Selective Catalytic Reduction of NOx by M. Pilat (3/9/98)

Given: Principal Chemical Reactions

$$4\,NO + 4\,NH_3 + O_2 \xrightarrow{\text{catalyst}} 4\,N_2 + 6\,H_2O \qquad (1)$$

$$2\,NO_2 + 4\,NH_3 + O_2 \xrightarrow{\text{catalyst}} 3\,N_2 + 6\,H_2O \qquad (2)$$

Cylindrical tube of Catalyst of Diameter D and Length L inside a honeycomb matrix

The NO_x, NH_3, and O_2 diffuses to the inside surface of the cylindrical tube catalyst and is assumed to react quickly (i.e. reaction rate constant k_r = extremely large number). In the easiest first case, it can be assumed that the reaction rate is so fast (i.e. k_r = very large compared to k_m) that the reaction of the NO or NO_2 with the NH_3 is limited by the rate of mass transfer (diffusion) to the catalyst surface. The pressure drop from the tube inlet to outlet is small (less than 3" H_2O) and hence the gas velocity is assumed to be constant in the x or L direction.

The nomenclature is as follows:

C	=	concentration of the NO in the air	gms NO/cm^3
a	=	surface area of catalyst / unit volume of reactor	cm^2/cm^3
D	=	effective diameter of the tube of channel	cm
K_o	=	overall mass transfer coefficient	cm/sec
k_m	=	mass transfer coefficient	cm/sec.
k_r	=	reaction rate constant of NO with NH_3	cm/sec
L	=	Length of the catalyst reactor channel	cm
L_m	=	Length of one mass transfer unit	cm
N	=	Number of mass transfer units	
v	=	velocity of the gas in the catalyst tube	cm/sec
ϑ	=	diffusion coefficient of NO in air	cm^2/sec

The change in the NO concentration down the tube caused by the diffusion to the wall and catalytic reduction to N_2 and H_2O is given by the equation

$$\frac{dC,\ \dfrac{\text{gm NO}}{\text{cm}^3}}{dx,\ \text{cm}} = -\frac{\left(a\ \dfrac{\text{cm}^2\ \text{area}}{\text{cm}^3\ \text{volume}}\right)\left(K_o\ \dfrac{\text{cm}}{\text{sec}}\right)\left(C\ \dfrac{\text{gm NO}}{\text{cm3}}\right)}{(v,\ \text{cm / sec})} \qquad (3)$$

Rearranging equation 3

$$\frac{dC}{C} = -\frac{(a)\,(K_o)\,dx}{v} \qquad (4)$$

and integrating from the tube inlet (x = 0 and $C = C_o$) to some distance x (where x = x and the NO conc. is C)

$$\int \frac{dC}{C} = -\int \frac{(a)\,(K_o)}{v}\,dx \qquad (5)$$

The results of the integration are

$$\ln C - \ln C_o = \ln\frac{C}{Co} = -\frac{(a)(K_o)(x)}{v} \qquad (6)$$

$$\frac{C}{C_o} = \exp\left(-\frac{a\ K_o\ x}{v}\right) \qquad (7)$$

With no vapor pressure of NO over the catalyst surface, number of mass transfer units is given by

$$N = \ln\left(\frac{C_{inlet}}{C_{outlet}}\right) \tag{8}$$

For one mass transfer unit, $N = 1 = \ln[\, C_{inlet} \,/\, C_{outlet} \,]$ (9)

$$e^{1} = \left(C_{inlet} / C_{outlet}\right) \qquad e^{-1} = \left(C_{outlet} / C_{inlet}\right) \tag{10}$$

Equating equations 7 and 10

$$\frac{C_{outlet}}{C_{inlet}} = \exp\left(-\frac{a\ K_o\ x}{v}\right) = e^{-1} \tag{11}$$

Taking the ln of eq. 11 and solving for x for one mass transfer unit, $N = 1$, gives L_m

$$\frac{a\,K_o\,x}{v} = 1 \quad \text{Solving for x for 1 mass transfer unit:} \quad x = \frac{v}{a\,K_o} = L_m \tag{12}$$

Equation 12 provides the distance L_m the gas must travel in the catalyst to reduce the NO concentration by one mass transfer unit (63.21 % reduction of NO).

For catalyst with small tubes, the gas flow is in laminar flow (i.e. Re < 2100). In laminar flow, the gas film mass transfer coefficient k_m is related to the Sherwood Number (which has the magnitude of 4.4 for cylindrical channels) by:

$$Sh = \frac{\text{Total mass transfer}}{\text{molecular mass transfer}} = \frac{k_m\ D}{\vartheta} \tag{13}$$

Solving for the gas film mass transfer coefficient k_m

$$k_m = \frac{4.4\ \vartheta}{D} \tag{14}$$

The surface area a (cm^2/cm^3) inside the tube of the honeycomb catalyst is given by

$$a = \frac{L\ \pi\ D}{L\ \pi\ \left(D^2/4\right)} = \frac{4}{D} \tag{15}$$

Solving for the tube diameter $D = 4/a$ (16)

Some example data (assuming that $K_o = k_m$) is shown below:

		Holes/sq. inch of catalyst support		
		200	300	400
Open Area	(%)	72	65	77
Effective Hole Diameter	(inches)	.059	.046	.044
Gas Vel. in holes	(ft/sec)	27.7	30.8	26.0
Reynolds Numbers		153	133	107
Length of 1 Mass Transfer Unit	(inches)	0.80	0.54	0.42
Gas Pressure Drop	(" H_2O)	1.8	2.0	1.5

Effect of Reaction Kinetics The reduction reactions shown in equations 1 and 2 are not actually "instantaneous" and hence the effect of the reaction kinetics on the NO reduction should be included. The overall mass transfer coefficient K_O can be given by:

$$\frac{1}{K_o} = \frac{1}{k_m} + \frac{1}{k_r} \qquad (17)$$

where k_r is the reaction rate constant. In reality, there are a number of reaction rate constants, however, for this example they will be combined into the one reaction rate constant, k_r. One then can calculate the overall mass transfer coef. K_o and then use the equation 7 to obtain the concentration ratio C/C_o

$$\frac{C}{C_o} = \exp\left(-\frac{a\ K_o\ x}{v}\right) \qquad (7)$$

How does one obtain the magnitude of this pseudo reaction rate coefficient k_r from experimental data? An example calculation is provided below.

Example Calculation of NO Catalytic Reduction Reaction Rate Constant k_r

Given: 200 CPSI cell density, T=350°C (662°F), Space vel. = 20,000 hr^{-1}, $NH_3/NO = 0.95/1$

Diffusivity of NO at 662°F = 0.8 cm^2/sec. Hole Dia. = 0.059 " = .00492 ft Cat. L = 4.5 ft

NOx reduction = 95% for 42 ppm NO at cat. inlet (Fig. 13 or Engelhard paper by Durilla, et al)

Find: Magnitudes of k_m, k_r, and K_o

a. Solve for catalyst surface area a $a = (4/D) = (4/.00492 ft) = 813.56\ ft^2/ft^3$

b. Solve for gas vel. v v = (Space Vel, hr^{-1}) (Cat. Length) = (20,000 hr-1)(4.5 ft) = 25 ft/sec.

c. Solve for K_o

$$K_o = -\frac{v}{a\,x}\ln\left(\frac{C}{C_o}\right) = -\frac{(25\ ft/sec)}{(813.56\ ft2/ft3)(4.5\ ft)}\ln(0.95) = -(.006829)(-0.051293) = .0003503\frac{ft}{sec}$$

d. Solve for k_m with equation 14

$$k_m = \frac{(4.4\ \vartheta)}{D} = \frac{(4.4)(0.8\ cm^2/sec)}{(0.00492\ ft)(30.48\ cm/ft)} = 23.473\frac{cm}{sec} = 0.7701\frac{ft}{sec}$$

e. Solve for k_r with equation 17

$$\frac{1}{k_r} = \frac{1}{K_o} - \frac{1}{k_m} = \frac{1}{0.0003503\ ft/sec} - \frac{1}{0.7701\ ft/sec} = 2{,}854.7 - 1.2985 = 2{,}853.40\ sec/ft$$

k_r = 0.0003505 ft/sec = 0.010682 cm/sec

Gas Pressure Drop Across the Catalyst

The gas pressure drop across the catalyst can be calculated by $\Delta p = \frac{2\ f\ L\ v^2\ \rho}{g_c\ D}$

The Fanning friction factor f is 16/Re for circular tubes and 14/Re for square channels.

The other variables are L = total length of catalyst tube, v the gas velocity, ρ the fluid gas density, g_c the gravitational constant, and D the effective diameter of the channel or tube.

Natural Gas Fueled Gas TurbineNOx Exhaust Gas Concentrations

Given: The exhaust gases from a gas turbine plant (burning natural gas) has the following composition at 1.0 atm. pressure:

74.0% N_2
16.0% O_2
3.6% CO_2
6.4% water vapor at 1,340°F or 999.66°K

Molecular wt of NO = 30.01

$$C_{NOx}\left(\text{corrected to } 15\%\ O_2\right) = \left\{\frac{20.9\ -\ 15\%O_2}{20.9 - \text{Stack Gas }\%O_2}\right\}\left(\text{stack gas } C_{NOx}\right)$$

New Source Perf. Std. for Gas Turbines = 0.2 lb NOx per million Btu heat input (pp 77 WW&D)

F_d= 8740 ft^3 gas emitted per million Btu heat input for nat. gas combustion

$$E\frac{\text{lb NOx}}{10^6\ \text{Btu Heat Input}} = \left(\text{NOx}\ \frac{\text{lb}}{\text{ft}^3}\right)\left(F_d, \frac{\text{ft}^3}{10^6\ \text{Btu Heat Input}}\right)\left(\frac{20.9}{20.9 - \text{O2Dry}}\right)$$

where O2Dry is the % oxygen in the gases on dry basis (i.e. 0% water vapor)

Find:

a. Conc of NO in exhaust gases corresponding to the 0.2 lb/10^6 Btu NSPS allowed emission

____________ppm NO dry corrected to 15.0% dry O_2

b. Will the NO equilibrium conc. @ 1,340°F calc. meet the NSPS EPA standards?
In other words, there is an equilibrium reaction $N_2 + O_2 \Leftrightarrow 2\,NO$

The equilibrium constant K_p $$K_p = \frac{[NO]^2}{[N2][O2]} = 7.5 \times 10^{-9} \text{ at } 1{,}340^\circ F$$

This K_p is from Table 8-4 pp 435. [NO] is the NO concentration.

Note that the NO, N2, and O2 need to all be in the same concentration units.

One can use this relationship to calculate the NO equilibrium concentration using the known Kp, N2 conc. of 74.0% and O2 conc. of 16.0% (these are wet basis concentrations).

(see pages 434-446 WW& Davis for discussion of NO and NO_2 formation)

NOx Exhaust Gas Concentrations and Emission Standards
Gas Turbine burning natural gas as fuel

Exhaust Gases of 74% N_2, 16% O_2, 3.6% CO_2, and 6.4% water vapor T=1,340 Deg F

a. Concentration of NO corresponding to NSPS of 0.2 lb NOx/million Btu Heat Input

EPA Federal Emission Standards for Gas Turbines were established in 1979 for NOx and SO2
NSPS = 0.2 lb NOx per million Btu heat input = E Fd = 8740 cubic ft gas / million Btu Heat input

$$E := 0.2\cdot\left(\frac{\mathbf{lb}}{1000000\cdot\mathbf{BTU}}\right)$$

Cd=NOx conc., lb NOx / dscf

O2Dry = oxygen conc., % by vol., dry

$$Fd := 8740\cdot\left(\frac{\mathbf{ft}^3}{1000000\cdot\mathbf{BTU}}\right)$$

$$\mathbf{O2Dry} := 15.0$$

$$E := (\mathbf{Cd})\cdot(\mathbf{Fd})\cdot\left(\frac{20.9}{20.9-\mathbf{O2Dry}}\right) \qquad \mathbf{Cd} := \frac{E}{\left(8740\cdot\frac{\mathbf{ft}^3}{1000000\cdot\mathbf{BTU}}\right)\cdot\left(\frac{20.9}{20.9-\mathbf{O2Dry}}\right)}$$

$$\mathbf{Cd} = 6.45987759\cdot10^{-6}\ \cdot\frac{\mathbf{lb}}{\mathbf{ft}^3}$$

Vol. 1 lb mole @ 68 deg F = (359) (528R/492R)= 385.2683 cubic ft

Conversion Factor = (30.01 lb/mole) / [(385.2683 cf/mole) (million)] = 7.7894 E-8 (lb/cf)/(ppm NO)

$$\mathbf{ppm} := \frac{\left(\frac{\mathbf{Cd}}{\frac{\mathbf{lb}}{\mathbf{ft}^3}}\right)}{7.7894\cdot10^{-8}}$$

NSPS allowed NO conc.
corrected to 15.0% oxygen = ppm = 82.93164545

NSPS allowed Emission NO Conc. corrected to 15.0% Oxygen = 82.9316 ppm

b. Calc. of NO Equilibrium Conc. at 1,340 Deg. F or 999.66 Deg K @ Kp = 7.5 x 10-9 pp 435 WW&Davis

Using gas conc. on a wet basis

$$\mathbf{Kp} := \frac{\mathbf{NO}^2}{(\mathbf{N2})\cdot(\mathbf{O2})} \qquad \mathbf{N2} := 74.0\cdot\% \quad \mathbf{O2} := 16.0\cdot\% \quad \mathbf{Kp} := 7.5\cdot10^{-9}$$

Solving for NO

$$\mathbf{NO} := \left[\left(7.5\cdot10^{-9}\right)\cdot(74.0\cdot\%)\cdot(16.0\cdot\%)\right]^{0.5}$$

$$\mathbf{ppm} := .0001\cdot\% \qquad \mathbf{NO} = 2.979933\cdot10^{-3}\ \cdot\% \qquad \mathbf{NO} = 29.79932885\cdot\mathbf{ppm}$$

NO Equil. Conc. at 1,340 Deg F, 6.4% water vapor, & 16% oxygen = 29.80 ppm

Correct from NO wet to NO dry concentration & at 15.0% Oxygen

$$\mathbf{NOwet} := 29.79933\cdot\mathbf{ppm} \qquad \mathbf{BWS} := 0.064$$

$$\mathbf{NOdry} := \frac{\mathbf{NOwet}}{(1-\mathbf{BWS})}$$

BWS = fractional Conc. water vapor

$$\mathbf{O2wet} := 16.0\cdot\% \qquad \mathbf{NOdry} = 31.83689103\cdot\mathbf{ppm}$$

$$\mathbf{O2dry} := \frac{\mathbf{O2wet}}{(1-\mathbf{BWS})} \qquad \mathbf{O2dry} = 17.09401709\cdot\% \qquad \mathbf{Diff} := 20.9 - 17.09401709$$

$$\mathbf{NOcorrected} := (\mathbf{NOdry})\cdot\left(\frac{5.9}{\mathbf{Diff}}\right) \qquad \mathbf{Diff} = 3.80598291$$

NO Corrected to 15% Oxygen

$$\mathbf{NOcorrected} = 49.35325814\cdot\mathbf{ppm}$$

NO Equil. conc. dry @ 15.0% Oxygen = 49.35 ppm by gaseous volume

Thus NO Equilibrium Conc of 49.35 ppm will meet NSPS of 82.93 ppm NO corr. to 15% O2
This implies that NSPS is not a very restrictive emission std (which is typical for EPA NSPS).
Note that new installations must meet EPA BACT, not merely NSPS.

VNX™ SCR Catalysts

Engelhard's VNX family of SCR catalysts is based upon vanadia/titania as the principle catalytic material. Vanadia/titania SCR catalysts are used in numerous NOx reduction applications, and have been successfully demonstrated in reciprocating engine, gas turbine and utility/industrial boiler applications.

Engelhard VNX catalysts feature composite honeycomb configurations which use highly active vanadia/titania catalytic coatings on ceramic structures. The honeycomb structures are available in a range of cell sizes to facilitate catalyst designs which meet individual application requirements.

Temperature Range

- ☐ 600 to 750°F optimum
- ☐ 575 to 800°F maximum
- ☐ Under 575°F, NO_x efficiency is reduced with increased NH_3 slip
- ☐ Above 800°F, catalytic efficiency decreases with time

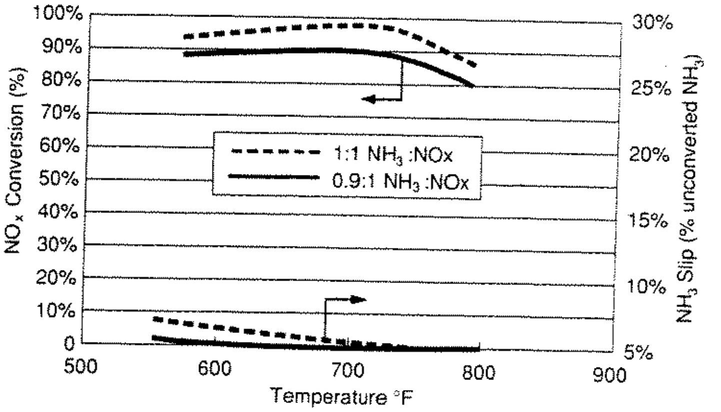


FIGURE 1

Performance

- ☐ NH_3 reacts with NO_x to form nitrogen and water
- ☐ NO_x conversion increases with NH_3 injection
- ☐ With 0.9:1.0 NH_3:NO_x ratio 90% NO_x conversion and low NH_3 slip from 575 to 700°F (Figure 1)
- ☐ Higher operating temperatures decrease NH_3 slip; but increase NH_3 consumption (Figures 2 and 3)

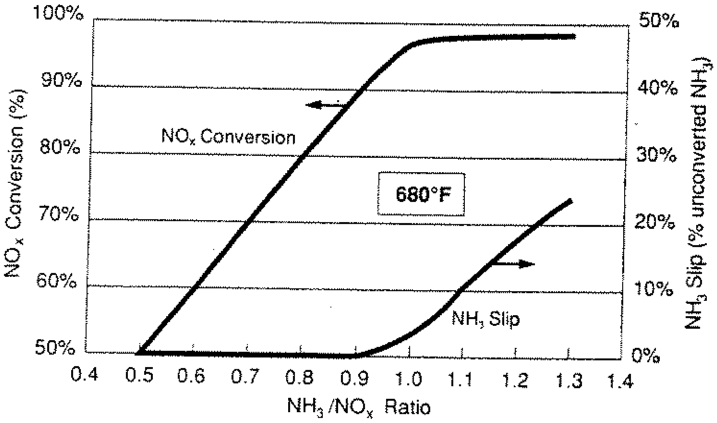


FIGURE 2

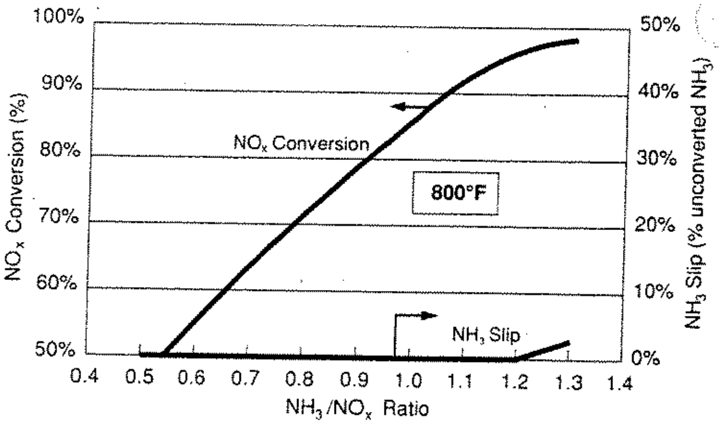


FIGURE 3

For additional information contact:
Engelhard Corporation, Environmental Catalysts Group, 101 Wood Avenue, Iselin, NJ 08830-0770
Telephone: (908) 205-6634 • Fax: (908) 205-6146 • Telex: 219984

ENGELHARD
EXCEPTIONAL TECHNOLOGIES

EC-6337 Rev. 2/91

CEE494 NOx Control with SCR

Given: Three Coal-Fired Power Plants with Hitachi Plate SCR

1. **AES Somerset power plant near Buffalo, New York retrofitted with SCR in 1999. Burns coal primarily from Pennsylvania with heating value of 13,100 Btu/lb and 3% Sulfur.**
2. **Kansas City Power & Light Hawthorn power plant near Kansas City burns Wyoming Powder River Basin bituminous coal with SCR operational since May 2001.**
3. **Carolina Power & Light Roxboro #4 power plant near Roxboro, North Carolina**

Hitachi plate type catalyst with 6 mm pitch, vanadium & molybdenum on TiO_2 base plate wall thickness = 0.9 mm

area open to gas flow is calculated to be about 85% based on 6 mm pitch, 5.1 mm between plate surfaces, and 0.9 mm wall thickness but Hitachi reports open are for flow at 82% (the difference is probably due to structural members and spacing between modules).

photo of Roxboro plant's Hitachi catalyst shows the parallel plates (probably steel) with S-shaped bends spaced about 67 mm or 6.7 cm or 2.6" apart - most likely for structural stiffness and perhaps to maintain the about 6 mm-0.9 = 5.1 mm spacing between the plates.

Find: (put final answers below; attach calculations)

a. **Catalyst surface area/volume ratio (ft^2/ft^3) Hitachi plate type catalyst with 6 mm pitch**

b. **Overall mass transfer coefficient K_o including reaction rate constant for Hitachi plate type catalyst for NOx reduction with NH_3 at temp for the 3 power plants in table.**

c. **Catalyst space velocity θ (1/hr) for each of the three power plants**

d. **Catalyst length in direction of gas flow (ft) for each of the three power plants.**

	Somerset	Roxboro	Hawthorn
Generating Capacity MW)	675	735 or 367.5 ?	550
Fuel	Bituminous	Bituminous	Sub-bituminous
Cat configuration	high dust	low dust	high dust
Gas Temp (°F)	649	735	695
Gas flow	6,500,000 lb/hr	1,725,300 scfm	5,595,000 lb/hr
Inlet NOx (ppm)	340	278	135
O_2 (%)	3%	3.25	3.5
H_2O (%)	7%	6.5	13.6
SO_2 (ppm)	1140-3490	1140-3490	420
Dust	5 grain/scf	100 mg/Nm^3	32,710 mg/Nm^3
Outlet NOx (ppm)	34	58.5	59.2
NH_3 Slip (ppm)	3	2	2
Catalyst Volume (m^3)	897	314	477
Gas Vel (m/sec)	6.0	6.0	5.7
Pressure Drop ("WG)	2.8	1.3	2.0
Ko (cm/sec)			
Catalyst Space Vel θ (1/hr)			
Catalyst Length (ft)			

Email Response from Hitachi's Dr. Howard Franklin May 23, 2002

1. We (Hitachi) use 330 m^2/m^3 = 100.6 ft^2/ft^3

2. We define space velocity as Nm^3/hr of flow/Cat volume in m^3 (N = 1 atm and 0^oC)

   a. AERS = (2,241,230 Nm^3/hr/Reactor) /(897m^3 reactor) = 2,498.58/hr Eff = 90%

   b Hawthorn = (1,161,925 Nm^3/hr) / (477m^3 reactor) = 2,435.90/hr Eff = 55.6%

   c. Rox = (1,206,000 Nm^3/hr) / (318.8 m3 reactor) = 3,831.00/hr Eff = 78.95%

3. Each block is made up 2 wide x 4 deep 2 high UNITs as shown in the attachment. Each unit is approximately 454 mm x 454 mm and thus a block has a catalyst surface area of about 1.650 m^2 (= 0.454 x 0.454 x 8). *Pilat guesses this is area perpendicular to gas flow.* Plate lengths are about 10 mm in length incrementss.

4. AES has 12 wide x 12 deep x 3 high = 432 blocks Depth = 897 m^3/144 x 1.65 = 3.778 m (plate depth 3778/6 = 630 mm) *3.778 meters = 12.395 ft*

5. Hawthorne has 6 wide x 11 deep 2 high = 132 blocks Depth = 238 m^3/Reactor/66 blocks x 1.65 = 2.921 m (plate depth = 2921/4 = 550mm) *2.921 meters = 9.583 ft*

6. Rox has 16 wide x 6 deep x 2 high = 192 blocks Depth = 314.8 m^3/96 block x 1.65 = 1.988 m (plate depth = 1988/4 = 500 mm) *1.988 meters = 6.522 ft*

Pilat's Comments:

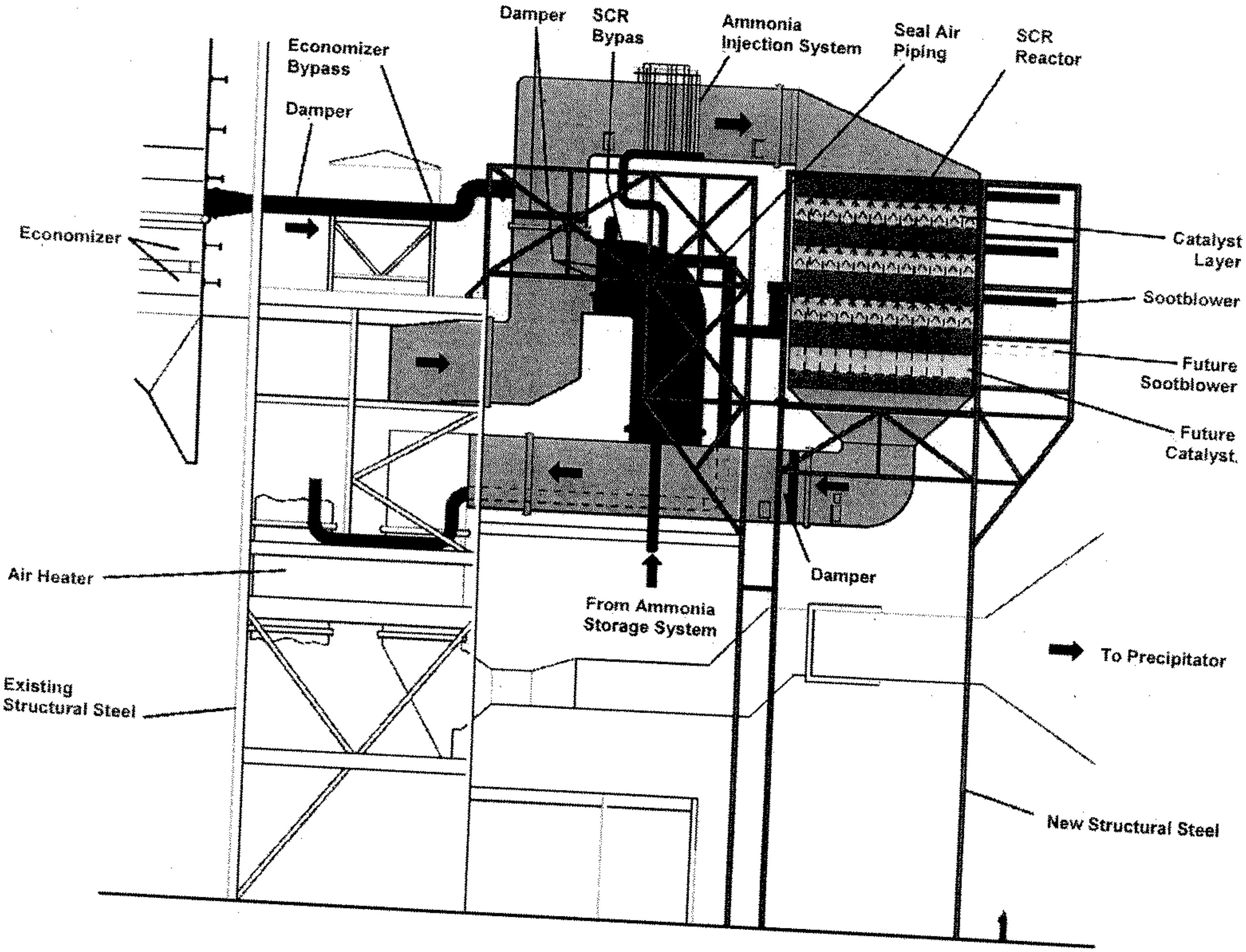
1) Note that Dr. Franklin uses gas volumetric flow rate in "normal conditions" to calculate space velocity. *I think that convention is to use flow at actual conditions.*

2) Franklin'Rosboro flow = 1,206,000 Nm^3/hr = 709,928.725 cfm @ O^oC = 761,874.7 scfm. *Is Hitachi's article showing 1,725,3000 scfm in error?*

3) Franklin's NOx conversion efficiencies agree with our NO inlet and outlet concentrations.

4) Width & depth is area perpendicular to gas flow. "3 high implies 3 layers of catalysts".

5) A photo of the Hitachi catalytic "UNIT" is shown on the internet web site at http://www.hitachi.com/products/power/techpapers/index.html in paper APC 2002 "Recent Experiences with SCR Catalyts for PRB Coal", April 15-17, 2002 conference.


Damper
SCR Bypas
Ammonia Injection System
Seal Air Piping
SCR Reactor
Economizer Bypass
Damper
Economizer
Catalyst Layer
Sootblower
Future Sootblower
Future Catalyst.
Air Heater
Damper
From Ammonia Storage System
To Precipitator
Existing Structural Steel
New Structural Steel

Kansas City Power & Light Hawthorn Power Station
500 MW Coal-Fired Boiler, 5 miles NE Downtown Kansas City

Unit 5 explosion destroyed boiler but electrostatic ppt survived. New pulverized coal-fired boiler installed about June 2001. Using Powder River Basin coal.
4 million lb steam/hr at 2520 psig & 1005 °F Natural circulation, balanced draft, subcritical boiler
Uprated GE G3 turbine generator expected to produce 550 MW net of plant auxiliaries

Air Pollution Control Equipment:
- B&W DRB-4Z ultra-low NOx burners
- Selective catalytic reduction (SCR) NOx control with NH_3
  - located between economizer and air preheater, 66 catalyst modules, 3' x 6' module
  - Temp = 700°F, Outlet NOx 59ppm (0.08 lb NOx/million Btu), NH_3 slip 2ppm @ 3% O_2
  - Hitachi plate type catalyst with 6 mm pitch, vanadium & molybdenum on TiO_2 base
- spray dryer injection of alkaline (lime + fly ash slurry) for SO_2 control
  - 1,830,000 to 1,895,000 acfm @ 270°F inlet, 155 to 160°F outlet, gas residence time = 10 to 12 sec, Outlet SO_2 = 20 to 30 ppm, 94% SO_2 reduction; lime stoichiometry = 1.08
- 10 compartment pulse-jet filter baghouse installed inside existing el ppt building,
  - 13,520 bags - 26,3 ft x 5.9"dia. (8 meter x 15 cm dia)
  - Flow = 1,720,000 acfm at 161°F Air/cloth = 3.62 ft/min net, 3.26 ft/min gross
  - inlet = 160,000 lb/hr maximum; outlet particles = 0.018 lb/million Btu heat input

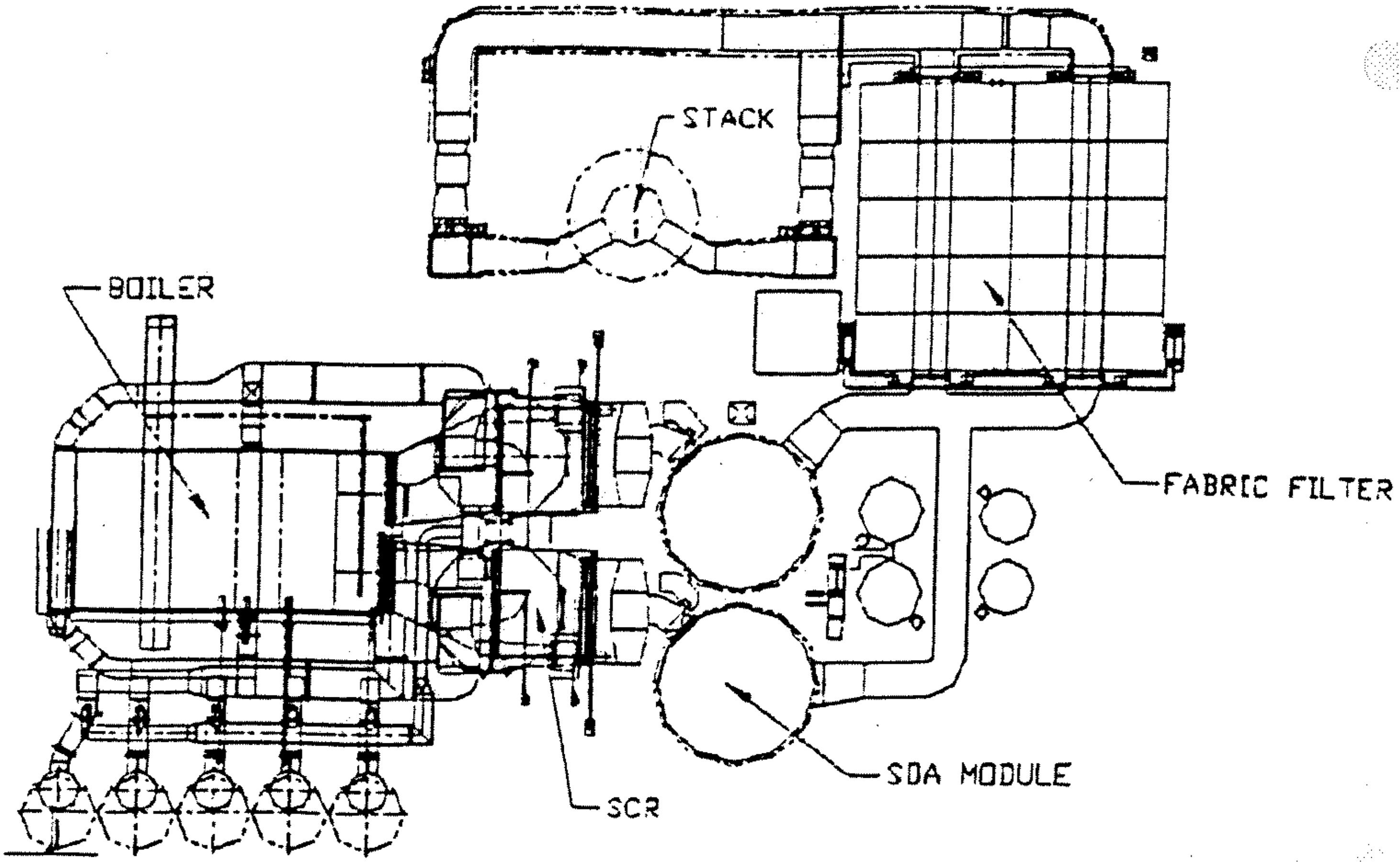
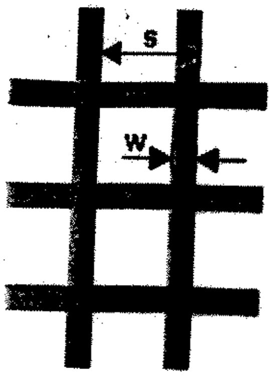


Figure 1 Hawthom emissions control equipment arrangement.

Honeycomb Cellular Monolith Catalyst Substrates (square cell matrix geometry)

Cell density = number of channels/unit cross-sectional area
Cell wall thickness = w
cell repeated distance = s = cell width + wall thickness
Specific geometric surface area
a_g = catalyst channel surface area/unit volume of catalyst



Repeat distance s
Wall thickness w
Cell density N
$N = 1/s^2$

For illustration, assume s = 6, w = 1 $s := 6 \cdot mm$ $w := 1 \cdot mm$

For square cells $ag := 4\dfrac{(s-w)}{s^2}$ $ag = 169.333\,\dfrac{ft^2}{ft^3}$

It can be seen that this equation gives the square catalyst surface area/catalyst volume

The hydraulic diameter dh of the substrate channels is used to identify the size for non-circular channels in most hydraulics, mass transfer, and heat transfer calculations. dh = 4(channel open area)/(channel wetted perimeter)

$dh := \dfrac{4\cdot(s-w)^2}{4\cdot(s-w)}$

$dh = 5\,mm$

Open frontal area OFA is the area open for gas flow and is often expressed as the % of total substrate cross-section perpendicular to the flow direction. For square cells, the ratio of open area to total cross-sectional area is gven by

$OFA := \dfrac{(s-w)^2}{s^2}$

$OFA = 0.694$

The hydraulic diameter dH can also be expressed in terms of the OFA as

Notice that in this case the hydraulic diameter = open width of this square channel

$dH := \dfrac{4\cdot OFA}{ag}$ $dH = 5\,mm$

EPA video says "pitch is center to center distance between channels"

Now let us look at an example of the calculation of the NOx conversion % versus some of the parameters. NOx conversion is to the NOx reduction efficiency = (Cinlet - Coutlet)/(Cinlet) = 1 - (Coutlet/Cinlet)

$NOxConversion := 1 - Penetration$ $Penetration := \left[\exp\left[-\left(\dfrac{area\cdot Ko\cdot Length}{velocity}\right)\right]\right]$

Using the information from the Example calculation in Pilat's class handout (which used the data from Fig. 13 of the Engelhard paper by Durilla et al.) Cell density = N = 200 cells/sq inch, Temp = 662F = 1122R, Space vel = θ = 20,000 hr^{-1}, s = 1.796051mm

$T := 1122\cdot R$ $N := 200\cdot in^{-2}$ $s := \sqrt{\dfrac{1}{N}}$ $s = 1.796051\,mm$ $Wallthickness := 0.2975\cdot mm$ $i := 0..9$

$dh := s - Wallthickness$

$w := Wallthickness$

$dh = 1.499\,mm$ $dh = 0.05900\,in$ $\theta := 20000\cdot hr^{-1}$ $Length := 4.5\cdot ft$

$area := 4\dfrac{(s-w)}{s^2}$ $area = 566.382\,\dfrac{ft^2}{ft^3}$ $velocity := \theta\cdot Length$ $velocity = 25.00\,ft\cdot sec^{-1}$

The difference between this 566.38 and the 813.6 ft²/ft³ in the Pilat handout has to do with the cell wall thickness, the % of area open for gas flow, and assumption in handout that holes are circular.

$x := \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \end{bmatrix}\cdot ft$

$Ko := -\left(\dfrac{velocity}{area\cdot Length}\right)\cdot \ln\left(\dfrac{5}{100}\right)$ $Ko = 0.89565\,\dfrac{cm}{sec}$ $Ko = 0.02938\,\dfrac{ft}{sec}$

xx is for meter to ft conversion

$\eta_i := 1 - \exp\left[-\left(\dfrac{area\cdot Ko\cdot x_i}{velocity}\right)\right]$ $Pt_i := \exp\left[-\left(\dfrac{area\cdot Ko\cdot x_i}{velocity}\right)\right]$ $xx := \left(\dfrac{100}{2.54}\right)\cdot\left(\dfrac{1}{12}\right)\cdot x$