Coal Combustion and Biomass Conversion for Modern Power Generation

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ASTT Conference 2018

Advanced Steam Traction Trust

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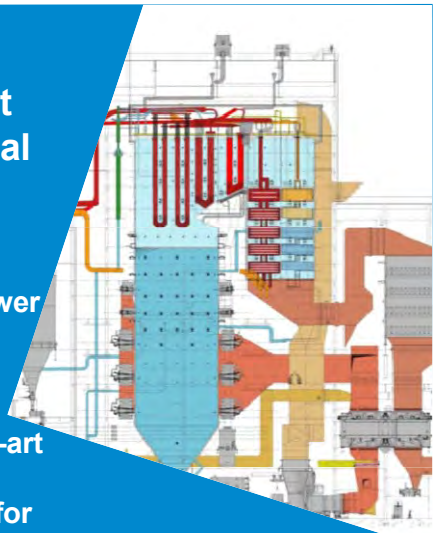
Meeting Increasingly Stringent Emissions Regulations for Coal Fired Power Plants



- Emissions limits for Coal Fired Power Plants – status and trends
- Boiler and emission controls technologies – current state-of-the-art
- Focus on combustion technology for coal and biomass conversions

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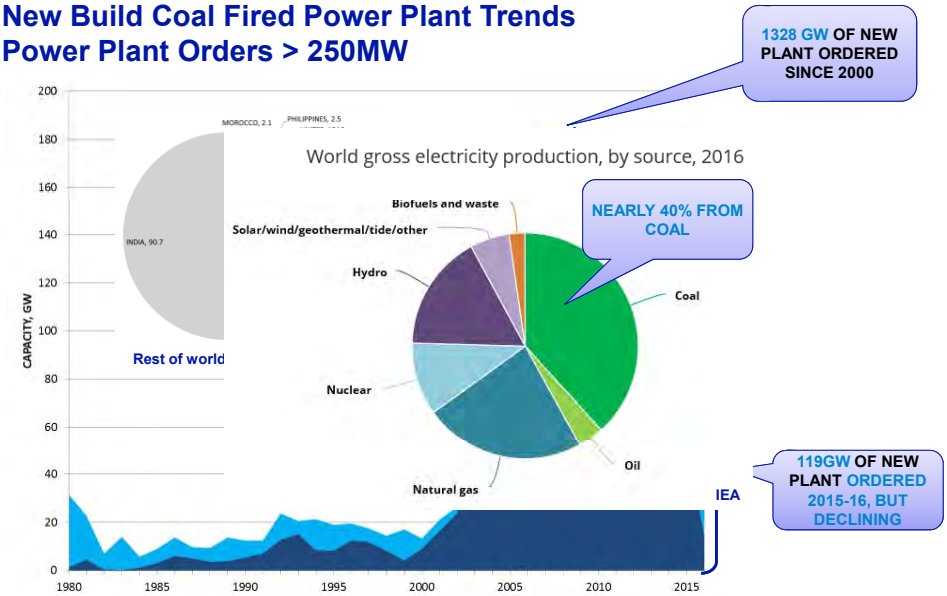
New Build Coal Fired Power Plant Trends
Power Plant Orders > 250MW



All coal fired power plant orders for unit sizes above 250MWe (Gross)
[Raw data from McCoy Power Reports]

New Build Coal Fired Power Plant Trends
Reducing Stack Emissions Limits

Pollutant	IED / European Standard	World Bank (WB) IFC, (1)	CHINA GB 13223-2011	TURKEY	INDONESIA	INDIA[3,4]	SOUTH KOREA[2]
NOx	150 mg/Nm³	200 mg/Nm³	100 mg/Nm³ (6)	200 mg/Nm³	750 mg/m³ (10)	(300 mg/Nm³) **100 mg/Nm³**	164 mg/Nm³ (80 ppm)
SO2	150 mg/Nm³	200 mg/Nm³	100 mg/Nm³ (6)(9)	200 mg/Nm³	750 mg/m³ (10)	(200 mg/Nm³) **100 mg/Nm³**	228.8 mg/Nm³ (80 ppm)
PM	10 mg/Nm³	30 mg/Nm³	30 mg/Nm³ (8)	30 mg/Nm³	100 mg/m³ (10)	(50 mg/Nm³) **30 mg/Nm³**	20 mg/Nm³
HG	Not defined / 0.03 mg/Nm³ (5)	Not defined	0.03 mg/Nm³ (7)	Not defined	Not defined	0,03 mg/Nm³	Not defined

mg/Nm³ = milligrams per normal cubic meter at 6%O_2 , 273,15°K and 1.013 bar except Indonesia – note 10

1. *Emission guidelines from World Bank IFC, 2008 Environmental, Health, and Safety Guidelines. (for DA areas (DA = Degradated Airshed = poor air quality)).*
2. *Generation capacity > 500MWe, from 1st Jan 2005 to 2016*
3. *Values in brackets 2004 – 2016)*
4. *Bold values for new plant after Jan 01 2017 Plant > 500MWe*
5. *From German Regulation / 13. BimSchV,*
6. *Increased to 200 in certain provinces.*
7. *From 2015*
8. *Reduced to 20 for certain regions.*
9. *Reduced to 50 for certain regions.*
10. *mg/Nm³ = milligrams per normal cubic meter at 7%O_2 25°C and 1.013 bar.*

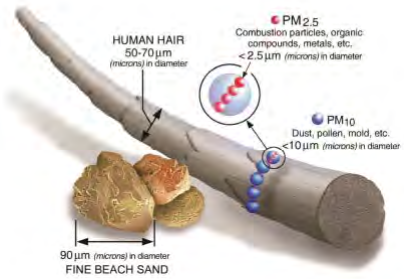
New Build Coal Fired Power Plant Trends Reducing Stack Emissions Limits

Future Ultra-Low Emission Limits

- Drive to even lower emission limits for NOx, SOx and PM – eg new South Korean limits:
  - PM – 5 mg/Nm^3
  - SO_2 – 25ppm (71.5 mg/Nm^3)
  - NO_2 – 15ppm (30.8 mg/Nm^3)

$PM_{2.5}$

- In most countries particulate matter from coal fired power plant is not distinguished by size at the stack, but may be distinguished in ambient air.
- $PM_{2.5}$ concern because of possibility for deep penetration to lungs.
- $PM_{2.5}$ classified as primary and secondary:
  - Primary is filterable fine particulate matter (eg fly-ash)
  - Secondary is formed by reactions of other pollutants (eg SOx, NOx, NH_3)



Source: US Environmental Protection Agency - EPA

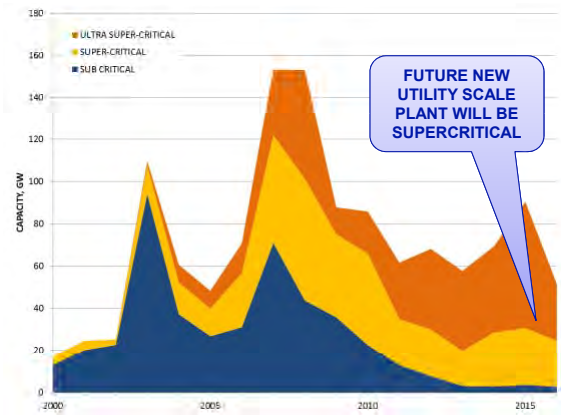
Doosan State-of-the-Art Technologies for Boilers and Emission Controls

Ultra-Supercritical Boiler Technologies for High Efficiency

- Highest efficiency achieved via steam cycle optimisation by a combination of:
  - USC steam parameters at turbine inlet
  - Regenerative feedwater heating to increase boiler feed water temperature
  - Condenser pressure / LP Turbine last stage blade optimisation
- Emission reduction resulting from higher efficiency is substantial:

Parameter	Supercritical	Ultra-Supercritical
Main Steam Pressure / Temperature	245 bar / 565 C	280 bar* / 600 C
Reheat Steam Pressure / Temperature	40 bar / 565 C	60 bar** / 610 C
Net Plant Efficiency (% LHV)	41.8	44.0
Emissions (CO_2 SO_2, NOx, PM)	Base	-5%

*280 bar ≈ 4060 psi
**60 bar ≈ 870 psi



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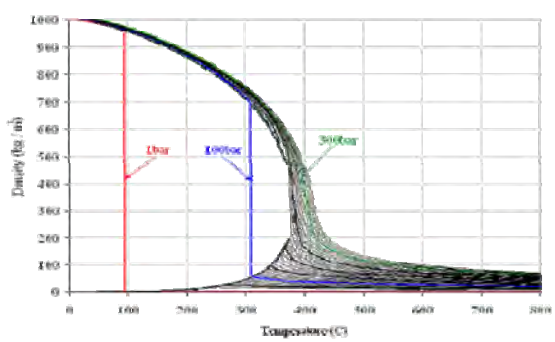
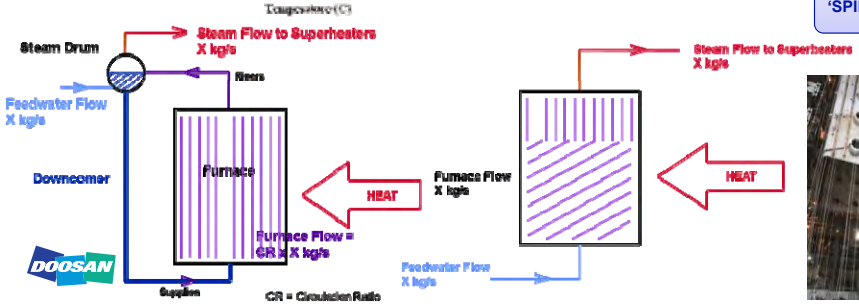
Ultra-Supercritical Boiler Technologies for High Efficiency

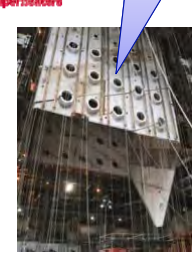


What happens when we use higher temperature and pressure?

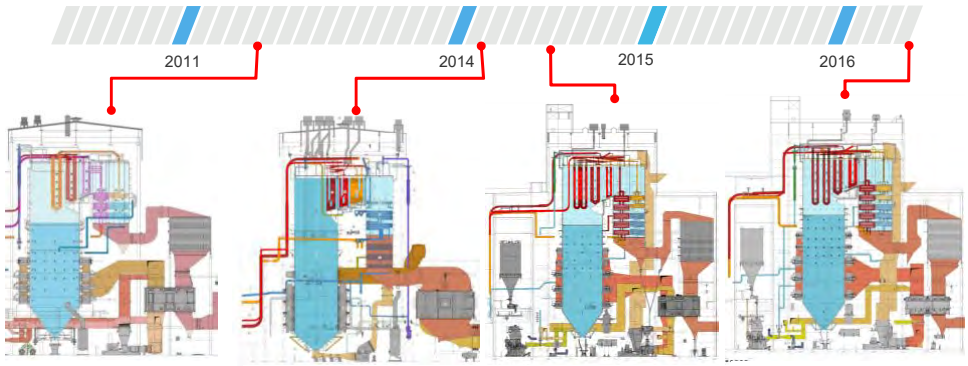
- When water is above 221 bar and 374C we no longer have any phase change between water and steam – we just have a continuous change in density as the fluid is heated
- Because there is no phase change we can no longer use a traditional 'natural circulation' type boiler and we instead use a 'once-through' boiler



'SPIRAL' FURNACE



Ultra-Supercritical Boiler Technologies for High Efficiency



GHECO-ONE, THAILAND
1 x 700MW
SH 569℃/ RH 569℃ 255 atg
Sub-bituminous Coal

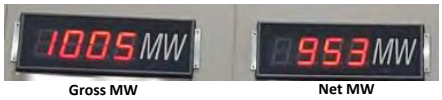
AIN SOKHNA, EGYPT
2 x 650MW
SH 540℃/ RH 540℃ 265 atg
Mazout Oil

YEONG HEUNG 5,6, S. KOREA
2 x 870MW
SH 569℃/ RH 596℃ 251 atg
Sub-Bituminous and Bituminous Coals

SHINBORYEONG, S. KOREA
2 x 1000MW
SH 613℃/ RH 624℃ 274 atg
Sub-Bituminous and Bituminous Coals

EVOLUTION IN STEAM CONDITIONS

First 1000 MW USC Boiler in Korea



Gross MW Net MW

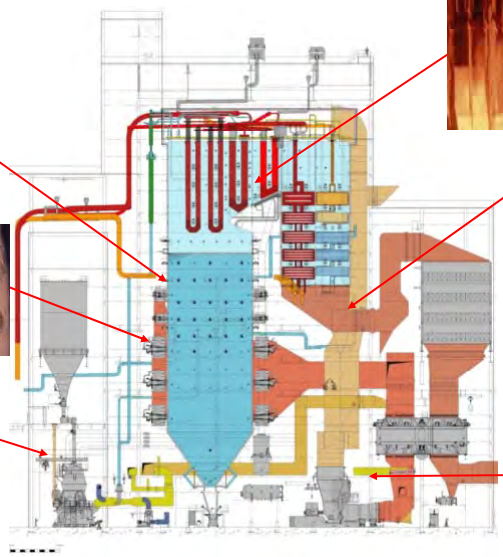
Unit #1 (21st Mar. 2017)

Gross MW Net MW

Unit #2 (21st Mar. 2017)

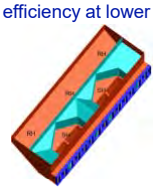
Name of Plant	Shinboryeong #1,2
Capacity	1,000MW x 2
Country	KOREA
Customer	KOMIPO
Contract Award	Nov. 2011
COD	Jun. 2017 (Under Commissioning)
Fuel	Sub-bituminous Coal HHV = 5,600 kcal/kg Moisture = 17% , Ash = 7.8%
Type of boiler	PC Boiler (Opposed firing) Ultra Supercritical Pressure Once-Thru Balanced Draft
Steam Condition	SH **613℃/ RH 624℃**, 274atg
Emissions (Stack)	**NOx: 35ppm** **SOx: 50ppm** **PM: 15mg/Nm^3**

Ultra-Supercritical Boiler Technologies for High Efficiency
Boiler Features – 1000 MW Design



Proven Two pass arrangement (Pendent and Horizontal)

Stable RH steam temperature control for wide range coals with flue gas bias damper – higher efficiency at lower load



Once-Through boiler technology with proven lower spiral wall tube and upper vertical wall tube

High performance Low NOx burner And OFA

Vertical mills with dynamic classifiers

Proven capability for rapid starting with two shift operation
- 2 Axial FD fans
- 2 Axial ID fans
- 2 Axial PA fans
- 2 Trisector AHs

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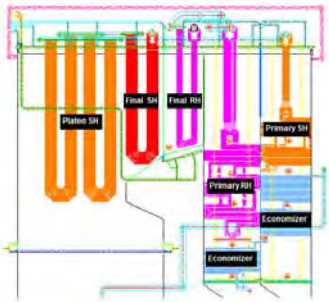
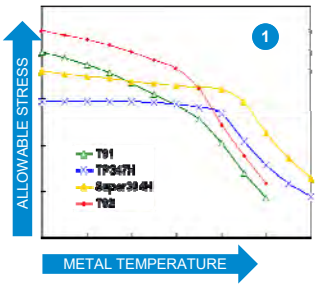
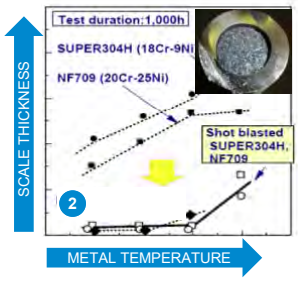
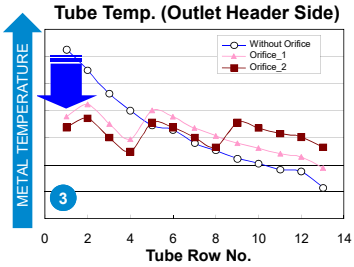
Ultra-Supercritical Boiler Technologies for High Efficiency
Materials for USC Conditions







- Current USC steam parameters require a spectrum of ferritic and austenitic alloy steels for highest temperature components.
- Material selection mainly depends on (1) strength as a function of tensile and creep properties and (2) resistance to steam side oxidation.
  - Careful design of flow distribution can reduce operating conditions (3)



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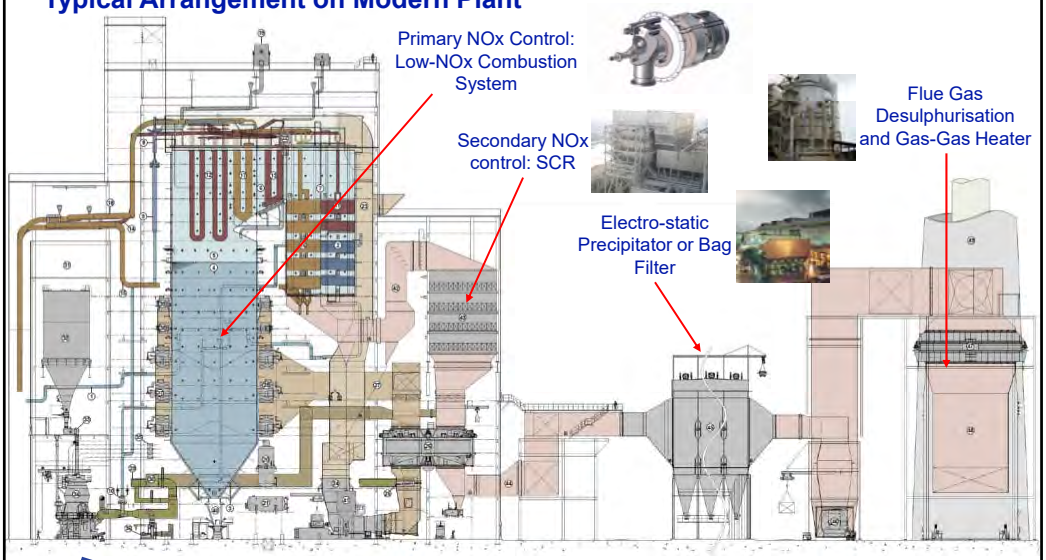
State-of-the-Art Emissions Controls Technologies
Typical Arrangement on Modern Plant



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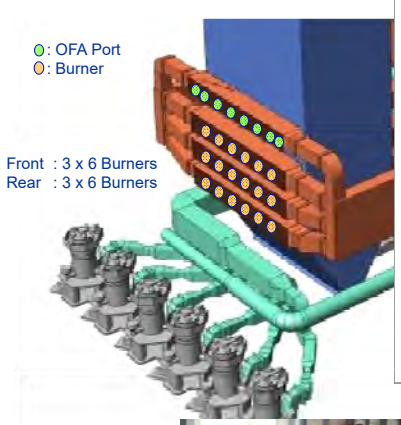
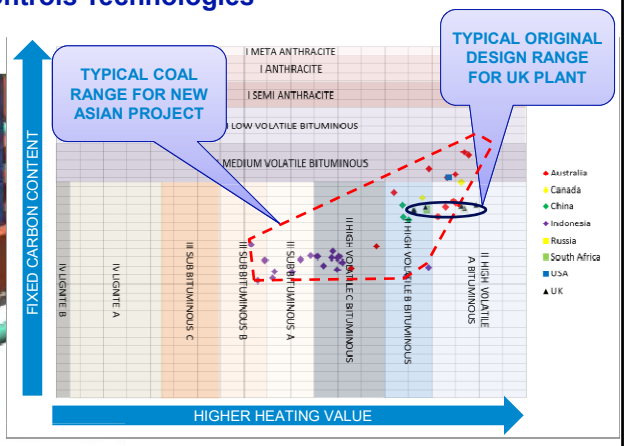
State-of-the-Art Emissions Controls Technologies
Primary NOx Control





- Project fuel ranges become ever wider to ensure flexibility to accommodate changes in international coal sourcing.
- Mature low NOx combustion systems deliver primary NOx reduction
  - Current performance expectation circa 200 to 300 mg/Nm^3 NOx with <3% Carbon in Ash

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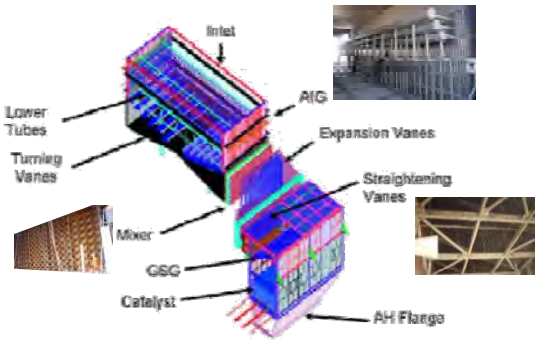
State-of-the-Art Emissions Controls Technologies
SCR for NOx Control

- Capable of up to 80-90% NOx reduction



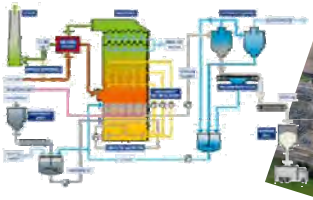
Case Study:
Ratcliffe, United Kingdom
4 x 500 Mwe Units

Case Study:
Castle Peak B, Hong Kong
BOFA System for Primary NOx control
Compact "In-Duct" SCR Arrangement

State-of-the-Art Emissions Controls Technologies
Flue Gas Desulphurisation

Wet Lime / Limestone FGD

- 205 absorbers installed (110 absorbers in China)
- 71 GW_e total capacity
- Maximum absorber size: 1,000 MW_e



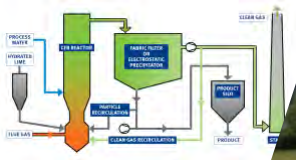
Case Study:
Rugeley, United Kingdom
WLFGD retrofit
Plant output: 2 x 500 MW

Seawater FGD

- 14 absorbers installed
- 8 GW_e total capacity
- Maximum absorber size: 700 MW_e

Circoclean® FGD / FGC

- 90 reactors installed (18 reactors in China, 26 in the USA)
- 13 GW_e total capacity
- Maximum reactor size: 305 MW_e



Case Study:
Lanesborough / Shannonbridge, Ireland
1 x 100 MW / 1 x 150
Circoclean ® FGD units

Combustion Technology for Coal

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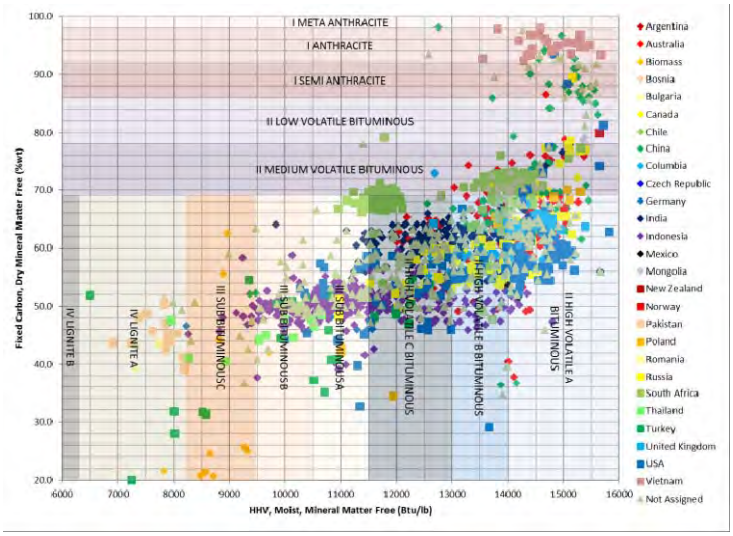
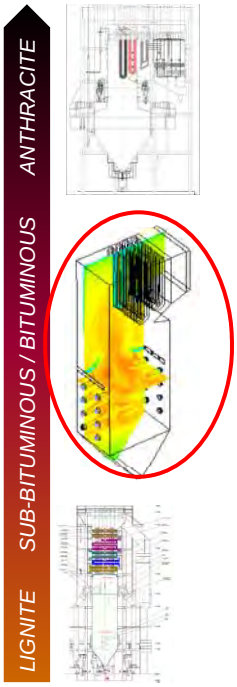
Fuel Rank (ASTM)





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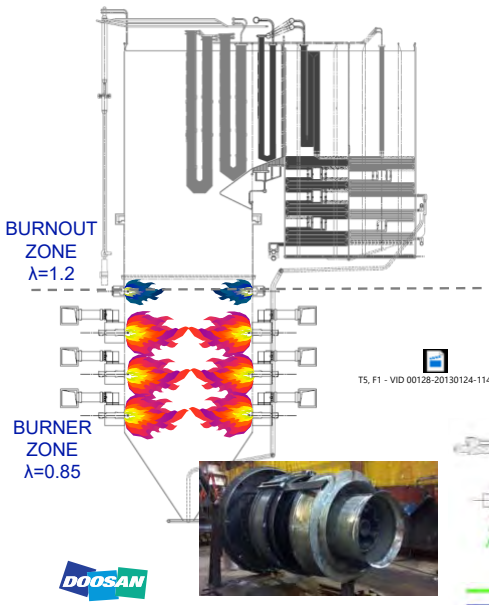
Combustion System



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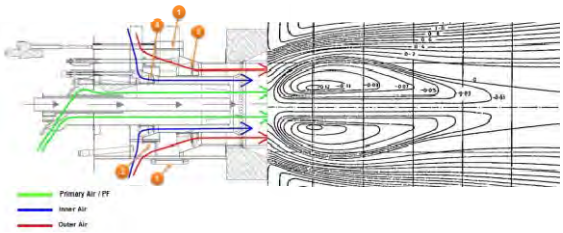
Low NOx Combustion

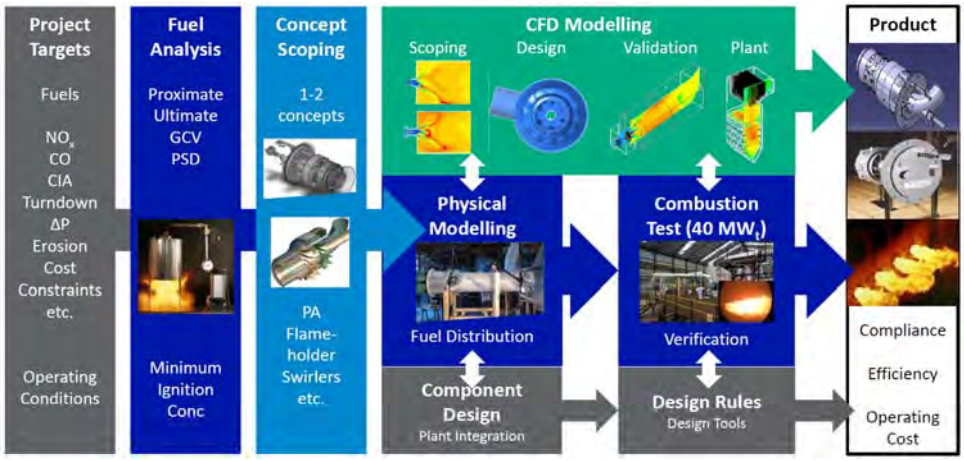
- Control the availability of Oxygen to the combustion process
- Reduce peak temperatures in combustion zone
- Fuel NOx preferentially goes to N2
- Carbon in ash and CO increase!

Low NOx Burner

- Ignition and flame stability
- High rate of de-volatilisation to get Nitrogen out of fuel quickly
- Segregate air from fuel to control the rate of NOx formation



Combustion System Development Approach



Development Timescale 18-24 Months

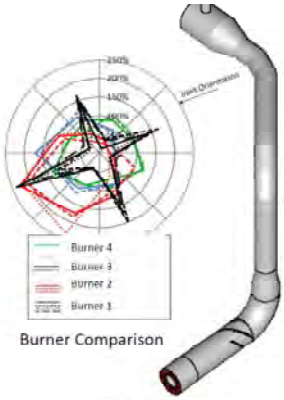
Combustion System Development Approach

Upstream Pipework

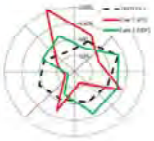
- ½ or ¾ Geometric scaled models
- Pumice to represent pulverised coal
- Characterise outlet distribution and pressure drop
- Indication of fuel drop-out and erosive wear
- Validation of CFD models

CFD vs. Test

Physical Model of Advanced Burner PA



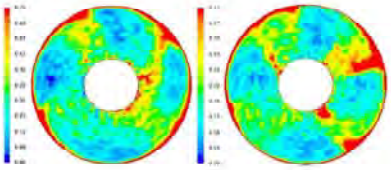
Burner Comparison



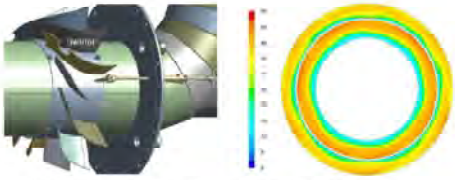
Comparison of CFD Models

Combustion System Development Approach

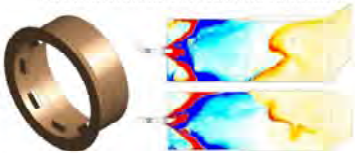
CFD Modelling - Component Design and Combustion System



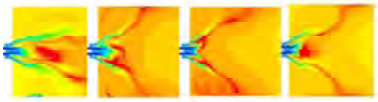
Fuel Concentration at Load and Turndown



Swirler Vane Optimisation and Velocity Distribution

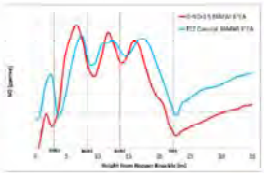


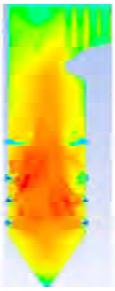
Flameholder Optimisation and NO Rate



Min Swirl Design Max Swirl Fuel Change

- Optimise PA, flameholder, deflector, swirler designs
- Confirm robust design
  - Fuel supply
  - Fuel type
  - BZS (λ)
  - Flow split
  - Swirl
  - Furnace





Furnace Temperature and NO Profiles

Combustion System Development Approach

Combustion Test Facilities

2 MW$_t$ Flame

40 MW$_t$ Flame

	ERTF 160kW$_t$	Single Burner Test Facility 3MW$_t$	Clean Combustion Test Facility 90MW$_t$
Location	Renfrew, UK	Changwon, Korea	Renfrew, UK
Nominal Load (MW$_t$)	0.16	2	40
Fuels	Gas, Coal	Gas, Coal	Gas, Oil, Coal, Biomass, Blends
Air Staging	Multi Level	Multi Level	Multi Level
Carbon Capture	Oxyfuel, PCC	-	Oxyfuel

- Isothermal aerodynamic characterization (swirl number and k factor)
- Parametric testing of burner settings, design / off design operation (PA:PF, stoichiometry excess air, residence time, turndown)
- In-flame gas and solids sampling / flame mapping – CFD validation

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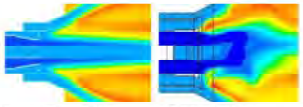
Combustion System Development Approach

Advanced D-NOx Burner

Description

- Deep Stage (<110 ppm, 3% CIA)
- Developed 2016-17
- Simulation-led (2 concepts)



Concept and Component Modelling

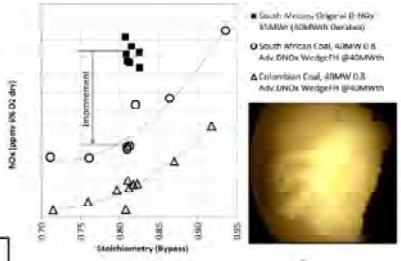
Key Features

- Swirled PA
- Toothed flameholder
- TA deflector
- High swirl
- Low RDL (1 kPa)

λ_P	0.8
NO_x	100 ppm

Key Results

- CFD comparable to test
- 33% improvement on D-NO_x for similar UBL
- Turndown to 33% (3:1)



Large Scale Test

Test Burner

Furnace CO Iso-surface

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Biomass Conversion of Coal Plant

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How Does a Switch to Biomass Control Emissions?

- Conventional Pollutants
  - Biomass has lower levels of pollutant causing elements such as sulphur and nitrogen
  - Biomass burns with a cooler flame reducing NOx
- Carbon Dioxide
  - Biomass is renewable
  - Biomass can lead to net carbon removal from the atmosphere in combination with CCS

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CCS Carbon capture & storage

How Does a Switch to Biomass Control Emissions?

	Coal use 1990
Sulphur % ar	1.5
Nitrogen % ar	1.4
Ash % ar	15
Chlorine % ar	0.3

Cleaner fuels = lower emissions

	Coal use 1990
SO_2 mg/Nm^3	3750
NOx mg/Nm^3	650
Dust mg/Nm^3	50
HCl mg/Nm^3	400

Typical values for UK market
ar is "as received"
All emissions at standard 6% O_2 dry conditions

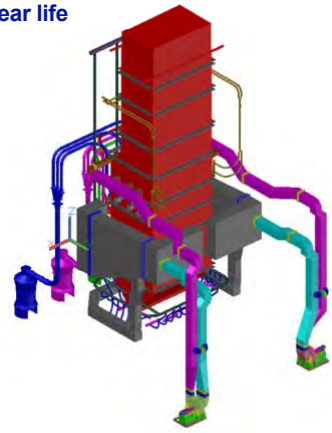
Lynemouth Power Station: a Good Candidate for Biomass

Closure at the end of 2015 due to lack of SOx and NOx controls to meet IED TNP limits	Biomass conversion offered a way to meet emissions limits because biomass is cleaner
Power station was becoming uneconomic due to rising price of carbon	Biomass conversion offered a way to avoid the carbon floor price because the fuel is renewable
Biomass is an expensive fuel and efficiency is important	North Sea cooling, upgraded turbines & condensers; despite moderate size and steam conditions probably UK's most efficient coal station
Benefit of a CfD from the UK government of £105/MWh, ratified by EC, for 10 year period	Drive to maximise availability, efficiency and power output and extend life
3x140 MWe size made logistics manageable	Helped gain EC approval
Power station can reuse most of the systems and components which have good residual life	Reducing capital cost for green electricity

CfD Contract for Difference
EC European Commission

Lynemouth: Comprehensive Conversion

40% unit efficiency to be maintained
140MWe power output to be retained
IED minimised emissions
Maximum safety
10 year life



- New fuel feeding system
- Mill modifications and new dynamic classifiers
- Replacement PF piping
- Heat balance correction by PA cooler
- New low NOx bespoke biomass burners
- New BOFA system for further NOx control
- Upgraded oil system
- Furnace and heating surface cleaning extension
- No heating surface changes
- 36 new fans across the 3 units
- New dry bottom ash system
- ESP upgrade
- New fly ash system

BOFA Boosted over-fire air
PA Primary air
ESP Electrostatic precipitator

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Lynemouth: Comprehensive Conversion

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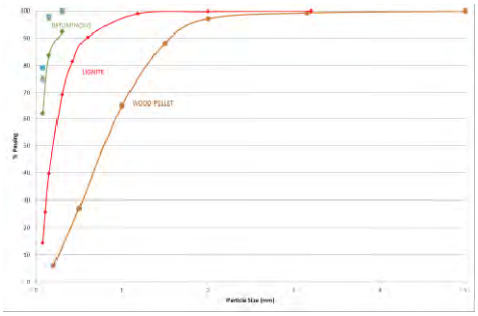
BIOMASS COMBUSTION SYSTEM

Biomass Burner Development and Application - Challenge



Typical coal particle sizing:

70-80% < 75 microns
99% < 300 microns

Wood pellets
30-55% < 500 microns
95 – 98% < 2000 microns

- Properties of wood pellets and biomass in general differ significantly from coal – greatest challenge is the difference in milling characteristics and resultant particle size which presents a challenge to ignition point and stability.
- Integrated combustion system solution:
  - Mill modification with dynamic classifier to provide adequate fineness and reduced to size to aid early ignition and combustion efficiency.
  - Replacement PF pipework and fans to ensure no fuel dropout and optimum distribution by installing the VARB trifurcator.
  - Replacement burners and reduced burner zone stoichiometry to ensure 180 mg/Nm^3 NOx capability
  - Boosted Over-Fire Air to control burnout and CO production at acceptable levels.

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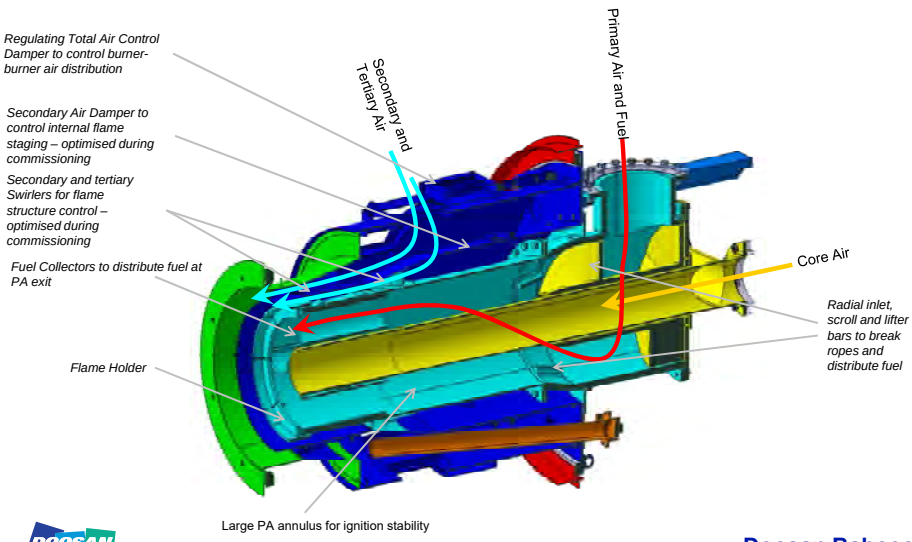
BIOMASS COMBUSTION SYSTEM

Low-NOx biomass burner Design and Features



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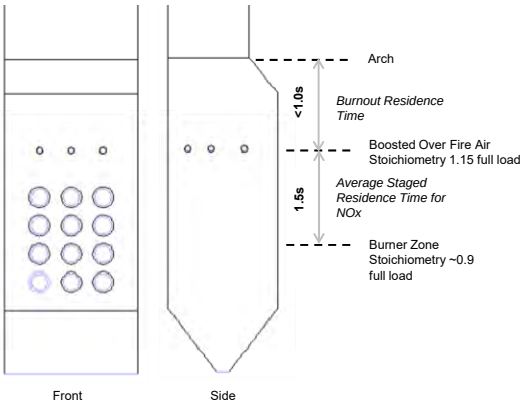
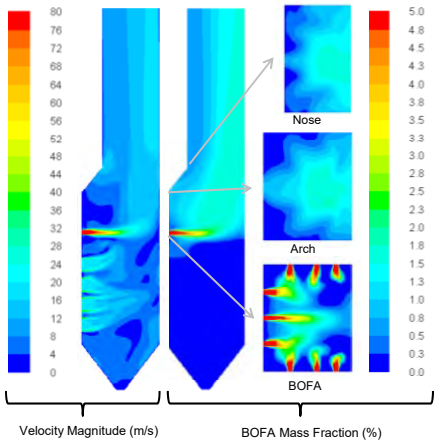
BIOMASS COMBUSTION SYSTEM

Boosted Over Fire Air





- Boosted OFA achieves generous staged residence time for NOx control whilst also giving sufficient burn-out residence time to control combustion efficiency.
- Anticipated NCV loss 0.5% and CO < 250 mg/Nm^3
- BOFA Port velocity 80 m/s with front and side-wall ports position optimised via CFD mixing study.

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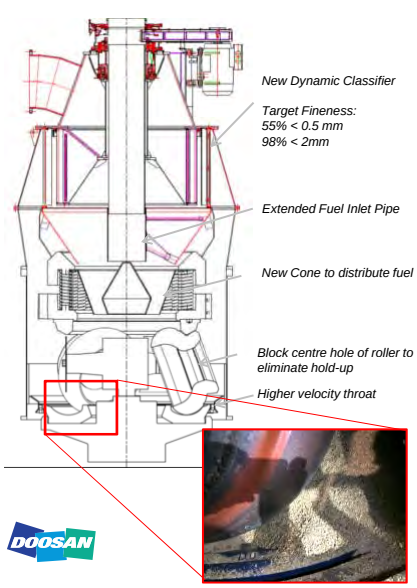
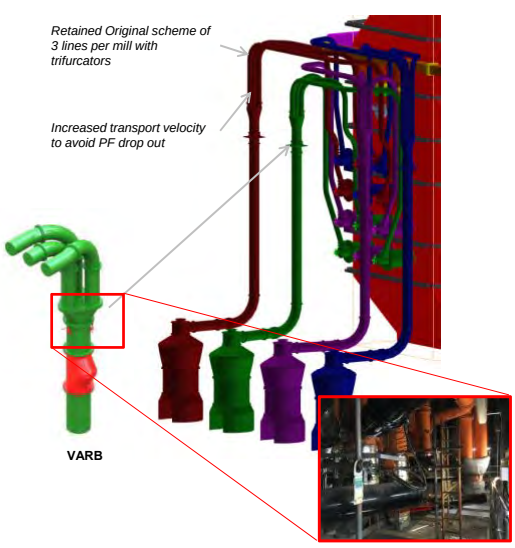
BIOMASS COMBUSTION SYSTEM

Fuel Delivery





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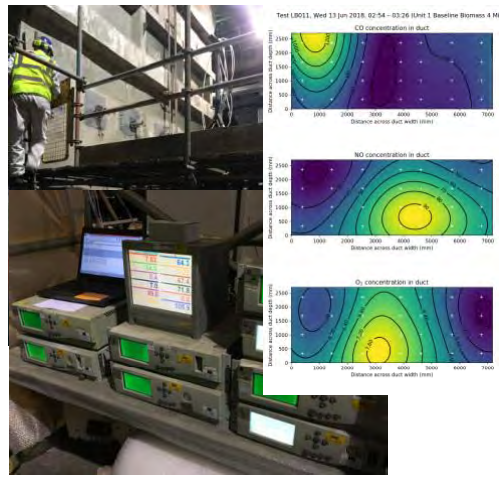
BIOMASS COMBUSTION SYSTEM

Combustion Tuning



Conclusions

- Energy demand growth in Asia, India and some other regions continues to drive investment in new coal fired power plants.
- Ultra-Supercritical Technology with steam temperature > 600C is now state-of-the-art with unit sizes between 350MW and 1000MW – project developers and financers are implementing this technology with consequent increase in efficiency and reduction in emissions for new coal fired fleet.
- Emissions legislation is rightly becoming increasingly stringent, both in emission limits and in scope albeit with some regional anomalies.
- State-of-the-art emissions control technologies can meet the requirements of the current legislation, project developers and financers. However, the time is never more urgent for R&D efforts for ever greater emissions reduction.
- Biomass conversion offers an effective route to life extend exsiting coal fired assets with significantly lower emissions.

Thank you

Questions?

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BIOMASS COMBUSTION SYSTEM

Biomass Burner Development and Application

2011 | 2015 | 2017

TILBURY

Single Stage

Modified MK III Burner

- Reduced CA tube size to reduce PA velocity via PA annulus area increase

IRONBRIDGE

Single Stage

Modified Robtas Burner

- Reduced CA tube size 9 to 6 in to reduce PA annular velocity to 20 m/s via PA annulus area increase
- Modifications to fuel delivery (removal of collectors, straighteners and lifter bars) to generate stable ignition

DRAX

Two Stage

Modified MK III Burner

- Reduced PA velocity
- Single air register

CCTF

Low NOx Two Stage

Verification of optimised MK III burner for two-stage Biomass firing:

- Large PA annulus
- Dual register design
- 45-50% NOx reduction

Yeong Dong 1

Low NOx Two Stage

Conversion of 125MW plant with downshot fired boiler

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