TECHNICAL PUBLICATION

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## INTRODUCTION

The increasing importance of high plant efficiency in new generation additions to the deregulated U.S. market is further reinforced through tightening emissions regulations such as those for $CO_2$ production. While natural gas-fired combined cycle plants have garnered much attention in recent years, the continued and predicted rise in natural gas prices suggests that this will not always be so. Meanwhile, the abundant supply of coal and the continued advances in practical steam cycle design will help coal-fired technology maintain a prominent position in the U.S. – and worldwide – markets for the foreseeable future.

Until recently, plant designs with advanced steam parameters have generally not been favored by the regulated U.S. market economics. Elsewhere, especially in Europe and Japan, supercritical pressure designs are more common and have attractive, proven experience. Current advances in materials development are facilitating design of steam power cycles with efficiencies approaching those of combined cycle plants.

## TYPICAL CURRENT UTILITY DESIGNS

The economic factors present during the rapid North American generating capacity growth in the 1960s and 1970s favored the moderately high-pressure, sub-critical, single reheat steam cycles already well-demonstrated in industry. The cycle pressures were generally sub-critical and ranged from 1800 psig to 2600 psig at the turbine inlet. Advanced steam conditions were still pursued in the U.S., but not to the extent driven in the European and Japanese markets. The regulated nature of the U.S. industry, its economics, and the general lack of costly emissions controls contributed to acceptable life-cycle cost structures for the modest, but proven, sub-critical pressure cycle efficiencies. The localized, regulated markets allowed utilities to plan for the regional capacity growth, and the bulk of the generation additions could safely be assumed to be large-scale and base-loaded units. These factors led to the continued use and adaptation of the natural-circulation steam generator design.

As a reference point for these discussions, we review the basic performance and features of the following typical 350 MW steam power system:

*Table 1  Steam Conditions for Typical 2400 psig / 350 MW Plant*

| | | |
|---|---|---|
| Main Steam Flow Rate | 2,500,000 lb/hr | 315 kg/sec |
| Main Steam Pressure, at turbine inlet | 2400 psig | 165 barg |
| Main Steam Temperature, at turbine inlet | 1000 / 1000°F | 538 / 538°C |
| Feedwater Temperature | 490°F | 254°C |

Based on firing a typical North American bituminous coal, the following performance is typical of such plants:

*Table 2  Power Cycle Heat Balance for Typical 2400 psig / 350 MW Plant*

| | | |
|---|---|---|
| Fuel Heat Input, HHV basis | MBtu/hrMW | 3,272959.0 |
| Fuel Heat Input, LHV basis | MBtu/hrMW | 3,144921.3 |
| Heat Added to Steam | MW | 863.1 |
| Turbine Shaft (Mechanical) Power | MW | 381.3 |
| Power Generation, gross | MW gross | 376.3 |
| Power Generation, net | MW net | 350 |

As a matter of clarification, several performance measures are defined in Table 3 below.

*Table 3  Power Cycle Efficiency Measures*

| Term | Definition | Typical Value, HHV Basis | Typical Value, LHV Basis |
|---|---|---|---|
| Net Plant Efficiency | $\frac{\text{Net Electrical Generation}}{\text{SG Fuel Heat Input}}$ | 36.5% | 38.0% |
| Gross Plant Efficiency | $\frac{\text{Gross Electrical Generation}}{\text{SG Fuel Heat Input}}$ | 39.2% | 40.9% |
| Thermal Efficiency | $\frac{\text{Turbine Shaft Power}}{\text{SG Fuel Heat Input}}$ | 39.8% | 41.4% |
| Turbine Efficiency or Cycle Efficiency | $\frac{\text{Gross Electrical Generation}}{\text{Heat Added to Steam}}$ | 43.6% | |

Each efficiency measure may also be expressed in a corresponding reciprocal form with specific units and termed “Heat Rate”. The conversion in US units is:

$$\text{Heat Rate (Btu / KW hr)} = \frac{1}{\text{Efficiency}} \times \frac{3412.1\ \text{Btu/hr}}{\text{KW}}$$

To reduce the duplication of figures in multiple units systems, this discussion will refer to the dimensionless, and more intuitive, figures of efficiency.

## STEAM GENERATOR FEATURES FOR HIGHER EFFICIENCY

### Steam Pressure

By increasing the final steam conditions above those developed in the condenser, the cycle efficiency is driven higher. Current high-pressure units are designed for up to 4500 psig (310 barg), and higher pressure units are planned for the future. The obvious limit is the practical containment of such high pressures, with regard to both the cost of material and the wall thickness of components. The thickness of pressure vessels is of concern where the part is subject to temperature cycles or ramps, and the resulting stresses must be properly limited or managed.

If, by reference to the baseline unit, the design steam pressure were increased from 2400 psig to 4200 psig (165 to 290 barg), the net plant efficiency would be increased by approximately 2.7% points. The benefit is clear when, considering the baseline efficiency of 36.5% (HHV), this translates into 7% more power for the same heat input.

### Steam Temperature

As for steam pressure, increasing the steam temperature differential in the power cycle will yield greater efficiency. Current high-temperature units drive the superheat and reheat temperatures to 1150°F (621°C). By increasing the baseline unit’s SH/RH steam temperatures from 1000/1000°F to 1100/1150°F (538/538°C to 593/621°C), the net plant efficiency would be increased by another 2% points.

Figure 1 shows a generalized trend of net plant efficiency as a function of design steam conditions.

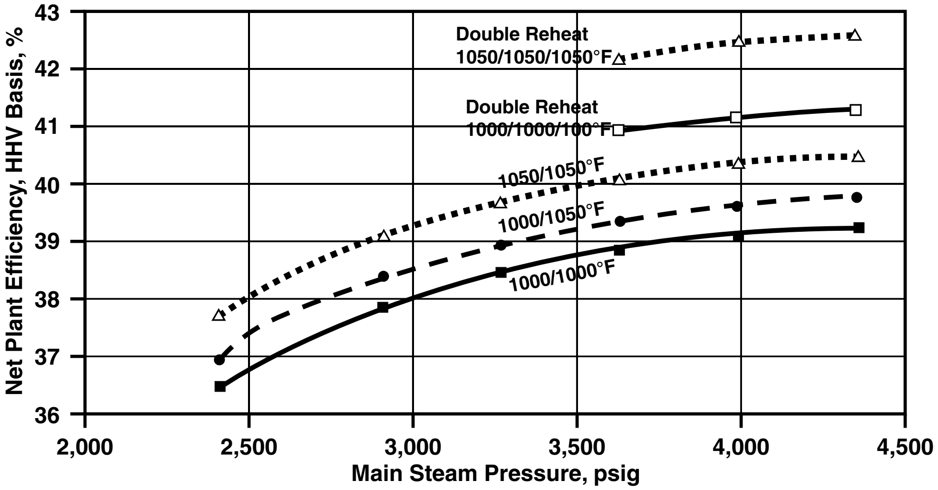


*Figure 1 Net Plant Efficiency: Effect of Steam Pressure and Temperature*

Metal component strength, stress, and distortion are of concern at elevated temperatures in both the steam generator and the steam turbine. In the steam generator's heating process, the tube metal temperature is even higher than that of the steam, and concern for accelerated corrosion and oxidation will also influence material selection.

ASME and other organizations worldwide, such as EPRI, CURC, and Thermie, are currently researching new and improved materials to facilitate the economical use of elevated steam conditions. Babcock Borsig Power is intimately involved with the research and testing of these materials.

Table 4 lists a partial summary of enhanced materials already approved or being reviewed by the ASME committee for practical use in steam generators. Design for elevated steam conditions will ultimately require the graduation from ferritic to austenitic materials in pursuit of desirable properties including greater strength and resistance to corrosion and oxidation.

*Table 4 New Materials for ASME B&PV Code Section I Construction*

| Material | Chemistry | ASME Status | Temp. Limit, °F | Comments |
|---|---|---|---|---|
| SA-213 T23 | 2.25Cr -1.6W -V- Cb | CC 2199 | 1200 | · Material has weld cracking issues. |
| SA-213 T24 | 2.25Cr-1 with V, T1, and B | Code Case in process | 1200 | · European material<br>· Better weld ability than T23.<br>· Equal strength to T23. |
| SA-213 T92 | 9Cr-2W | CC 2179 | 1200 | · Higher strength than T91. |
| 347HFG | 18Cr-10Ni-Cb | CC 2159 | 1350 | · Good internal oxidation resistance.<br>· Allowable stress 20% greater. |
| T911 | 9Cr-1Mo-1W-.2V-.08Cb | Code Case in process | | · European material.<br>· Stronger version of T91. |
| Seamless 12Cr-2W Also known as T122 | 12Cr-2W | CC 2180 | 1200 | · Non austenitic material. |
| WB36 | Same as DIN 15Ni-Cr-Mo-Cb5 | Code Case in process | 700 | · European material.<br>· Thick wall piping - cyclic applications. |
| Super 304H | .1C-18Cr-9Ni-3Cu-Nb-N | Code Case in process | 1350 | · Higher strength than 304H & 347H.<br>· Similar to 347H with higher oxidation resistance. |
| SA-213 TP310H-Cb-N Also known as HR3C | 25Cr-20Ni-Cb-N | In Code. Previously Code Case 2115. | 1350 | · Good corrosion resistance. |

## Exit Gas Temperature

The major power loss from the steam generator is the heat of the exit flue gas. Reduction of the exit gas (stack) temperature is typically limited by material selection and concern for dew point and corrosion. By proper evaluation of fuel properties and utilization of corrosion-resistant materials in the final heating surfaces, the stack temperature may be optimized according to each plant. The operating temperature requirements of emissions control equipment such as selective catalytic reduction (SCR) and flue gas desulfurization (FGD) systems place additional constraints on the system, including stack- and plume-related concerns. Proper arrangement of equipment and heating surfaces is required to achieve a balance between full load efficiency optimization and desired operating flexibility. In some instances, partial feedwater heating by the flue gas can be used to improve not only steam generator efficiency, but also the overall net plant efficiency. While the exit gas temperature limitation will vary for specific plants and fuel ranges, Figure 2 suggests the potential plant efficiency benefit as the design exit gas temperature is modified. A 25 °F (14 °C) reduction in exit gas temperature would improve the net plant efficiency (HHV) by approximately 0.25% points.

Specifically, for regenerative air heaters, used very commonly on utility-sized fossil fuel-fired steam generators, corrosion-resistant and enameled heating surfaces may be installed to allow a lower design exit gas temperature. Additionally, adoption of an air leakage recirculation system, as shown in Figure 3, would reduce the air leakage rate to the flue gas

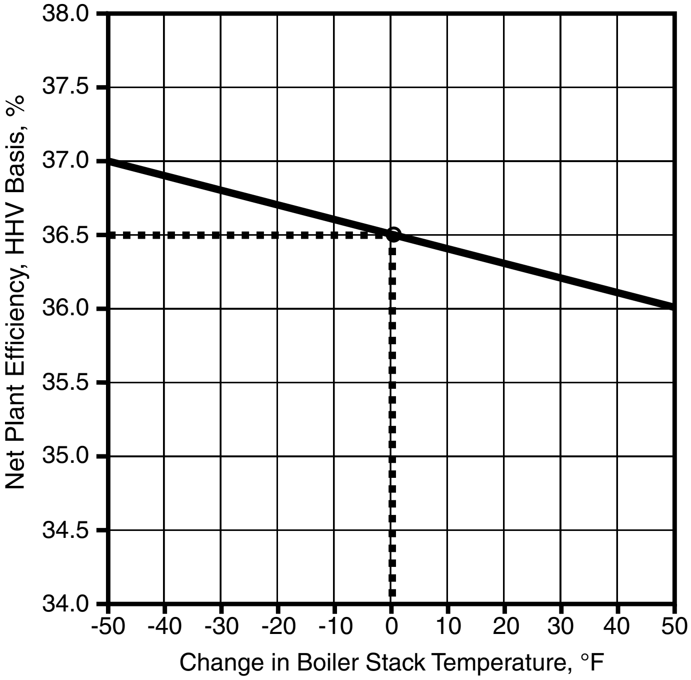


*Figure 2 Effect of Stack Temperature on Plant Efficiency*

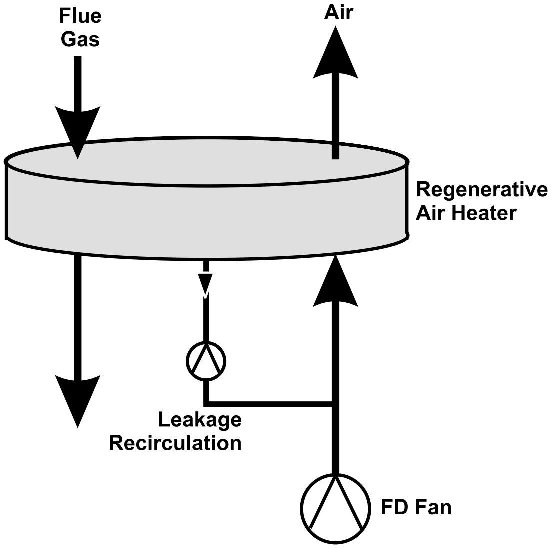


*Figure 3 Air Heater Leakage Recirculation*

stream, and effectively allow a lower undiluted gas temperature for the same cold-end element conditions. While the net air fan power consumption would not appreciably change, the ID fan power consumption and flue gas flow rate through downstream equipment would be reduced. Both the reduced stack temperature, by way of improved boiler efficiency, and the reduced ID fan power, will result in a slight benefit to the overall net plant efficiency.

**Excess Air and Unburned Carbon**

Besides the exit gas temperature, another operating parameter with direct effect on the stack heat loss is the level of excess air used. Flue gas is the mixture and byproducts of vaporized combustibles and the total air supplied. Therefore, at a given stack temperature, a reduction in air flow rate will reduce the heat carried out through the stack. Ideally, to release the full heating value of the fuel, one would like to supply only that air which is required for full combustion of the fuel – that is, zero percent excess air or an air ratio of 1.0. Because of heterogeneous mixing of the combustible and oxygen molecules and other fuel- and combustion-related conditions, an excess supply of air is provided to promote complete combustion of the fuel. Therefore, the optimal excess air level is a compromise between stack heat losses and combustion inefficiency losses as measured by unburned carbon in the ash and further indicated by CO emissions. Figure 4 illustrates this relational balance for a hypothetical unit.

The efficiency of combustion is dependent not only on the fuel characteristics, but also on the design and operation of the complete combustion system. In addition to proper pulverizer and burner selection and operation, as well as furnace sizing and conditions, the following additional measures may be taken to control the mixing of fuel and oxygen.

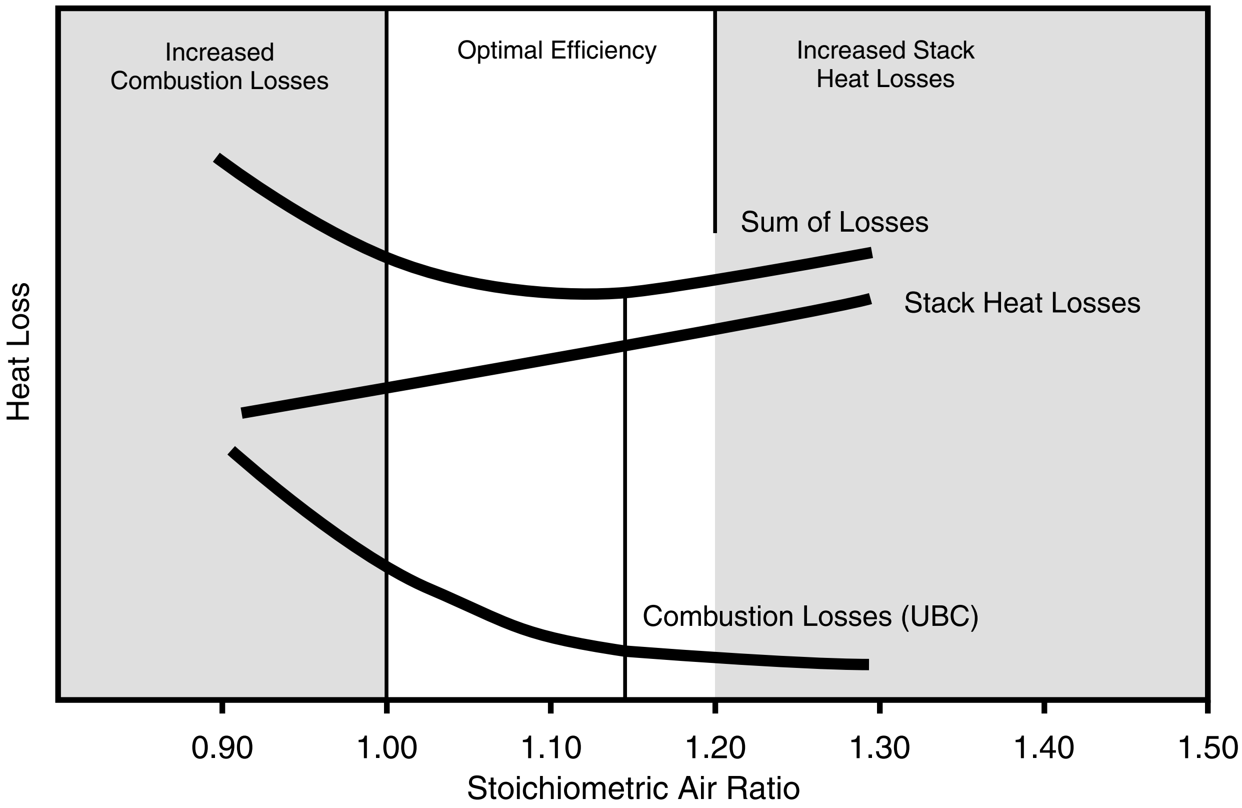


*Figure 4 Optimization of Excess Air and Boiler Efficiency*

### Coal Fineness

For a wide range of coals, the MPS vertical-spindle pulverizer may be utilized. Its hydraulic adjustment of the grinding force affords some control of fineness for extreme ranges of fuel properties. In addition, dynamic/rotating classifiers are selected, rather than static classifiers, to maximize coal fineness and provide greater surface area for immediate reaction with oxygen in the combustion chamber. Table 5 compares typical performance for bituminous coal with 9.5% ash content:

*Table 5 Coal Fineness and Unburned Carbon for Static vs Dynamic Classifiers*

| | Static Classifier | Dynamic Classifier |
|---|---|---|
| Percent through 50 mesh | 98.0 | 99.5 |
| Percent through 200 mesh | 70 | 80 |
| Unburned Carbon in Ash | 5% wt | 4% wt |
| Boiler Efficiency Loss (HHV) Due to UBC | 0.60% | 0.47% |

### Fuel/Air Mixing

Low $NO_X$ burner technology is based on controlling and extending the mixing of fuel and air in the furnace. This runs counter to the above stated objective of immediate mixing of components for complete combustion. As such, the overall success of a low $NO_X$ combustion system is strongly dependent on providing the proper air-to-fuel ratio at each and every burner. Otherwise, a fuel-rich burner would produce high unburned carbon and CO, and a fuel-lean burner would burn relatively hot and generate more $NO_X$. Secondary airflow measurements at each burner can be used to automatically modulate the air shroud damper and control the air flow distribution to within 5 to 10 percent deviation. Coal pipe flow is balanced through a rigorous coal pipe system analysis and the application, where necessary, of fixed or variable coal pipe orifices. Also, when dynamic classifiers are used, coal pipe flow balance is further enhanced across load and operating ranges, on account of the continuously active internals and uniform flow distribution within. Successful adoption of these measures and the use of dynamic classifiers for a typical bituminous coal application can yield up to a 0.1% point benefit to net plant efficiency.

With such combustion system optimization, the optimal excess air for the efficiency loss balance described above will typically fall in the 15% (1.15 air ratio) range. Compared to the conventional 20% excess air level for bituminous coal, this could result in a 0.05% point benefit in net plant efficiency, plus the incremental savings in air and gas fan power consumption and the corresponding direct effect on net plant efficiency. Additionally, air and flue gas equipment capacity requirements are slightly reduced for possible capital savings.

## BENSON BOILERS

### Overview

As steam pressure approaches the supercritical point (3208 psia, 221 bara), the density difference between liquid and vapor phases – the motive force for natural boiler circulation – diminishes. Therefore, a forced-circulation or a once-through steam generator circuitry system must be utilized.

Benson boiler technology employs a once-through circuitry with the water proceeding through the economizer, evaporator, and superheater surfaces without recirculation through any subsystem during normal operation. Historically, adequate cooling of the furnace walls with a single, once-through steam pass has been achieved by designing proper steam mass flow rates through inclined wall tubes, generally progressing up the furnace in a spiral arrangement. Multiple steam separators, or Benson vessels, are provided to allow phase separation while operating at sub-critical pressures.

There is a considerable installed base of Benson boilers, with over 950 boilers installed worldwide and with units serving generating systems as large as 1000 MW. Experience is proven with a wide range of fuels, and both tower and two-pass arrangements are employed.

## Advanced Steam Conditions and Efficiency

The ability to realize supercritical steam conditions and the associated high plant efficiencies is a main advantage of Benson boiler technology. Boiler designs have been generated for steam conditions up to 4500 psig (310 barg) and 1150°F (621°C). Both single and double reheat applications have been demonstrated. Figure 5 reiterates the potential improvement in net plant efficiency due to increased steam parameters possible with a Benson boiler, while for the most part retaining conventional ferritic/martensitic materials.

An intrinsic benefit to improved plant efficiency is, of course, reduced specific fuel consumption and $CO_2$ production. To quantify some of the emission benefits from improved plant efficiency, an analysis has been conducted to compare two 600 MW plants: one operating at 2400 psig, 1000/1000°F (165 barg, 538/538°C), and another operating at 4200 psig, 1112/1148°F (290 barg, 600/620°C). The comparison is made for units burning both western Kentucky bituminous and Powder River Basin coals whose analyses are shown in Table 6.

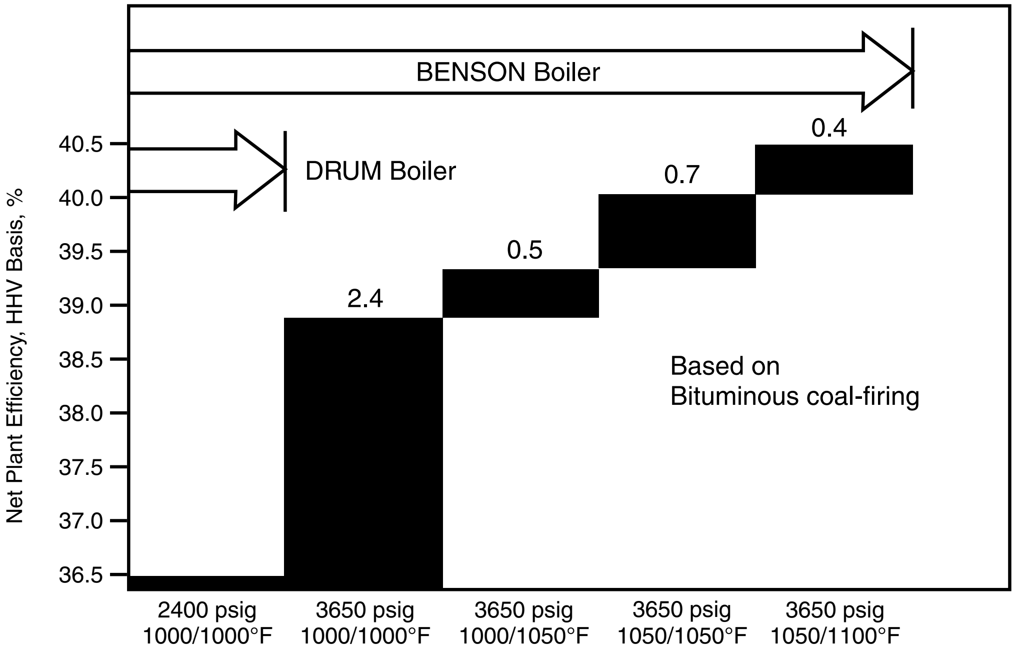


*Figure 5 Effect of Boiler Steam Conditions on Net Plant Efficiency*

Annual emission rates, based on a 90% capacity factor, are compared in Figure 6, which shows the significant reduction of fuel and emissions as a result of the higher plant efficiency. The 14% reduction indicated is a result of the steam cycle pressure and temperature change only. With other design features usually incorporated into higher efficiency plants, the effect can be up to 20%. Fuel, ash, and $CO_2$ will be directly reduced, whereas for $NO_x$ and $SO_x$ emissions limited by permit, the reduction in uncontrolled rates represents the savings in capital cost, reagent/operating costs, and size of the associated emissions control equipment.

*Table 6 Typical Coal Analyses*

| Coal Description | Western Kentucky Bituminous | Powder River Basin |
|---|---|---|
| Coal Analysis, % weight | | |
| Carbon | 61.98 | 50.61 |
| Hydrogen | 4.19 | 3.31 |
| Nitrogen | 1.22 | 0.73 |
| Sulfur | 3.79 | 0.23 |
| Oxygen | 5.54 | 14.39 |
| Ash | 13.78 | 4.18 |
| Moisture | 9.50 | 26.55 |
| Higher Heating Value (HHV) | 11,171 Btu/lb<br>(25.99 MJ/kg) | 8,638 Btu/lb<br>(20.09 MJ/kg) |

## Operating Flexibility

Modern plants with Benson boilers are typically operated in modified sliding pressure mode. Under such operation, the steam pressure is maintained constant from 100% down to 85% load, and is then reduced linearly as load is further reduced. Steam temperature, meanwhile, is maintained at a constant level down to 40% load typically, and thus high efficiency is maintained even in the part load range.

The low heat storage mass and the use of smaller components to limit wall thickness allow relatively high load ramping rates in conjunction with the modified sliding pressure mode. Ramp rates of 7% are typical in the load range of 50-90%, and short start-up times are the norm.

## Fuel Flexibility

Another useful benefit of the Benson boiler is its relative insensitivity to fuel property variation. This arises, in part, due to its inherent variable evaporation end-point characteristic.

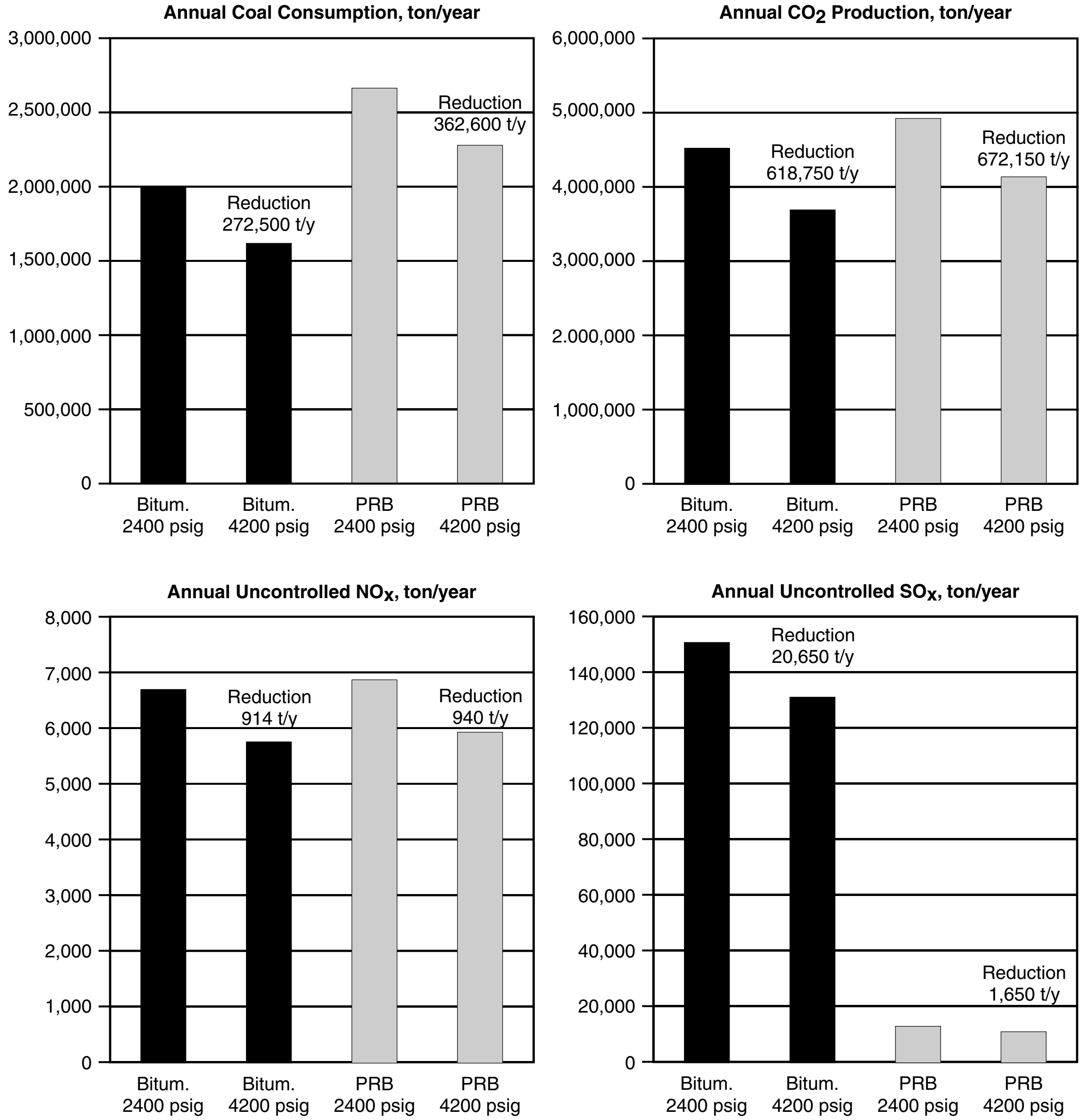


*Figure 6 Annual Fuel and Emissions Rate Comparison*
*2400 psig/1000°F Cycle vs 4200 psig/1112°F/1148°F Cycle*
*Based on 90% Capacity Factor*

Figure 7 compares the behavior of a natural circulation boiler and a Benson boiler with a hypothetical ± 10% deviation of furnace heat absorption due to varying combustion and slagging characteristics. In the natural circulation boiler, the result of reduced furnace heat absorption is an increased furnace exit gas temperature and a higher steam attemperation rate. In the case of enhanced furnace heat absorption, the attemperation rate is gradually reduced to zero and the superheater outlet temperature drops. In contrast, the Benson boiler balances differences in heat absorption via the variable evaporation end-point. The allocation of the evaporative and superheat duties to the various surfaces may vary according to differential heat absorption of the furnace as well as with changing load. By controlling the firing rate according to final steam temperature, rather than to drum pressure, the Benson boiler achieves the desired steam temperature, at nearly constant attemperation rate, largely independent of shifts in heat absorption of the heating surfaces.

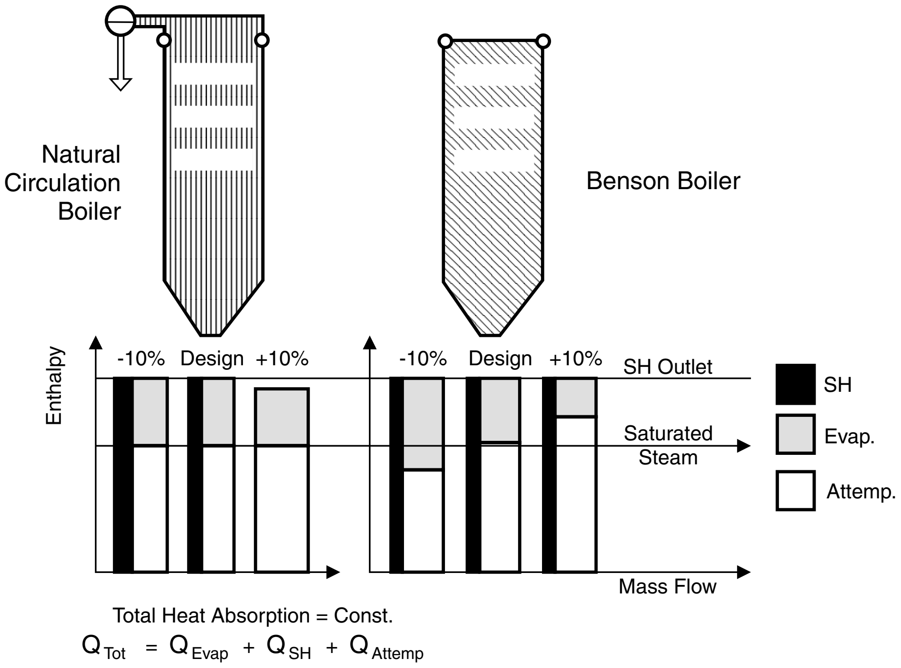


*Figure 7 Boiler Behavior with Changed Heat Absorption of the Furnace*

## Stability

By use of the spiral tube wall construction, the consistent upward progression of the evaporative circuitry through the combustion chamber reduces many of the flow stability problems encountered with other once-through unit designs. Stable operation is afforded under both sub-critical and supercritical pressures. As such, Benson boilers are relatively easy to start-up and boiler availability is generally as high as that of natural circulation boilers. Figure 8 shows the documented availability comparison of German power plants from 1988 through 1997.

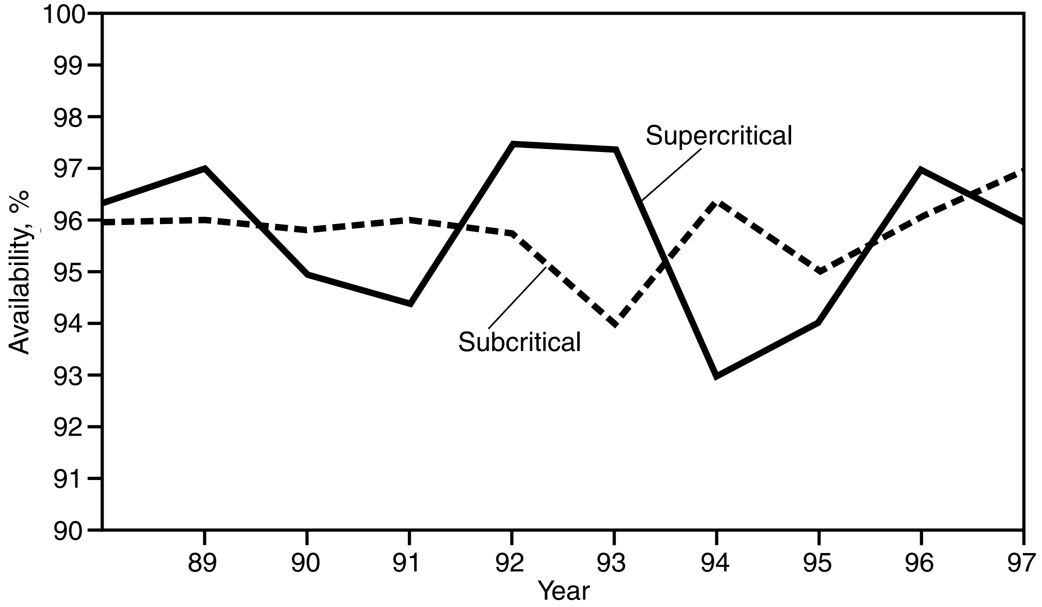


*Figure 8 Availability Comparison, German Power Plants*

## BENSON BOILER ARRANGEMENTS

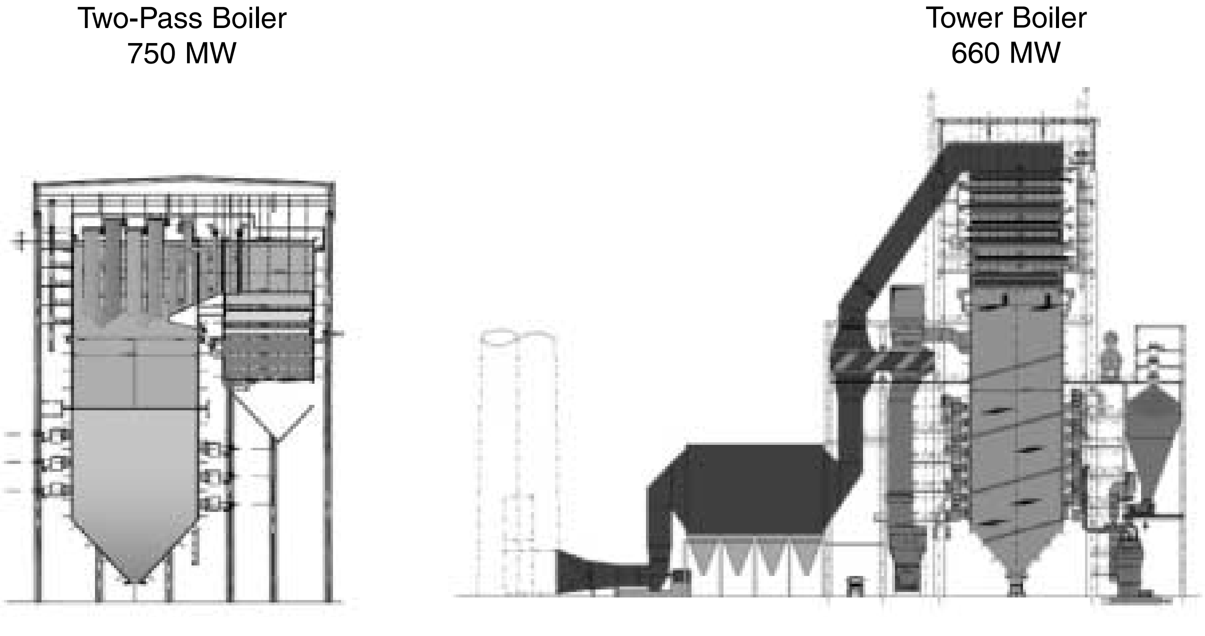
Benson boilers are designed and constructed in two basic arrangements, the two-pass or tower type. Both perform equally well. The selected arrangement is generally driven by customer preference and site-specific factors. Some particular advantages of the two-pass design are:

- Small plant profile (height);
- Lower cost construction;
- More optimized heating surface size because of decoupling back-pass from furnace section;
- Smaller stack height requirement, depending on regulations.

The tower arrangement also has certain advantages. They are:

- Small plant footprint, especially if fitted with SCR;
- Even flow distribution of flue gas and particulates;
- Lower flue gas velocity and erosion potential;
- Direct load transmission to the boiler roof and free expansion;
- No temperature differences between adjacent wall systems;
- Ease of extreme cycling operation.

Typical steam generator arrangements of these two main styles are shown in Figure 9.



Two-Pass Boiler
750 MW

Tower Boiler
660 MW

*Figure 9 Examples of Once-through Boilers*

## EXAMPLE BENSON BOILER PLANTS

### Rostock, Germany

The KNG Power unit at Rostock, Germany is a 550 MW Benson boiler design that fires world-source bituminous coals. Plant startup was in 1994. The unit is two-shifted daily with evening shutdowns and morning startups. Over 200 startups per year are performed under load ramping rates as high as 7% per minute. Boiler availability is outstanding. For the four-year period after startup, documented availability has been 98.5%. A cross-section of the boiler is shown in Figure 10. Outlet steam conditions are 1013°F (545°C) superheat, 1044°F (562° C) reheat, and 3845 psig (265 barg) pressure.

A sister, or duplicate, unit to Rostock is Unit #5 at the Staudinger Power Plant near Frankfurt, Germany. This unit burns coal with some of the widest ranges of chemical characteristics as is handled anywhere in the world. Spot market coal purchases at low pricing drives the type of fuel fired in any given week. Because of the excellent Benson boiler design characteristics, boiler performance and reliability continue to be excellent regardless of the fuel type used.

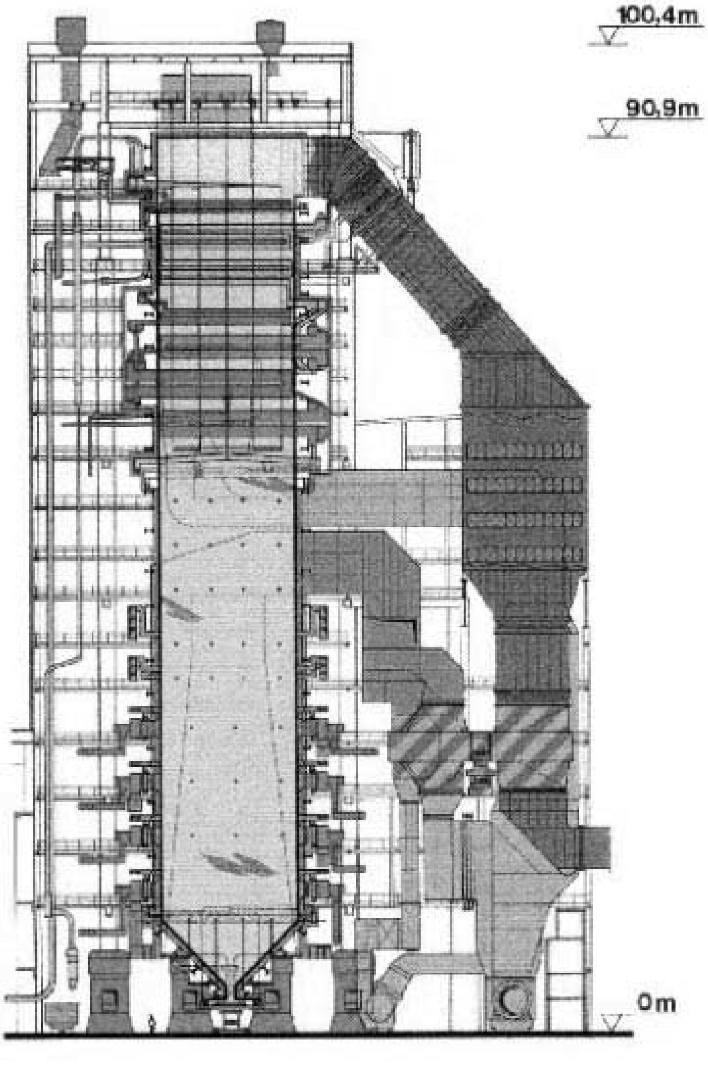


*Figure 10 PS Rostock, Germany*

### Kogan Creek, Australia

Babcock Borsig Power won the contract for Kogan Creek in 1999. The unit will produce 700 MW gross firing various types of Australian mine mouth coal. It will operate as a base-loaded unit for the first 15 years of its life and then switch to modified sliding pressure and two-shift operation. Flue gas re-circulation is utilized for reheat steam temperature control. The design is a two-pass arrangement and is shown in more detail in Figure 11.

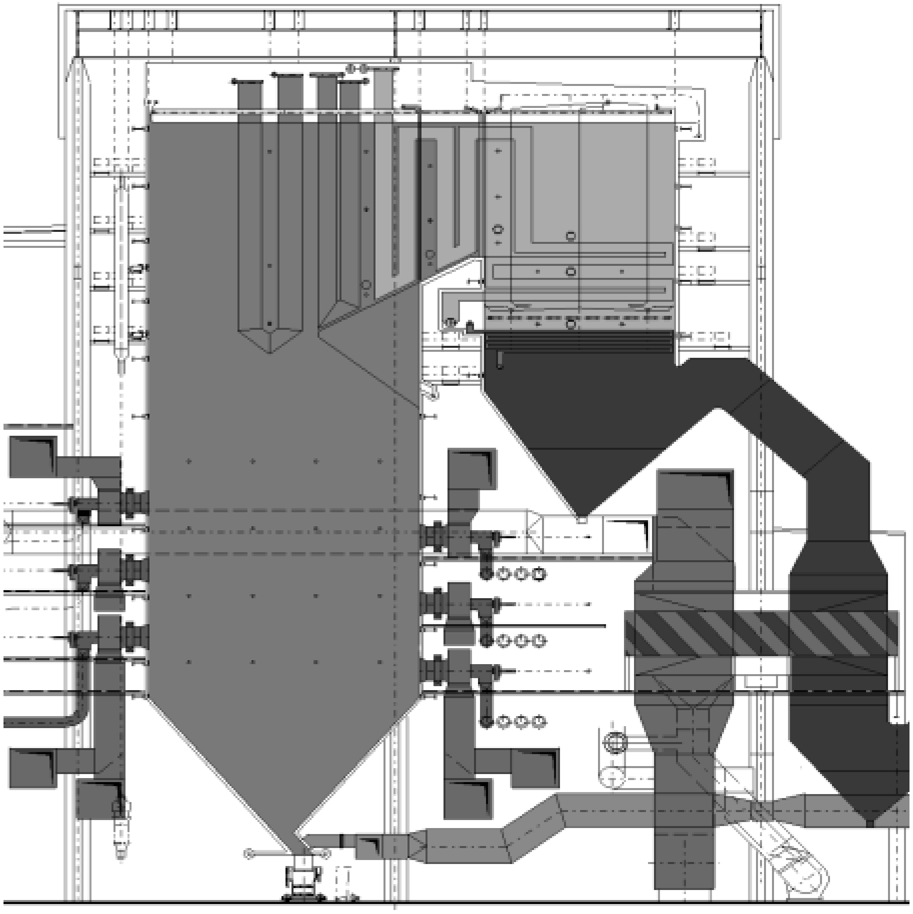


*Figure 11  PS Kogan Creek, Australia*

### Westfalen, Germany

Babcock Borsig Power is currently designing the boiler system for the Westfalen project in Germany. The plant, with output of 350 MW net, is scheduled for startup in 2004. The tower-type Benson boiler is shown in Figure 12, and is designed for world-source bituminous coal firing, with cycling operation under sliding pressure. The boiler and plant feature advanced steam parameters with corresponding plant efficiency as summarized in Table 7.

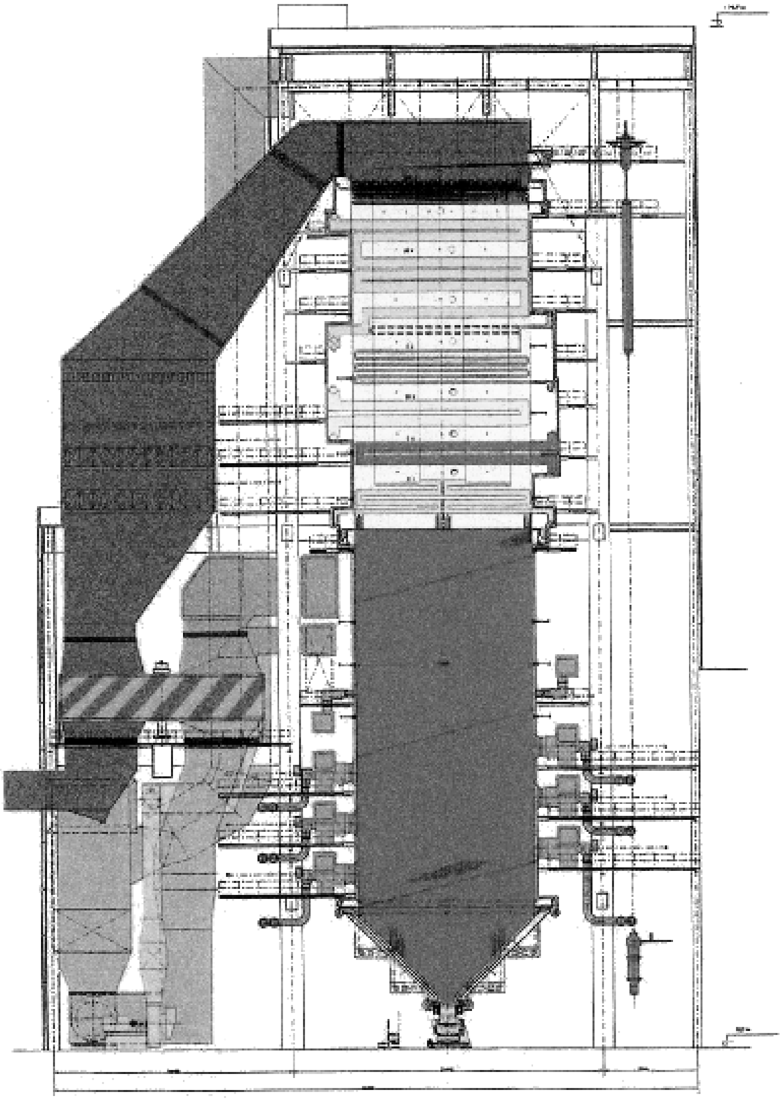


*Figure 12  Westfalen Project*

*Table 7  Westfalen Plant Design Data*

| | | |
|---|---|---|
| Main Steam Flow Rate | 2,042,077 lb/hr | (257.3 kg/sec) |
| Main Steam Pressure, at turbine inlet | 4206 psig | (290 barg) |
| SH/RH Steam Temperature | 1112 / 1148°F | (600 / 620°C) |
| Exit Gas Temperature | 239°F | (115°C) |
| Excess Air | 15% | (1.15 ratio) |
| Net Plant Efficiency | 45.31% (HHV) | (47.25% (LHV)) |

## High Efficiency Features

The high plant efficiency of plants like Westfalen is the result of positive design characteristics associated with the steam generator, turbine/generator, and balance of plant. Table 8 summarizes the plant efficiency effect of selected design features with reference to the baseline 2400 psig plant firing bituminous coal.

*Table 8 Effect of Westfalen Design Features on Net Plant Efficiency*

| **Base Net Plant Efficiency, HHV basis**<br>Typical 350 MW, 2400 psig / 1000°F/1000°F, Bituminous coal-fired | **36.50%** |
|---|---|
| Reduce stack temperature by 25 F° | +0.25% points |
| Eliminate RH spray at normal load | +0.15% points |
| Mill air / feedwater heat exchanger | +0.10% points |
| Reduce excess air from 20% to 15% | +0.05% points |
| Increase steam pressure to 4200 psig | +2.70% points |
| Increase superheat temperature to 1112°F | +0.75% points |
| Increase reheat temperature to 1148°F | +1.25% points |
| Minimize auxiliary power | +1.25% points |
| Reduce condenser pressure from 2" Hg to 1" Hg | +1.00% points |
| Reduce turbine and valve leakages | +0.73% points |
| Increase turbine sectional efficiencies | +0.50% points |
| Miscellaneous BOP efficiencies | +0.08% points |
| Total Effect | +8.81% points |
| **Design Net Plant Efficiency, HHV basis** | **45.31%** |

## SUMMARY

High efficiency coal-fired power plants are available which, through new approaches and developments in boiler, turbine/generator, and balance of plant designs, yield plant efficiencies similar to those produced with natural gas combined cycle designs.

For the case of the boiler design, the key to high plant efficiency is to utilize proven Benson supercritical arrangements with ultra-high steam pressure and temperatures and, in some cases, double reheaters. The Benson supercritical boiler enjoys a worldwide reputation of reliability and availability. Its ability to accommodate a wide range of fuels, while minimizing impact on performance, shows flexibility superior to that of any drum boiler design.

Since production of emissions is directly related to achievable plant efficiency, 20% reduction in specific mass flow rates of fuel, $CO_2$, CO, $NO_x$, $SO_x$, and particulate is the result of this new power plant design philosophy.

## REFERENCE

Schuster, H., "Benson Boilers for Difficult Coal and Wide Coal Ranges". Presented at Power-Gen Europe, Milan, Italy, June 9-11, 1998.