduction in the existing visibility impairment, ultimately helping the State show progress towards its goals, Drake assumes that ADEQ will only move forward with requiring emission reductions if the emission reductions can be demonstrated to be needed to show further reasonable progress towards the goals established based on the uniform rate of visibility improvement that is required to be demonstrated.

Therefore, the purpose of this report is to provide information to the ADEQ and U.S. EPA Region 9 on available control technologies for NO_x emissions reductions and its applicability to the Paulden Facility.

The information presented in this report considers the following four factors for the emission reductions:

Factor 1. Costs of compliance
Factor 2. Time necessary for compliance
Factor 3. Energy and non-air quality environmental impacts of compliance
Factor 4. Remaining useful life

The approach contained in this four factor report was to first identify all technically feasible measures by conducting a step-wise review of emission reduction options in a top-down fashion like the top-down approach that is included in the U.S. EPA RHR guidelines[1] for conducting a review of Best Available Retrofit Technology (BART) for a unit[2]. These steps are as follows:

Step 1. Identify all available retrofit control technologies
Step 2. Eliminate technically infeasible control technologies
Step 3. Evaluate the control effectiveness of remaining control technologies
Step 4. Evaluate impacts and document the results

Once technically infeasible control measures were eliminated in Steps 1 through 3, the remaining Factors 2, 3, and 4 are addressed in Step 4.

[1] The BART provisions were published as amendments to the EPA's RHR in 40 CFR Part 51, Section 308 on July 5, 2005.

[2] References to BART and BART requirements in this Analysis should not be construed as an indication that BART is applicable to the Paulden Facility.

The steps of this four-factor analysis are as follows:

Step 1. Identify all available retrofit control technologies
Step 2. Eliminate technically infeasible control technologies
Step 3. Evaluate the control effectiveness of remaining control technologies
Step 4. Evaluate impacts and document the results

Note that the kiln currently has a low NO_x burner and SNCR installed, both of which are considered BACT for new kilns being permitted today.[3] Additionally, Drake utilizes preheater riser duct firing on the kiln.

3.1. STEP 1: IDENTIFICATION OF AVAILABLE RETROFIT NO_X CONTROL TECHNOLOGIES

NO_x emissions are produced during fuel combustion when nitrogen contained in the fuel and combustion air is exposed to high temperatures. The origin of the nitrogen (i.e. fuel vs. combustion air) has led to the use of the terms "thermal" NO_x and "fuel" NO_x when describing NO_x emissions from the combustion of fuel. Thermal NO_x emissions are produced when elemental nitrogen in the combustion air is admitted to a high temperature zone and oxidized. A small portion of NO_x is formed from nitrogen in the fuel that is liberated and reacts with the oxygen in the combustion air.

Step 1 of the top-down control review is to identify available retrofit control options for NO_x. The available NO_x retrofit control technologies for the Drake kiln (preheater/precalciner) are summarized in Table 1-1.

Table 1-1. Available NO_X Control Technologies for the Drake kiln

NO_X Control Technologies	
Combustion Controls	Low-NO_X Burners (LNB) (Already Installed) Preheater Riser Duct Firing (Already Installed)
Post-Combustion Controls	Selective Catalytic Reduction (SCR) Selective Non-Catalytic Reduction (SNCR) (Already Installed)

NO_x emissions controls, as listed in Table 1-1, can be categorized as combustion or post-combustion controls. Combustion controls reduce the peak flame temperature and excess air in the kiln burner, which minimizes NO_x formation. Post-combustion controls, such as selective

[3] Based on the RACT/BACT/LAER Clearinghouse database (RBLC).

catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) convert NO_x in the flue gas to molecular nitrogen and water.

3.1.1. Combustion Controls

3.1.1.1. Low-NO_X Burners (LNBs)

These burners have already been installed on the kiln and as a result are not discussed in detail. Baseline emissions are based on the operation of these LNBs. All alternative methods of NO_x control in this analysis will assume that the kiln continues to operate this burner.

3.1.1.2. Preheater Riser Duct Firing

Drake currently utilizes riser duct firing in preheater. This means that a portion of the fuel is fired in the riser duct to increase the degree of calcinations in the preheater. Baseline emissions are based on the operation of the riser-duct firing. All alternative methods of NO_x control in this analysis will assume that the kiln continues to operate the riser-duct firing.

3.1.2. Post Combustion Controls

3.1.2.1. Selective Catalytic Reduction

SCR is an exhaust gas treatment process in which ammonia (NH_3) is injected into the exhaust gas upstream of a catalyst bed. On the catalyst surface, NH_3 and nitric oxide (NO) or nitrogen dioxide (NO_2) react to form diatomic nitrogen and water. The overall chemical reactions can be expressed as follows:

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

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

When operated within the optimum temperature range of 500˚F to 800˚F, the reaction can result in removal efficiencies between 70 and 90 percent.[4] The rate of NO_x removal increases with temperature up to a maximum removal rate at a temperature between 700˚F and 750˚F. As the temperature increases above the optimum temperature, the NO_x removal efficiency begins to decrease. SCR use in the cement industry is incredibly limited, with only a handful of uses in Europe and one instance, i.e. the Joppa Cement Plant operated by LaFarge Holcim in the United States.

[4] Air Pollution Control Cost Manual, Section 4, Chapter 2, Selective Catalytic Reduction, NO_x Controls, EPA/452/B-02-001, Page 2-9 and 2-10.

3.1.2.2. Selective Non-Catalytic Reduction

In SNCR systems, a reagent is injected into the flue gas within an appropriate temperature window. The NO_x and reagent (ammonia or urea) react to form nitrogen and water. A typical SNCR system consists of reagent storage, multi-level reagent-injection equipment, and associated control instrumentation. Drake cement has already installed a SNCR system on the kiln and has demonstrated compliance with federally enforceable NO_x emission rates of 95 pounds/hr and 1.95 pounds/ton clinker.[5] The SNCR system at the Paulden Facility operates with minimal ammonia slip.

3.2. STEP 2: ELIMINATE TECHNICALLY INFEASIBLE NO_X CONTROL TECHNOLOGIES

Step 2 of the top-down control review is to eliminate technically infeasible NO_x control measures that are identified as available reduction options in Step 1. Since the LNB and SNCR are already installed on the kiln along with preheater riser duct firing, only SCR has been evaluated for technical feasibility in this section.

The discussions below outline multiple technical considerations which resulted in the determination that a SCR system is not technically feasible for the current configuration of the Kiln at the Paulden Facility.

3.2.1.1. Availability of SCR

In the U.S. EPA's guidance[6] for regional haze analysis, the term "available," one of two key qualifiers for technical feasibility in a BART analysis, is clarified with the following statement:

> *Consequently, you would not consider technologies in the pilot scale testing stages of development as "available" for the purposes of BART review.*

The U.S. EPA has also acknowledged, in response to comments made by the Portland Cement Association's (PCA) comments on the latest edition of the Control Cost Manual, that:

> *For some industrial applications, such as cement kilns where flue gas composition varies with the raw materials used, a slip stream pilot study can be conducted to determine whether trace elements and dust characteristics of the flue gas are compatible with the selected catalyst.*

Only pilot scale testing has been completed on preheater/precalciner kilns and hence, SCR technology is not commercially available for such kilns. Additionally, the Joppa kiln is a long, dry kiln which is significantly different from the preheater/precalciner kiln at the Paulden Facility.

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[5] Per ADEQ Class I Permit #65587

[6] Contained at 40 CFR Part 51 Appendix Y IV.D.1

Based on these conclusions, SCR is not widely available for use with cement kilns, in large part because the site-specificity limits the commercial availability of systems. Therefore, for this analysis, SCR is considered as a technically infeasible control technology for additional NO_x reductions at the Paulden Facility.

3.2.1.2. Operating temperature limitation

In their design report, Joppa specifies that for SCR application, the kiln must operate at a temperature range of approximately 500-800 °F.[7] If the temperature is too low, it will directly and negatively impact SCR effectiveness for NO_x reduction and result in the formation of byproducts such as, ammonium sulfate and ammonium bisulfate. It also causes increased ammonia slip. If the temperature is too high, oxidation of the NH_3 to NO can occur and run the risk of damaging the catalysts.[11] The Drake kiln operates at approximately 2000°F which is outside the acceptable temperature range for proper operation of the SCR.[8] Due to the high temperature of the kiln exhaust gases, it is not feasible to install an SCR upstream of the kiln baghouse and downstream of the kiln, i.e. "dirty side" installation.

Based on the above discussion, the SCR could potentially to be installed downstream of the kiln baghouse, i.e "clean side" installation. However, the outlet baghouse exhaust temperature for Drake plant ranges from 260 °F to 450 °F[9] which is much lower than the desired reaction temperature range of between 500 °F to 800 °F.

Additionally, the Illinois Environmental Protection Agency (Illinois EPA) has also shown concerns for temperature fluctuations that can occur during kiln operation which result in additional NO_x or ammonia slip when these variations occur at the SCR.[10]

Overall, the temperature of the kiln exhaust stream at the Paulden Facility is not amenable to installation of an SCR.

3.2.1.3. Clean-side installation Constraints

Other emissions possibly affected by SCR include increases in PM emissions (from ammonia salts in a detached plume), SO_3 emissions (from oxidation of SO_2 on the catalyst), and mercury emissions due to elevated temperatures within the catalyst region.

In the presence of calcium oxide and ammonia, SO_3 forms calcium sulfate and ammonium bisulfate via the following reactions:

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[7] Per Lafarge-Joppa plant, design report dated 10/27/2010, Document # JPA-K1-SCR-DR-001

[8] Per call meeting notes with Drake 10/28

[9] Per call meeting notes with Drake 10/28

[10] Per letter from EPA Region 5 to LaFarge Joppa Plant dated 01/18/2011

$$SO_3 + CaO \rightarrow CaSO_4$$

$$SO_3 + NH_3 \rightarrow (NH_4)HSO_4$$

Calcium sulfate can deactivate the catalyst, while ammonium bisulfate can plug the catalyst. Catalyst poisoning can also occur through the exposure to sodium, potassium, arsenic trioxide, and calcium sulfate.[11]

Dust buildup on the catalyst is influenced by site-specific raw material characteristics present in the facility's quarry, such as trace contaminants that may produce a stickier particulate than is experienced at sites where the technology is being demonstrated. This buildup is typical of cement kilns, resulting in reduced effectiveness, catalyst cleaning challenges, and increased kiln downtime at significant cost.[12]

3.2.1.4. Space and Design Constraints

As previously mentioned, to reduce fouling the catalyst bed with the PM in the exhaust stream, an SCR unit can be located downstream of the baghouse. In the current set-up, the kiln exhaust, the raw mill exhaust, and the coal mill exhaust feed into the baghouse which is routed to the main stack. In order to install the SCR on the clean side, the catalyst will have to be placed downstream of the main stack. Due to space constraints with the current design of the pyroprocessing system, it is not feasible to install the catalyst downstream of the SCR and obtain a "clean-side" SCR application.

3.3. STEP 3: RANK OF TECHNICALLY FEASIBLE NO_X CONTROL OPTIONS BY EFFECTIVENESS

Step 3 of the top-down control review is to rank the technically feasible options to effectiveness. As noted in Step 2, there are no technically feasible or readily available NO_x control options that could be retrofit on the kiln in its current design and configuration. All technically feasible control options (LNB, SNCR, Preheater Riser Duct Firing) have already been voluntarily installed by Drake.

3.4. STEP 4: EVALUATION OF IMPACTS FOR FEASIBLE NO_X CONTROLS

Despite being technically infeasible for the Paulden Facility, SCR controls have been evaluated in this Step 4 of the top-down control review. The impact analysis considers the:

- Cost of compliance
- Energy and Non-air quality impacts; and

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[11] Air Pollution Control Cost Manual, Section 4, Chapter 2, Selective Catalytic Reduction, NOx Controls, EPA/452/B-02-001, Page 2-6 and 2-7.

[12] Preamble to NSPS subpart F, 75 FR 54970.

- The remaining useful life of the source

3.4.1. Cost of Compliance

The currently installed and operating NO_x controls are the most efficient cost-effective option for NO_x emissions reduction and control at this facility. However, for illustration purposes, the cost of compliance and incremental control efficiency was estimated using the U.S. EPA Cost Control Manual and Design Reports from the Joppa Facility.

Joppa's optimization report shows that an 80% removal efficiency was achieved at a maximum ammonia flowrate of 10.6 liters per minute. At this flowrate NO_x emissions were reduced from 9.71 pounds/ton clinker to 1.87 pounds/ton clinker.[13] Joppa was approved for a post SCR emission limit of 3.21 lb/ton clinker on a 30-Day Rolling Average (DRA) basis. The approved SCR emission of 3.21 lb/ton clinker yields approximately a removal efficiency of 65%[14]. Drake's post SNCR emission limit is 1.95 lb/ton clinker on a 30 DRA basis resulting in a 54% control efficiency.[15] Therefore, any potential SCR installation would yield an incremental control efficiency of only 11%.

Based on the cost manual, direct capital costs were conservatively estimated to be ~12.9 million for SCR design and installation. Drake also consulted with other vendors regarding costs for SCR and based on initial discussions the capital cost budget for design and installation is expected to be well above the EPA cost manual used for purposes of this analysis. In addition, potential costs for any additional controls (such as PM controls discussed in Section 3.2.1.2 of this report) or downtime associated with installation that may be required were conservatively not included in this cost analysis.

The cost of design and installation of a hypothetical SCR system based on the above-mentioned conservative approach is approximately $35,327/ton with a total capital cost of $12.9 million and annual direct and indirect operating cost of $2.95 million per year. Details of the cost calculations are contained in Appendix A. Drake reserves the right to supplement this report in the future with any additional vendor specified cost information.

3.4.2. Timing for Compliance

Since the retrofit of the SCR system is deemed technically infeasible for the Paulden Facility, the time required for the re-design and re-configuration of the Paulden Facility to accommodate the SCR System installation is unknown at this time. Note that it took almost 6 years[16] for Joppa to design and test the SCR system in order to achieve compliance with the consent decree. Based on

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[13] Per Lafarge-Joppa plant, Kiln 1 optimization report dated January 16th, 2014, Document # JPA-K1-SCR-OR-001

[14] Ibid, and based on interpolation from Joppa's report

[15] Controlled efficiency calculated based on emission factor from AP-42, Section 11.6, Table 11.68 for preheater/precalciner kiln.

[16] From the issuance of the Clean Air Act Settlement with U.S. EPA in January 21, 2010 to the approval of the final SCR demonstration report in September 10, 2015

EPA's 2019 guidance[17], if it is determined that a facility must install controls per 40 CFR § 51.308, these controls must be installed by 2028 and there is no requirement to install controls prior to December 31, 2028.

3.4.3. Energy Impacts and Non-Air Quality Impacts

As noted above, since the SCR system is technically infeasible, the associated energy and non-air quality impacts are unknown. However, any SCR system has the following potential impacts:

- Generation of Used Catalyst Waste
- Increased energy demands to operate the SCR System

3.4.4. Remaining Useful Life

It is conservatively estimated that the SCR system would remain in service for a 20-year period before it needs any significant modification or reconstruction[18].

[17] EPA's 2019 Regional Haze Guidance §§ II.B.4(d) and II.B.5(b) dated August 20, 2019.

[18] Per definition contained in 40 CFR § 60.14 and §60.15

APPENDIX A : SCR COST EFFECTIVENESS

Table A-1a. Drake Cement - 4 Factor Analysis - SCR for Kiln - Costs

Parameter	Short name	Calculation	Cost	Units	Reference
Location	Paulden				
Kiln Make	Vulcan				
Exhaust Parameters					
Heat Input Rate	Q_b		248.2	MMBtu/hr	2018 Yearly Heat Input Average (conservative assumption, SCR is expected to require additional heat input)
Exhaust Flow	$q_{fluegas}$		132,129	acfm	Average of 2018 exhaust flowrate
Operating Temperature	T		1,872	deg F	Average of 2018 operating temperatures (conservative assumption). Full production kiln temperatures are typically above 2000 F.
Operating Hours Per Year	AOH	Max	7,358	hours	Assuming 2018 Operating Hours
Inlet Concentration	NOx_{in}		0.38	lb/MMBtu	Post SNCR controlled emission rate (95 lb/hour)
Outlet Concentration	NOx_{out}		0.29	lb/MMBtu	Based Joppa's SCR control efficiency of 65%
Available Cost Data					
Capital Cost of Ammonia Catalyst	$CC_{initial}$	$(8000/m^3)/(35.1347\ ft^3/m^3)$	249	$/ft^3	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, footnote 4. Adjusted from 2010 dollar.
Capital Cost of 19% Ammonia	$CC_{NH3solu}$	$3.56/gal/$Den_{NH3}$	0.11	$/lb	Based on $0.832/gallon from 2018 procurement data
Arizona Average Industrial Electricity Rate	$TAIE_{cost}$		0.065	$/kWh	Per 2018 electricity rates for Drake Cement
Chemical Properties and Constants					
19% Ammonia Solution Density	Den_{NH3}		7.74	lbs/gal	Density of Ammonia Solution procured by Drake Cement
Ammonia Molecular Weight (MW)	$M_{reagent}$		17.03	g/mol	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction
NO_2 MW	M_{NOx}		46.01	g/mol	
Ratio of Equivalent Moles of NH_3 per Mole of Reagent Injected	$SR_{theoretical}$		1	mol NH_3:mol reagent	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction
Ratio of Equivalent Moles of NH_3 per mole of NOx	SRF		1.05	mol NH3:mol NOx	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.3.7
Constant 1	C1		7	ft	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.3.12
Constant 2	C2		9	ft	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.3.12

Table A-1a. Drake Cement - 4 Factor Analysis - SCR for Kiln - Costs

Parameter	Short name	Calculation	Cost	Units	Reference
SCR Design Data					
Empty Catalyst Layers	n_{empty}		0	layers	Value assumed for lowest capital cost
Nominal Height of Each Catalyst Layer	h'_{layer}		3.1	ft	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.3.12
Number SCR Chambers	n_{scr}		1	chamber	Value assumed for lowest capital cost
Allowable Slip	Slip		2	ppm	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.2.2. Minimum range of allowable slip.
Pressure Drop due to Duct	ΔP_{duct}		3	in	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.5
Pressure Drop due to Catalyst	$\Delta P_{catalyst}$		1	in	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.5
Operating Life of Catalyst in Hours	$h_{catalyst}$		12,000	hours	Average of 8,000-16,000 hours (per US EPA Letter dated 12/13/2010 to Joppa Cement Plant)
NOx Removal Efficiency	η_{NOx}	$(NOx_{in}-NOx_{out})/NOx_{in}*100\%$	24	%	Calculated
Cross Sectional Area of Catalyst	$A_{catalyst}$	$q_{fluegas}$/(16ft/sec x 60 sec/min)	138	ft^2	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.28.
Cross Sectional area of SCR reactor	A_{SCR}	$A_{catalyst}$*1.15 (15% greater than $A_{catalyst}$)	158	ft^2	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.29.
Temp Adjustment	T_{adj}	$15.16-(0.03937*T)+(0.0000274*(T^2))$	37.50	deg F	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.27
Slip Adjustment	$Slip_{adj}$	(1.2835-(0.0567*Slip))	1.17		Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.24
Inlet NOx Adjustment	NOx_{adj}	$(0.8524+(0.3208*NOX_{in}))$	0.98		Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.25
NOx Efficiency Adjustment	η_{adj}	$(0.2869+(1.058*\eta_{NOx}))$	0.54		Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.23
Volume of Catalyst	Vol_{cat}	$2.81*Q_b*\eta_{adj}*NOX_{adj}*Slip_{adj}*T_{adj}/n_{scr}$	16,112	ft^3	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.22
Height of catalyst layer	h_{layer}	$Vol_{catalyst}/(N_{layer}*A_{catalyst})+1$	4	ft	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.32
Number of catalyst layers	n_{layer}	$Vol_{catalyst}/(h'_{layer}*A_{catalyst})$	38	layers	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.31
Total Number of catalyst layers	n_{total}	$n_{layer} + n_{empty}$	38	layers	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.33
Height of SCR	h_{scr}	$n_{total}*(C1+h_{layer})+C2$	430	ft	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.34
Mass flow of reagent	$m_{reagent}$	$(NOx_{in}*Q_b*\eta_{NOx}*SRF*M_{reagent})/(M_{NOx})$	9	lb/hr	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.35
Mass flow of solution	m_{sol}	$m_{reagent}/C_{sol}$	46	lb/hr	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.36
Direct Costs					
Catalyst Cost	f(Vol)	$Vol_{cat}*CC_{initial}$	4,016,860	$	Calculated
Ammonia Flow Adjustment	f(NH3)	$411/(lb/hr)*m_{reagent}/Q_b-$ $47.3/MMBtu/hr	-51	$/(MMBtu/hr)	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Equation 2.38 Adjusted from 1998 dollar
SCR height Adjustment	$f(h_{scr})$	$6.12/(ft-MMBtu/hr)*h_{scr}-$ $187.9/MMBtu/hr	3,784	$/(MMBtu/hr)	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Equation 2.37 Adjusted from 1998 dollar
New "Boiler" Adjustment	f(new)	-$728/MMBtu/hr	-1,127	$/(MMBtu/hr)	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Equation 2.40 Adjusted from 1998 dollar
New Bypass	f(bypass)	$127/MMBtu/hr	197	$/(MMBtu/hr)	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Equation 2.42 Adjusted from 1998 dollar
Ammonia Slip Monitoring	MON_{cost}	70,000	80,891	$	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.2.2 Adjusted from 2009 dollar
Total Direct Cost	DC	$Q_b[3,380/MMBtu/hr+f(h_{scr})+f(NH3)+f(new)+f(bypass)](3500/Q_b)^{0.35}+f(Vol)+MON_{cost}$	9,134,156	$	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Equation 2.36 Adjusted from 1998 dollar

Table A-1a. Drake Cement - 4 Factor Analysis - SCR for Kiln - Costs

Parameter	Short name	Calculation	Cost	Units	Reference
Indirect Costs					
Performance Test	PT_{cost}	Budgetary Cost	20,000	$	Testing of Catalyst Core (estimated)
General Facilities	GF_{cost}	0.05*DC	456,708	$	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Table 2.5
Engineering and Home Office Fees	EO_{cost}	0.10*DC	913,416	$	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Table 2.5
Process Contingency	PC_{cost}	0.05*DC	456,708	$	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Table 2.5
Total Indirect Installation Costs	B	$PT_{cost}+GF_{cost}+EO_{cost}+PC_{cost}$	1,846,831	$	Calculated
Project Contingency	C	0.15*(DC+B)	1,647,148	$	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.4.1
Total Capital Investment					
Total Plant Costs	D	DC+B+C	12,628,135	$	-
Preproduction Costs	G	0.02*D	252,563	$	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Table 2.5
Inventory Capital	H	$CC_{NH3solu}*m_{sol}$*14 days*24 hr/day	1,678	$	Based on 14 days of SCR operation, 24 hrs/day
Total Capital Investment	**TCI**	**D+G+H**	**12,882,376**	**$**	**Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Table 2.5**
Total Annual Costs					
			Direct Annual Costs		
Operator Labor Rate	OL_{cost}	AOH*50% manned operation*$66.8/hr	245,746	$	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Section 2.5, Adjusted from 2016 dollar
Supervisor Labor	SL_{cost}	$0.15*OL_{cost}$	36,862	$	Per 2019 EPA Cost Manual
Annual Maintenance Costs	AM_{cost}	0.015*TCI*2	386,471	$	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Equation 2.46 (multiplied by two to include maintenance labor and materials)
Annual Reagent Costs	AR_{cost}	$CC_{NH3solu}*m_{sol}$*AOH	36,751	$	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Equation 2.58
Annual Electricity Costs	AE_{cost}	$0.105*Qb*(NOx_{in}*\eta_{NOx}+0.5(\Delta P_{duct}+n_{total}+\Delta P_{catalyst}))*AOH*TAIE_{cost}$	256,636	$	Per 2002 EPA Cost Manual Chapter 2 Selective Catalytic Reduction, Equations 2.48 and 2.49
Annual Relative Accuracy Test Audit	$RATA_{cost}$		30,000	$	Budgetary Cost (estimated)
Quarterly Portable Tests			10,000	$	$2500 per test, performed quarterly
Catalyst Replacement Costs	CR_{cost}	$n_{scr}*Vol_{cat}*(CC_{initial}/n_{layer})$	105,707	$	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.63.
Future Worth Factor	FWF	$i*[1/(1+i)^{hcatalyst/AOH}-1)$	0.6		Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equations 2.65 and 2.66
Annual Catalyst Replacement Cost	ACR_{cost}	CR_{cost}*FWF	64,798	$	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.64.
Direct Annual Costs	DA_{cost}	$OL_{cost}+SL_{cost}+AM_{cost}+AR_{cost}+AE_{cost}+RATA_{cost}+ACR_{cost}$	**1,172,971**	**$/year**	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.56.
			Indirect Annual Costs		
Administrative Charges	A_{cost}	0.03*OLcost+0.4*AMcost	161,961	$/year	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.69.
Overhead Costs		$0.6*(OL_{cost}+SL_{cost}+AM_{cost})$	401,447	$/year	Per 2019 EPA Cost Manual
Indirect Annual Costs	IAcost	A_{cost}	**563,408**	**$**	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.68
			Annualized Capital Costs		
Interest Rate	i		7.00%		Per EPA Cost Manual Chapter 2 Cost Estimation: Concepts and Methodology
SCR System Life	Life		20	years	Based on life of kiln. Also, per ADEQ guidance, the SCR will be installed closer to the 2028 deadline
Capital Recovery Factor	CRF	$i(1+i)^{life}/((1+i)^{life}-1)$	9.44%		Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.71
Annualized Capital Cost	AC_{cost}	CRF*TCI	**1,216,005**	**$/year**	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.70
Total Annual Costs	**TAC**	**ACcost+DAcost+IAcost**	**2,952,385**	**$/year**	**Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.72.**

Table A-1a. Drake Cement - 4 Factor Analysis - SCR for Kiln - Costs

Parameter	Short name	Calculation	Cost	Units	Reference
Cost Effectiveness					
NOx Removed Per Year	$NOx_{removed}$	$NOx_{in} * \eta_{NOx} * Q_b * AOH / 2{,}000$ lb/ton	83.57	ton/yr	Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.11
Cost Effectiveness		**$TAC/NOx_{removed}$**	**35,327**	**$/ton**	**Per 2019 EPA Cost Manual, Chapter 2 Selective Catalytic Reduction, Equation 2.73**

[1] Chemical Engineering Plant Cost Index:

Year	Index
1995	381.1
1996	381.7
1997	386.5
1998	389.5
1999	391.8
2000	394.1
2001	394.3
2002	395.6
2003	402
2004	444.2
2005	468.2
2006	499.6
2007	525.4
2008	575.4
2009	521.9
2010	550.8
2011	593.2
2012	584.6
2013	567.3
2014	576.1
2015	556.8
2016	541.7
2017	567.5
2018	603.1
2019	-