NOx RECLAIM
Working Group Meeting

January 22, 2014

Agenda

- Welcome & Introductions
- Control Technology & Cost Effectiveness Analysis Approach
- Refinery Sector
  - FCCUs
- Non-Refinery Sector
  - ICEs
  - Cement Kilns
- Discussion
- Schedule/Next Meeting

Progress in Rulemaking Analysis
Refinery Sector (September 2013)

DRAFT - Refinery Sector & Preliminary Assessment						
	No of Units	2011 Emissions (tpd)	2005 BARCT	2011 Emissions at 2005 BARCT (tpd)	2013 BARCT Under Consideratio n	2011 (or 2023) Emissions at 2013 BARCT (tpd)
		a		b		c
FCCUs/CO Boilers	8	1.08	85% red	0.60	5 ppmv	0.45
Turbines/Duct Burners	21	1.33	62.27	2.61	2.5 ppmv	0.97
Coke Calciner	2	0.55	30 ppmv	0.25	5 ppmv	0.04
Sulfur Recovery/Tail Gas Incinerators	17	0.43	RV	0.43	80% red	0.09
Boilers/Heaters > 110 mmbtu/hr	73	4.88	5 ppmv	0.82	2 ppmv	0.33
Heaters 40-110 mmbtu/hr	69	2.00	25 ppmv	0.97	5 ppmv	0.20
Heaters 20-40 mmbtu/hr	52	0.45	9 ppmv	0.10	5 ppmv	0.06
Heaters <20 mmbtu/hr	18	0.06	12 ppmv	0.02	9 ppmv	0.01
Furnace > 110 mmbtu/hr	1	0.01	30 ppmv	0.00	2 ppmv	0.00
Others	4	0.10	RV	0.10	RV	0.10
Total (tpd)	**265**	**10.90**		**5.92**		**2.25**

Note: The cost analysis for the 2013 BARCT standards under consideration is still on-going and therefore this assessment is subject to further analysis and refinement.

Progress in Rulemaking Analysis (cont.)
Non-refinery Sector (September 2013)

DRAFT - NON-REFINERY SECTOR & PRELIMINARY ASSESSMENT								
	POWER PLANTS	**# of Units**	**2011 Emissions (tpd)**	**2005 BARCT**	**2011 Emissions at 2005 BARCT**	**2013 BARCT under consideration**	**2011 Emissions at 2013 BARCT (tpd)**	**2023 Emissions at 2013 BARCT (tpd)**
			a		**b**		**c**	**d = c x GF**
Boilers		16	0.44	7 ppm	0.68	2 ppm	0.21	0.24
Turbines/Duct Burners		21	0.83	No new level	1.50	No further control	1.50	1.72
ICEs		6	0.18	No new level	0.22	11 ppm	0.04	0.04
	TOTAL	**43**	**1.45**		**2.40**		**1.76**	**2.01**
	NON-POWER PLANTS							
Boilers		16	0.08	9-12 ppm	0.07	5 ppm	0.03	0.04
Heaters		3	0.01	60 ppm	0.01	No further control	0.01	0.01
Furnaces		12	0.79	RV	0.79	80% Reduction	0.30	0.44
Glass Melting Furnaces		3	0.41	RV	0.41	80% Reduction	0.08	0.10
Gas Turbines		20	1.93	No new level	1.36	2 ppm	0.19	0.22
ICEs		31	0.38	No new level	1.16	11 ppm	0.23	0.29
Cement Kilns/Dryers		4	1.61	RV	1.61	0.5 lb/ton	0.30	0.45
	TOTAL	**89**	**5.21**		**5.41**		**1.13**	**1.55**
TOTAL NON-REFINERY		**132**	**6.67**		**7.81**		**2.88**	**3.56**

Note: The cost analysis for the 2013 BARCT standards under consideration is still ongoing and therefore, this assessment is subject to further analysis and refinement.

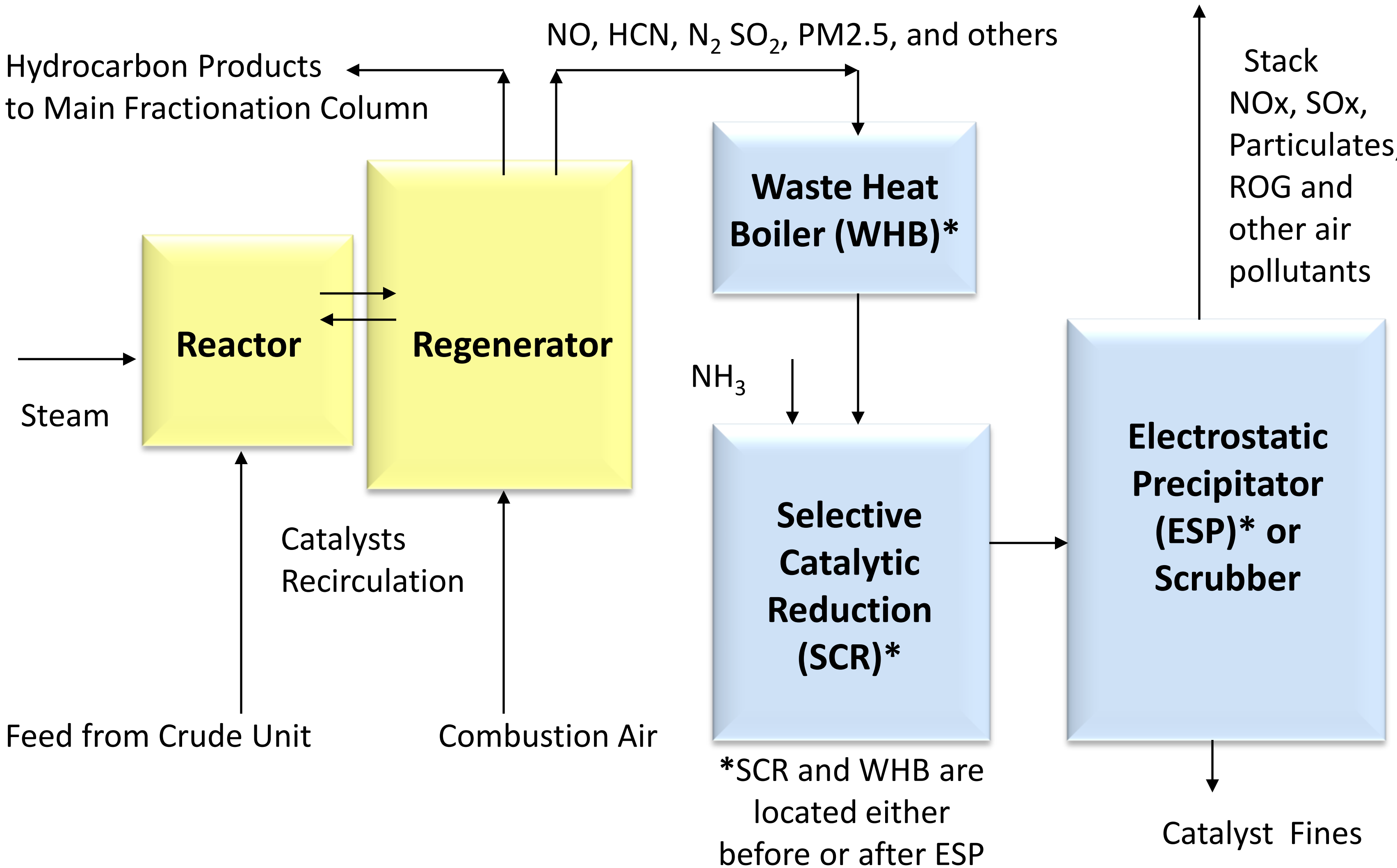
***Permit Limit emission level used for 2011 calculated emissions for Power Plant boilers and turbines. Year 2000 ending emission factor used for 2011 calculated emissions (Column b) where no new level is listed for 2005 BARCT.**

Status

Category	Control Equipment Manufacturer Contacted	Preliminary Cost Effectiveness Analysis Completed
FCCU	X	X
Cement Kilns	X	X
Gas Turbines	X	In progress
Coke Calciner	X	In progress
Glass Furnaces	X	In progress
Metal Melting Furnaces	In progress	In progress
SRU/Tail Gas	In progress	In progress
ICEs	X	X
Boilers/Heaters	X	In progress

Refinery Sector
Fluid Catalytic Cracking Units

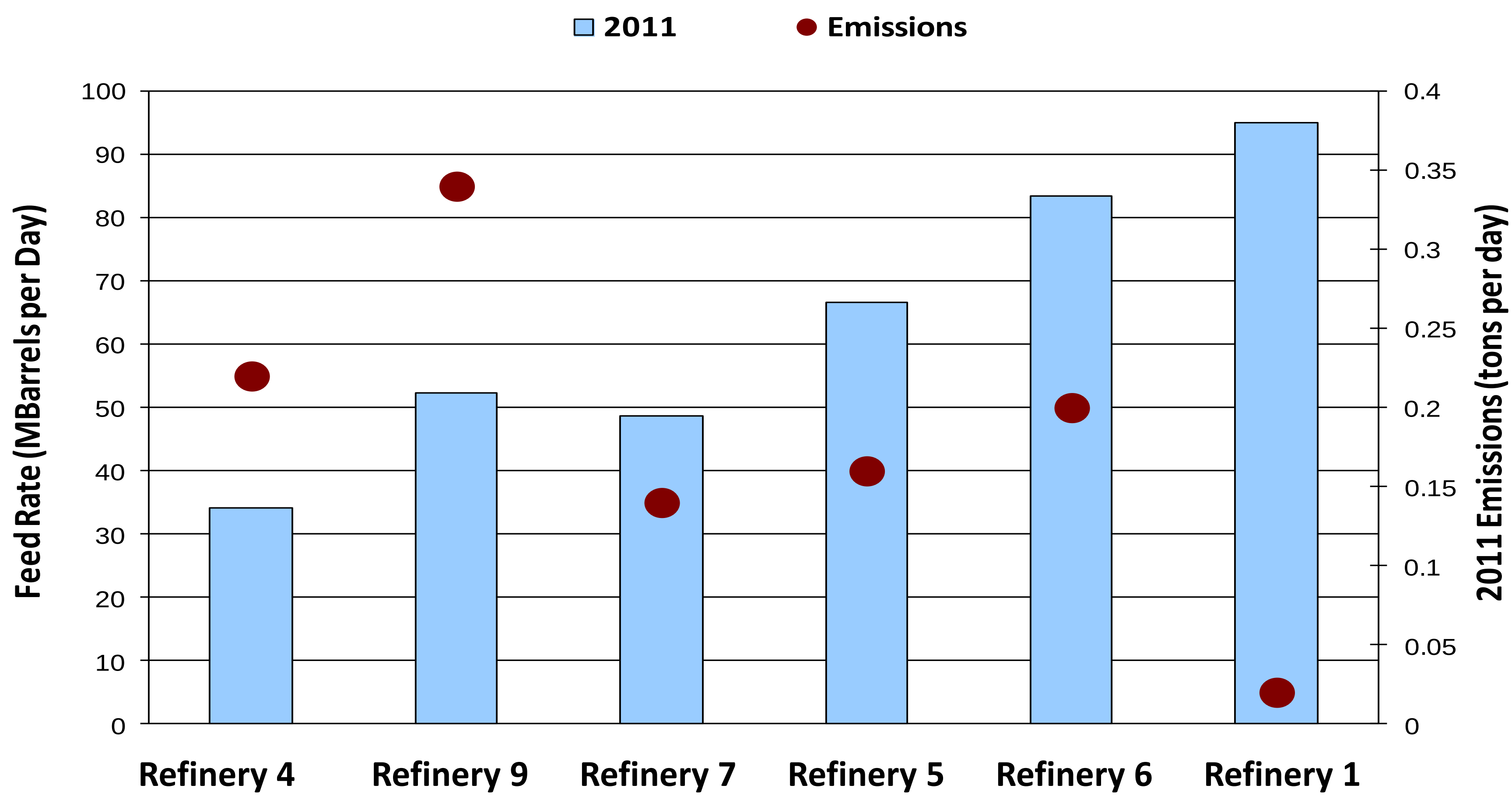
Simplified Fluid Catalytic Cracking Process



NOx Formation in FCCUs

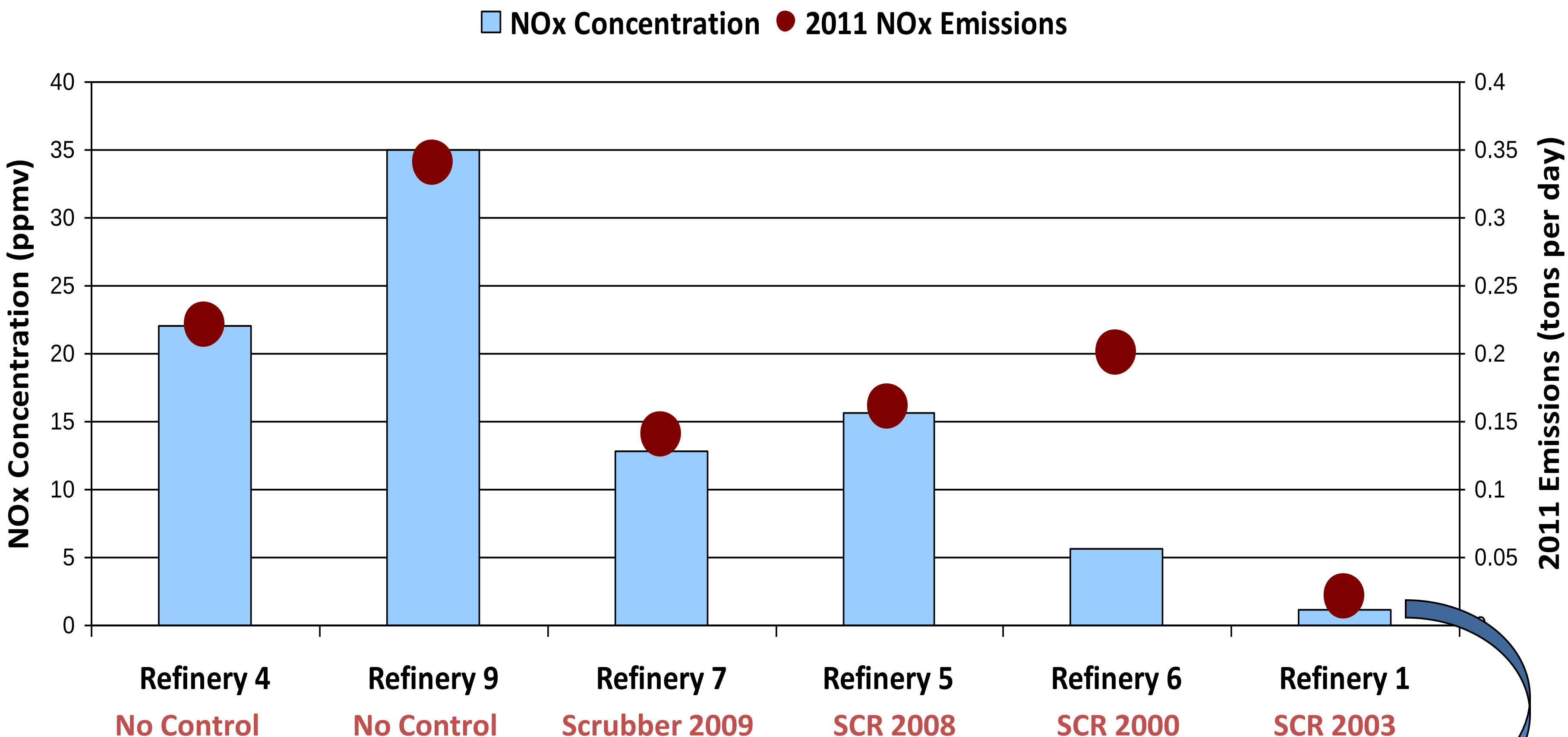
- "Fuel" NO_x from Coke Burned-Off in Regenerator
  - Nitric Oxide (NO), Nitrogen Dioxide (NO_2)
  - Nitrous Oxide (N_2O)
  - Ammonia (NH_3), Hydrogen Cyanide (HCN), and Others
- Small Amount of "Thermal" and "Prompt" NO_x
- NO_x from Regenerator = 40 ppmv – 180 ppmv
- Parameters Affecting NO_x Emissions
  - Feed Rate
  - Nitrogen in Cat-Cracker Feed
  - Oxygen in Regenerator
  - Air Pollution Control Used

Lower Emissions Even with Higher Feed Rates



Note: Refinery feed rates are from source test reports and the U.S. Energy Information Administration Website – Refinery Capacity Report www.eia.gov

Well-Designed Control Equipment Can Reduce NOx to 2 ppmv



2013 BARCT under consideration = 2 ppmv NOx (with 5 ppmv NH_3 Slip) Achieved in Practice

Potential Control Technologies for FCCUs

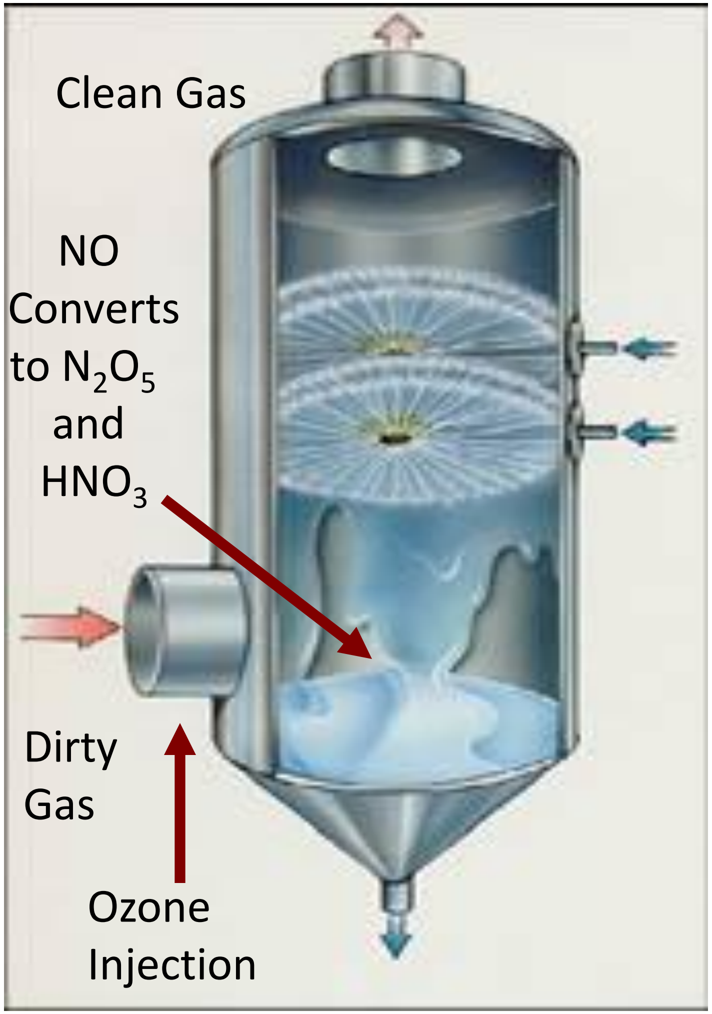
- Selective Catalytic Reduction (SCR)
- Low Temperature Oxidation (LoTOx)
- DeNOx Catalysts

SCR Review

- Aqueous ammonia (19%-30%) with molar ratio $NH_3:NO_x$ = 1:1 minimum
- Operating temperature at 600^o F or above to prevent ABS formation
- Performance confirmed by SCR manufacturers
  - It is possible to achieve NO_x removal rate higher than 98% with an ammonia slip lower than 2 ppmv. (1)
  - It is now possible to remove 95% of NOx (2)

Note: 1) "Combating NOx from refinery sources using SCR." Haldor Topsoe. Presentation at the 2nd Annual World Refining Technology Summit & Exhibition, 2010, Abu Dhabi. www.topsoe.com. 2) Cormetech website, www.cormetech.com/nox-reduction.htm

Scrubber with LoTOx



- LoTOx™ = Low Temperature Oxidation
- Developed by Linde (previously BOC) and licensed to Dupont BELCO Clean Air Technologies for refinery FCCUs
- 2001 CARB's Clean Air Innovative Technology Demonstration at RSR Quemetco (1)
- Convert insoluble NO through ozone injection to highly soluble N_2O_5 and HNO_3

Note: 1) www.arb.ca.gov/research/apr/past/icat99-2.pdf, 2) picture from www.dupont.com and www.digitalrefining.co

Scrubber with LoTOx (cont.)

- Simplified Chemistry

$NO + O_3 \rightarrow NO_2 + O_2$	Fast
$2\ NO_2 + O_3 \rightarrow N_2O_5 + O_2$	Fast
$N_2O_5 + H_2O \rightarrow 2\ HNO_3$	Fast
$HNO_3 + NaOH \rightarrow NaNO_3 + H_2O$	Fast
$SO_2 + O_3 \rightarrow SO_3 + O_2$	Very slow

- $NOx{:}O_3$ = 1.75 – 2.5 for 90% - 95% reduction
- No conversion of SO_2 to SO_3. No ammonia. No ABS.
- Very low ozone slip (0-3ppmv), sulfites are ozone scavenger.
- Absorbed readily in NaOH scrubbing solution.

Scrubber with LoTOx (cont.)

- Concurrently reduce particulates and SOx (refer to SOx RECLAIM Staff Report for information on SOx scrubbers)
- 90+ scrubber installations with 30+ LoTOx in refineries worldwide. Applications in gas-fired and high sulfur coal-fired units met 95% control and/or 2-5 ppmv
- Current installations in refineries met 8-10 ppmv, and manufacturers positively confirmed that LoTOx can be designed to achieve 2 ppmv NOx

Note: "Preparing wet scrubbing system for a future with NOx emissions requirements" Dupont Belco; "Wet scrubbing-based NOx control using LoTOx technology – first commercial FCC start-up experience. Belco and Marathon Petroleum. www.digitalrefining.com, and numerous other papers by Dupont Belco.

NOx-Control Additives

- Intercat (Johnson Matthey), NOxGetterA or B [1, 2]
  - 30% - 76% NOx reduction with 0.5%-5% wt% catalyst addition
  - Trial run in 20 FCCUs
  - Short 8-day trial run to establish baseline and efficiency
- Grace XNOx W [3,4]
  - 65% NOx reduction
  - Trial run at Petroplus Coryton UK Refinery
- BASF CLEANOx [5]
  - 72% NOx reduction with 1.4 wt% of Catalyst Addition

Note: 1) "FCC Flue Gas Scrubber Alternatives: Part I", Intercat (Johnson Matthey), 2009. www.digitalrefining.com. 2) "Reducing FCC Unit NOx Emissions", Intercat (Johnson Matthey), 2008. www.digitalrefining.com. 3) "Controlling FCC NOx Emissions", September 2011, Grace FCC Technology Conference in Munich, Germany, www.refiningoperations.com. 4) "FCC catalysts and additives for cost and emissions control." Grace Catalysts Technologies. www.digitalrefining.com. 5) Product and Performance Data on www.basf.com

Cost Analysis for SCR – 2 ppmv
Approach 1 - Using Refinery 1 Information

- Used for Refinery 5, 6, 7 with similar range of flow rates
- Refinery 1's SCR installed in 2003 achieves below 2 ppmv NOx, 5 ppmv NH_3
- Present Worth Value (PWV) of Refinery 1's SCR assuming 4% interest rate and 25-years life for SCR

$$PWV_{Ref\ 1} = TIC_{Ref\ 1} + (15.62 \times AC_{Ref\ 1}) + (2.52 \times CR_{Ref\ 1})$$

where $TIC_{Ref\ 1}$ = Total Installed Costs

$AC_{Ref\ 1}$ = Annual Operating Costs

$CR_{Ref\ 1}$ = Catalyst Replacement Costs

- Operating costs during 25-year life of SCR = 20% $TIC_{Ref\ 1}$
- $PWV_{Ref\ 5,\ 6,\ 7} = PWV_{Ref\ 1} \times (Flow_{Ref\ 5,\ 6,\ 7}/Flow_{Ref\ 1})^{0.7}$

Cost Analysis for SCR – 2 ppmv (cont.)

Approach 2 - Using Manufacturer C and EPA Information

- Manufacturer's cost data available. Manufacturer C provided equipment costs (EC) for Refinery 4 and Refinery 9 to achieve 2 ppmv NOx
- Using EPA's Office of Air Quality Planning and Standards (OAQPS) approach to estimate TIC

$$TIC_{\text{Ref 4, 9}} = EC + \text{instrument} + \text{sales tax} + \text{freight} + \text{installation} = 1.86 \times EC_{\text{Ref 4, 9}}$$

- Operating costs in 25-year life = 20% $TIC_{\text{Ref 4, 9}}$
- Contingency factor of 1.5 to account for cost variation
- $PWV_{\text{Ref 4, 9}} = 1.2 \times TIC_{\text{Ref 4, 9}} = 1.2 \times 1.86 \times EC_{\text{Ref 4, 9}}$
- Cost Effectiveness = PWV / Emission Reduction

Cost Analysis for SCR – 2 ppmv (cont.)

	Fac ID	Emission (tpd)	NOx (ppmv)	% Control	Emission Reduction (tpd)	PWV ($M)	CE ($/ton)
for reference	1	0.02	<2	95%	-	41	(10,181)
Approach 1	5	0.16	15	87%	0.14	33	< 25,259 *
Approach 1	6	0.20	6	64%	0.13	57	< 49,408*
Approach 1	7	0.14	13	84%	0.12	27	25,455
Approach 2	4	0.22	21 - 23	91%	0.20	16	8,961
Approach 2	9	0.34	34 - 52	95%	0.32	19	6,537
	Summary for Ref 4, 9, 5, 6, and 7				**0.91**	**152**	**< 18,422 ***

Note: * Because of the inclusion of SCR costs that already have been installed.

Cost Analysis for SCR – 2 ppmv (cont.)

- Two approaches based on full installation cost.
- Refineries with equipment already installed may add additional layer of catalysts instead of retrofitting the entire SCR.
  - Based on Manufacturer D information, an increase of 10% catalyst volume would reduce the outlet NOx concentration from 10 ppmv to 2 ppmv at a cost of $396,000

Cost Analysis for SCR – 2 ppmv (cont.)

- Manufacturer B and D: install a monitoring device for NH_3 slip to help monitor the mixing of NH3 and the flue gas
- Manufacturer B: investigate in the use of DeNOx catalysts to lower the inlet NOx concentrations to the SCR
- Staff will use this information to refine analysis

Cost Analysis for LoTOx - 2 ppmv Using Manufacturer Information

- Manufacturer A provided TIC and annual operating costs for Refinery 4, 7 and 9 to meet 2 ppmv level

  $$PWV_{Ref\ 4,\ 7,\ 9} = TIC_{Ref\ 4,\ 7,\ 9} + (15.62 \times AC_{Ref\ 4,\ 7,\ 9})$$

- A contingency factor of 2 is used to account for additional modification costs at the site if needed
- $PWV_{Ref\ 5} = PWV_{Ref\ 4} \times (Flow_{Ref\ 5}/Flow_{Ref\ 4})^{0.7}$
- $PWV_{Ref\ 6} = PWV_{Ref\ 7} \times (Flow_{Ref\ 6}/Flow_{Ref\ 7})^{0.7}$

Cost Analysis for LoTOx – 2 ppmv (cont.)

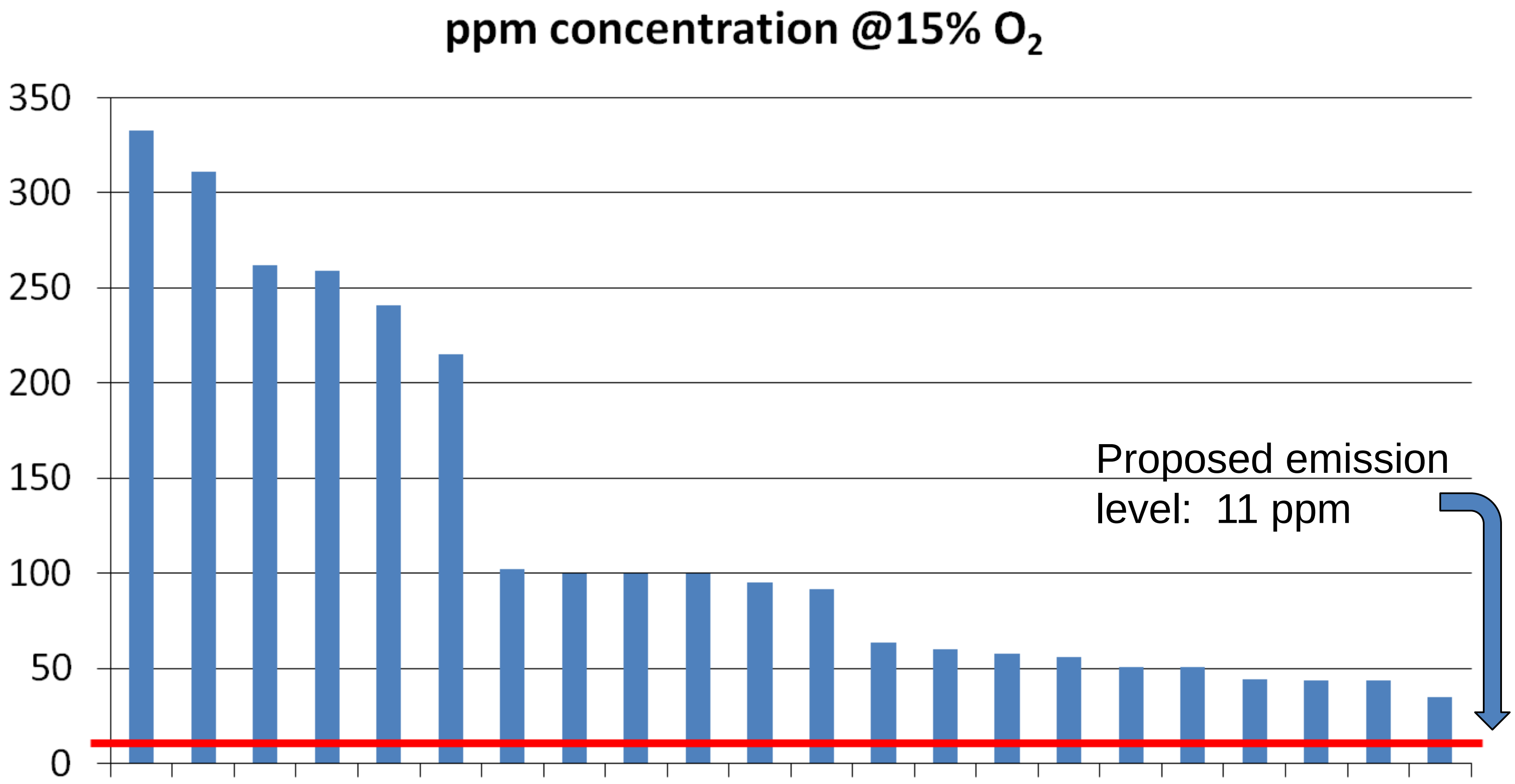
Fac ID	Emission (tpd)	NOx (ppmv)	% Control	Emission Reduction (tpd)	PWV ($M)	CE ($/ton)
4	0.22	21 - 23	91%	0.20	19	10,767
7	0.14	13	84%	0.12	16	15,199
9	0.34	34 - 52	95%	0.32	32	10,631
5	0.16	15	87%	0.14	24	18,590
6	0.20	6	64%	0.13	34	29,502
Summary for Ref 4, 7, 9, 5 and 6				**0.91**	**125**	**15,124**

Incremental Cost Analysis

	PWV ($ million)	Emission Reduction (tpd)
SCRs for 85% Control	139	0.48
SCR for 2 ppmv	152	0.91
LoTOx for 2 ppmv	125	0.91
Incremental Cost Effectiveness SCR - SCR	(13/0.43/25/365) = 3,444 $/ton	
Incremental Cost Effectiveness SCR - LoTOx	(-14/0.43/25/365) = -3,521 $/ton	

Non Refinery Sector
Preliminary Cost Effectiveness

Non Refinery ICE Emissions



Cost Analysis for ICEs (Spark-Ignited, Lean Burn)

- Fueled on Natural Gas
- No new BARCT level in 2005
- Proposed BARCT level: 11 ppm @15% O_2*
- Proposed control technology: Selective Catalytic Reduction (SCR)

*Amended Rule 1110.2 NOx emission level (Feb. 2008)

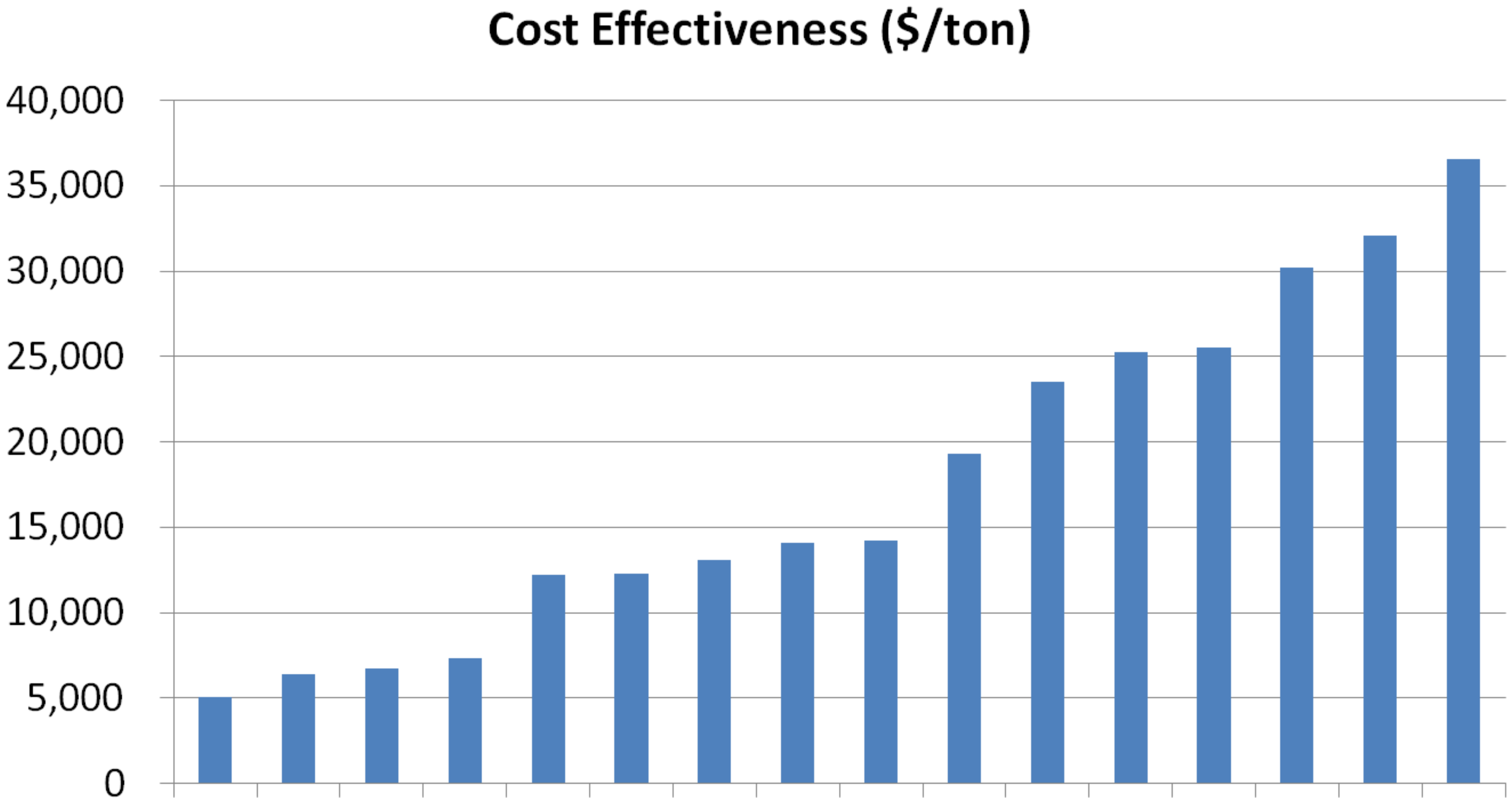
Cost Analysis for ICEs (Spark-Ignited, Lean Burn)

- SCR manufacturer equipment costs and achieved-in-practice installation costs used for Total Installed Costs (TIC) and includes air compression
  - Achieved-in-Practice installation is the SCR unit at Orange County Sanitation District
- Achieved-in-practice Annual Costs (AC) used for urea, catalyst replacement, power, maintenance, and testing.
- Present Worth Value (PWV) assumes a 4% interest rate and a 25-year equipment life

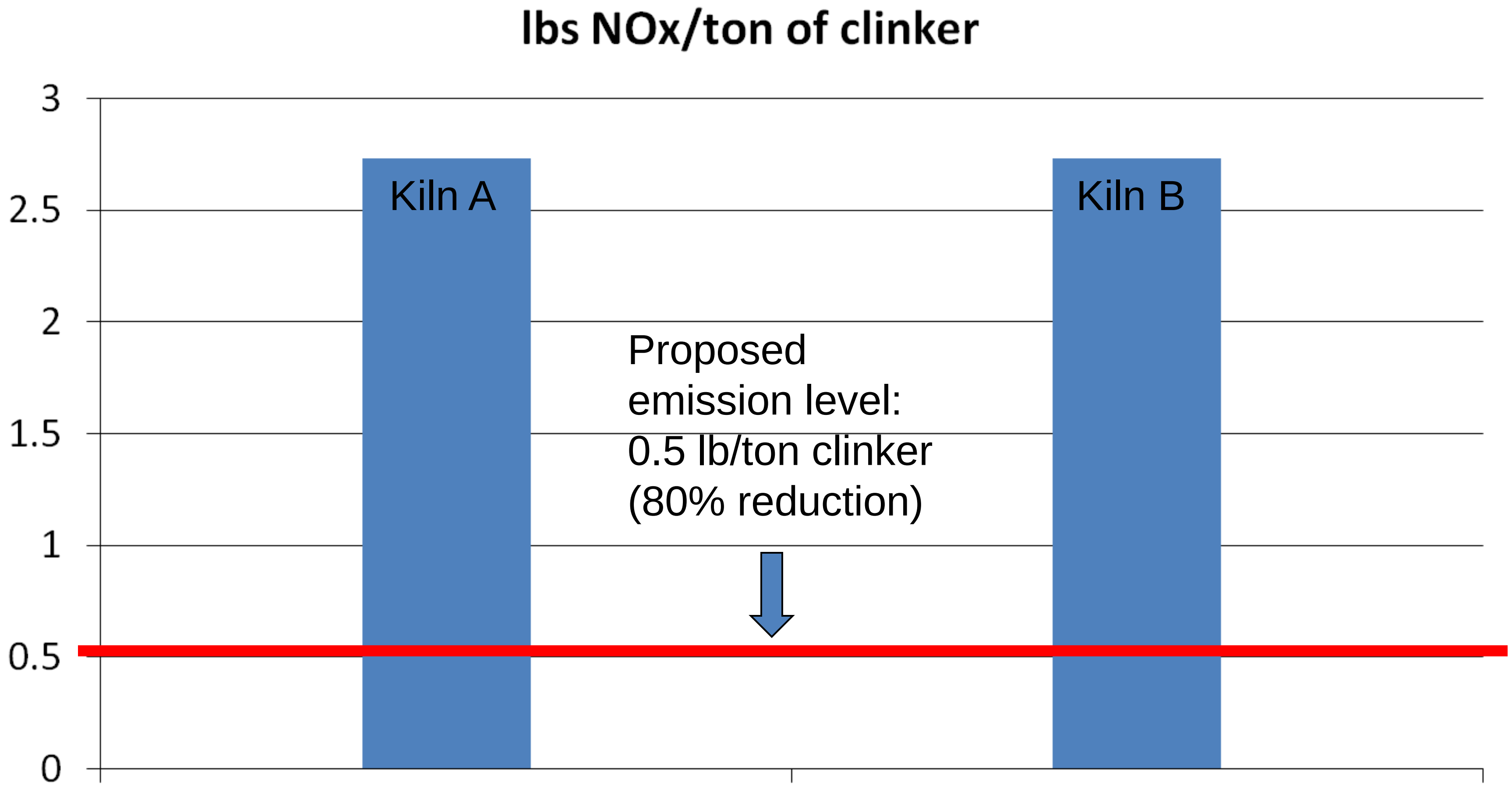
Cost Analysis for ICEs (Spark-Ignited, Lean Burn)

- PWV = TIC + (15.622 x AC)
- Emission Reductions (ER) for this category
  - 0.275 tons per day
- Cost Effectiveness = PWV / (ER x 25 years)
- Cost Effectiveness Range
  - $5,000 - $36,000 / ton

Cost Analysis for ICEs (Spark-Ignited, Lean Burn)



Cement Kilns - Emission Level



Cement Kilns

- No 2005 BARCT
- Proposed BARCT level: 80% reduction
- Proposed Control Technologies
  - Selective Catalytic Reduction
  - Ultra Cat Ceramic Filters

Selective Catalytic Reduction

- As described previously, NO and NO_2 are reduced to N_2 gas and water in the presence of a catalyst
- In a cement kiln, however, PM plugging becomes an issue and can mask active catalyst sites and reduce effectiveness
- SCR can be placed on the “cold side” of PM control equipment, but the temperature can be too low for catalyst operation

Selective Catalytic Reduction

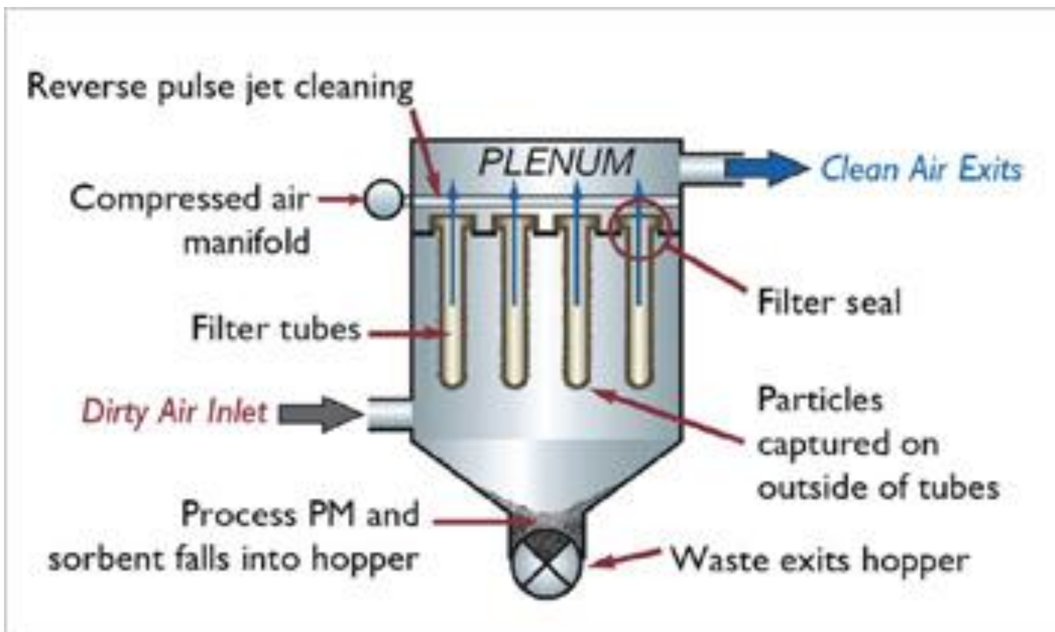
- Several installations in Europe use blowers to prevent catalyst plugging on “hot side” installations
- SCR technology can be installed before PM control equipment at a temperature that can facilitate NOx removal

Ultra Cat Ceramic Filters

- Ceramic fiber filters can provide multi-pollutant control of NOx, SOx, and PM
- NOx is controlled by urea injection and reaction with embedded catalyst on the filter tube walls
- SOx is controlled via dry sorbent injection with resultant particulates captured on outside of filter walls
- PM is captured on outside of filter walls

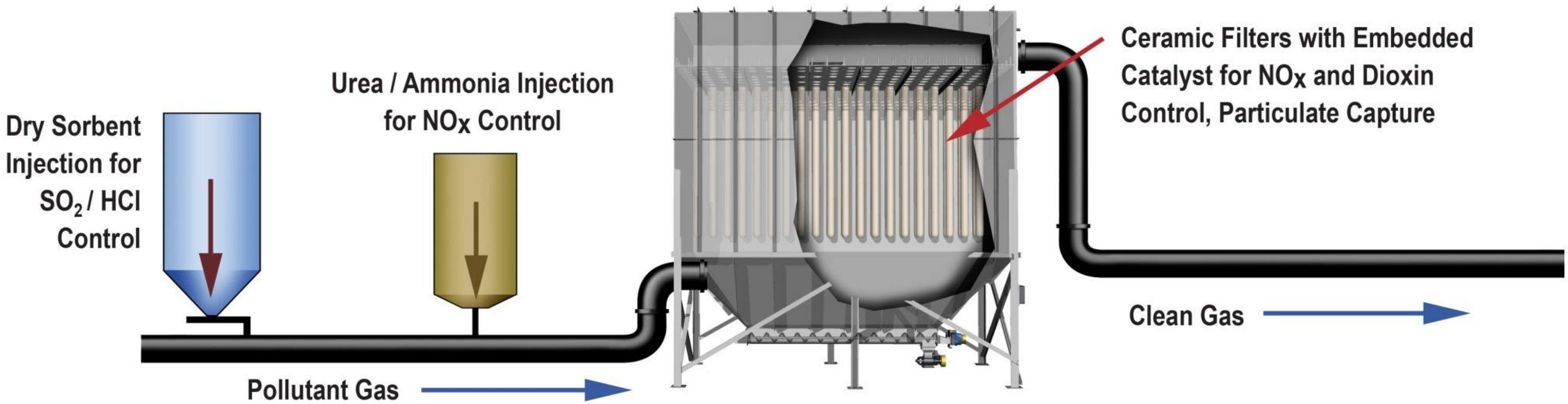
Ultra Cat Ceramic Filters

- Accumulated solids are removed with a pulsed jet of air through the filter and resultant solid waste is collected underneath the housing



Ultra Cat Ceramic Filters

- Ceramic fiber filters are arranged in a baghouse-like housing
- 80% NOx reductions guaranteed



Cost Analysis for Cement Kilns (SCR)

- Capital and Annual Costs supplied by SCR Vendor A with experience in cement kiln applications worldwide
- Pending costs from SCR Vendor B
- 60% contingency applied for contractor labor and construction cost for Vendor A
- PWV = TIC + (15.622 x AC)
- Assumes 4% interest rate and 25 year equipment life

Cost Analysis for Cement Kilns (Ultra Cat Ceramic Filters)

- Capital and annual operating costs supplied by vendor with nationwide experience across various source categories
- PWV = TIC + (15.622 x AC)
- Assumes 4% interest rate and 25 year equipment life

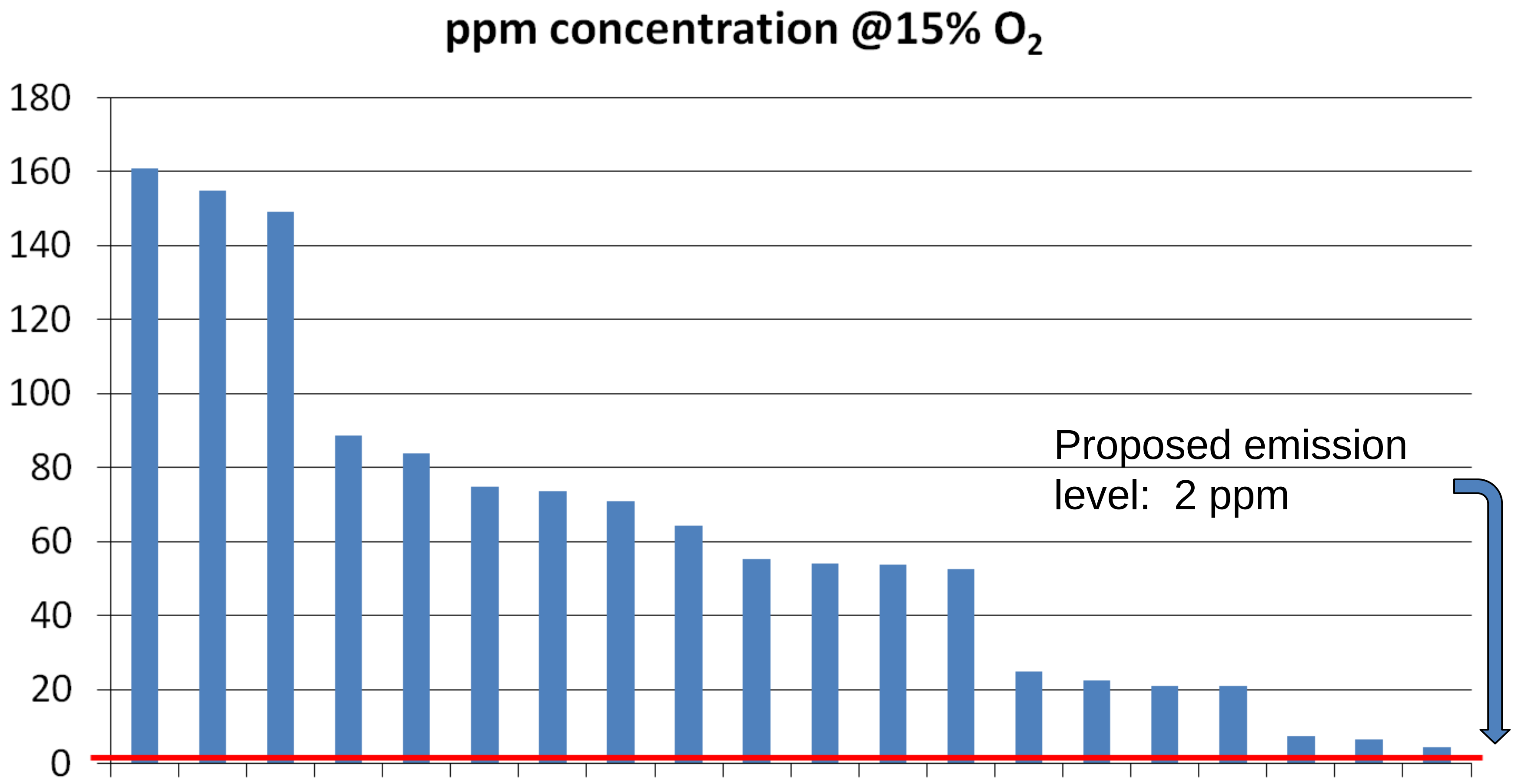
Cost Analysis for Cement Kilns

- PWV_{SCR} = \$26.4 M
- $PWV_{Ultra\ Cat}$ = \$45.6 M
- Emission Reductions (ER) for this category
  - 1.287 tons per day
- Cost Effectiveness (CE) = PWV / (ER x 25 years)
- NOx CE_{SCR} = \$2,300 / ton
- NOx $CE_{Ultra\ Cat}$ = \$3,900 / ton

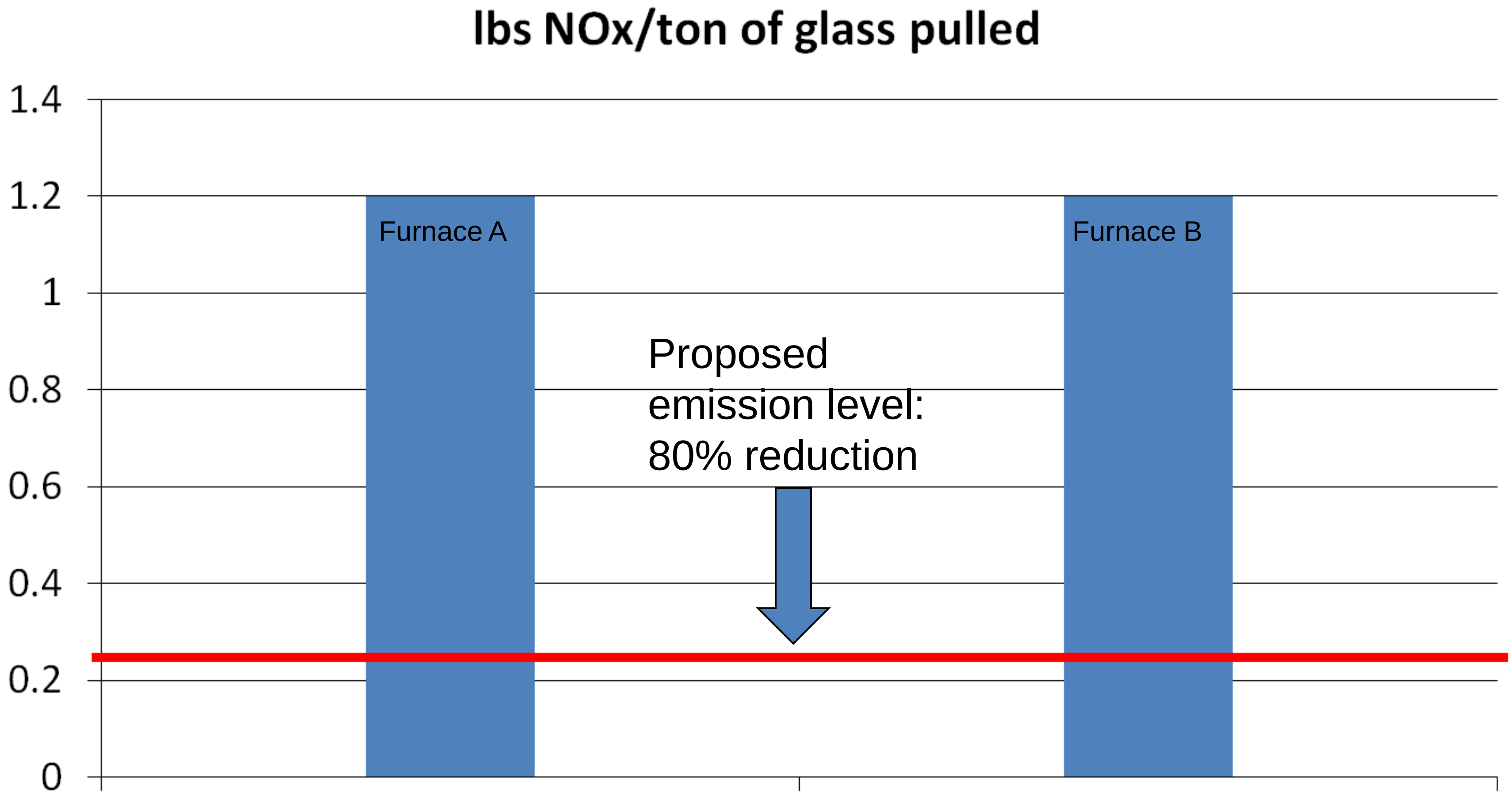
Other Non Refinery Sector Emission Levels by Category

[Cost-effectiveness analysis ongoing]

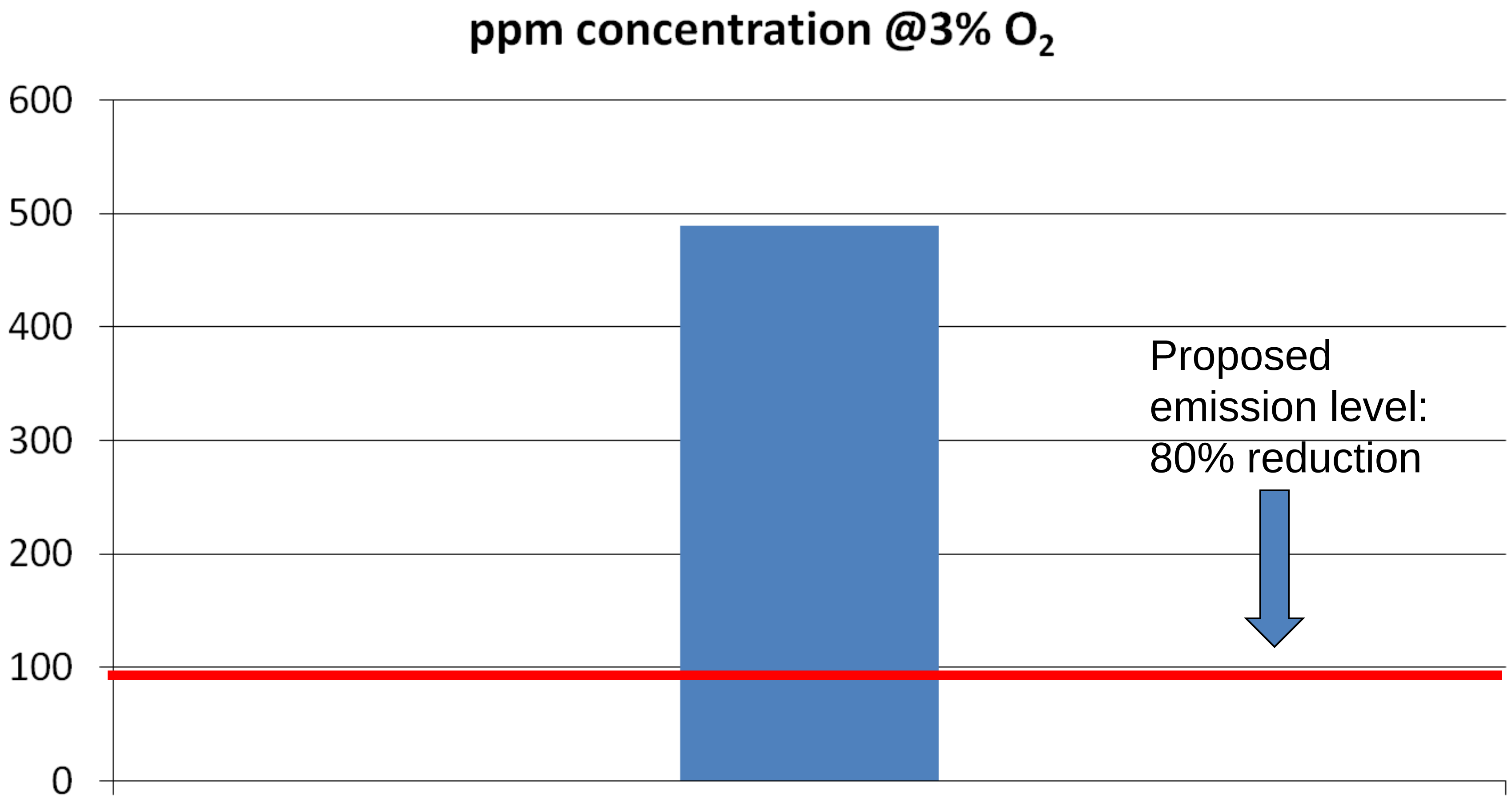
Non Refinery Gas Turbines



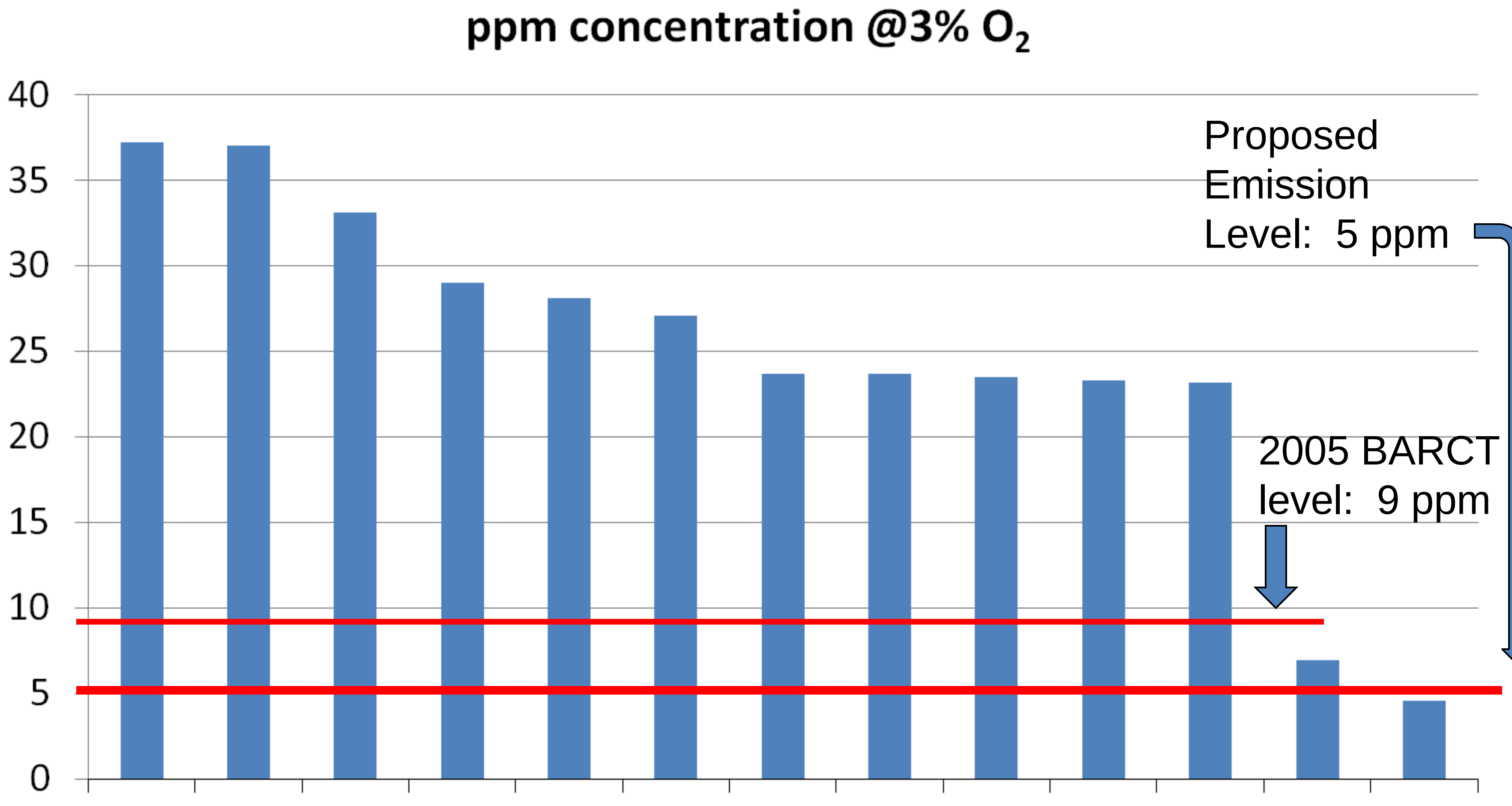
Glass Melting Furnaces (Container Glass)



Glass Melting Furnace (non-container glass)



Non-Refinery Boilers
>20 MMBTU/hr



Next Steps

- Complete BARCT Analysis
- Schedule next meeting February/March 2014
- Ongoing individual meetings to review BARCT

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