Predicting/Mitigating Impact of Boiler Fly Ash Erosion Tube Failures

Motivation - *Major Impact on O&M Costs and Unit Availability*

- *Boiler-HRSG tube failures account for a loss of 4% in unit availability[*]*

- *Single tube failure in a 500 MW boiler requiring four days of repair work can result in a loss of more than $1,000,000 apart from the generation loss[**]*

** "Guideline for Control and Prevention of Fly Ash Erosion", EPRI Abstract, ID: 1023085, 4/11/15*

***Bright Hub Engineering, http://www.brighthubengineering.com/power-plants/34265-understanding-tube-failures-in-high-pressure-boilers*

*Objective: Identify & Develop Tube Failure Prediction Techniques**

If We Can Predict Time of Individual Tube Failure, We Can:

1. *Set Up a Tube Monitoring Program to Track Tube Degradation*
2. *Replace/Plug Tubes Using Just-In-Time Maintenance Strategies During a Scheduled Outage*
3. *Perform Cost-Benefit Analysis to Determine Advisability of Individual Tube Fix or Bundle Replacement*

** i.e., That can be Optimally Embedded in Performance Monitors and Asset Managers*

Ignoring Manufacturing Issues, There are Generally Five Classes of Boiler Tube Failures*

1. ***Stress rupture***
   - ☐ *Short term overheating failure*
   - ☐ *Long term overheating failure (called also as creep failures)*
   - ☐ *Dissimilar metal weld failure*
2. ***Fatigue***
   - ☐ *Fatigue caused by vibration*
   - ☐ *Thermal fatigue due to temperature fluctuation*
   - ☐ *Corrosion fatigue failures*
3. ***Water side corrosion***
   - ☐ *Caustic corrosion inside the tube*
   - ☐ *Hydrogen damage in water wall internal surface*
   - ☐ *Tube internal pitting*
4. ***Erosion***
   - ☑ *Fly ash erosion*
   - ☐ *Falling slag erosion*
   - ☐ *Soot blower erosion*
   - ☐ *Coal particle erosion*
5. ***Fire side corrosion (Also Called "High temperature Corrosion")***
   - ☐ *Low temperature flue gas corrosion*
   - ☐ *Fire side water wall corrosion*
   - ☐ *Coal ash corrosion*
   - ☐ *Oil ash corrosion*

*For Additional Information See: http://www.steamforum.com/pictures/e1013153.pdf

Tube Failures Initially Considered

Erosion Failures*

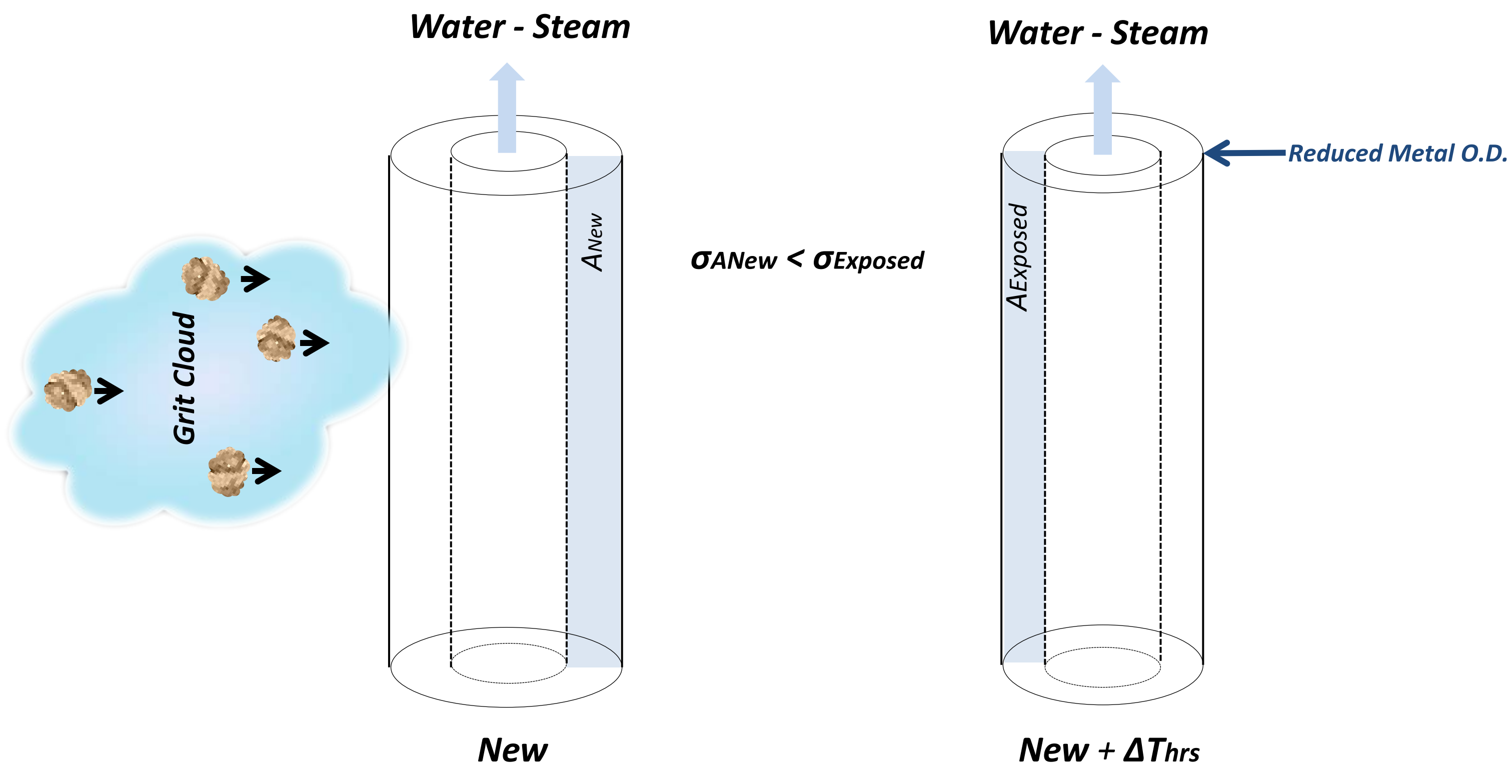
Thinning of Outside Austenitic & Ferritic Tube Surfaces
Leading to Stress Rupture Failures
*Causes: Sootblowing and Fly Ash Erosion (FAE)***

**"Nova Scotia Power's Point Aconi plant overcomes CFB design problems to become rock of reliability" Dr. Robert Peltier, PE, Power Magazine, 09/15/2006*

*** 25% of all tube failures are due to fly ash erosion ("Guideline for Control and Prevention of Fly Ash Erosion" 4/11/2011, EPRI).*

Erosion Induced Tube Failures

Mechanisms of Fly Ash Erosion (FAE)Tube Failure



Typical Economizer Tube

FAE Model Requirements

The Model Must Predict:

1. *Combustion Gas & Particulate Mass & Volume Flows*
2. *Flow & Velocities Within A Convective Path Stage*
3. *Tube Erosion*
4. *Tube Life/Failure*

Requirement #1.) Predict: Combustion Gas Composition & Particulate Flow

- *Solution: ASME PTC 19.1 Combustion Analyses to Predict Gas Composition and Mass*
- *Input Coal Description Using Proximate Analyses*
- *Fly Ash Generation ~80% Fuel's Ash Composition**
- *Volume Flows NIST Shomate - Based Gas properties*

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[*]Per American Coal Association in 2012 821,400,000 tons of coal were consumed producing 52,100,000 tons of recoverable fly ash, corresponding to an ash content of [52.1/821.4]=0.063 or 6.3%.

Per www.netl.doe.gov/.../QGESS_DetailCoalSpecs_Rev4_20130510.pdf May 7, 2013 - "Detailed Coal Specifications, Quality Guidelines for Energy ..." NETL describes as typical (coal) a non-super compliant PRB sub-bituminous coal with an ash content of 8.2%. Assuming that [6.3/8.2]~80% and 20% of ash stream is lost to slag and bottom ash.

#2.) Predict: Flow & Velocities

1.) Homogenous Equilibrium Flow

Ignores Flow Maldistribution Underestimating Erosion

2.) Computation Fluid Dynamics, CFD

Most Widely Used

O&M Support Staff Doesn't Exist

Modeling is an Art

Best CFD Models are Benchmarked w/Operating Data

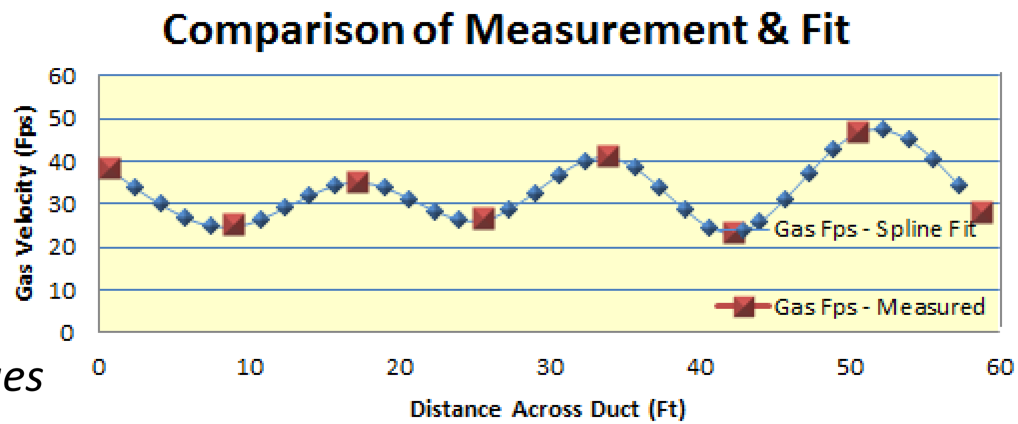
3.) Extrapolation of Cold Air Velocity Test (CAVT) Results

Can be Performed While Off-Line

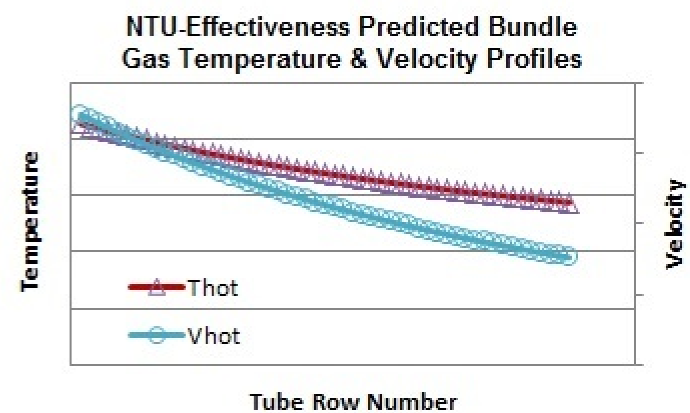
Measurements of Actual Flow Fields

Extrapolation of CAVT Results

CAVT Measurements are Superimposed on Homogenous Calculated Combustion Gas Flow Entering Bundle and Extrapolated To Channel Using Cubic Spline Fitting Techniques



To Obtain Temperature and Velocity Profiles Throughout Bundle, U_{mon_bundle} is found and Used to predict T & V_{el} between Flue Gas Inlet and Exit.



Ntu-Effectiveness Used to Extract U_{mon}

$$U_{mon} = (C_{min} * ((Log((\mathcal{E} - 1) / ((C_{min}/C_{max}) * \mathcal{E} - 1))) * (1 / ((C_{min}/C_{max}) - 1))) / S_{area}) \quad \textit{Eqn. 4}$$

Ntu-Effectiveness Used to Generate Profiles

$$\mathcal{E} = \frac{(1 - e^{(-1 * Ntu * (1 - (Cmin/Cmax)))})}{(1 - (C_{min}/C_{max}) * e^{(-1 * Ntu * (1 - (Cmin/Cmax)))})} \quad \textit{Eqn. 5}$$

Where: $Ntu = U_{mon} * S_{area} / C_{min}$

#3.) Predict: Tube Erosion Modeling

Tube Erosion Factors Considered Include the Effects of:

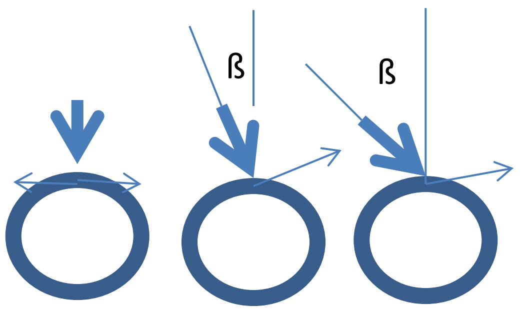
a. Collision Angle
b. Particle Velocity
c. Particle Size
d. Surface Hardness

$$\varepsilon = K_e I_e(x) \rho_m \rho_p^{1/2} V^3 \sin^3 \beta / \sigma_y^{3/2} \qquad \textit{Eqn. 6}$$

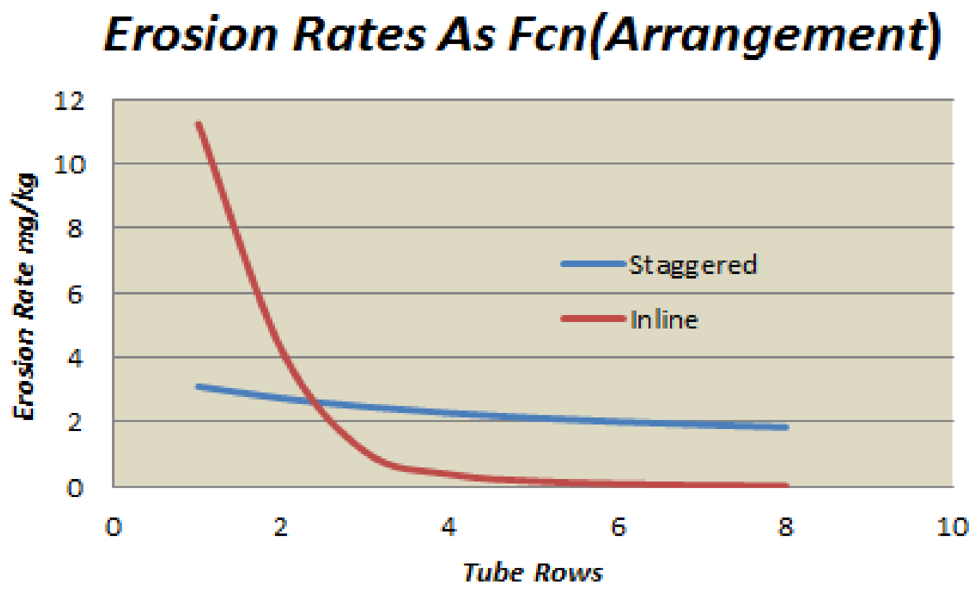
Das, Suchandan K and Godiwalla, K M and Mehrotra, S P and Dey, P K (2006) Mathematical modelling of erosion behaviour of impacted fly ash particles on coal fired boiler components at elevated temperature. High Temperature Materials And Processes , 25 (5-6). pp. 323-335. NML Granted Permission 9/1/14 Dr. A.K. Sahu, Technical Officer, CSIR-NML Jamshedpur-831007, India

3a.) Tube Erosion Modeling-Effect of Collision Angle

*Mechanisms**



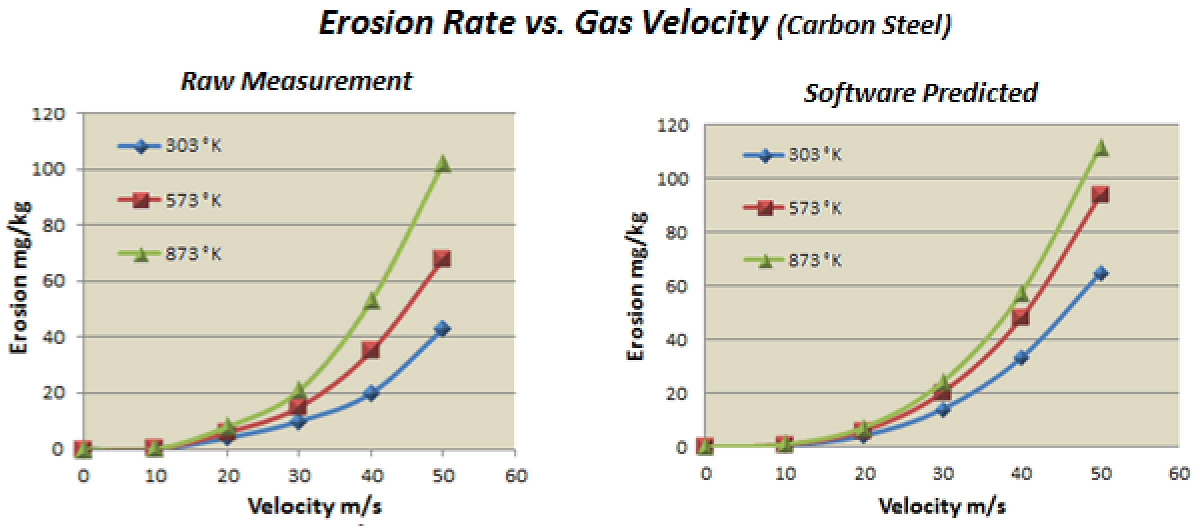
ß = 0-20° Mode of Material Removal: Rubbing & Scratching	ß = 20-30° Mode of Material Removal: Cutting & Cracking	ß > 30° Mode of Material Removal: Extrusion



** "Analysis of boiler-tube erosion by the technique of acoustic emission Part I. Mechanical erosion" L. Zhang , V. Sazonov , J. Kenta, T. Dixon, V. Novozhilov Wear 250 (2001) 762–769*

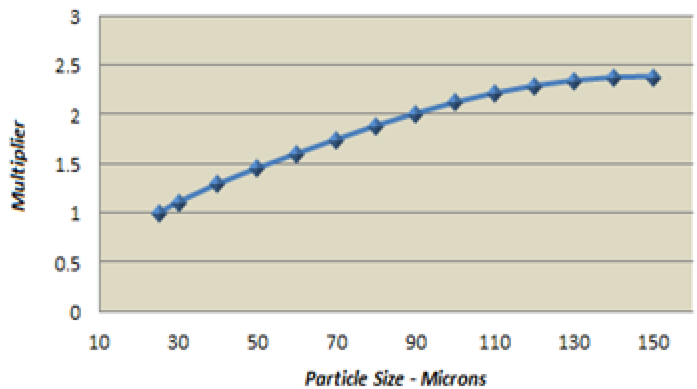
*** Das, Suchandan K and Godiwalla, K M and Mehrotra, S P and Dey, P K ibid*

3b.) Tube Erosion Modeling-Effect of Velocity



3c.) Effects of Particle Size* & 3d.)Surface Hardness**

Effect of Particle Size



Linear 25-100 Microns
Above 100 Microns Effects of Self-Shielding By Rebounding Particles

Effect of Surface Hardness

- *Surface Work Hardening Can Be Factor*
- *Also Function of Particle Hardness*
- *Observed Erosion Rates for Differing Materials w/~Same Hardness Can Vary*

Default:

$$ER_X = ER_Y \{ H_{Brinnel\ Y}{}^{-0.59}{}_{mat\ X} / H_{Brinnel\ Y}{}^{-0.59} \}$$

*"Experimental studies on the erosion rate of different heat treated carbon steel economiser tubes of power boilers by fly ash particles" T.A. Daniel Sagayaraj, S. Suresh, and M. Chandrasekar, International Journal of Minerals, Metallurgy and Materials Volume 16, Number 5, October 2009, Page 534 Materials

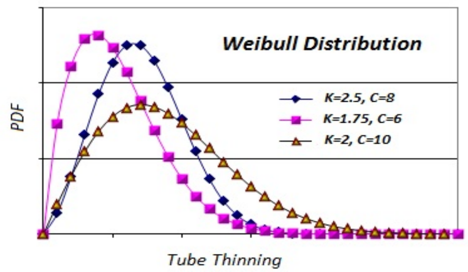
**Per Power Engineering reprint of a 02/01/2008 article entitled "Testing Predicts Fan Erosion and Leads to Design Changes" by Stephen Mick, Robinson Industries Inc.

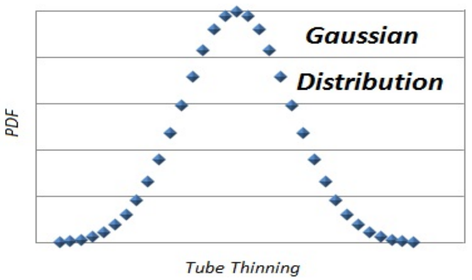
#4.) Predict Remaining Life

Method of life estimation:

a) *Estimating creep life of boiler tubes in presence of corrosion and erosion processes by Zarrabi.* * *This is based on calculation of reference stress for the tube as a function of time assuming constant thinning rate on either side of the tube. Uses Larson-Miller*

b) *A reliability-centered maintenance analyses assuming that tube failures follow a Gaussian or Weibullian distribution*





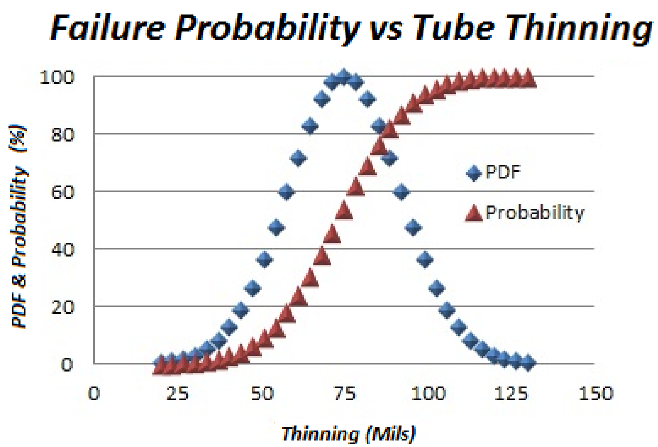
PDF=C exp$^{(-(x-b)2/(2\ \sigma 2))}$

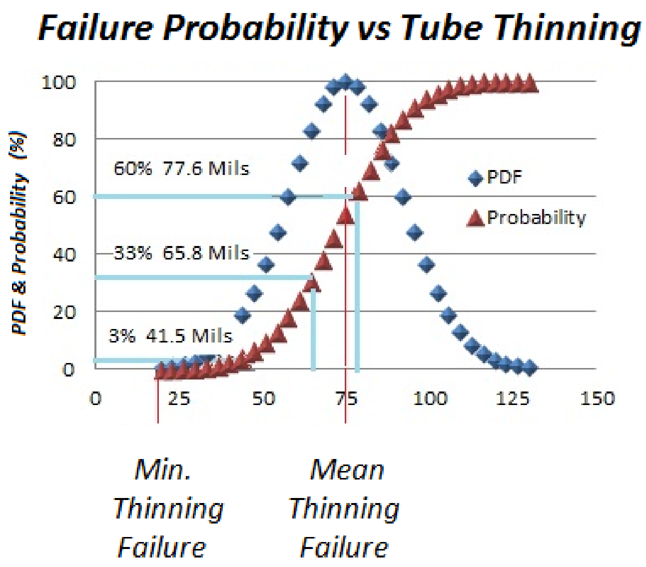
PDF = K (C^{-K}*) (X* $^{(K-1)}$*) (exp*$^{(-((X / C)\ ^\wedge\ K))}$*))*

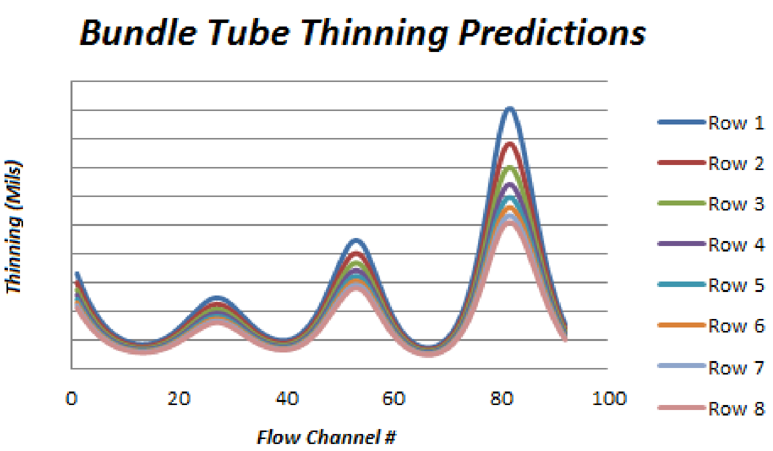
** "Life Prediction Of Boiler Tubes in Corrosive Environments" S. Chaudhuri National Metallurgical Laboratory Jamshedpur 831 007 National Workshop „n Boiler Corrosion. 11-12th April. 1 445. NMI. Jamshedpur. 1NI)IA*

*** "Heat Exchanger Design " Arthur P. Fraas - 1989 - Technology & Engineering pg 209 and "Reliability engineering principles for the plant engineer" Drew Troyer, Noria Corporation, for reliability-centered maintenance see http://www.reliableplant.com/Read/18693/reliability-engineering-plant*

4b.) Gaussian Tube Failure Assumption

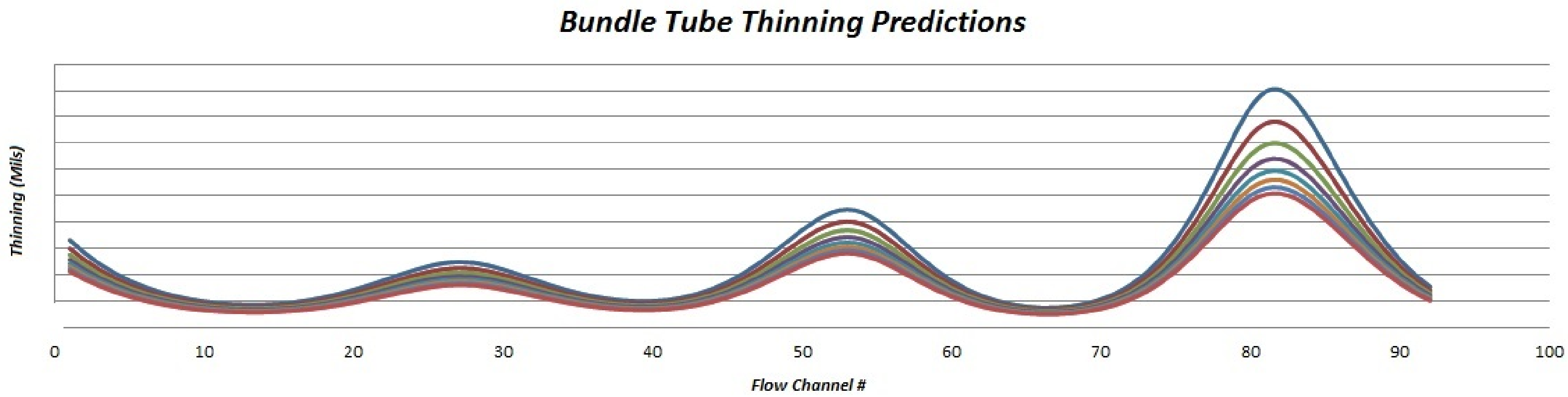


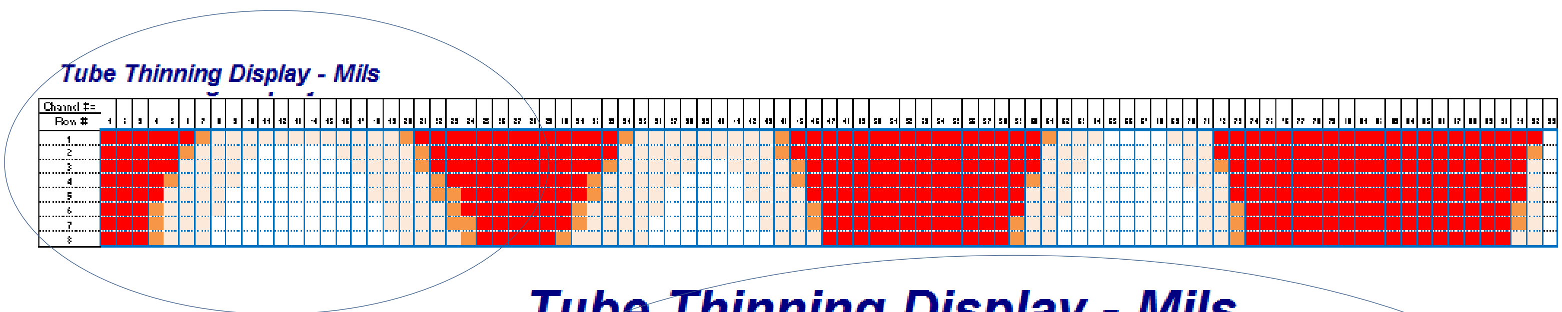


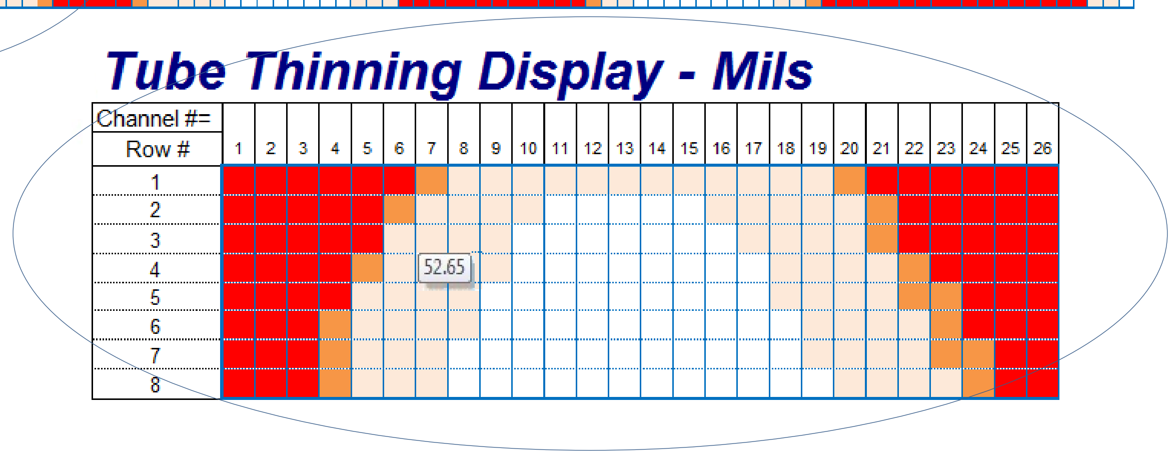


Note: ***From the above plot the number of tubes likely to fail between the probability of 3 and 33% will have wall thinnings between 41.5 and 65.8 mils***

Long-Term Tube Erosion Failure Results







Thank You for Your Time and Attention