ADVANCED BOILER DESIGN

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1 ABSTRACT

Introducing advanced boiler concepts in the design of thermal power stations is nowadays becoming mandatory. Not only from an economic point of view, but also as a proactive step towards reduction of emissions, the enhancement of efficiency becomes inevitable.

The increase in the cycle efficiency in modern power stations is mainly achieved by increasing the steam parameters. The technological steps in advanced boiler design therefore imply shifting steam parameters from subcritical to supercritical to ultra supercritical. In addition to elevated steam parameters other measures like double reheat and increased boiler efficiency are key players in achieving the desired maximization. Such performance achievements comes only through a 360 approach involving design features like:

- Fuel Flexibility
- Tangential Firing System
- Full Air Fuel Ratio Control (Individual Burner Control)
- Reduced Air Excess
- Safe Evaporator Design
- Easy SCR Implementation
- Effective Air PreHeater Design
- Single Flue Gas Train
- Compact Design (Short Routing)

Danish power plants are in this sense design and performance wise understood to define the elite. These plants are designed and supplied by Burmeister & Wain Energy (BWE) which over decades has build knowledge and experience to design boilers with unmatched efficiency and reliability. This paper outlines the expertise in achieving the goal of high boiler and cyclic efficiencies.

Benefits of the Tower Type Boiler design in comparison with Two Pass Type Boiler design are analyzed and described. Operational flexibility of modern power stations is achieved by the Benson technology in combination with sliding pressure, a well proven, reliable and effective operational mode.

The material selection in a modern boiler, as the key player of supercritical and ultra supercritical design, is described and showing good results on long term basis. The controlled safety valve concept is analyzed in comparison with the spring load type. Finally knowledge and experience within multi fuel concepts as well as co-combustion of biomass in ultra supercritical boiler are summarized.

BWE has been a member of the European COMTES700 initiative on advanced USC technology. The highlights are touched in view to see synergistic possibilities with the similar Indian program.
2 INTRODUCTION

The objective of this paper is to describe the main features of advanced utility boilers reflecting the state of the art clean coal technology adopted and developed.

It is an update of a paper issued in January 2012. It has been updated with information about latest development and experience from design and operation of commissioned boilers, and highlights the advantages and limitations of once through tower type boiler with advanced steam parameters and the more well known two pass drum boilers with moderate steam parameters.

3 TOWER TYPE OR TWO PASS TYPE

Since the mid 19th century two pass boilers have been the preferred boiler design in Europe. During this period mainly two pass boilers has been supplied to the Danish utilities in the range from 80 MWe to 640 MWe. Since the oil crisis in the 1970’s, utility boilers have all been pulverized fuel (PF) fired based on imported coal, typically bituminous coals, from Poland.

In the 1980’s the market required more flexible and effective boilers with high focus on boiler efficiency, load change rate and fuel flexibility. It was decided to introduce the tower type design for utility boilers. In 1984 a 150 MWe front fired tower type boiler for Volkswagen in Germany and following this in 1988 a 400 MWe tangential fired tower type boiler for Walsum as Unit 9 in Germany were supplied. Since then the main part of the 400 MWe class boilers in Denmark have been of the tower type design and supplied.
3.1 ADVANTAGES & DISADVANTAGES

The tower type design has in comparison with the two pass design a number of advantages such as the reduced foot print, reduced weight of boiler pressure part, easy installation of selective catalyst reactor (SCR), fully drainable pressure part, no intermediate extraction of fly ash and uniform flue gas temperature profile over furnace cross section.

3.1.1 FOOT PRINT

The foot print of the tower type boiler will be smaller than the one of the two pass boiler. The tower type design also enables a very compact design of the boiler, SCR and APH (air pre heater). The reduced foot print subsequently leads to a reduced boiler steel structure even though the total height is increased.

3.1.2 HEATERS

Since the heating surfaces of a tower type boiler are affected by a flue gas flow perpendicular to the banks, the heating surface will be fully effective in contrast to the hanging super heaters of the two pass boiler where the heat absorption are less defined and the efficiency reduced. Subsequently the weight of the pressure part of a tower type boiler will be reduced compared to a two pass boiler.

All heating surfaces are arranged horizontally resulting in a fully drainable pressure part. Especially during start up condensate can leave the system, pipes heated up and steam temperature increased faster. For short overhauls dry preservation can easily be used.

Steam side oxidation and increased formation of magnetite ($\text{Fe}_3\text{O}_4$) layers inside super heater tubes is critical in USC boilers. The risk of blocking the super heaters by exfoliated magnetite is considerably reduced in tower type boilers with horizontally arranged super heaters.

Figure 2: Nordjylland Unit 3 (NJV3) 415 MWe, Denmark. USC Tower Type Boiler
3.1.3 Flue Gas Path

The arrangement of boiler and APH makes it intuitive and easy to install SCR. Ammonia injection will be installed after the boiler outlet, followed by a static mixer ensuring a uniform flue gas distribution at the SCR reactor inlet.

With a flue gas path arrangement from the boiler top and down through the SCR and APH no additional or intermediate fly ash extraction is needed. This would be the case for a two pass boiler design as the flue gas flow changes from downward to upward below the ECO.

When leaving the APH, the flue gas proceeds horizontally, allowing the hoppers below the APH to be designed only for APH washing water collection and not for fly ash extraction. All the fly ash will end up in the filter.

The tower type design in combination with tangential firing results in a very uniform flue gas temperature profile entering the first super heater. Temperature peaks in the flue gas profile are thus avoided resulting in less temperature imbalances in the super heaters. This is highly important for materials operating at their limit within the creep range.

3.1.4 Erection

The dominating advantage of the two pass boiler is it’s lower height and easier erection of the boiler top including headers, heating surfaces and boiler ceiling. However the design of the boiler top of a two pass boiler is often quite complicated. The boiler ceiling of the tower type on the other hand is uncooled and the boiler suspension is simple and does not require penthouse. In light of a better performance over a life time of more than 35 years a few extra months for construction of the tower type boiler should easily be accepted.

3.1.5 Design Features

The two pass boiler has a number of design limitations which are difficult to avoid. Temperature difference between first pass and vestibule / second pass membrane wall will often lead to cracks after some years of operation. The tower type boiler has a very simple design of membrane walls and a smooth increase in temperature.

When the flue gas leaves the first pass and enters into the second pass another problem arises. Particles within the flue gas concentrates in proximity of the rear wall of the second pass and evoke erosion of the super heater banks. For high ash coal this is a challenge that normally calls for erosion shields.

The two pass boiler has some geometrical limitations which makes it difficult to optimize the boiler pressure part design. The pitch of the first hanging super heater bank SH-1 requires a mutual distance (400-800 mm) to avoid blocking of slag. In the tower type boiler the first super heater bank SH-1, which is typically arranged just above the final reheater, can be designed with
smaller pitch (100-200mm). The number of parallel tubes can thus be higher and subsequently the pressure loss will be smaller.

**Boiler Type Comparison**

<table>
<thead>
<tr>
<th>Tower Type</th>
<th>Two Pass Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform flue gas profile.</td>
<td>Uneven flue gas flow profile.</td>
</tr>
<tr>
<td>Reduced temperature peak in pressure part</td>
<td>High ash concentration on 2. pass rear wall</td>
</tr>
<tr>
<td>Excellent RH temperature characteristic</td>
<td>Cold built in conditions for final RH</td>
</tr>
<tr>
<td>Effective heating surfaces.</td>
<td>Partly ineffective heating surfaces</td>
</tr>
<tr>
<td>No ineffective (dead) zones.</td>
<td></td>
</tr>
<tr>
<td>Reduced footprint &amp; Increased height.</td>
<td>Enlarged footprint &amp; Reduced height.</td>
</tr>
<tr>
<td>Low pressure loss due to high number of parallel tubes in super heater banks</td>
<td>Higher pressure loss due to limitation in heating surface design</td>
</tr>
<tr>
<td>Easy SCR installation</td>
<td>Complicated installation of SCR and increased duct work</td>
</tr>
<tr>
<td>Smooth membrane wall temperature increase</td>
<td>Thermo stress and cracks in membrane wall between first pass and vestibule - second pass</td>
</tr>
<tr>
<td>No extraction of fly ash</td>
<td>Extraction of fly ash below ECO</td>
</tr>
<tr>
<td>Fully drainable super heaters.</td>
<td>Risk of blocking the hanging super heaters by exfoliated magnetite.</td>
</tr>
<tr>
<td>Fast start up.</td>
<td></td>
</tr>
<tr>
<td>Simple boiler suspension.</td>
<td>Complicated boiler suspension.</td>
</tr>
<tr>
<td>Penthouse not required</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 Comparison of Tower Type and Two Pass boiler design.

4 **ULTRA SUPER CRITICAL**

The USC boiler operates at high efficiency resulting in lower fuel consumption for electricity generation. The combustion in the USC boilers will therefore lead to a reduced CO2 emission compared with other type of boilers.

**Plant Reference Table**

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Asnæs Unit 5</td>
<td>1981</td>
<td>640</td>
<td>Two Pass</td>
<td>Denmark</td>
<td>Single</td>
<td>263</td>
<td>190</td>
<td>540/540</td>
<td>40</td>
</tr>
<tr>
<td>Walsum Unit 9</td>
<td>1987</td>
<td>410</td>
<td>Tower</td>
<td>Germany</td>
<td>Single</td>
<td>253</td>
<td>200</td>
<td>535/532</td>
<td>39</td>
</tr>
<tr>
<td>Fyn Unit 7</td>
<td>1991</td>
<td>400</td>
<td>Two Pass</td>
<td>Denmark</td>
<td>Single</td>
<td>280</td>
<td>250</td>
<td>540/540</td>
<td>44</td>
</tr>
<tr>
<td>Staudinger²</td>
<td>1992</td>
<td>550</td>
<td>Tower</td>
<td>Germany</td>
<td>Single</td>
<td>275</td>
<td>262</td>
<td>545/562</td>
<td>43</td>
</tr>
<tr>
<td>Skærbæk Unit 3</td>
<td>1997</td>
<td>415</td>
<td>Tower</td>
<td>Denmark</td>
<td>Double</td>
<td>298</td>
<td>290</td>
<td>582/580/580</td>
<td>49¹</td>
</tr>
<tr>
<td>Nordjylland Unit 3</td>
<td>1998</td>
<td>415</td>
<td>Tower</td>
<td>Denmark</td>
<td>Double</td>
<td>298</td>
<td>290</td>
<td>582/580/580</td>
<td>47</td>
</tr>
<tr>
<td>Avedøre Unit 2</td>
<td>2001</td>
<td>415</td>
<td>Tower</td>
<td>Denmark</td>
<td>Single</td>
<td>320</td>
<td>305</td>
<td>582/600</td>
<td>49¹</td>
</tr>
<tr>
<td>Porto Tolle Unit 2, 3 &amp; 4</td>
<td>Design</td>
<td>3650</td>
<td>Tower</td>
<td>Italy</td>
<td>Single</td>
<td>315</td>
<td>252</td>
<td>604/612</td>
<td>45</td>
</tr>
</tbody>
</table>

¹ Avedøreværket Unit 2 & Skærbækvarvet Unit 3 are designed for coal, but are operating on BIO & NG. Calculated plant efficiency for Avedøreværket on coal is >48 %.
² Scope partly by BWE and partly by Deutsche Babcock.

Figure 4 Plant Reference Table of SUBC, SC and USC.

BWE has designed a number of 400 MW USC boilers which have been in operation since 1998. The data from actual operation shows a very high plant efficiency and high availability, please refer to Figure 16. The boilers are operated with steam parameters of 290-305 bar and 580-600
New USC boilers like Porto Tolle 3x660 MWe have been designed using steam temperatures of 600-610 °C.

4.1 PRESSURE PART MATERIAL SELECTION

4.1.1 SUPER & REHEATERS

The elevated steam parameters require higher grade pressure part materials. Final HP superheater banks and final RH banks are made in austenitic steel. In order to reduce steam side oxidation, fine grain austenitic materials are selected. Relevant materials are TP347HFG (ASME Code case 2159) and TP304CuCbN (ASME code case 2328) 310N/HR3C and Sanicro25. The two latter with 25% Cr and subsequently high raw material cost. TP304-CuCbN calls for inner shot peening in order to obtain sufficient fine grain structure. An enhanced version of TP304 is the Super304H material.

For main steam and hot reheat steam lines at 600 – 610 °C the traditional material P91 is no longer sufficient. On the 400 MW USC boiler at Avedøre Unit 2 (AVV2) the outlet headers and the steam lines are made fully in P92. P92 is a 9% Cr martensitic steel like P91 however with improved creep range data due to W alloy.

4.1.2 MEMBRANE WALL

When ultra super critical boilers operate the materials after the evaporator are mostly in the creep range. Due to the elevated steam temperature, the materials operate in the creep range on the edge of what is possible. A small increase in temperature will result in a tremendous reduction of allowable stress. It is therefore essential to reduce the temperature imbalances in the boiler by correct boiler design. This is possible by a number of well proven measures as uniform flue gas profile as result of Tangential Firing, intermediate outlet headers, crossover of steam from left to right boiler side and extraction of main steam via four outlet headers instead of only two.

I has to some extent become the perception that T22 (2,25Cr-1Mo) and T12 (13CrMo4-5) do not have sufficient creep strength to be used in membrane water walls of ultra super critical boilers. Contrary to this perception BWE design has proven that T12 material for up to 300 bar is highly reliable. Also the upper pass with vertical membrane wall is often made in T12 material with

![Figure 5 Allowable Stress Chart: T91, T92, TP347HFG & Super304H.](http://www.NTPCGETS.com)
design temperatures up to 500 °C. Today 15 years of successful experience with several USC boilers operating with membrane walls made in T12 are obtained.

A membrane wall design using T12 is however only possible through a detailed and careful design with focus on reduction of temperature imbalances and stress concentrations. This requires and integral investigation of every individual tube performance in the membrane wall and subsequent design corrections. Actual operation has shown that chemical cleaning of the evaporator after 70-90,000 hours is needed.

An important precondition for a proper evaporator design is a combustion system resulting in well distributed heat absorption. On the tangential fired boilers the spiral helical rotation is opposite to the combustion vortex resulting in minimum temperature imbalances at spiral transition outlet. Figure 6 shows a membrane wall study with an even heat flux distribution as a result of a proper designed evaporator and combustion system.

4.1.3 Extended Material Selection

It is possible to increase the steam parameters even further by using T23 material (ASME Code case 2199). The T23 material has good creep resistance up to 550 °C and was developed in order to avoid PWHT. T23 is an extension of T22 modified by adding mainly W and reducing Mo and C content.

However T23 is very sensitive to deviation in welding parameters. Also some investigations concerning secondary hardening of steels containing vanadium show, that non-tempered welded joints undergo a significant increase in hardness during exposure at operating temperature.
PWHT is therefore unavoidable for larger dimensions but might still be avoided for smaller dimensions. In 2009 a small Benson boiler of 350 MWt heat input using T23 as membrane wall material was successfully commissioned.

In order to avoid PWHT concern has been directed to the design of T24 (7CrMoVTiB7-7). T24 is a further development of T23 and modified by adding Ti, increasing Mo and removing W. T24 however has not fulfilled the design intention and does as T23 require PWHT. Cracks in T24 membrane wall welds without PWHT have been reported in some European power plants. In some cases severe to an extent requiring replacement of the entire membrane wall.

4.2 Feed Water System

Studies of the cycle calculations including a number of preheaters have indicated that there is an optimum plant efficiency using FW temperatures at approximately 320 °C.

Using the traditional material SA-106 C for the FW system and inter connecting piping down to the evaporator inlet results in high wall thicknesses. When introducing USC technology with design pressure above 250 bar, it should be considered to use alternative materials.

In Europe it has been a common practice for more than 20 years to use the material 15NiCuMoNb5-6-4 also known under the trade name Wb36 (ASME Code Case 2353). Wb36 is a weldable high temperature copper-nickel-molybdenum steel alloyed used up to 371 °C (450 °C acc. EN Code).

Using Wb36 the wall thickness can be reduced by 25 % resulting in cost savings on material, welding, induction bending, hangers, support structures and resulting in a more flexible pipe system. Valve manufacturers have today included the material in their standard program.

4.3 Return of Investment

When the total amount of materials for the boiler pressure part is evaluated, it is clear that the extra cost of applying USC steam parameters is very limited compared to the total amount of materials for boiler pressure parts (additional cost 6-8%). When the remaining part of the boiler or the plant is taken into consideration the extra cost for an USC boiler is negligible.
Advanced USC boilers will have a plant efficiency above 45%. It now becomes obvious that the investment will be returned in relatively short time. The coal fired 400 MW USC boiler Nordjylland in Denmark designed with double reheat cycle was supplied and has been in operation since 1998 with a proven plant efficiency of 47%.

5 DOUBLE REHEAT

One of the obvious initiatives to increase cyclic efficiency is to introduce the double reheat cycle. This will increase the plant efficiency by approximately 1%. Two of the 400 MW USC boilers supplied are designed with double reheat cycle. When boilers are designed with double reheat it is important to make accurate boiler calculations and to balance the heat absorption between the two RH parts.

Even with increased cost for the turbine, for additional pipe work and for valve arrangement it is commercially attractive to design with double reheat cycle in countries with high electricity costs and emission taxation. Double reheat is a natural and well proven technology to be used in the effort towards the 50% efficiency (LHV).

6 ONCE TROUGH DESIGN

Since 1852 steam generating plants for industry and power stations has been supplied. It is thus one of the oldest still existing manufacturers of steam boilers in the world. In 1955 BWE acquired a license for the Benson once-through boiler design and has since then been one of the leading companies for advanced boiler designs.

The tendency in Europe is that all new boilers from 300 MWe and upwards are of the once through design. However drum type boilers are still in the portfolio, since small scale boilers and specially grate fired biomass boilers with heat input 50-125 MW are still of the drum type design. The advantages of a once through boiler design is described below in detail.

First of all once through boilers are not limited in pressure as the drum boilers where circulation is linked to the difference in water and steam density. Thus the plant cycle can be increased by increase of steam parameters above the critical point. The limitation on once through boilers is mainly linked to the selected materials for pressure part and turbine design.

Furthermore when a drum boiler is designed to operate close to the critical pressure, the split between the evaporator and the super heater becomes a challenge. If no special designs are introduced, the evaporator part of the boiler often becomes too large since the membrane walls of the first pass all are designed as evaporator.
When the boiler has to be designed for a variation of coal types available on the market and is to operate according, the sizing of the evaporator becomes critical. The different coals result in different heat absorptions and for drum boilers the evaporator is fixed. Once through boilers are more flexible with respect to heat absorption since the evaporation fully takes place in the furnace and superheating starts already in the membrane wall.

6.1 BENSON MINIMUM

Below a certain load called the Benson minimum load it is necessary to maintain sufficient flow through the evaporator by forced circulation. The forced circulation is established by a circulation system working either via dedicated boiler circulation pump (BCP) or via circulation through Feedwater Tank, Deaerator and FW Pump.

The Benson Minimum load is normally at 35 % boiler load depending on the design of furnace membrane wall. A proper boiler design includes correct decision on number of parallel tubes, pitch and inner diameter of membrane wall tubes.

In circulation mode (< 35 %) the water and steam leaving the evaporator is separated in the cyclone separators and the water is lead to the level vessel. From the level vessel the water goes to the circulation system.

6.2 MINIMUM BOILER LOAD

Recently utilities have required boilers capable of operating at low load condition and ready to follow the electricity demand quickly. Subsequently it has therefore become essential to keep the boiler in operation during night and weekends at low load condition.

Minimum Boiler Load on coal without support firing is typically possible down to 25% boiler load depending on coal composition and mill design.

6.3 LOAD JUMP & LOAD CHANGE RATE

The drum type boiler has a certain amount of energy accumulated in the large portion of water in the evaporator and drum. Load jumps can therefore be performed by reducing pressure and release more steam to the turbine.

The amount of water in the once through boiler is very limited however load jumps can easily be made by known and proven methods. Load jumps can e.g. be executed via bypass of HP preheaters, LP preheaters or condensate stop depending on the cycle arrangement. Planned load jumps can also be executed via prethrottling of either HP or IP turbine valves by operating the boiler in modified sliding pressure mode as described below.
The once through boiler with a BWE designed combustion system can firmly follow a load change rate of 5 %/min in the range from 40-90 % boiler load.

7 ADVANCED COMBUSTION SYSTEM

The combustion system consists of Low NOx Burners, Over Burner Air (OBA) and Over Fire Air (OFA). The combination is well proven and since 1990 more than 500 of burners handling a variety of fuels have been commissioned worldwide.

In addition a tangential firing technique has been developed using circular burners with air staging. By inclusion of OFA this system supports in-furnace air staging resulting in further reduced NOx formation. The complete combustion system is used in the most recent USC boilers in Denmark and with a fuel range including Coal, HFO, NG and Wood Dust. For Fuel Flexibility please refer to Section 0.

7.1 AIR STAGING

Air Staging is a key feature in Low NOx burner design. It builds upon a principle of sequential combustion which basically means applying enough air in each stratum to make the combustion stable, but not enough to allow nitrogen to be oxidized to NO or NO2. The main parameters governing NOx formation is local gas temperature and composition which are kept under control through Air Staging.

In Low NOx burner designs the combustion air is controlled to form a stratified mixing of fuel and air. The result is stretched flames and combustion zones where simultaneous high temperature and high Air Fuel Ratio (AFR) are avoided.

Low NOx Burners with air staging involves individual control of the SA and TA air for NG Combustion and in addition to that a certain control of the PA air for Coal Combustion. The split between SA and TA air is also controlled. For optimal operation SA and TA can be added swirl using the SA & TA turbulators which can either be positioned manually or electrical actuated. The required air staging and swirl depends on a number of factors such as load, fuel composition and burner level.
The purpose of the swirl is to control and ensure a homogeneous and optimal air-fuel mixture in the stratum. It also serves to control the penetration of the flame into the furnace. A high swirl leads to a short flame and an internal recirculation zone. This implies a flue gas recirculation at each combustion zone which together with the air split control supports Low NOx formation.

It is important to stress that Low NOx Burners in Wind Box applications requires special techniques at commissioning for determination of various burner settings. BWE uses an in-house developed algorithm during commissioning to obtain optimized Low NOx operation.

7.2 NOx PERFORMANCE

The combustion systems five air flows can be summarized as below, and of which the first three are located concentrically within the burner.

1. Primary Air (PA)
2. Secondary Air (SA)
3. Tertiary Air (TA)
4. Over Burner Air (OBA, Above each burner)
5. Over Fire Air (OFA, Air nozzles above the burner zone)

By implementing Low NOx Burners the NOx level can as a single entry be reduced by 40-50% compared to traditional coal burners. With air staging the overall Air Fuel Ratio in the burner zone is reduced to just above stoichiometry ($\lambda \approx 1.05$) which results in an enhanced NOx performance.

By extending the air staging to the furnace by use of OBA and OFA the NOx level is reduced by 60-70% compared to a high NOx combustion installation.

7.3 CO CORROSION PROTECTION

In contrast to traditional jet burners in similar tangentially fired systems, the circular burner provides an annular airside protection against CO corrosion of the furnace membrane wall.

This protection is enhanced by the use of the OBA which maintain a boundary layer at the membrane wall with higher stoichiometry.
8 TANGENTIAL FIRING OR OPPOSED FIRING

When the Tangential Fired furnace is considered in a cross section, it is clear that there are no dead corners. It is also clear that front and opposed fired boilers will have dead corners near the burners close to the side walls.

On this basis it is possible to operate a T-fired boiler with lower air excess without the risk of CO corrosion at the membrane walls than a front or opposed fired boiler. T-firing system for coal combustion with air excess down to 1,15 at ECO outlet are design.

The combustion system for T-firing will have over burner air (OBA) injected just above each burner. The OBA is part of the air staging and contributes to a reduction of NOx formation. Furthermore the OBA ensures sufficient oxygen content along the membrane wall and in this way protecting the membrane walls against CO corrosion. No CO related corrosion is reported on T-fired boilers with such combustion system installed.

The T-firing concept results in a very uniform flue gas temperature profile at the outlet of the furnace. The temperature imbalance in the first heating surfaces caused by the flue gas profile is therefore reduced significantly. In USC boiler design this is essential since the materials operates in the creep range where the allowable stress is dropping fast when the temperature is increased.

Front, opposed or even worst box type boilers will have high temperature peaks in the flue gas temperature profile at the furnace outlet resulting in temperature peaks in the superheater banks.

By T-firing it is possible to operate with longer flames and without swirl in tertiary air sectors of the burner. Front and especially opposed fired boilers are very sensitive to variation in the coal composition and the related shape of the flame. Often it is required with heavy swirl in order to reduce the flame length. In opposed fired boilers the flames will meet at the middle of the furnace and generate NOx.

Figure 12 CFD calculation of a 660 MWe tangentially fired USC boiler.
9 FUEL FLEXIBILITY

9.1 CO-COMBUSTION

Co-combustion of biomass and coal in utility boilers is today a proven technology. A heat input of 10-15 % on biomass and possibly more is possible while maintaining the possibility of using the fly ash for cement production. The biomass can be straw, wood chips or wood pellets.

Co-combustion of biomass can be conveyed through the PF coal piping or dedicated wood dust piping by installing a centre lance in the burner injecting pulverized biomass to the furnace. As for biomass, RDF (Refused Derived Fuel) can be injected into the furnace via an inner tube in the centre of the PF burner.

9.2 MULTI FUEL CONCEPT

The combustion system and burners are designed for a multi fuel concept. The standard PF burner as presented in the Section 0 can be designed with an inner gas lance simultaneously with an inner HFO/LFO lance.

The combustion system can be designed for 100 % coal, 100 % wood, 100 % gas and 100 % oil firing. In this way the fuels can be changed quickly and it is also possible to operate with different fuels on different burner levels.

9.3 CASE: AVEDØRE UNIT 2 (DENMARK)

The 400 MWe multi fuel USC boiler Avedøre Unit 2 has 4 burner levels of each 4 burners each originally designed for coal, oil and gas. Shortly after commissioning the unit was converted to operate on 80 % wood dust and 20 % Natural Gas.

In this case the coal pulverizes were rebuild for biomass grinding and conveyed via the existing PF piping to the burner. The retrofitted pulverizers work well but do not reduce the wood pellets particulate composition or particle size distribution significantly beyond its base.

Operating with relatively coarse base composition in such design does however not pose a threat to combustion quality, when implemented on a tangentially fired boiler. As the particle trajectory is controlled by the furnace swirl and the travel thus much longer compared to opposed or front fired arrangements. The increased particle velocity and interaction facilitates particle burn out.

The fuel concept on AVV2 up till today is a heat input of approximately 640 MWt of wood dust corresponding to 130 ton/h with an addition of 160 MWt of Natural Gas. Just recently AVV2 has been converted to 100 % wood dust firing.
9.4 CASE: HAZIRA UNIT 1 & 2 (INDIA)

The 2x150 MWe multi fuel SUBC drum boilers Hazira Unit 1 & 2 has opposed burner arrangement in 3 levels with a total of 20 burners each.

The multi fuel concept is composed to handle various waste fuels from a steel plant in Hazira. Burners and fuel systems are adequately designed to handle Coal, Corex Gas, HFO, LDO & Coal Dust that is emitted from the steel production.

The Multi Fuel concept is a major advantage of the steel manufacturer as it uses the waste streams from the steel production as fuel. This is one of the strongest pay back cases. As the fuel primarily is waste from steel production, its cost is already incorporated in the steel unit price.

Industries like the steel industry is demanding new boilers designed with a multi fuel firing concept capable of utilizing the waste fuels from the steel production in order to improve the plant profitability and to avoid loss of energy.

10 SINGLE TRAIN OR DOUBLE TRAIN

Single or Double Train Systems are often chosen by clients based on a matter of preference and tradition. The choice is to some extent value based, but there are a number of perspectives that can be applied to assess which might in fact be the more advantageous, economic and reliable.

In Germany and Denmark there is a strong tendency to design new utility boilers with single train flue gas path and mono components and for several years boilers have been designed with only one Air PreHeat. Based on operational experience the availability of these plants is very high. All critical components like bearings can be designed for a high life time e.g. APH bearing typically for 200.000 h.
9.5 ADVANTAGES & DISADVANTAGES

For the Double Train solution the duct system and related equipment and are arranged as two parallels. This design therefore demands two ID Fans, FD Fans, PA Fans, APHs, SCRs etc. and in addition to that as large number of dampers. The components are normally arranged in ways that allows to run the boiler at 60 % load with one FD Fan out of operation.

<table>
<thead>
<tr>
<th>Train Design Comparison</th>
<th>Single Train</th>
<th>Double Train</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD Fan</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PA Fan</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>ID Fan</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>APH</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Dampers</td>
<td>0</td>
<td>16³</td>
</tr>
<tr>
<td>Duct Work</td>
<td>Reduced</td>
<td>Extended</td>
</tr>
<tr>
<td>Pressure Loss</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>SCR</td>
<td>1 x 100 %</td>
<td>2 x 60 %</td>
</tr>
<tr>
<td>NH3 Injection</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

¹ To avoid high starting current, two fans can be installed in a Single Train Design.
² With two drives for redundancy.
³ Including sealing air.

Figure 14 Single & Double Train Comparison

For the Single Train solution the duct system and related equipment are arranged as a single and simplified path. This design therefore demands one ID Fan, FD Fan, PA Fan, APH, SCR etc. and with no dampers exposed to the flue gas. This Train Design Comparison is consolidated in Figure 14.

Looking at the APH and analyzing the effect of single and double train it becomes clear that performance is vastly improved by single train while the total weight is slightly reduced.

<table>
<thead>
<tr>
<th>APH Design Comparison</th>
<th>Single Train</th>
<th>Double Train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity [ ]</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Type [ ]</td>
<td>Quad Sector</td>
<td>Tri Sector</td>
</tr>
<tr>
<td>Rotor Diameter [m]</td>
<td>23,44</td>
<td>16,11</td>
</tr>
<tr>
<td>Total Air Leakage [kg/s]</td>
<td>29,2</td>
<td>38,7</td>
</tr>
<tr>
<td>Total Weight [ton]</td>
<td>1890</td>
<td>1910</td>
</tr>
</tbody>
</table>

Figure 15 APH Design for Single respectively Double Train on a 660 MWe boiler.

APH is equipped with two 100 % drives. The two drives can be in operation simultaneously. In case one drive fails, the other will take over. From the comparison tables the main advantages of the single train design can be extracted:

- Lower Cost & Complexity (reduced number of components)
- Lower APH Leakage Rate (reduced from 8 % to 6 %)
• Less Power Consumption
• SCR Design 100 % (not 2 x 60%)
• No Temperature Imbalances
• No Flow Imbalances
• No Dampers

The disadvantages are not quite as obvious, however the following becomes true:

• Higher Load on Single Steel Columns (APH & SCR)
• Higher Starting Current (FD & PA Fan)

The Single Train & Mono Component concept is referenced on plants up to 800 MWe and is strongly recommended for advanced boiler design.

9.6 AVAILABILITY

The single train and mono component concept has been used for a number of boilers for more than 20 Years. The 400 MWe USC boiler at Nordjylland (NJV) Denmark has been in operation since 1998 with a very high availability, see Figure 16.

When calculating the availability factor of single train mono component configuration, it can be proven that the total availability plant is higher than for double train and redundant systems, since the risk of failure is reduced significantly.

For the Double Train configuration the quantity of components that actually can experience failure and affecting the load is simply superseding the quantity in the single train system. From a pure statistically point of view it is therefore more likely that a double train system will suffer failure that causes load reduction or trip.
9.7 SINGLE TRAIN DESIGN

Beside being simpler the single train and mono component layout is also more compact.

The SCR and APH are layout wise arranged in a tower like design. The single APH is typically arranged at elevation +35.000. A single centre column is positioned at the boiler centre line supporting the APH main rotor bearing. Due to the large diameter (Ø23.5 m) of the APH rotor, the APH casing is supported by beams exceeding the footprint of the boiler itself.

When mono component design is applied care must be taken to the electrical system in order to meet the required electrical loads. For a 660 MWe plant the typical electrical installation for FD and PA would be:

- FD Fan Motor: 3800 kW @ 745 RPM
- PA Fan Motor: 4000 kW @ 1000 RPM

10 SELECTIVE CATALYTIC REDUCTION

The installation of an SCR has become mandatory in many countries. The operational requirements of the boiler influence the SCR design as it must be functional in the entire load range from 25 % to 103 % boiler load. The operational requirements for the SCR on the other hand also influence the boiler design.

The acceptable flue gas temperature window for proper SCR operation is from 315 to 400 °C. Short time operation of 2-3 hours below the 315 °C is acceptable preconditioned that the temperature is increased above 350 °C afterwards.
Previously boilers have been designed with SCR bypass used during start up. The Zero SCR Bypass concept is based on a full flow through the SCR during start up. All reference plants and recently built coal fired plants in Germany are designed without SCR bypass.

11 **Split Economizer**

The split of the economizer heating surface is necessary to ensure the best possible operating conditions for the SCR over the entire operating range of the boiler. The acceptable flue gas temperature window for proper SCR operation is from 315 to 400 °C.

The tower type design makes it easy to arrange a split economizer. The economizer is simply divided into two separate heating surfaces located before and after the SCR plant in the flue gas stream. The feed water is first lead to the economizer located after the SCR and from here it is led to the economizer at the boiler top. The total heating surface of the two economizers is sized to maintain the same heat absorption as for the basic design with a single economizer.

The split ECO will lead to a reduction of the boiler steel structure and a reduction of the membrane wall height by about 1,5 m.

**12 Controlled Safety Pressure Relief Systems (CSPRS)**

**12.1 CSPRS or Traditional Safety Valve**

Preferably hydraulically operated safety valves are used in Advanced Boiler Design to protect the pressure part in power stations. In comparison to the use of spring loaded safety valves, the number of installed components can be reduced drastically by the use of combined bypass and safety valves.

<table>
<thead>
<tr>
<th>Safety Valve Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Controlled Pressure Relief</strong></td>
</tr>
<tr>
<td>100 % HP Combined Bypass Units with Safety Function Hydraulic Spring Loaded (two valves)</td>
</tr>
<tr>
<td>116 % RH Safety Valve Hydraulic Spring Loaded (two valves)</td>
</tr>
<tr>
<td>Shut Off Valves in Front of HP Bypass (two valves)</td>
</tr>
<tr>
<td>100 % RH Spring Loaded Safety Valves (two valves)</td>
</tr>
</tbody>
</table>

Figure 18 Section view of Porto Tolle 3·660 MWe arrangement of split ECO.

Figure 19 Comparison of CSPRS and Traditional Safety Valve System.
Advanced boilers are typically equipped with following valves:

- 100% HP Hydraulic Spring Loaded Bypass with Safety Function (two valves)
- 100% +16.5% RH Hydraulic Spring Loaded Safety Valve (two valves)

The arrangement is shown schematic on in Figure 20. This arrangement secures that sufficient flow through the reheater will be available. The RH safety valves will be designed for 100% flow from the HP part plus a spray water flow of e.g. 16.5%.

The span between normal operation pressure at MCR 103% and the set pressure of the safety valves can be used for overload operation. By having combined HP bypass and HP safety valves, the whole span can be used.

It is normally foreseen that the LP bypass valves at the turbine will have a capacity of 60-70%. At turbine trip the RH safety valves will open and the boiler load will be reduced down to 60-70% load. When the RH safety valves close the full RH flow will pass through the LP bypass valves.

12.2 OPERATIONAL MODES

The controlled HP bypass and the RH safety valves can be designed and programmed for three types of operation:

- Safety Relief (opening time < 2 s)
- Quick Opening (opening & closing time 5 s)
- Control Operation (opening & closing time 15-20 s)

The Safety Relief control unit will open the valves at the set pressure as if they were simple spring loaded safety valves. The hydraulic relief system is in line with EN 12952-10.

The Quick Opening function relieves the pressure at low load and part load when the sliding pressure is exceeded by a certain margin. In this way the quick opening function avoids stagnation in the steam flow in the superheaters and reheaters which is essential for the sufficient cooling.
The Control Operation mode is used for pressure and flow control during start up conditions. By continuous boiler operation after a turbine trip, the HP bypass valves are used to control the boiler pressure and follows the sliding pressure curve.

The safety valve design described is in line with the references of BWE and in line with the design of USC Boilers in Northern Europe.

12.3 PIPE LAYOUT

As a consequence of CSPRS the pipe layout will be simplified due to a reduced number of safety, bypass and vent valves. The amount of piping on a 660 MWe unit will thus be reduced by approximately 50 tons of P92 material and in addition 6 large tee pieces.

The HP bypass valves are connected closely to the main steam line and in this way kept at sufficient temperature. The two HP bypass valves will always operate in parallel avoiding temperature imbalances between the left and the right side of the boiler outlet.

The RH safety valves will be equipped with exhaust pipes and silencers. Only the RH safety valves require a small bore heating line.

Figure 21 Layout HP piping Porto Tolle 3-660 MWe.

13 APH SEALING SYSTEM

The introduction of a SCR plant increases the overall pressure drop and hence increases the pressure difference between the air side and flue gas side. This will entail a larger air leakage and as a consequence reduce the plant efficiency and net production.

Today requirements for quick load changes and frequent start and stop have increased the benefits of having flexible and automatic systems which ensures optimum leakage conditions under all loads.

13.1 SEALING SYSTEMS

Reduced APH leakage is thus vital for a proper and efficient operation of the boiler. A first step is to choose the single train and mono component concept in new designs as described in Section 9.5 and Figure 15. Another and just as important step is to install Advanced Sealing Systems.
The Advanced Sealing System can be divided into the following main groups:

- **Sealing systems between the air and flue gas sides.** These systems are the radial sealing system and the axial sealing system.

- **The bypass sealing.** The circumferential sealing system prevents the air and flue gases from bypassing the rotor on the outside.

- **Sealing to the outside.** The shaft sealing system, i.e. rotor drive seals and soot blower seals, prevents flue gas and air from leaking to the atmosphere.

As direct leakage is proportional to the square root of the pressure difference between air and flue gas sides doubling the number radial walls makes possible to obtain a 30% reduction of the leakage.

### 13.1.1 Active Leakage Control System

The primary sealing system is the radial sealing system that is formed by labyrinth seals between the radial sealing plates and the rotor. The sealing system prevents leakage from the air sides to the flue gas side.

Radial sealing plates are installed at the top between the rotor and the top sector beam and at the bottom between the rotor and the bottom sector beam.

For small to medium size APH the radial sealing plates are typically kept as one section. For larger size APH the radial sealing plates are divided into more sections to ensure an optimum adaptation to the thermal deflection of the rotor along the entire rotor diameter.

Because of the temperature difference from top to bottom, the rotor will deflect due to the enhanced thermal expansion of the upper parts. With Active Leakage Control System it is ensured that the radial seal plates follow the thermal deflection and thereby reduces the leakage to minimum independent on the boiler load. The displacement of the radial seal plates is controlled by an Active Leakage Control System which keeps the radial seal plates at a constant distance.
Figure 22 shows a cross sectional of the APH and the function of the Active Leakage Control System at both top and bottom. Left side shows the rotor and sealing system in cold condition and right side shows the rotor and sealing system in normal operating position.

13.1.2 Seal Gap Sensor

The gap between the radial seal plate and the APH rotor is measured by a Seal Gap Sensor. Action is taken to correct any deviation from the desired distance and each radial seal is controlled individually.

BWE has developed a reliable Seal Gap Sensor that is temperature resistant continuously up to 420 °C and can be installed in hot flue gas condition without external cooling.

The Active Leakage Control System and Seal Gap Sensors are installed in APH and GGH at new power plants and retrofitted into a number of existing boilers including. Below a few operational plants.

<table>
<thead>
<tr>
<th>Place Name</th>
<th>Country</th>
<th>Type</th>
<th>Kind</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maja</td>
<td>India</td>
<td>APH</td>
<td>NEW</td>
<td>2015</td>
</tr>
<tr>
<td>Hazira</td>
<td>India</td>
<td>APH</td>
<td>NEW</td>
<td>2012</td>
</tr>
<tr>
<td>Enna</td>
<td>Italy 2012</td>
<td>APH</td>
<td>NEW</td>
<td>2012</td>
</tr>
<tr>
<td>Staudinger Unit 5</td>
<td>Germany</td>
<td>APH</td>
<td>REHAB</td>
<td>2012</td>
</tr>
<tr>
<td>Brindisi South Unit 4</td>
<td>Italy</td>
<td>APH</td>
<td>REHAB</td>
<td>2012</td>
</tr>
<tr>
<td>Fusina Unit 3</td>
<td>Italy</td>
<td>APH</td>
<td>REHAB</td>
<td>2010</td>
</tr>
<tr>
<td>Torrevaldaliga North</td>
<td>Italy</td>
<td>APH</td>
<td>REHAB</td>
<td>2010</td>
</tr>
<tr>
<td>Amager Unit 3</td>
<td>Denmark</td>
<td>APH</td>
<td>NEW</td>
<td>2008</td>
</tr>
<tr>
<td>Fyn Unit 7</td>
<td>Denmark</td>
<td>APH</td>
<td>REHAB</td>
<td>2007</td>
</tr>
<tr>
<td>Litoral de Almeira</td>
<td>Spain</td>
<td>GGH</td>
<td>NEW</td>
<td>2015</td>
</tr>
<tr>
<td>Puk-Pyeong</td>
<td>South Korea</td>
<td>GGH</td>
<td>NEW</td>
<td>2015</td>
</tr>
<tr>
<td>Taean</td>
<td>South Korea</td>
<td>GGH</td>
<td>NEW</td>
<td>2015</td>
</tr>
<tr>
<td>Dangjin</td>
<td>South Korea</td>
<td>GGH</td>
<td>NEW</td>
<td>2014</td>
</tr>
<tr>
<td>Gumi</td>
<td>South Korea</td>
<td>GGH</td>
<td>NEW</td>
<td>2012</td>
</tr>
<tr>
<td>Jorf Lasfar</td>
<td>Marocco</td>
<td>GGH</td>
<td>NEW</td>
<td>2012</td>
</tr>
<tr>
<td>Honam</td>
<td>South Korea</td>
<td>GGH</td>
<td>NEW</td>
<td>2012</td>
</tr>
</tbody>
</table>
14 Future Advanced Boiler Design

The next step in advanced boiler design is to increase steam parameter further. Studies performed in the late 1990’s proved that an increase of steam temperatures to 650 °C is not possible with the martensitic steel P91 & P92.

Instead the use of nickel alloy materials as alloy 174, 263, 617 and 740 is required. Since these materials are not limited by creep below 650 °C, it seems natural to take a large step up to 700 °C steam temperature.

Some of the relevant materials were tested under the COMTES700 program. Test results of the manufacturing and operational test showed that machining, bending and welding of high nickel alloy materials were highly challenging. Also cracks appeared in welding of thick walled components and internally in valves, like excessive corrosion were observed on the certain superheater sections.

The COMTES700 project concluded that there are still many technical challenges to overcome before a 700 °C boiler can be operated reliably.

Technically a 700 °C boiler design is therefore presently not realistic. Commercially it seems more attractive to improve the present known USC design based on the 600/610 °C boiler concept. On short term aiming at 50 % plant efficiency by use of low mass flux vertical evaporator tubing, double reheat and flue gas heat transfer system (condensate and feed water heating by further flue gas cooling) seems more feasible.

15 Conclusion (BAT)

The use of BAT (Best Available Technology) is becoming a political demand. BAT conclusions stating the achievable emission limits and efficiency will become benchmark for the power industry. With BWE technology it is proven that USC Boilers can be operated with steam
parameters up to 600 / 610 °C and cyclic efficiencies of 46-49 % (LHV & EN) in a reliable manner by using well known and commercial materials.

The technology is heading towards achieving 50 % rankine cycle efficiency. This article elucidates the intricate challenges related to various technological improvements in boiler component design adopted towards achieving this goal.

With ongoing programs on superior metallurgy in place in near future BWE is on the door step to maximize the revenue of their customers and the revenue globally as a cleaner and greener environment.