2nd U.S-China NO_X and SO_2 Control Workshop

Boiler OP

Tools for Combustion Optimization & NOx Reduction

锅炉燃烧优化和降低NO_X排放的工具

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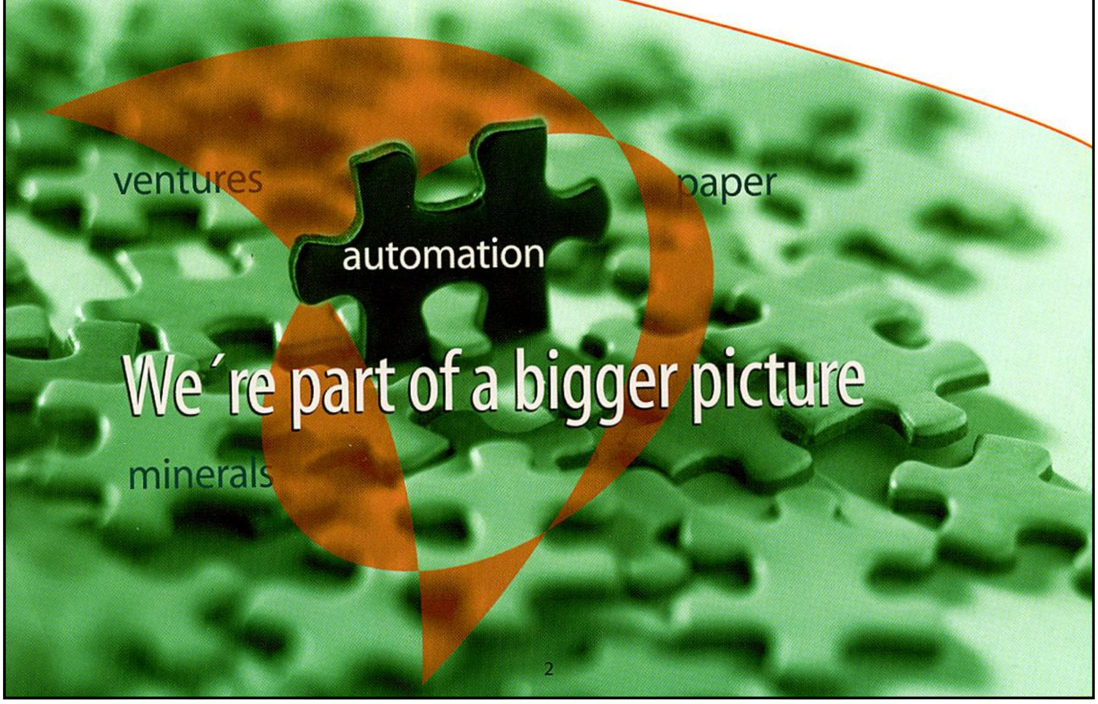
Metso (美卓)



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Yesterday: Leeds & Northrup Lagacy
公司的前身—美国的利诺公司

- **History in power plant control going back to 1920s**
  发电厂控制历史可追溯到上世纪的**20**年代
- **Leader in central station power plant controls**
  在发电厂控制中心的开发上处于领先地位
- **Divested in 1994 - 1997**
  1994至1997年期间利诺公司解体
- **Metso Automation USA Center for Power Plant Systems**
  通过购并，美卓自动化再次成为美国的发电厂控制系统中心

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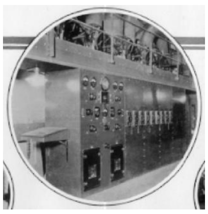
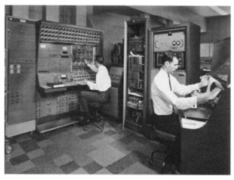
Today: Over 300,000MW power generating capacity controlled by MAX systems
由几代 MAX 系统控制的发电容量超过 300,000 MW



1920's

In China: MAX systems are controlling 84 units, over **23,000MW** power capacity

在中国，MAX 系统正控制着84台发电机组和超过**23,000MW**的发电容量



1960's

1940's

2000's: maxDNA

1980's

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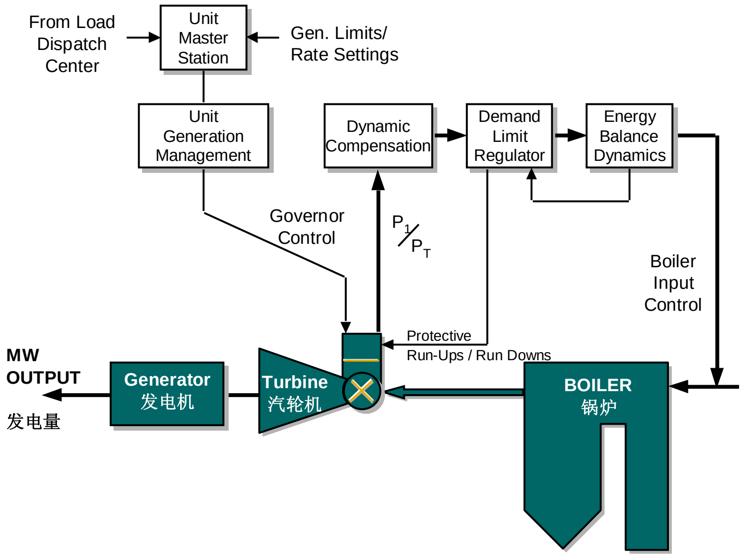
Boiler Control Optimization: DEB 400
锅炉控制的优化工具：DEB 400



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Combustion Optimization: Boiler OP
锅炉燃烧优化的工具： Boiler OP

- **Developed by Energy Research Center of Lehigh University**

  由美国理海大学的能源研究中心(**ERC**)研究开发
- **Boiler OP: Modifications to boiler control settings to achieve desired NOx level with minimum impact on unit performance or other parameters, subject to specified constraints.**

  Boiler OP 通过调整锅炉的控制设定，在规定的约束条件下取得期望的**NOx**排放量，同时对机组的性能或其他参数产生最小的影响
- **Number of boiler control parameters that are involved is large. Manual determination of optimal control settings is not possible.**

  由于大量与锅炉运行有关的控制参数的计算，通过人工方法决定锅炉控制的最优设定是不可能的

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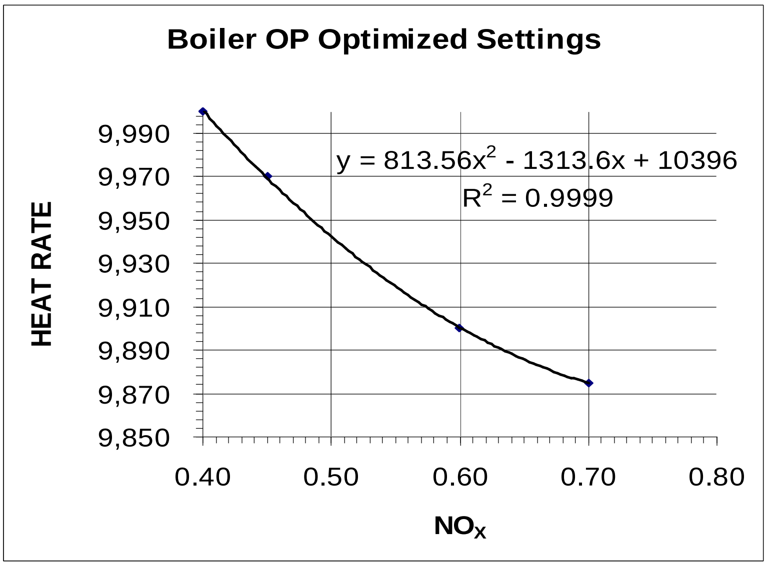
Boiler OP: Optimized result
Boiler OP 的燃烧优化结果



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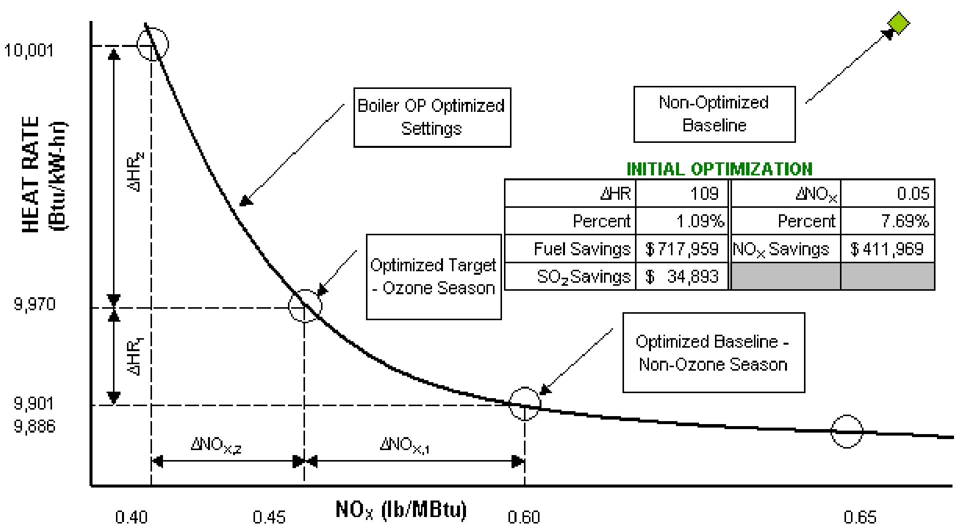
Boiler OP: Financial Analysis
Boiler OP: 经济分析



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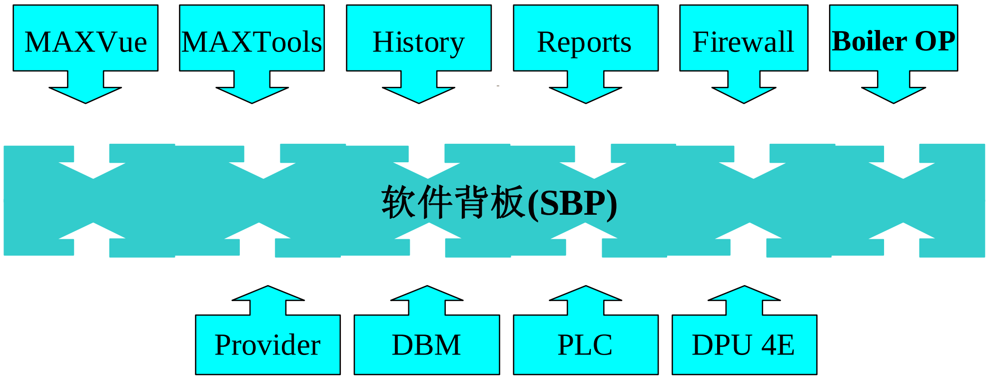
Boiler OP: Resides on maxNET
Boiler OP: 通过软件背板与maxDNA系统无缝衔接



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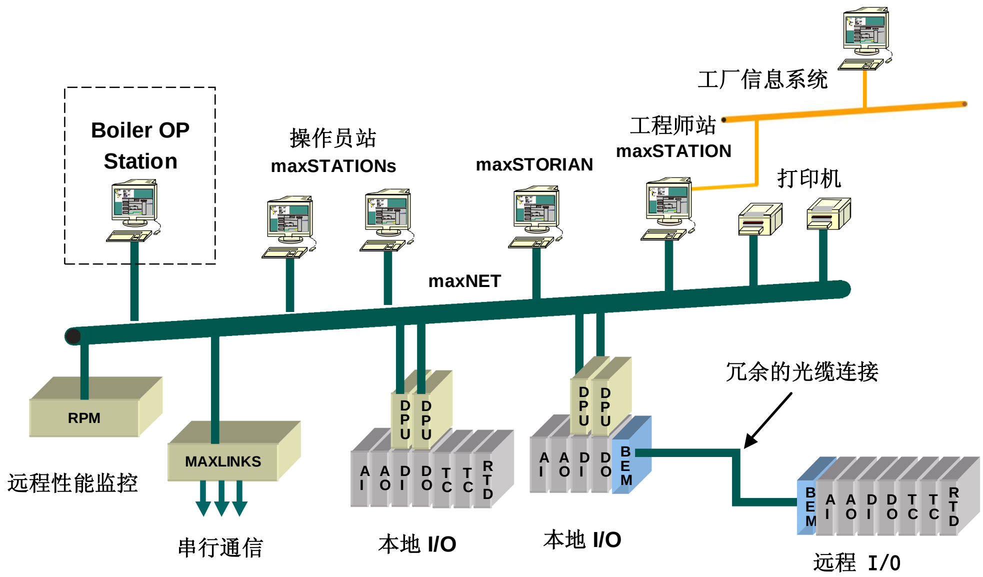
OPEN

maxDNA 系统结构



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Boiler OP: Background
Boiler OP 的开发背景

- An intelligent combustion optimization code, **Boiler OP** was developed by the ERC and PEPCO to:

  Boiler OP 是由**ERC**和波多马可电力公司在上世纪**90**年代中期联合开发的智能燃烧优化工具，主要用于：
  - Guide parametric testing （指导参数测试）
  - Automate creation of database （自动生成数据库）
  - Correlate test data （关联测试数据）
  - Determine optimal boiler control settings（决定最优的锅炉控制设定）
- **Boiler OP** combines and expert system, neural networks and an optimization algorithm into a single computer program.

  Boiler OP 将专家系统，神经网络和优化算法集成在一套计算机程序中

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NO_x Regulation
NOx 减排的法规

- Under 1990 Clean Air Act

  1990年洁净空气法修正案规定
  - Acid Rain 酸雨控制
    - 0.45 lb/MBtu for tangentially-fired boilers

      切圆燃烧锅炉NOx排放控制在0.45lb/MBtu
    - 0.50 lb/MBtu for wall-fired boilers

      墙燃炉Nox排放控制在0.50lb/MBtu
  - Ozone Non-Attainment 新鲜空气不达标
    - 65 to 75 percent reduction from 1990 levels

      在1990年的水平上再减排65-75%
    - 0.15 lb/MBtu by 2003

      2003年NOx排放控制在0.15lb/MBtu

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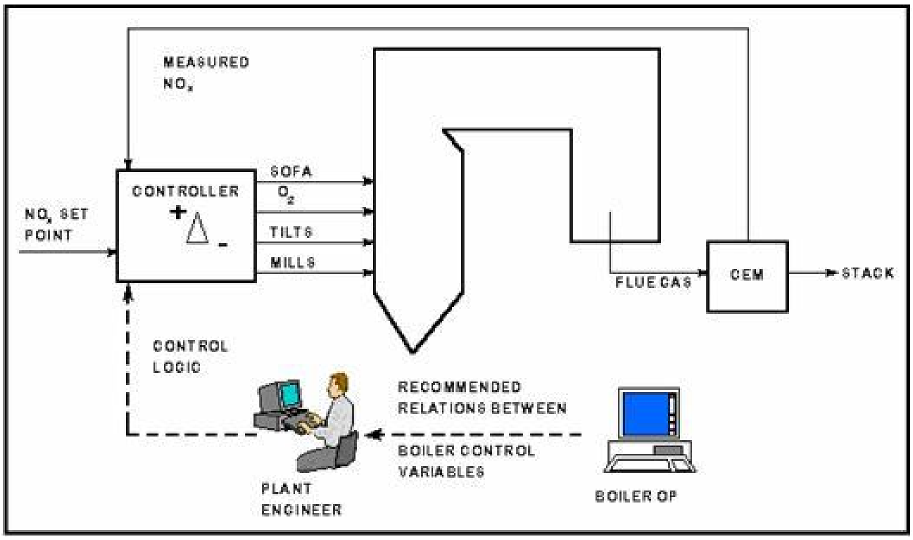
PEPCO Potomac River
波多马可河电站 #1-#5 机

- Four 108 MW & one 150 MW Units
  4台108MW和1台150MW机组
- Tangentially-Fired Pulverized Coal, Eastern Bituminous
  切向燃烧煤粉锅炉，燃用美国东部烟煤
- Conventional Burners – Original Firing System
  常规燃烧器，燃烧系统未改造
- Four Burner Elevations – All Four Mills Needed for Full Load
  四层燃烧器布置，满负荷时需投入全部四台磨煤机
- **Option** to Meet NOx Regulations: Install Low-NOx burner (cost 37 M USD)
  为了满足环境法规必须安装低氮燃烧系统
- **Alternative:** Optimize Boiler Control Setting Without Converting to Low NOx Burners
  优化锅炉的控制设定避免了安装昂贵的低氮燃烧器

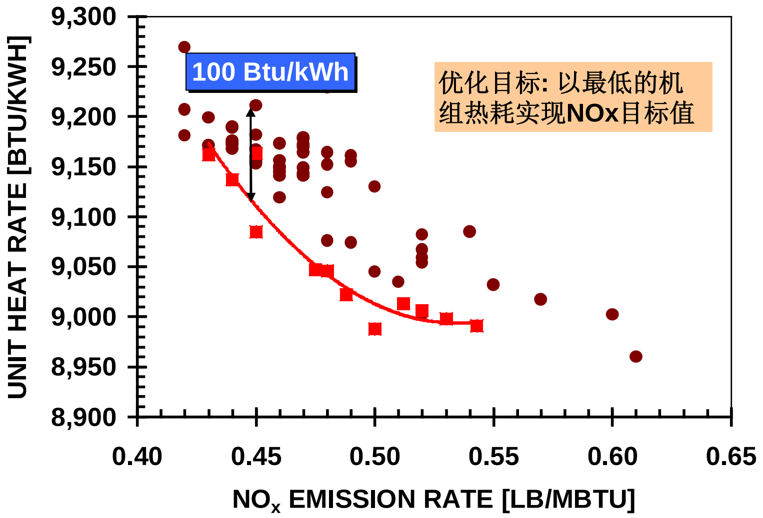
PEPCO Potomac River
波多马可河电站 #1-#5 机

- 56 sets parametric testing on Unit 4 to find the minimum heat rate subject to a target NOx of 0.45 lb/MBtu.
  对4号机进行了56组参数测试，寻找0.45 lb/Mbtu目标NOx对应的最低热耗
- Parametric testing sequence: economizer O_2 level, burner tilt angle, combined economizer O_2 levels and burner tilt angles, mill loading pattern, auxiliary air damper position, fuel air damper position, and combined auxiliary air damper positions and burner tilt angle.
  测试的参数包括：省煤器O_2，燃烧器摆角，省煤器O_2和燃烧器摆角组合，磨煤机负荷分配模式，辅助风挡板位置，燃料风挡板位置，辅助风挡板位置和燃烧器摆角组合
- 39 input parameters used in Boiler OP. Unit load, main and hot reheat steam temperatures, burner tilt angle, and various mill parameters were available on-line from the plant DCS. Remaining parameters were recorded from instruments and the CEM system. Net unit heat rate was calculated and manually entered into the database.
- Boiler OP用了39个输入参数。机组负荷，主再热器和热段再热器蒸汽温度，燃烧器摆角，以及各种磨煤机参数等可以从电厂DCS在线获得，其他参数则由控制室仪表和CEM系统记录。机组净热耗在计算后人工输入数据库

Boiler OP: Online Closed Loop Control
Boiler OP 用于在线闭环控制



Boiler OP: Optimization Result
Boiler OP 的优化结果



Boiler OP: Combustion Optimization Savings
Boiler OP 燃烧优化的经济效益

PEPCO saved $37 Million

by Avoiding Low-NOx Burners

5台机组实施的燃烧优化使电站前业主

波多马可电力公司(PEPCO)符合了CAAA的要求

并使安装低氮燃烧系统的计划推迟到2008年以后

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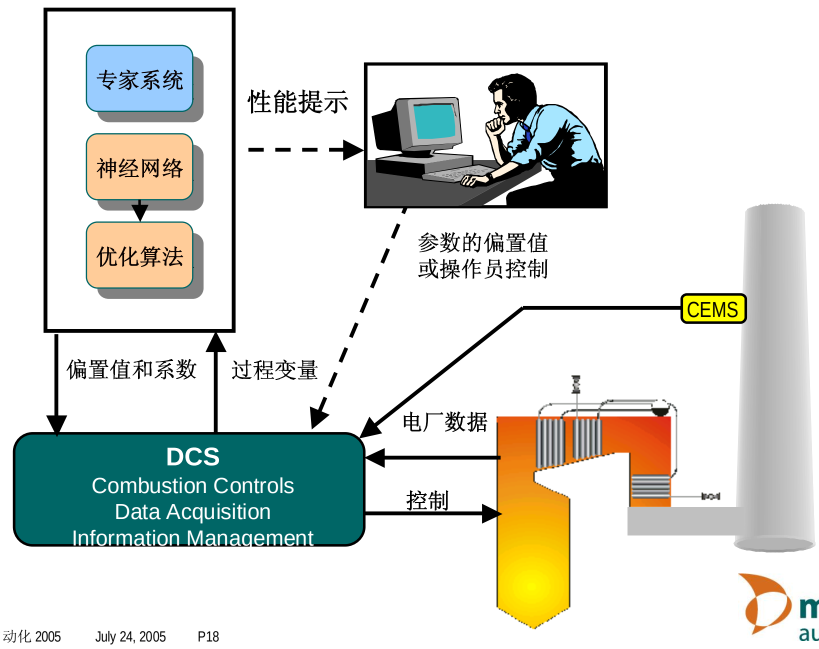
What is Boiler OP?
Boiler OP 是什么？



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Why Boiler OP

为何要优化燃烧过程

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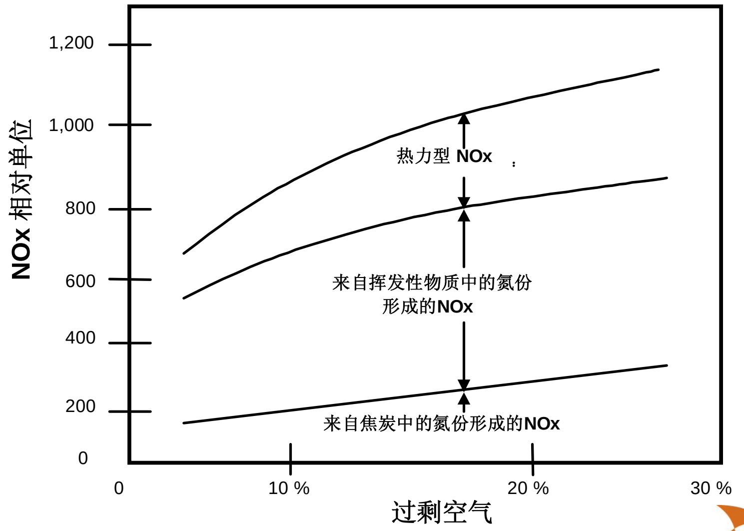
Source of Nox vs.Excess Air
NO_X 的成因以及与过剩空气的关系

Sources of NOx vs. Excess Air



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NOx Formation as a Function of Temperature
NOx 的形成与温度的函数关系

- **Most NOx above 1800°F**

  大部分**NOx** 在**>1800°F(980°C)** 开始形成

  Minimize NOx by keeping average flame temperature low

  保持较低的平均火焰温度能够使 **NOx** 排放最小化
- **Use the same heat in the process, just make the burnout longer**

  在过程中生产相同的热量，但使燃烬的时间尽量延长
- **Flame is lengthened - provide more time for burnout, which lowers combustion temperature**

  使火焰伸长 **–** 可增加燃烬的时间**,** 同时降低燃烧的温度

NOx formation as a function of time
NOx 形成与时间的函数关系

- **Longer time required for fuel burn out produces lower NOx levels**

  燃料燃烬所需的时间越长，排放的**NOx**水平越低
- **Complete burnout is important (particle size should be minimum)**

  完全燃烬的重要性 **(**使燃料的颗粒最小**)**
- **Must set classifier for smallest particle size**

  设置颗粒分选机使燃料的颗粒最小
- **Fuel/air mixing rate regulates the burn rate and thus the resulting average combustion temperature**

  燃料**/**风 混合率可调节燃烧率，从而也能调节平均燃烧温度

Turbulence...
紊流的影响

- Necessary for mixing fuel

  燃料混合的必要条件
- Excessive turbulence promotes rapid burnout and high average combustion temperature

  过度的紊流会加速燃烬并产生较高的平均燃烧温度
- Low NOx burners mix fuel and air in stages and quantities for low NOx production

  低氮燃烧器分级、分量混合燃料和空气以减少 NOx 生成
- Goal: reduce air to core burner zone

  目的: 减少燃烧器焰心的风量

NO_X influenced by...
锅炉控制设定和仪表对NO_X 形成的影响...

- Less then optimal Boiler Control Settings

  锅炉控制设定未在最佳点：
  - O_2 Levels 氧量(O_2)
  - Furnace exit gas temperature 炉膛出口烟气温度
  - Secondary Air Damper Positions二次风挡板开度
  - Burner Tilts 燃烧器摆动角度
  - Overfire Air Damper Positions燃烬风挡板位置
- Boiler Air Leakage 锅炉漏风
- Dirty Boiler 肮脏的锅炉
- O_2 Sensor Problems 氧量探头的问题
- CEM System Problems CEM 系统的问题

Optimization for NO_X Impacts…
优化 NO_X 排放将影响…

- **CO levels** 一氧化碳排放
- **Opacity** 烟气黑度
- **LOI** 飞灰含碳量
- **Slagging** 结焦
- **Boiler Efficiency** 锅炉的效率
  (Excess O2, UBC, CO, Gas Temperatures).
- **Turbine Cycle Heat Rate** 汽机循环热耗
  (Steam Temperatures, Desuperheating Flow Rates).
- **Auxiliary Power Requirements** 增加厂用电量
  (Fan Loading, Pulverizers Settings).

Tuning the boiler control and firing equipment (air registers, coal mills, burners) eliminates or mitigates operating and environmental constraints.

整定锅炉控制和燃烧设备 (调风装置, 磨煤机, 燃烧器)的设置可以排除或减少运行和环境条件的约束.

Combustion Optimization: Impacts on unit heat rate
燃烧优化的参数对机组热耗的影响

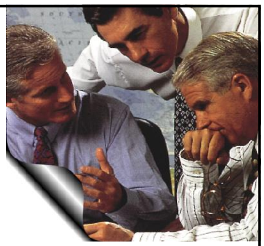
Boiler Component 锅炉参量	Parameters Affected 受影响的参数	Heat Rate Impact 对热耗的影响		
		η_{Boiler}	$H_{Turb.}$	$P_{Aux.}$
Excess Air 过剩空气	O_2, UBC, CO, T_{steam}, T_{gas}, Attemp., P_{fan},	√	√	√
Pulverizer 磨煤机				
Classification 颗粒分选机	UBC, CO, P_{mill}	√		√
Primary Air 一次风	UBC, CO, P_{fan}	√		√
Biasing 偏置值	O_2, CO, T_{steam}, T_{gas}, Attemp., P_{mill}	√	√	√
Burner system 燃烧器系统				
Seconary Air 二次风	O_2, UBC, CO	√		
Swirl 旋流	O_2, UBC, CO	√		
OFA 燃烬风	O_2, UBC, CO, T_{steam}, T_{gas}, Attemp.	√	√	
Tilt 摆动机构	O_2, UBC, CO, T_{steam}, T_{gas}, Attemp.	√	√	
Sootblowing 吹灰系统	T_{steam}, T_{gas}, Attemp., P_{fan}	√	√	√

Combustion Optimization
燃烧优化

"Modifications to the boiler control settings to achieve a particular objective (target emission level with minimum heat rate penalty), subject to operational and/or environmental constraints."

" 在运行和/或环境条件约束下，为了达到一个特定的目标而对锅炉控制设定的调整，例如：以最低的热耗代价取得排放的目标值."

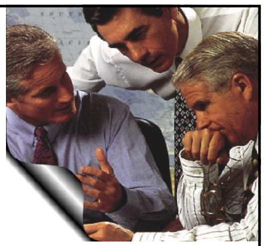
Objectives of Optimization
优化的目标



Objectives are specific to the unit and situation
目标仅针对特定的机组和工况，可以是：

- Lowest Possible Nox
  最低可能的 NOx
- Control NOx to Target
  控制 NOx 到一个目标值
- Minimize Heat Rate (Increase efficiency)
  使热耗最低 (提高效率)
- ***Enhance the performance of Low-NOx Firing Systems***
  增强低氮燃烧系统的性能

Constraints Applied
施加的约束条件



Constraints can be applied

可以施加各种约束，如：

- LOI　飞灰含碳量
- CO　一氧化碳
- Opacity　烟气黑度
- Steam Temperatures　主蒸汽温度
- Gas Temperatures　烟气温度

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ERC Optimization Approach: Constraints
ERC 优化方法的不同之处：鉴别和校正约束条件

- Combustion optimization has been applied at approx. 200 power plants in USA to minimize emissions and optimize unit performance.

  在美国，已经有近200个电厂采用燃烧优化来降低排放和优化机组性能
- Many technical papers have been written on the subject, describing optimization software and achieved results. Little information presented on factors that limit the achievable emissions reduction.

  很多技术论文介绍采用了优化软件，效果和收益等. 但仅有很少的资料介绍制约取得减排效果的典型因素以及成功项目的全面的情况
- Misleading impression: combustion optimization can be easily accomplished in all cases, simply by installing and using combustion optimization software.

  误导的印象：任何情况只要简单地安装和使用了燃烧优化软件就能够容易地实现燃烧优化

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ERC Optimization Approach: Constraints
ERC 优化方法的不同之处：鉴别和校正约束条件

- In reality, many factors, such as maintenance status of the combustion equipment, degree of process automation, operating practices, and limitations imposed by local environmental regulations are involved.

  事实上，很多因素，例如燃烧设备的维护状态，过程自动化的程度， 运行习惯，以及当地环境法规强加的限制等都有关系

- ERC's optimization approach is based on the deep understanding of underlying physics and boiler operation to identify and rectify the maintenance and operating constraints that would reduce the effectiveness of a combustion optimization

  ERC的优化方法基于对内在特性和锅炉的运行的深层的理解, 注重在实施中鉴别和校正会削弱燃烧优化效果的电厂维护及运行约束条件

- Combustion tuning is integral part of the ERC approach. Systematic Steps are required to achieve maximum emission reduction and to overcome operating and other constraints

  燃烧调整是ERC优化方法的一个整体部分.取得最大限度的减排并克服运行和其他的约束需要按一套系统的步骤来执行

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Anatomy of an Optimization Project
剖析一个优化项目

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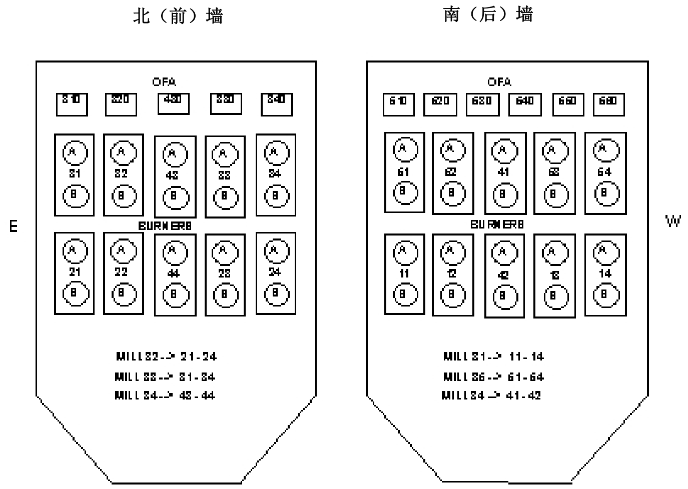
Low Nox Burner System Layout
低氮燃烧系统的布置



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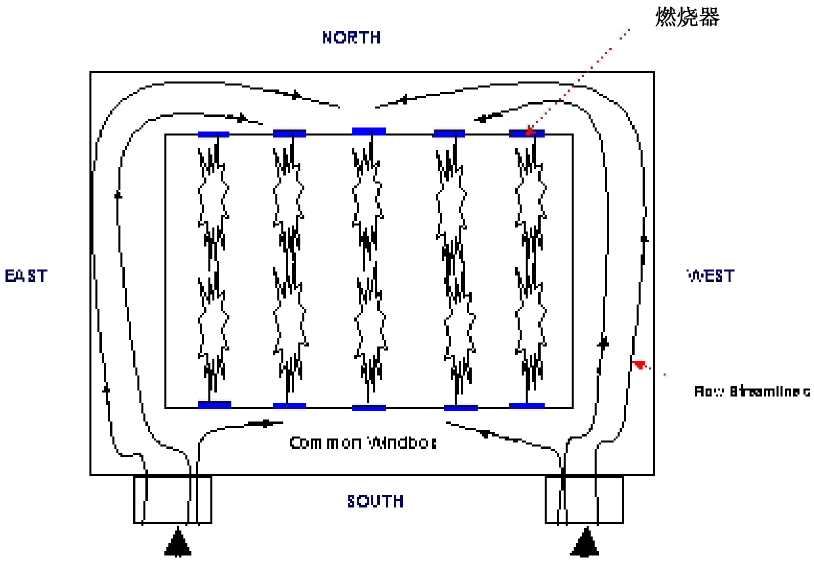
Windbox Configuration
风箱设计



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Objectives of Combustion Optimization
燃烧优化的目标

- The unit is characterized by a high volumetric heat release and consequently high FEGT.
  机组的特点是热释放容量大，因而炉膛出口烟温(FEGT)高
- State regulations limit CO emissions to 0.156 lb/MBtu on a 24-hour rolling average. This corresponds to a CO concentration limit of approximately 160 ppm_v
  州法规限定CO排放24小时滚动平均值为0.156lb/Mbtu,相当于CO浓度接近160ppm
- The unit also had a NOx emission objective of 0.38 lb/MBtu
  该机组同时还有0.38 lb/MBtu的 NOx排放目标值

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Step 1: Pre-Outage / Outage Inspection
第一步：停机前的检查和停机检查

- A pre-outage inspection was performed to assess performance of the combustion equipment, identify potential problems that could have an adverse effect on the combustion optimization tests,and inspect instrumentation used for the combustion process control. A survey of the burners provided information on the reference (baseline) settings.
  进行了一次停机前的检查来评估燃烧设备的性能，鉴别对燃烧优化测试有负面影响的潜在的问题，检查用于燃烧过程控制的仪表。对燃烧器的检查提供基准设定的信息
- A detailed inspection of burners and related equipment was performed during the plant outage
  电厂停机时对燃烧器和相关设备进行了仔细的检查
- An evaluation report was provided for the possible improvement
  根据检查的结果向电厂提交评估报告和改进的建议

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Step 1: Pre-Outage / Outage Inspection
第一步：停机前的检查和停机检查

- Step 1 is often neglected
  第一步通常会被忽略
- Results in tighter constraints and reduces optimization benefits
  忽略第一步的检查和评估会带来更紧的约束条件并削弱优化的好处

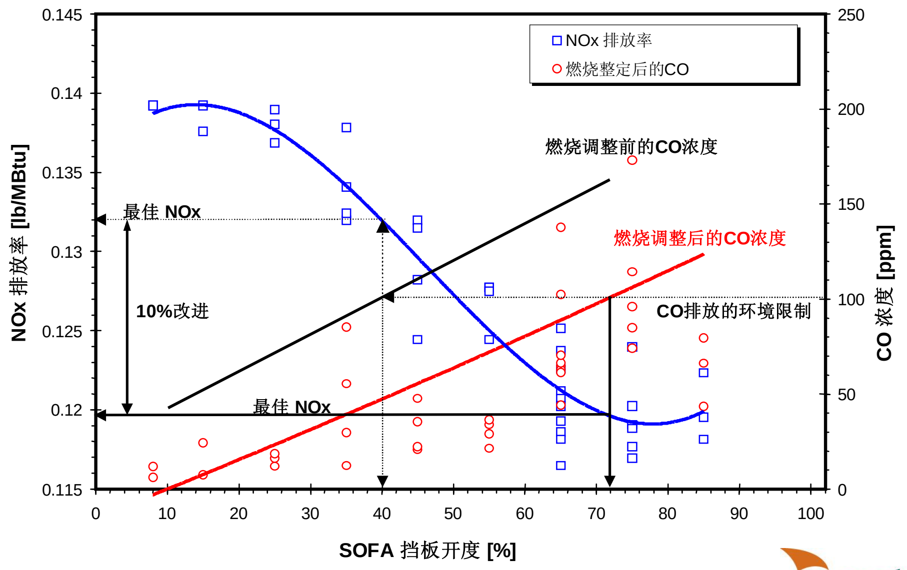
.

Step 2: Combustion Tuning
第二步：燃烧调整

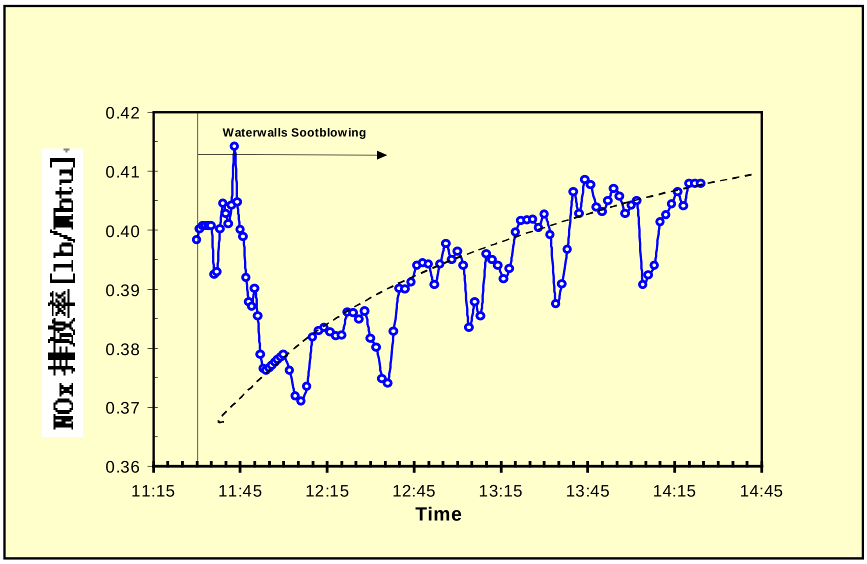
- Constraints increase minimum operating O_2 level or limit maximum SOFA register opening, reducing achievable NO_x reduction and/or increase unit heat rate.
  典型的约束条件如LOI和CO高会使运行所需的最低O_2增加，或限制SOFA挡板的最大开度，从而降低了可能减排的NOx和/或提高热耗代价
- High CO is typically caused by maldistribution of air and fuel to individual burners.
  - Balance coal flows in coal pipes.
  - Balance secondary air to individual burners *(W-fired boilers).*

  CO高通常是由于对各个燃烧器的燃料和风量分配不均匀造成的，也是一种强加的安全或环境约束。平衡煤粉管的煤流量以及墙燃炉中平衡各个燃烧器的二次风量能够减少燃料和风量分配不均匀
- High LOI levels depends on flyash resistivity can have a negative effect on ESP performance and impose operating constraints due to high opacity.
  LOI高与飞灰的阻力有关， 对静电除尘器性能有负面的影响，并因烟气黑度高而对运行额外强加了约束条件

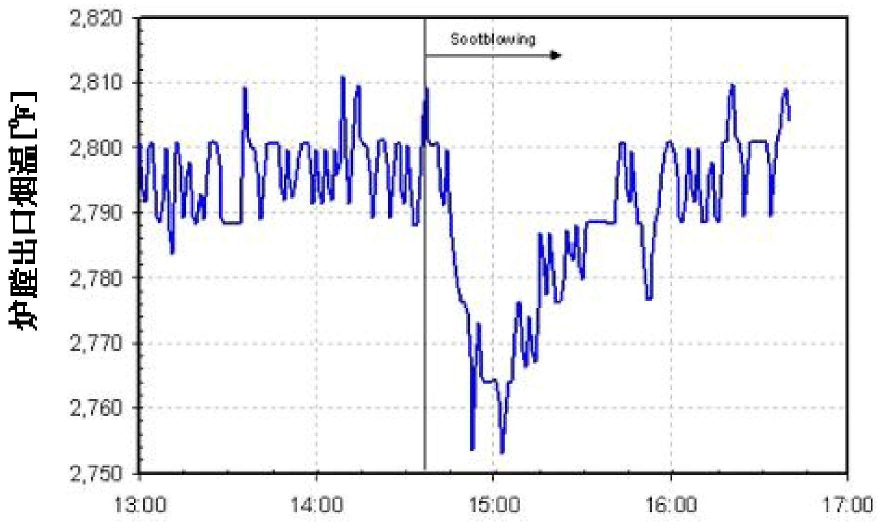
Effect of Combustion Tuning on NOx Reduction
燃烧调整对Nox减排的作用



Test Result: Effect of Sootblowing/Slagging vs. NOx
测试结果：炉膛吹灰和结焦对NOx 排放的影响



Test Result: Effect of Sootblowing/Slagging vs. FEGT
测试结果：炉膛吹灰和结焦对炉膛出口烟温的影响



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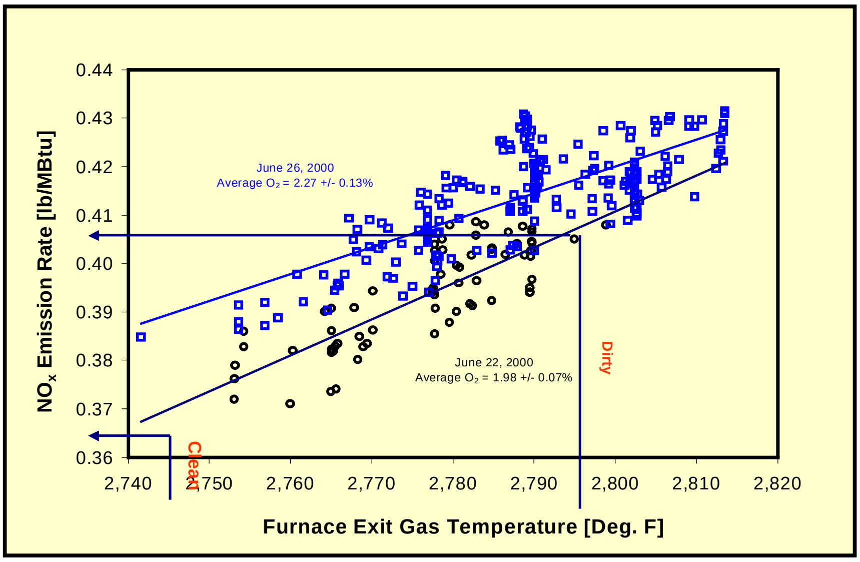
Effect of Furnace Exit Gas Temperature
炉膛出口烟温的影响



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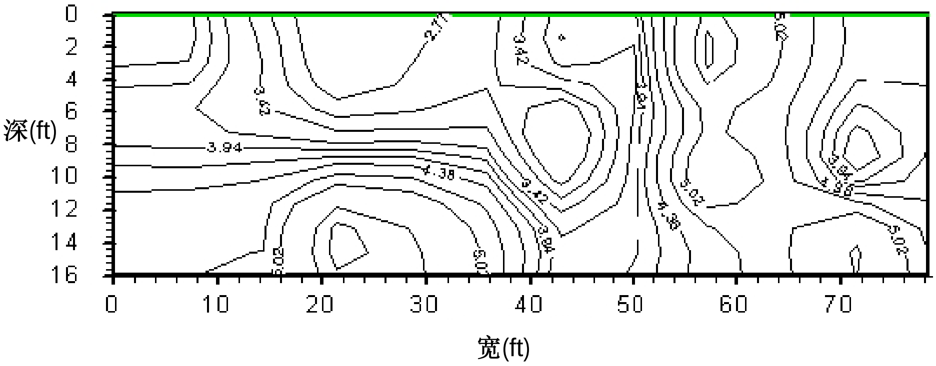
O_2 stratification and average O_2 value were affected by the boiler control settings.
锅炉控制设定对烟道中的O_2浓度的影响



O_2 的层化(等值线),平均 O_2 = 2.3%

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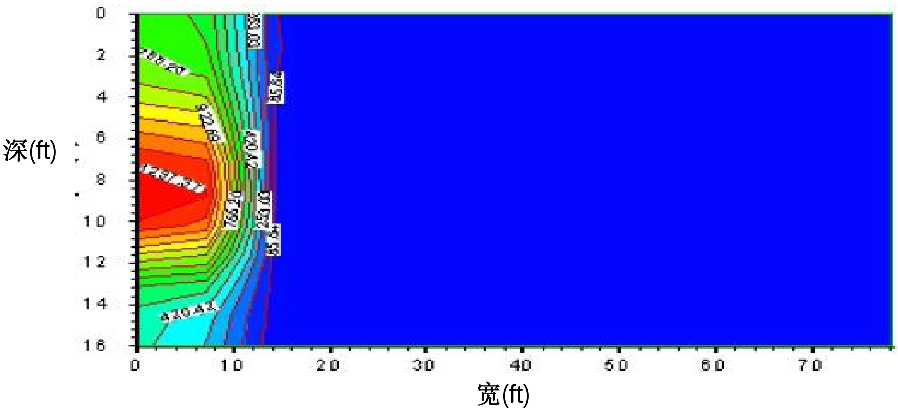
Higher CO concentration in the economizer gas outlet duct traced back to the improper setting of specific burners
烟道中的CO浓度分布反映了燃烧器的整定



燃烧调整前的CO等值线

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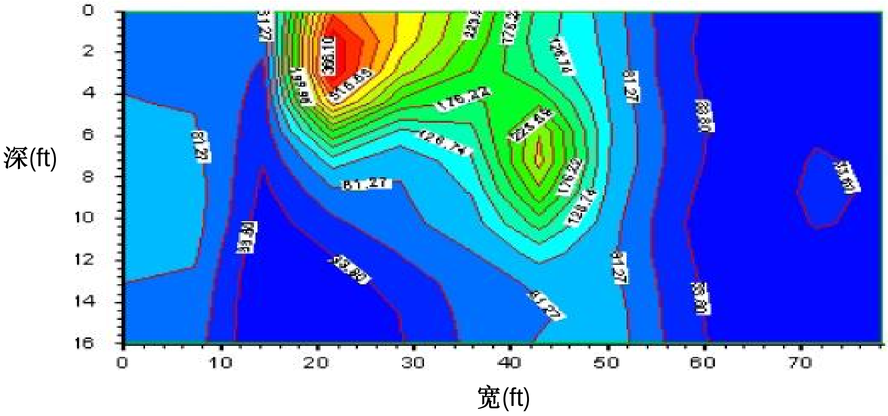
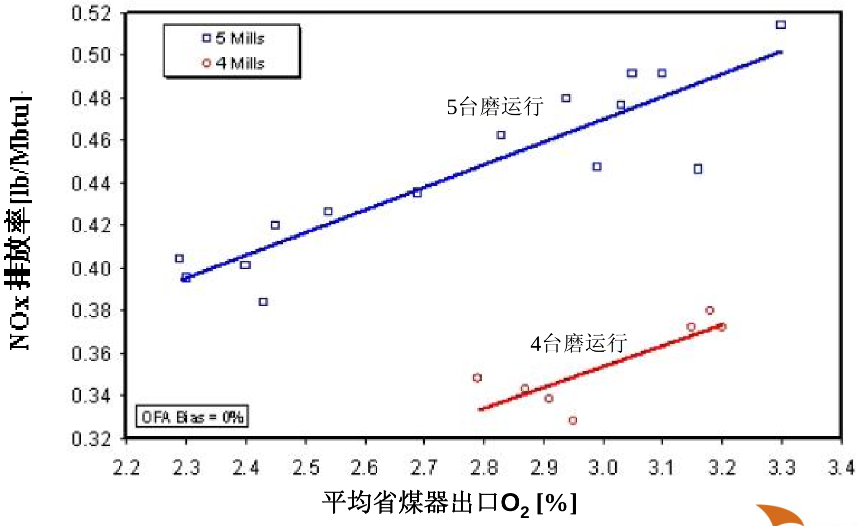
Proper adjusting secondary air registers on the burners obtained a much more uniform CO profiles
正确调整二次风控制设定可获得更均匀的CO 分布



燃烧调整后的CO等值线

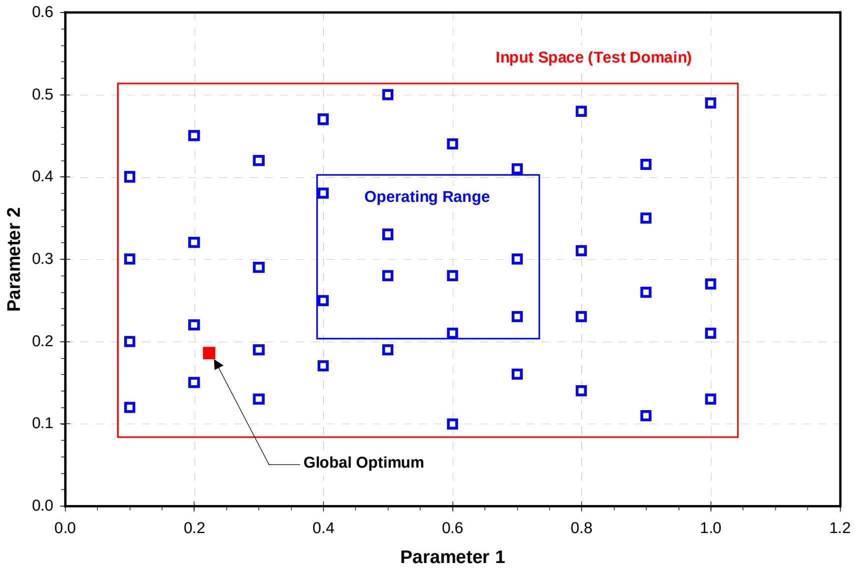
Effect of O_2 Level on NOx Emissions-after burner adjusting
燃烧器设定调整后O_2对NOx排放的影响



Step 3: Parametric Testing / Creation of Database
第三步：参数测试 / 生成数据库

- Database is needed to create a neural network (NN) model
  神经网络用数据库建立模型．没有正确的数据，就不会有正确的模型
  - Database relates the effect of boiler operating parameters (control settings) on emissions and performance.
    数据库反映锅炉运行参数(控制设定)对排放和性能有关参数的作用
  - Database is built by performing **parametric tests**.
    数据库必须通过参数测试建立
  - Performed by varying one parameter at the time and keeping the remaining parameters fixed.
    参数测试时通常一次只改变一个参数并保持其余参数不变

Step 3: Parametric Testing / Creation of Database
第三步：参数测试 / 生成数据库



Step 4: Correlation of Test Data of Database
第四步：关联测试数据

- Data-based model used to correlate boiler control settings *(inputs)* and emissions & performance *(outputs).* Artificial neural networks (ANNs) are typically used.

  Boiler OP 用神经网络关联锅炉控制设定(输入)与排放和性能参数。

  - NOx = f(O_2, Tilt, …)
  - Heat Rate = f(O_2, Tilt, …)
  - LOI = f(O_2, Tilt, …)
  - Opacity = f(O_2, Tilt, …)

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Step 5: Determination of Optimal Boiler Control Settings
第五步：决定最优的锅炉控制设定

- ANN model *(created from test data)* is used in conjunction with an optimization algorithm to determine optimal solution (*optimal boiler control settings*).

  网络模型开发和测试后，用一个优化算法来决定基于优化目标和强加的约束条件的优化方案(最优的锅炉控制设定)

- The Nelder Meade Simplex Method is used by the Boiler OP code. Optimal solution satisfies optimization goal and all imposed constraints.

  Boiler OP采用的Nelder-Meade单纯形法，由于周密地考虑了所有的运行约束条件， Boiler OP搜索到的不是数学最优点，而是实际最优点

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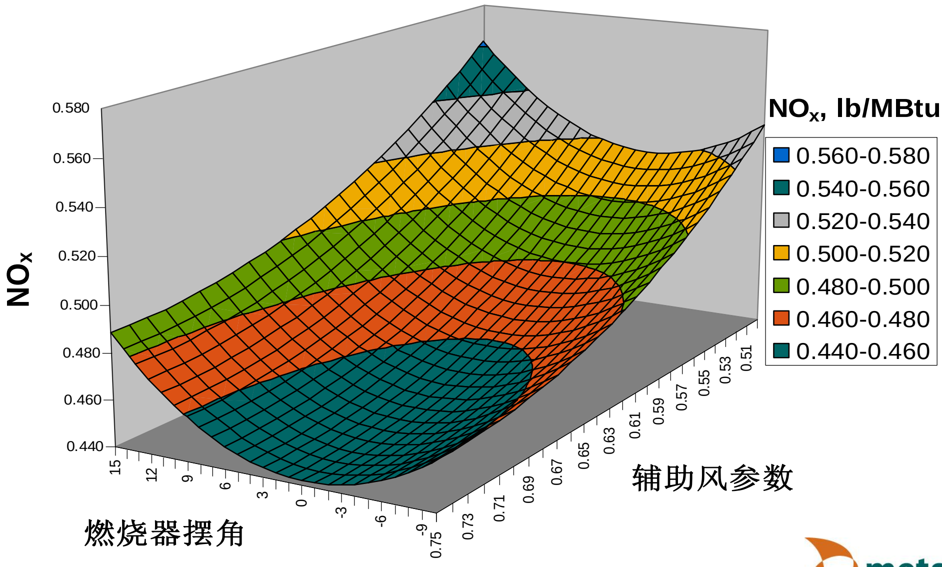
Step 5: Determination of Optimal Boiler Control Settings
第五步：决定最优的锅炉控制设定



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Step 6: Implementation of Optimal Settings
第六步：实施最优的锅炉控制设定

- Options for implementing optimal boiler control settings:
  实施Boiler OP决定的最佳设定可以有几种选择
  - Open-Loop Real-Time Advisory:
    - Process data used by **Boiler OP Advisory Code**
    - Provides <u>advice</u> to the operator <u>on the optimal settings</u>.
    - Calculates emission and performance penalties for not operating at optimal settings.

    开环、顾问方式下Boiler OP用过程数据计算结果向操作员提供最优设定的建议，以及不在最优设定下运行的排放和性能代价

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Step 6: Implementation of Optimal Settings
第六步：实施最优的锅炉控制设定

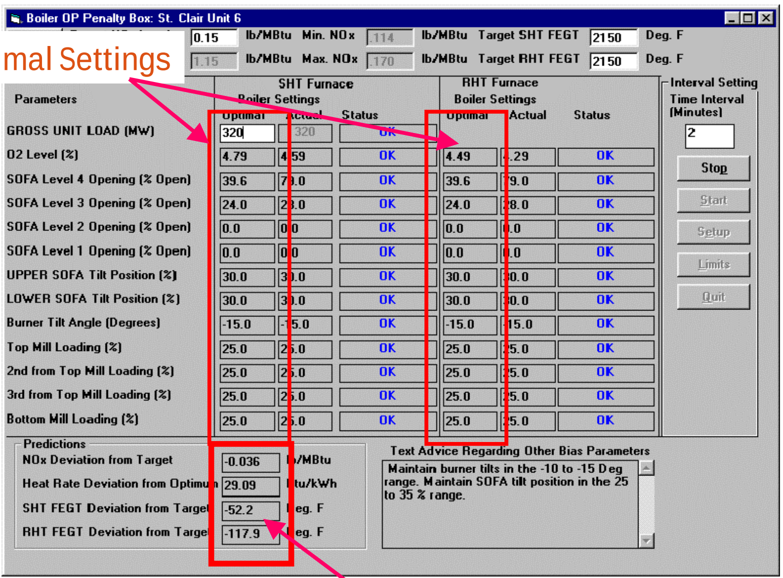
- Automatic Control:
  - Program optimal settings into plant DCS.
  - Implement closed-loop trim control for key operating parameter(s) to deal with daily variations in fuel quality and maintenance status.
    - Provides a cost-effective alternative to a full closed-loop network control.

自动控制方式将各种机组负荷下得到的最佳设定在电厂DCS中编程，为了解决每天煤质和燃烧设备维护状态的变化，可以实现对某个（或某些）关键参数的闭环控制(例如，SOFA 挡板开度)

这种方式可以调节该关键参数的值来维持希望的NOx排放值。相对于全部锅炉控制参数参与闭环控制策略的全闭环网络控制，这种方式提供了一种经济有效的替代方法

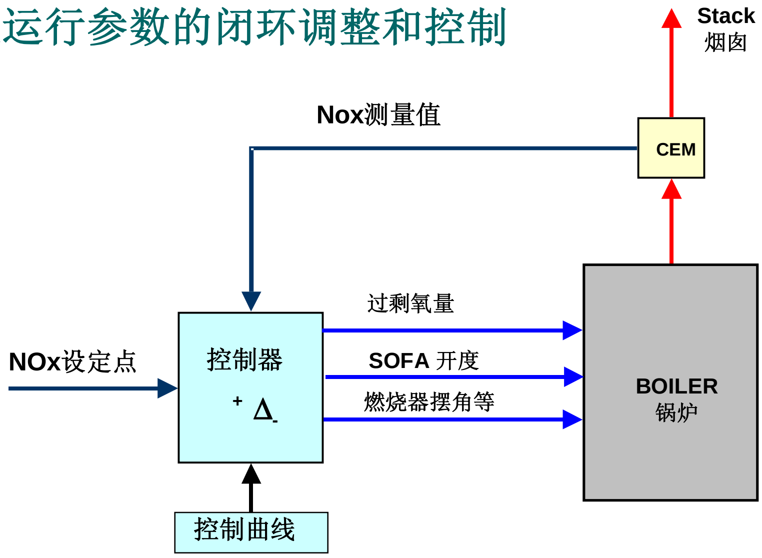
Boiler OP On-Line Open-Loop Advisory Sample Operator Screen 在线开环顾问方式的操作作员画面（例）

Optimal Settings

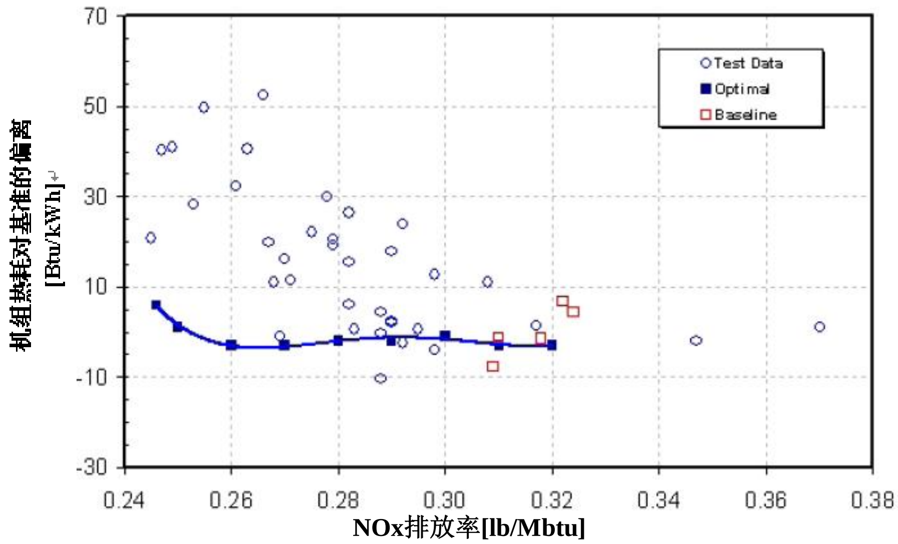


Penalty for not operating at Optimal Settings

Closed-Loop Trim Control for Key Operating Parameters
关键运行参数的闭环调整和控制

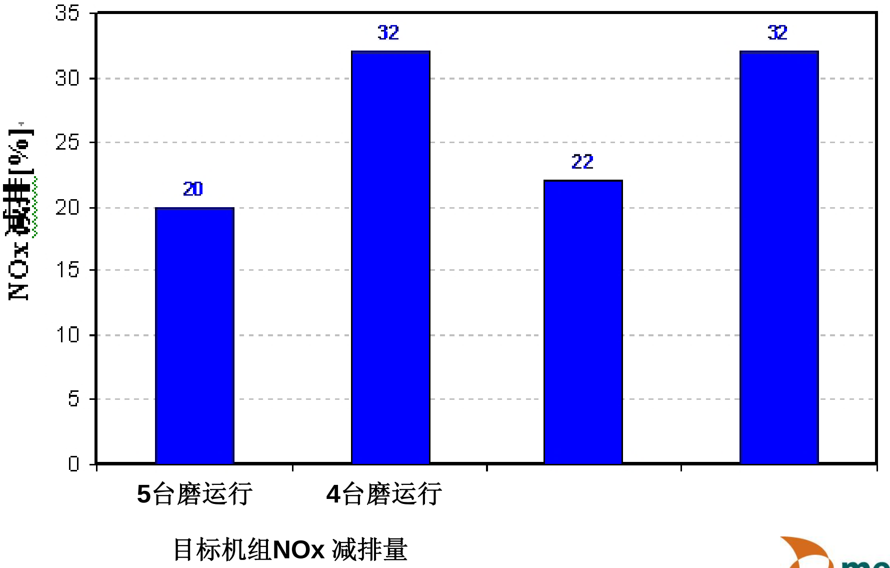


Boiler OP Result
Boiler OP优化控制的结果



目标NOx 对机组热耗的影响

Boiler OP Result
Boiler OP优化控制的结果



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ERC Proactive Approach for Best NOx Performance
优化控制设定的长期维护

- Maintain top performance of:
  - Firing system
  - Milling system
  - Instrumentation and controls

  保持燃烧系统，磨煤机系统，仪表和控制系统良好的工作状态
- Perform inspection of combustion hardware during Spring outage, perform adjustments.

  停机检修时完成例行的燃烧设备的检查和调整
- Perform combustion tuning before start of the Ozone Season.

  在空气质量要求高的季节到来之前完成燃烧的整定
- Train operators to respond correctly to maintenance- and fuel quality-related issues.

  培训运行人员使其能够正确地响应与维护和煤质有关的问题

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Boiler OP: Conclusion
Boiler OP：结论

- Combustion optimization is an alternative to expensive combustion hardware modifications for NO_x reduction.
  燃烧优化是相对采用昂贵的燃烧设备而言的另一种减排NOx的方法
- Can be used in conjunction with hardware modifications to maximize performance of low-NO_x firing and post-combustion control systems
  可以结合设备改造一起使用，使低氮燃烧系统和燃烧后处理系统的性能得到最大的发挥.
- A practical and cost-effective procedure and software has been developed for combustion optimization.
  - Based on deep understanding of underlying physics and boiler operation.
  - Combustion tuning is integral part of the ERC approach.
    ERC开发和应用一套实用而经济的系统步骤和软件来完成燃烧的优化， 这是基于对内在的特性和锅炉的运行的深层的理解，燃烧调整是**ERC**优化方法的一个整体部分.

Boiler OP: Conclusion (Continued)
Boiler OP：结论(续前)

- Applied at more than 30 utility boilers:
  已经用于30多台电厂锅炉的燃烧优化.
- Tangentially and Wall-fired 可用于切向燃烧和墙燃式锅炉
- Size from 80 to 750 MW 机组容量 **80** 至 **750 MW**
- **Fuels:** Eastern, Western fuels, including PRB, foreign coals and fuel blends, co-firing fuel oil, natural gas, blast furnace gas and coke oven gas**.**
  适用燃料：美国东部煤，保德里弗盆地煤，混和煤，助燃油，天然气，高炉煤气和焦炉煤气等
- Achieved NO_x reduction levels range in 15 to 35 %
  实施后的**NOx**减排的典型值在**15-35%**的范围内
- Implementation Options: Open-Loop Advisory or Automated Control
  实现方法**:** 开环的顾问方式或自动控制（闭环）

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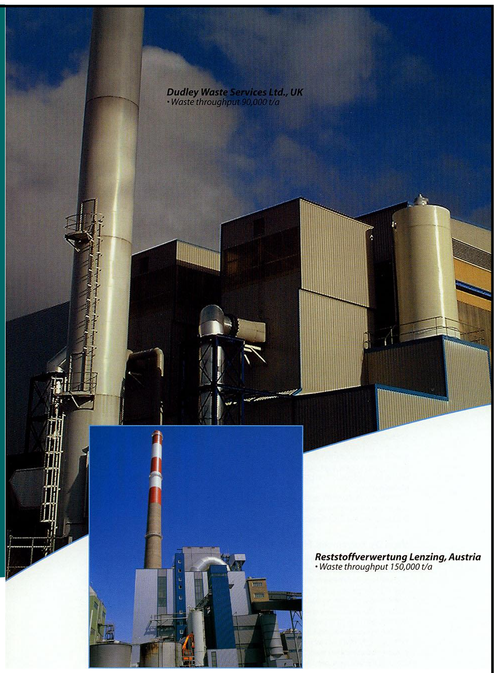

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