ULTRA-SUPERCRITICAL PULVERIZED COAL FIRED POWER PLANTS

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MIRO R. SUSTA, IMTE AG, POWER CONSULTING ENGINEERS, SWITZERLAND

WWW.MTEAG.COM info@imteag.com

ABSTRACT

Thermal power plants using conventional fossil fuels cover more than 70% of the total world's electricity production, with more than 40% coal contribution.

Currently the demand for all global energy is increasing at an average rate of approximately two percent (2%) per annum. This rate is also expected to continue in the next decade.

Since year 2000, sharp increases in price of crude oil and natural gas, coupled with steady growing demand and dwindling reserves as well as forecast of a further substantial rise in natural gas prices within a short outlook of few years together with worldwide tendency to use oil for other purposes than for power generation causes coal to enjoy its resurgence once again.

In the 21st century, the world faces critical challenge of providing abundant, cheap electricity to meet the needs of growing global population while at the same time preserving environmental values. Maintaining coal as a generation option in this century will require methods for addressing serious environmental issues.

The use of coal for power generation poses a unique set of challenges. Quantitatively, coal is the most important primary energy source with the largest reserves worldwide.

The worldwide coal-fired power plants installed capacity of about 1000GW has an average thermal efficiency of around 30%[1], much below any acceptable standards.

Therefore, the new available, modern coal-based power generation technologies as well as concepts and techniques for the reduction of negative environmental effects have to be widely commercialized and implemented to enable clean, coal-based, production of competitive power even if environment protection requirements will be tightened up in the future.

In other words, the need of further emissions reduction from coal combustion is driving growing interest in high-efficiency; low-emissions coal fired power plants.

A minor portion of reduction of GHGs from coal use may be achieved through options like CO_2 trading or credits for investing in emissions reduction projects.

However, substantial reduction in emissions from coal based power plants can be achieved only by employing most advanced and highly efficient, state-of-art, modern power generation technologies.

The most direct and economical route to this target is the evolutionary advance of increasing live steam temperatures and pressures, well beyond the critical point of water.

To allow this, advanced materials of high temperature and pressure resistance, in terms of strength, creep, and oxidation resistance, are required.

The need for higher efficiency, lower generation costs and lower emissions would extend application opportunities for wide implementation of supercritical (SC) and ultra-supercritical (USC) steam cycles.

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[1] EFFICIENCIES IN THIS PAPER REFER TO **NET LHV** EFFICIENCY.

Based on significantly higher steam temperatures and pressures, beyond those traditionally employed for conventional technology, the operating conditions of SC/USC units put new requirements on steam turbine and boiler design, particularly where the operational mode demands flexible, reliable cycling operation of power plant equipment.

USC power plants pose particular challenges for maintaining equipment reliability and flexible operation at more-advanced live steam conditions.

Many site-specific factors come into play in the selection of a SC/USC technology versus a conventional, sub-critical cycle, including the configured cycles' comparative expected reliability and availability.

INTRODUCTION AND BACKGROUND

The oldest of all power generation technologies, the coal fired, water/steam cycle based, power generation technology has been in common use for over a century.

By the end of 19th century, in 1895, three 100kW[2] radial flow Parsons steam turbine-generators were installed in Cambridge Power Station, UK, to power the first electric street lighting scheme in the city.

Early 20th century coal fired power plants were producing 1.0–5.0MW per unit (using Parsons Turbo-Generators) with live steam pressure of 1.0–1.4MPa (145-203psi) and temperatures around 200-260°C (392-500°F) reaching net plant efficiency (heat rate) no greater than 8% to 12% (42,650-28,435Btu/kWh).

At the beginning of world war I, 1914-15 military and commercial cargo ships have been driven by 6.0MW/3000rpm – 20.0MW/1000rpm STs with live steam pressure between 1.0-1.6MPa (145-232psi) and temperatures in the range of 300-350°C (572-662°F).

In its first thirty years of last century, the coal-fired power plants reduced the specific coal consumption (kJ/kW or Btu/kW) by more than 75%.

This was partly due to considerable improvements in turbine design technology, materials, unit size and mainly due to development of pulverized coal firing technology in late 1920's and early 1930's.

The latest led to higher combustion temperatures in the range of 300°C - 350°C (572°F - 662°F) giving net plant efficiency (heat rate) of 15% - 21% (22,750-16,250Btu/kWh).

Middle of last century (1950s) was a period of rapid unit size growth (from 50MW to 200MW within 5 years) and remarkable improvements in boiler and steam turbine technology.

During this period the single reheat cycle with operating pressure of 16.5MPa (2400psi) and live steam temperatures in the region of 538°C (1000°F) became commercially well established, resulting in improved net efficiency (heat rate) in the range of 28% to 30% (12,185-11,375Btu/kWh).

Late 1960s and early 1970s a first double reheat SC units were implemented be GE in USA (24.2MPa/538/552/566°C → 3510psi/1000/1025/1050°F).

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[2] POWER OUTPUTS IN THIS PAPER REFER TO **NET** POWER OUTPUT (IF NOT EXPLICITLY DECLARED AS "GROSS")

These units ranged in size from 350MW to 1000MW. With the introduction of SC technology on large thermal base load power plants during this period, net efficiency (heat rate) was boosted to level of 38% - 40% (8,980-8,530Btu/kWh).

The combination of past experience with single and double reheat units, together with the knowledge gained on the advanced steam conditions designs of the 1960s and 1970s served as the basis for implementation of advanced USC technology.

Today, operating at advanced USC steam conditions with pressures of above 30.0MPa (4351psi) and main/reheat steam temperatures of about 600/620/620°C (1112/1148/1148°F), large thermal power plants are hitting net efficiency (heat rate) level of 44% - 46% (7,755-7,420Btu/kWh).

Also America's growth has been underpinned by coal almost from the beginning in the 18th century. Coal has played a major role in electrical production since the first power plants that were built in the United States in the1880's.

Currently US has around 250 - 280 billion metric tons known coal reserves, enough coal to last over 200 - 250 years at today's level of use.

In 1903 - US first large capacity, 5MW, coal fired steam turbine-generator was placed in commercial service by the Commonwealth Edison Company in Chicago. The turbine was driven by live steam at 1.2MPa (174psi) and 190°C (374°F).

In 1929 first 'Mega' ST with power output of 208MW was put in operation in USA. This 1800rpm ST-Generator was working with live steam of 4.2MPa (609psi) and 375°C (707°F).

In 1941, 68MW ST with record live steam parameters, 16.9MPa (2451psi) and 505°C (941°F) was put in commercial operation at Twin Branch Power Plant, Indiana, USA.

Sixty-five years later, around 460GW (≈55% of the electricity produced in the country) comes from pulverized coal fired power plants in Unites States, averting the need to use large amounts of imported oil and gas for generating electricity.

However, two important questions confront us:-

- What role should coal play in the future power generation projects?
- Which power generation technology must be implemented to ensure stable, clean and affordable supplies of energy in future decades?

In conjunction with the post-world war II high oil prices caused by OPEC oil embargo in 1973-1974, the Iranian Revolution in 1979 and the recent price escalation of crude oil prices, the use of Fuel Oil (FO) for power generation in the United States has been slowing from 20% in the 1970s to around 1% last year.

Due to hardly acceptable crude oil prices and other technical and technological reasons, the role of FO in United States power generation market is expected to completely diminish during this decade.

Following LNG, the dry natural gas prices already started (even not as steep and unexpected as FO price) to follow the oil price trend.

Forecast of a dramatic rise in natural gas prices, due within an outlook of 5 to 10 years, causes coal to enjoy its resurgence once again.

According to Merill Lynch analyst Steve Fleishman statement, only Texas is planning to double the power generation capacity by adding 8.6GW of new pulverized coal fired power plants which will also replace most of existing natural gas fired plants which are already proposed for sale[3].

However, it is not known how many of these new power plant will employ SC or USC technology.

Emerging interest in new pulverized coal-fired SC/USC steam power plants has fueled development of new, cutting-edge technologies.

Power plants with record-breaking steam parameters approaching or exceeding levels of 30.0MPa (4351psi) and 600℃ (1112℉) have been commissioned during the last ten years in Japan, Korea, China, Germany, Russia and other countries.

This development can be described as an evolutionary advancement towards greater specific power output and higher efficiency.

Higher specific power output is based on improved and new materials, respectively, which are capable of sustaining higher stresses and enabling the design of bigger turbine modules, longer last stage blades as well as application of higher creep rupture stress materials for boiler furnace walls and austenitic steels for super-heater pipes.

Higher power plant efficiency has been and is being achieved by improved turbine and boiler efficiency on the one hand and by increasing the maximum steam parameter to SC/USC conditions on the other hand.

To make a clear distinguishment between SC/USC conditions, we are using ≥26.5MPa (≥3844psi) for USC conditions in this technical paper.

The advancement to limiting steam conditions is based on the improvement of thermo-dynamical efficiency by increasing the temperature and pressure at which heat is added to the power cycle.

The maximum temperatures and pressures for USC application that can be currently economically handled by state of the art ST and boiler design as well as material features are ≤30.0MPa (≤4351psi) and ≤600℃ (≤1112℉) for main steam and ≤620℃ (≤1148℉) for reheat steam conditions. Further increase in temperature capability of USC ST will certainly require the use of Ni-based super-alloys and system redesign.

However, the power industry believes that continuing development effort over the next decade will see a steam turbine under USC test operating conditions at 35.0MPa (5076psi) and temperatures of some 700 to 720℃ (1292 to 1328℉), resulting in a net efficiency (heat rate) of above 51% (6,690Btu/kWh) (Figure 1).

It is therefore, necessary, to develop appropriate USC ST and boiler material program, so that these power plant key components are available for reliable and safe USC operation.

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[3] NGI'S POWER MARKET TODAY, APRIL 24 & MAY 22, 2006

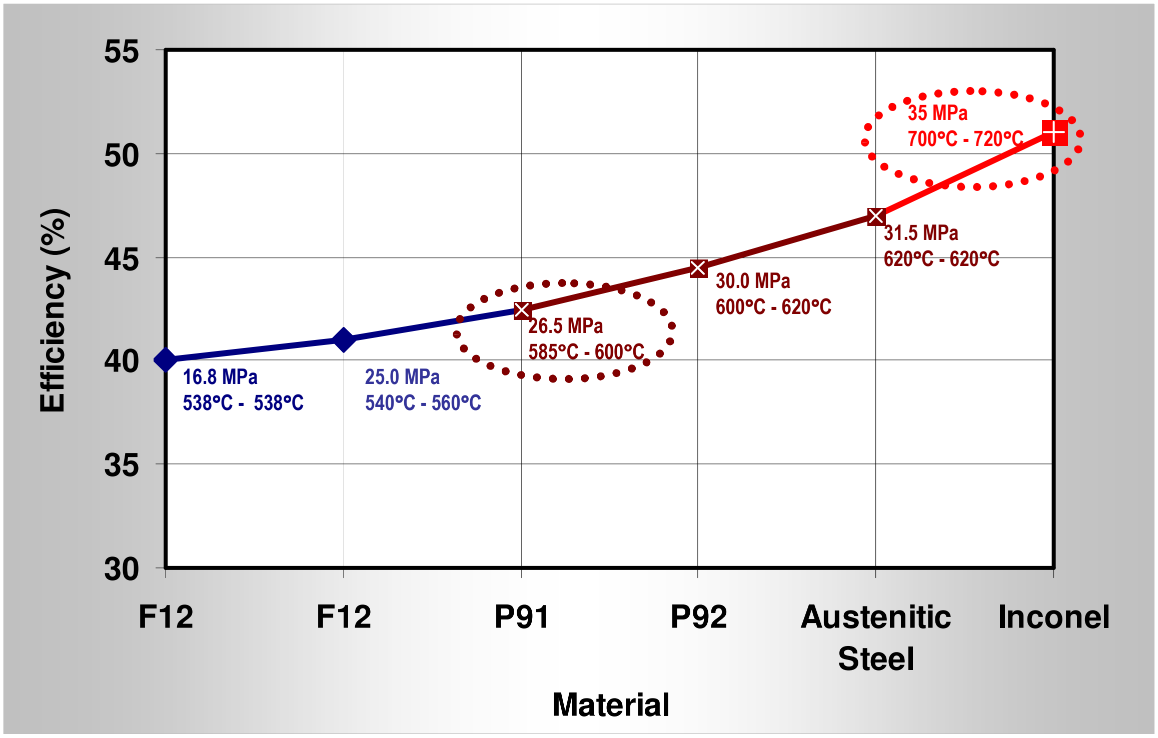

FIGURE 1
POTENTIAL INCREASE IN NET EFFICIENCY

The following properties of selected materials for high temperature and pressure components are very important for further USC development:-

- Oxidation and corrosion resistance;
- High resistance to thermal fatigue;
- Good weld-ability and cast-ability;
- Creep resistance; and
- High cycle fatigue resistance (mainly for HP blades).

USC technology can be defined as a mature high efficient fossil power generation technique, which is being continuously developed worldwide and it is listed in the category of clean coal power generation technology class. This is justified due to efficient coal utilization at lover environmental pollution.

More than 550 SC/USC units, installed in more than 400 power plants (status 2003), with total capacity above 300 GW, are in operation or under construction worldwide, including Europe, USA, Japan, Russia and number of developing countries (Figure 2).

China is now installing SC power plants as standard and Indian Government is also intensively promoting implementation of SC/USC technology for the future pulverized coal based thermal power plants.

The desire for increased efficiencies led already in the late fifties and early sixties to introduction of numerous SC/USC power plants operating at or above 565℃ (1049℉) and 24.0MPa (3481psi).

In United States, more than 155 SC/USC power plants with combined installed capacity of around 107 GW are currently in operation. But most of them came on-line prior to 1980.

One of the latest USC projects in United States is a MidAmerican Energy Company's of 790MW$_{GROSS}$ coal fired power plant at Council Bluffs Energy Center in Iowa which started construction in 2003 and is scheduled for COD in spring 2007.

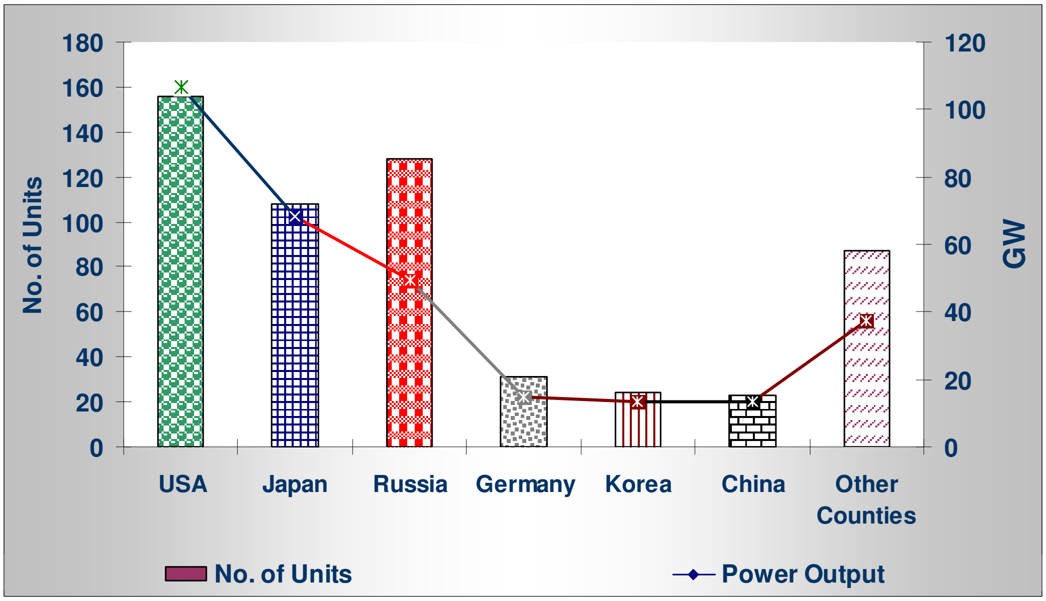

FIGURE 2
NUMBER AND CAPACITY OF SC/USC POWER PLANTS WORLDWIDE[4]

The most famous ones among USC power plants include a 120MW$_{GROSS}$ Philo 6 Power Plant[5], owned and operated by Ohio Power Company from 1957 till 1972 under design steam conditions of 31.0MPa (4500psi) and a 610/565/538°C (1150/1050/1000°F) as double re-heat temperature cycle and the famous 325MW$_{GROSS}$ Eddystone 1 Power Plant, owned and operated by the Philadelphia Electric Company since 1960.

This plant was designed to operate under steam conditions of 34.5MPa (5000psi) and 650/565/565°C (1200/1050/1050°F), however because mechanical and metallurgical problems the plant has been de-rated to 32.4MPa (4700psi) and 605°C (1125°F) and has been operating under these conditions for most of its service life.

Another well known international successful implementation example of early USC technology is 100MW unit with operating conditions of 30.6MPa/650/565°C (4438psi/1202/1049°F) in Kashira, Russia, commissioned in year 1966.

A strong decline in 1980's decade came after this boom. The main reasons for it were not only universal, like restructuring trends in the thermal power generation industry, but also ones cohering with "technological overheat" and abundant availability of price reasonable dry natural gas for power generation.

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[4] **Source USA DOE Newsletter, Winter 2003**
[5] **Designated as an ASME Historic Mechanical Engineering Landmark in August 2003**

SC/USC industry was suffering more from the bullish expansion and uncontrolled increase in the unit size rather than from extreme pressures and temperatures themselves. Before this decline, unit size had been gradually increasing from 200MW up to 500MW output within relatively short period between 1960 and 1975.

However, it is a fact that USC pulverized coal fired power plants with efficiencies of above 48% that produce less specific emissions (emissions per given power output) than sub-critical power plants have a great future in the coal fired power generation industry not only in United States but also worldwide.

ULTRA-SUPERCRITICAL TECHNOLOGY – PRESENT & FUTURE OPTION

In order to increase the efficiency of solid fuel based power generation, conventional pulverized coal fired power plants muss consistently improve steam parameters to higher levels.

Historically, it was widely foreseen that from the traditional 16.5MPa/538°C (2393psi/ 1000°F) single reheat cycle, dramatic improvements could be achieved by rising the live steam pressure to levels above 30.0MPa (4351psi) and temperatures to levels in excess of 600/620°C (1112/1148°F) resulting in a net (LHV) efficiencies of 46%-47%.

In the past decades, major arguments against SC/USC technology were more-or-less related to the higher maintenance costs and lower operational availability and reliability compared to well proven subcritical units.

Typical problems were linked to the steam turbine control valve wear, to the thermal stress and turbine blade solid particle erosion problems as well as to more complicated start-up process.

Another handicap was greater SC/USC potential for turbine water induction through the main steam system compare to drum-type subcritical units. SC/USC technology is also more sensitive to feedwater quality therefore a full-flow condensate polishing is required to protect the turbine from stress corrosion cracking.

On the other side, the SC/USC power plants which employ once-through (OT) boiler technology offers excellent higher loads operational dynamics with ramp rates in the range of 6%-8%/min compared to about 4%-5%/min for subcritical units.

Major ST designers & suppliers (namely Siemens Power Generation, GE, MHI, Alstom and others) are producing turbines capable of operating at these advanced steam conditions.

It has to be emphasized once more that limitations on achievable steam parameters are set by creep properties of currently available construction materials for high temperature boiler sections, live steam piping and other components, as well as high temperature corrosion resistance of super-heater and re-heater materials.

Higher steam temperatures make the change from ferritic steel to austenitic steel and inconel unavoidable.

For example Siemens engineers believe that continuing development effort over the next decade will see a steam turbine under test, operating at live steam conditions up to 37.5MPa/700/720ºC (5439psi/1292/1328ºF), giving a net efficiency of above 51%.

For the construction of USC power plants it is necessary to reduce investment cost and to point out an economic optimum between investment cost and efficiency. If this would be successful, CO_2 emissions from coal-fired power stations could be effectively lowered by wide application of these technologies.

In order to materialize this target a joint research project for a coal Reference Power Plant (RPP) in Germany with net efficiencies between 45.9% (basic design) and 47.3%[6] (final option with optimized pre-heating and condensing plant) was worked out in respect to optimize the economic and ecological aspects mentioned above.

This project is a very important milestone for a safe, environmentally friendly and economically justifiable power supply not only for Germany and Europe but also for other countries worldwide (Table 1).

⇒	Plant Gross Capacity	600 MW
⇒	Plant Net Capacity	552 MW
⇒	Auxiliary Consumption	8%
⇒	Plant Load Factor (PLF)	85%
⇒	ST Speed (Grid Frequency)	3000rpm (50Hz)
⇒	Average Coal LHV	25,000 kJ/kg (5971 kcal/kg – 10,748 BTU/lb)
⇒	Net Heat Rate / Efficiency	7843.1 kJ/kWh (7433.8 Btu/kWh) / 45.9 %
⇒	Live Steam Conditions	28.5MPa / 600°C (4134psi/1112°F/1148°F)
⇒	Reheat Steam	6.0MPa / 620°C (870psi/1148°F)
⇒	Feed Water Temperature	303ºC (578ºF)
⇒	Projected Investment Costs	478.5 Mio EUR (≈575 Mio USD)[7]
⇒	Specific Costs	798 EUR/kW$_{GROSS}$ (≈962 USD/ kW$_{GROSS}$)[5]
⇒	Power Generation Costs	0.0033 – 0.0035 EUR/kWh (0.00396 – 0.00422 USD/kWh)
⇒	ST Type	3-Casing, Single Reheat
⇒	Condenser Pressure	45 mbar (0.653 psi)
⇒	Boiler Type	Benson Tower with Vertical Tubing
⇒	Cooling System	Natural Draft Wet Cooling Tower (11ºC/52ºF $_{Ambient}$ - 18ºC/64ºF $_{Cooling\ Water\ Temp.}$
⇒	Steam Preheating	8-Preheter + External De-superheater
⇒	Last LP Blade	Titanium 1400 mm (55")
⇒	SOx - NOx - Particulates	200 - 200 - 30 mg/Sm^3 (0.15 – 0.15 – 0.02 lb/mil BTU)

TABLE 1
RPP-MAIN PARAMETERS

Project partners of this joint research project are German manufacturers, operators and scientific institutes, namely VGB PowerTech as coordinator, Babcock Borsing Power Systems GmbH for the steam generator, Siemens AG Power Generation for the steam turbine-generator including also the entire power plant design planning and construction.

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[6] **These values are based on inland conditions using cooling towers. Achievable net (LHV) efficiency with once-through cooling may be above 48%.**

[7] **Based on cost calculations (estimations) made in 2003.**

On the O&M side the following companies have been involved: EON Kraftwerke GmbH, Mark-E AG, RWE Power AG and STEAG AG.

RPP single reheat water-steam cycle as shown in Figure 3 mainly consists of USC (one-though) steam generator, three casing (HP-IP-LP) steam turbine, condenser with main condensate pumps, feed-water tank with pumps and LP & HP preheating lines.

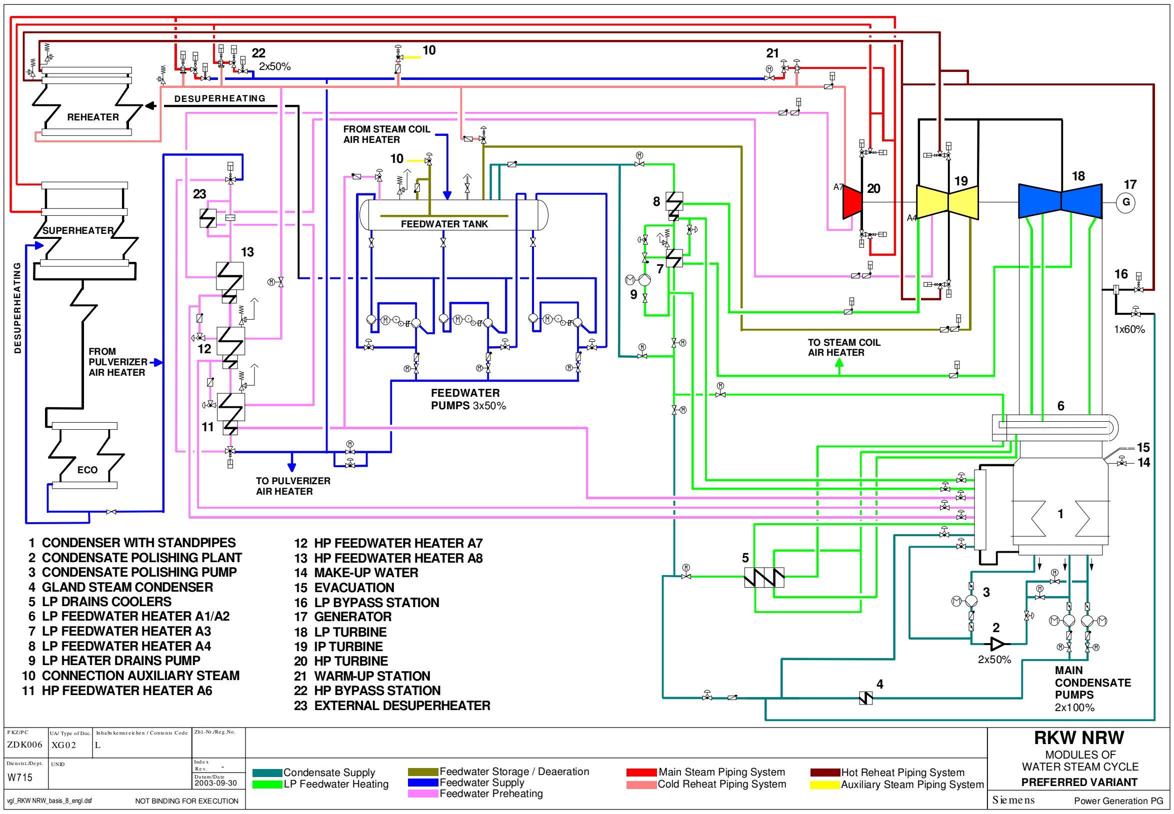

FIGURE 3
RPP WATER-STEAM CYCLE DIAGRAM[8]

Siemens and Mitsui have also embarked on a joint development program to take RPP 50Hz design basis for 60Hz applications. The resulting 60Hz USC RPP has a nominal rating 800MW$_{GROSS}$ (725MW$_{NET}$). The steam parameters of 28.5MPa/600/610ºC (4134psi/1112/1130ºF) were selected to incorporate good experience with large SC/USC, high temperature, coal fired power plants which are in operation mainly in Europe and Japan (e.g. 600MW$_{GROSS}$ Isogo, 1027$_{GROSS}$ Niedersaussen, and others.)

Today's design of a typical advanced, single reheat, ST for USC 1000MW-class applications, takes the form of a modular, tandem-compound, four- to six-cylinders arrangement with a single crossover pipe.

The live steam enters the HP turbine through main steam valves. The HP turbine has usually full arc admission and is designed for the highest steam conditions.

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[8] **Courtesy of Siemens**

Exhaust steam from the HP stage is reheated and fed to the double-flow IP turbine, being fed subsequently to the two low pressure (LP) double-flow STs via a single crossover pipe, giving a four-flow exhaust arrangement into the condenser.

The last-stage blades length for full-speed (3000rpm) 50Hz applications are up to 1140mm (45 inches) for steel and up to 1400mm (55 inches) for titanium.

WATER-STEAM CYCLE OPTIMIZATION

As stated earlier, the most important step in cycle optimization is the selection of live steam conditions, namely the pressure and temperatures, as well as optimization of feed water heating and steam rehearing system.

Even that the RPP under reference is of a single-reheat cycle, it shall be noted that since introduction of double-reheat cycle in 1960s it was clearly understood that improvement of power plant performances may be achieved by replacing the single-reheat by double-reheat cycle.

The benefits of using the double-reheat cycle are further enhanced by implementation of SC/USC pressures and temperatures.

However for any power generation application, the possible power output and efficiency gain with double-reheat must be thorough-fully evaluated against the higher investment costs attributable to greater equipment complexity in the boiler, steam turbine and piping system and at last but not least the fuel costs and environmental requirements.

Generally the selection of USC steam conditions automatically results in additional feed water heaters and higher feed water temperature.

One of the most important parts of any SC/USC power plant optimization is the selection of final feed water temperature (FWT) and reheat pressure (RP), resulting in possible improvement of relative efficiency of:-

- up to 0.8% for single-reheat; with optimum FWT of 316°C (601°F) and RP 6.0-7.0MPa (870-1015psi); and
- up to 0.5% for double-reheat; with optimum FWT of 327°C (621°F) and first RP 9.5-10.0MPa (1378-1450psi) and second RP 2.5-3.5MPa (363-508psi)

Another very important factor for cycle optimization is the steam temperature at LP ST inlet. The maximum allowable LP ST inlet temperature is limited by material considerations, mainly the rotor and cross-over hood. That why the optimization of RP and cross-over pressure (COP) and temperature plays a very important role in the cycle optimization. Typical recommended, guideline values for double-reheat cycle 31.0MPa/ 600/610/610°C (4496psi/1112/1130/1130°F):

FWT=327°C (621°F) ⇒ 1st RP=9.5MPa (1378psi) ⇒ 2nd RP=3.5MPa (508psi) ⇒ COP=1.0MPa (145psi)

STEAM GENERATOR (BOILER)

Boilers for power generation are either "drum" or "OT" types, referring to how water is circulated to cool the tubing.

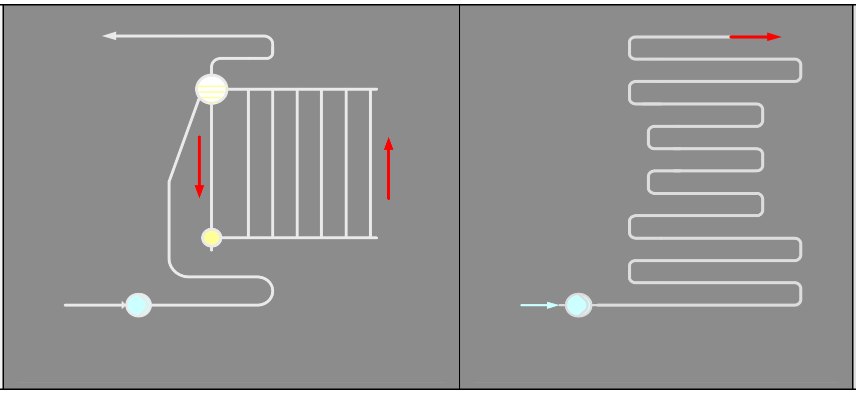
In drum-type units, the steam-flow rate is controlled by the fuel-firing rate only. Superheated steam temperature is determined by properly sizing the superheater heat-transfer surface, and is controlled by spray water.

In OT type boiler, the steam-flow rate is established by the boiler feedwater pump and the superheated steam temperature is controlled by the fuel-firing rate. Simple comparison between drum-type and OT boiler is shown in Figure 4.

Drum Type

Operating Pressure
1.0 – 18.0MPa

Water Wall Tubing
Vertical



OT Type

Operating Pressure
2.0 – 40.0MPa

Water Wall Tubing
Spiral
or
Vertical

Figure 4
Schematic Principle of Drum-Type vs. OT Type Boiler

Two types of SC/USC OT boiler designs are currently in use, those that operate with a constant pressure in the furnace tubes and those that vary pressure with load.

The latter is the popular design for SC/USC boilers today because it is not only more efficient at lower loads, but in combination with a circulation pump, it can also be cycled on and off much more rapidly.

These features permit the operator to follow the system demand more effectively. The constant pressure design, with vertically oriented tubes, has been used primarily in United States while the variable pressure design, with spiral tubes wrapped around the furnace, has been dominant in Europe.

The spiral design utilizes fewer tubes to obtain the desired flow per tube resulting in great benefit of passing all tubes through all heat zones to maintain a nearly even fluid temperature at the outlet of the lower portion of the furnace. However, the fabrication and erection of spiral design are considerably more complicated and costly.

On the other side, because of its relative simplicity and ability to self-support, the vertical tube furnace design is significantly less costly and easier to fabricate and construct than the spiral variable pressure furnace.

The ideal furnace design for an OT boiler would have vertical tubes and capability to operate with variable pressure operation over the load range while exhibiting natural circulation characteristics, thus protecting the tubes from overheating.

These characteristics should be achieved with as low a flow per tube as practical to obtain a low friction resistance to promote natural circulation, minimize furnace pressure loss, and reduce the pump power required.

Such design represents a significant advancement for tube protection in once-through boiler circulation technology.

Figure 5 shows schematic furnace arrangements for the high mass flow constant pressure vertical tube and spiral variable pressure designs as well as the relatively new advanced low mass flow vertical tube variable pressure design.

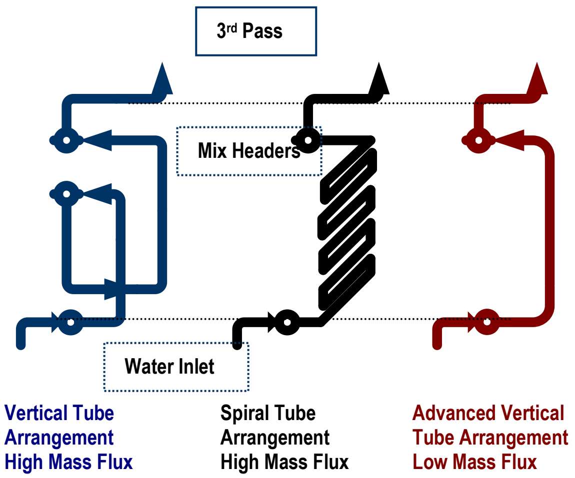


FIGURE 5
OT BOILER FURNACE ARRANGEMENTS

Since the OT boiler does not rely on the density difference between steam and water to provide proper circulation and cooling of the furnace enclosure tubes, it can be operated at SC/USC pressures, in other words:-

-*considering elevated steam conditions, OT boiler is the answer; only OT boiler can generate SC/USC pressure steam*-.

With about 1000 units built, the Benson boiler is by far the most widespread OT boiler (around 60% of all OT boilers). The following maximum operating parameters have been achieved with Benson Boilers:

- Output up to 1232 kg/s (2716lb/sec) [4435 t/h]
- Pressure up to 31.0MPa (5076psi)
- Temperature up to 650°C (1202°F)

The variable evaporation endpoint in Benson boilers enables achievement of high live steam temperatures over a large output range independent of operating conditions (i.e. also the load). This results in higher process efficiency for the power plant over a wide load range.

The fuel/feedwater flow ratio is controlled in the Benson boiler such that the desired steam temperature is always established at the live steam outlet. This is made possible by the variable evaporation endpoint.

The evaporation and superheating surfaces automatically adjust to operating conditions. In dynamic processes, desuperheaters support maintenance of constant live steam temperature.

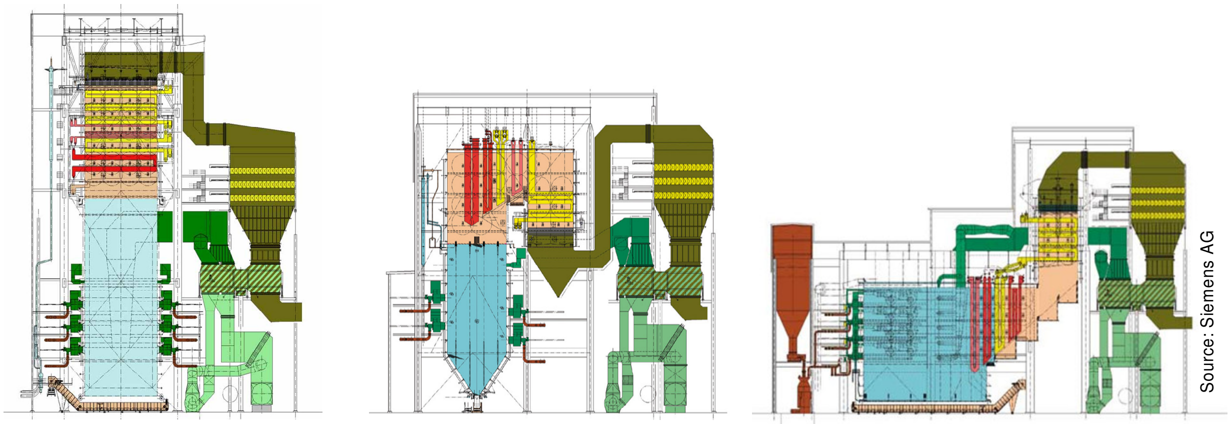
Minimum output in OT operation at high main steam temperatures is 35% to 40% for furnace walls with smooth tubes and is as low as 20% if rifled tubes are used.

The size and geometry of the furnace of a Benson boiler can be optimally matched to the fuel with no restrictions on the water/steam side. The Benson boiler enables dimensioning of the furnace based solely on combustion engineering aspects:

- The transition from evaporation to superheating is not fixed in location and can take place at any point in the upper section of the furnace. This enables dimensioning of the furnace without restrictions on the water/steam side.

- Forced flow in the evaporator tubes also enables implementation of complex furnace geometries such as for slag tap firing.

Figure 6 shows single-pass (tower-type), two-pass, and horizontal OT boiler. Al three types were investigated in the RPP concept study. The single-pass has the lowest mass of steel and pressure parts; on the other side the horizontal boiler has the advantages of short external piping. However, the economic evaluation of all three alternatives made the single-pass boiler the preferred alternative.


Source: Siemens AG

Floor space: 2,975 m²
Volume: 166,000 m³
Efficiency: 95%

SINGLE-PASS

Floor space: 4,164 m²
Volume: 197,000 m³
Efficiency: 95%

DOUBLE-PASS

Floor space: 4,600 m²
Volume: 209,000 m³
Efficiency: 95%

HORIZONTAL

FIGURE 6
DIFFERENT OT TYPE BOILERS[9]

Latest design of Benson Type OT boiler created within the EU-sponsored program Thermie 700, developed by Siemens, is based on horizontal furnace and internally rifled vertical pipes. Internal rifling is a microspiral grooved within the tubes.

It makes the medium inside the pipes to rotate along its trajectory and to throw the cooling medium droplets against the pipe walls via excentrical force (induced swirl). Cooling effect is boosted considerably in this manner.

The outstanding heat transfer characteristics of the optimized rifled tube can be utilized to reduce either tube wall temperatures or mass fluxes in rifled tubes. Boiler design technology is currently following the trend of ever higher creep rupture stress material.

Such are steels P91 to P92, austenitic steels 18-8 to 18-25 like Super 304H, Esshete 1250 as well as the high nickel alloys like Inconel 718 as shown in Table 2.

SC and USC power plants in Europe and Japan have already proven that P92 steel can handle the very high stresses under SC and USC steam conditions. Also in United States, ASME has approved the use of P92 steel in utility boilers, pressure vessels, and power plant HP piping.

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[9] Courtesy of Siemens

P92 is being heralded as a superior and lower-cost alternative to P91 steel for new power plants with pressures above 250bar (3626psi) and temperatures above 595°C (1103°F) applicable for SC/USC units proposed to be built in United States over the next few years. The switch from P91 to P92 would represent the next step in an evolution.

The extra costs of using nickel based alloys can be partly compensated by reduction in the amount of material, because of thinner pipe walls and smaller dimensions of machinery. Also austenitic steel slightly reduces the wall thickness.

Live steam		When	What	Equivalent to
Pressure MPa (psi)	Temperature °C (°F)			
<20.0 (<2900)	<520 (<968)	Since early 60's	X20	Cr Mo V 11 1
<25.0 (<3626)	<540 (<1004)	Since early 80's	P22	2 ¼ Cr Mo
<30.0 (<4351)	<560 (<1040)	Since late 80's	P91	9Cr – 1Mo
<33.0 (<4786)	<620 (<1148)	Since 2004	P92	X10CrWMoVNb9-1 EUROPE STBA29-STPA29 JAPAN
<35.0 (<5076)	<700 (<1292)	Start 2010	Super Alloys	CCA 617 - IN 740 – Haynes 230 – Save 12

TABLE 2
COAL FIRED POWER GENERATION-BOILER TEMPERATURE & MATERIAL DEVELOPMENT

This may appear to become the decisive factor for even more intensive expansion of SC/USC technology, because this particular problem of extremely high cost of special steels and alloys was traditionally the main obstacle with even wider application of SC/USC technology. For example, the achievement of the goals of EPRI program shall produce the capability to construct and operate a boiler to USC conditions of 760°C (1400°F) and 35.0MPa (5076psi).

The objective task of another program supported by DOE is to develop new-generation corrosion-resistant Mo-Si alloys for use as hot components in advanced fossil energy conversion and combustion systems in order to improve the thermal efficiency and to increase the service life of hot components exposed to corrosive environments at temperatures as high as 1600℃ (2912°F).

STEAM TURBINE

Future development of high efficiency advanced ST at advanced USC conditions is largely dependent on the parallel development of advanced materials and super-alloys capable of withstanding the extreme working environments both in terms of corrosion resistance and their creep rupture strength.

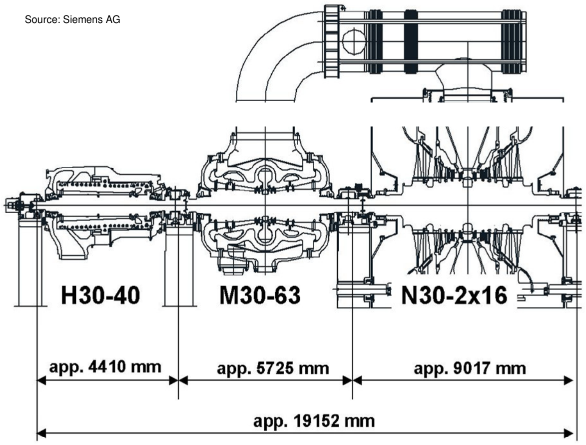
The optimum design figure for creep resistance after 100,000 hours as a function of temperature for steam turbine components is 100MPa (14504psi). Within these parameters, the upper temperature limit for chromium steel alloys with between 9% and 11% Cr is 620℃ (1148℉). Research which was currently carried out to extend the application range up to 650℃ (1200℉) has still not been successful (due to current non-availability of suitable materials).

The appropriate USC ST design and configuration is mainly determinated by unit output rating, LP back-pressure, number of reheats selected and other special requirements (e.g. process steam extraction).

STs for USC duty are an extra category among the family of steam turbines. Typical feature of modern USC STs is the relatively high capacity (between 300MW and 1300MW) and multi-casing (HP-IP-LP) design. Cross-section of 552MW, three-casing UST ST (with single double-flow IP and LP casing) designed by Siemens for RPP project is shown in Figure 7. In comparison to 50Hz ST (3000rpm) the rotating components of 60Hz ST (3600rpm) are exposed to higher centrifugal forces caused by higher operating speed (factor 1.44).

Due to scale-down of the last stage blade (LSB) from 50Hz to 60Hz application, the reduced steam exhaust area for single double-flow LP ST would be too small, resulting in low power output. That why it is recommendable to apply two double-flows LP sections with using smaller, 38" (965mm), LSB.

Internal design of SC/USC ST technology has undergone a long evolutionary development. Using CFD (Computational Fluid Dynamics) software, hydrodynamic regime and blade shaping has been processed on the basis of 3-dimensional (3-D) analysis, or advanced three dimensional analyses (3-DS).


Source: Siemens AG

In this way a complete range of new high-efficiency 3-DS ST blading has been developed.

Adopting the new design philosophy, Siemens has developed a new type of blading for HP and IP turbine, which in addition to the 3-D blade shape, allows also the reaction of each stage to be set on individual basis.

FIGURE 7
552MW, 3-CASING USC ST[10]

Known as 3-DV (3-D blading with variable stage reaction), the new variable reaction design is based on an extension of Siemens' existing, well-proven 3-DS blading. 3-DV blading combines the benefits of both, multistage reaction blading and low reaction impulse blading, because it offers greater design freedom.

There might be an optimal value regarding efficiency if a single stage is analyzed, but there is no clear answer for multi-stage blading that provides the most efficient solution with a uniform value for the stage reaction.

With 3DV blading the stage reaction and stage loading for each row can be numerically optimized to gain higher HP and IP efficiency than was possible with previous blading types, resulting in significant improvement in overall plant efficiency.

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[10] COURTESY OF SIEMENS

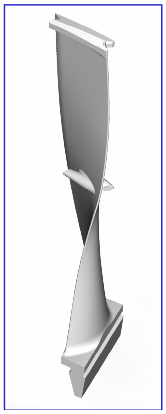
To reduce windage losses, modern USC turbines have the rotor blades fully shrouded by internal shroud blading (ISB). Usually, only the LSB row in the LP ST-section is free-standing, because of the high centrifugal forces acting in that area.

The exhaust diffuser provides for pressure recovery of the exhaust steam so that the exit pressure from that blading can be lower than the condenser pressure. MHI apply in their 1050 MW (reportedly the biggest and most efficient 60Hz SC turbine ever built) the longest 46" (1170 mm) LSB (refer to Table 4, Tachibana-Wan 2[11]).

Application of titanium alloys to the long last stage LP ST has been in development for more than 30 years and now it became a commercial reality.

Titanium blades which are already used for LSB are immune to pitting corrosion by the corrosive early condensates and are of relatively low weight resulting in lover centrifugal forces.

A disadvantage of titanium alloys is their low vibration damping capacity, which requires an addition of integral shroud and a mid-snubber for improvement of blade dynamic stability by maximizing of mechanical and aerodynamic damping.



Design features 16 m^2 - last stage blade	
• Rotor diameter	~ 1900 mm
• Blade length	1400 mm (55´´)
• Velocity at blade end	750 m/s (~ Ma = 2.0)
• Mach-number	Supersonic at blade end
• Blade connection	Shroud & snubber
• Exit losses	3D effects

Source: Siemens AG

FIGURE 8 LP ST 16M^2 TITANIUM LSB

Siemens is using 55" (1400 mm) titanium alloyed LSB's for their large 50Hz LP STs (38"/965mm for 60Hz grid). The profile of this blade has a 3-D design and shrouding with supporting snubber in the middle of the profile as shown in the Figure 8.

Tip clearance losses at the blade tip are reduced by the integral shrouding.

Additionally the integral shroud and the mid span snubber give an excellent dynamic stability of the entire stage. Advanced material application, especially of titanium for the LSB with lower density allows longer blades to be used and thus the exhaust annulus area to be increased.

The smaller LP blades are made of high chromium steel and are usually also equipped with integral shrouds to minimize leakage losses.

Advanced materials to be used for HP SC/USC turbine components are of higher quality grade compare to the conventional steam conditions of 538°C.

High pressure SC/USC ST materials - comparison of 700°C - 620°C class to conventional 560°C class for 50Hz grid is shown in Table 3.

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[11] CROSS-COMPOUND MACHINE WITH THE HP AND IP CYLINDERS POSITIONED ON THE HIGH-SPEED SHAFT (3600 RPM) AND TWO DOUBLE-EXHAUST LP CYLINDERS ON THE LOW-SPEED SHAFT (1800 RPM).

Main steam temperature	≤560°C	≤620°C	≤700°C
Rotor	1Cr Mo V forging 12Cr Mo V Nb N 26Ni Cr Mo V11 5	9-12Cr W Co forging 12Cr Mo W V Nb N	IN 625 / IN 740 CCA 617 Haynes 230
Nozzles / Valves	Cr Mo V Cast 10Cr Mo V Nb	9-10% Cr (W) Cast 12Cr W (Co)	CCA 617 IN 625 / IN 714
Inner Casing & Shells	1-2 Cr Mo Cast Cr Mo V Cast 9Cr 1Mo V Nb (up to 590°C)	9-12% Cr (W) Cast 12Cr W (Co)	CCA 617 IN 625 IN 740 (up to 760°C)
Blading	10Cr Mo V Nb N Titanium (last rotor row)	9-12% Cr W Co Titanium (last rotor row)	Wrought Ni-Base Titanium (last rotor row)
Bolting	9-12% Cr Mo V NI 80A IN 718	9-12% Cr Mo V IN 718	Nimonic105 / 115 / 718 Allvac 718 Plus Waspaloy

TABLE 3
COAL FIRED POWER GENERATION- ST TEMPERATURE & MATERIAL DEVELOPMENT[12]

The thermodynamic performance of the ST, more than any other plant component, determines overall power plant efficiency.

SC/USC ST improved design features include not only improved aerodynamics and application of most advanced materials but also new high-speed control valves, unique shaft and inlet seals, and many other innovations required for power plant safe and highly reliable operation.

Since the different parts of the ST are exposed to different stress-temperature-environment conditions for a given set of steam entry conditions, the distribution of these conditions needs to be defined in order to define the material properties required.

The steam conditions envisaged for the future USC ST generation (760°C/1400°F and 35.0MPa/5076psi) are well beyond the envelope of current experience.

The lack of materials with the necessary required resistance to creep, oxidation, corrosion, and thermal fatigue at the envisaged live steam temperatures and pressures currently limits the adoption of advanced USC steam conditions in pulverized coal-fired power plants.

SUPERCRITICAL STATE-OF-THE-ART

The dominant worldwide installed technology for coal fired power generation is still the subcritical pulverized coal fired technology.

However, in some regions, SC power plants with high efficiencies are now the standard for new generation equipment.

USC power plants, which can operate at even higher efficiencies (above 50%) are being developed in Europe, USA and Japan.

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[12] DUE TO THE HIGHER ST OPERATIONAL SPEED IN A 60HZ GRID, THE TEMPERATURE LIMITS FOR THE MATERIALS WILL BE SLIGHTLY DIFFERENT (FOR EXAMPLE ADDING OF BORON & COBALT FOR 9-12%CR STEEL TO INCREASE CREEP RESISTANCE AND REDUCE OXIDATION)

Comparing to subcritical pulverized coal-fired power plants, SC/USC technology is one example of a “clean coal” technique that burns coal more efficiently (currently up to 45% compared with an average of around 36% for subcritical units → IEA Clean Coal Centre 2002) and with fewer emissions.

SC/USC is an emerging technology with limited construction history, although it has been used more extensively in countries such as United States, Russia, Japan, Germany, Italy and Denmark.

The following Table 4 illustrates some selected projects representing state-of-the-art SC/USC technology with reputable parameters that have already been commissioned, or are currently under construction:

Pos	Power Plant Name	Country	Power Output MW_{GROSS}	Live Steam MPa /°C /°C (psi /°F /°F)	COD
01	Council Bluffs	USA (IA)	790	25.5 / 565 / 565 (3690/1050/1050)	2007
02	Weston 4	USA (WI)	500	26.2 / 580 / 580 (3800/1076/1076)	2007
03	Comanche 3	USA (CO)	750	26.2 / 570 / 570 (3800/1055/1055)	2009
04	Elm Road 1 & 2	USA (WI)	2 x 600	26.2 / 570 / 570 (3800/1055/1055)	2009
05	Iatan 2	USA (MO)	900	25.5 / 585 / 585 (3686/1085/1085)	2010
06	Genesee 3	Canada	495	25.0 / 570 / 568 (3626/1058/1054)	2005
07	RPP NRW_{60Hz}	USA	800	28.5 / 600 / 610 (4134/1112/1130)	2010[12]
08	Lippendorf	Germany	934	26.7 / 554 / 583 (3873/1029/1081)	1999
09	Boxberg 1	Germany	907	26.6 / 545 / 581 (3860/1013/1078)	2000
10	Niederaussem	Germany	1027	27.5 / 580 / 600 (3989/1076/1112)	2003
11	RPP NRW_{50Hz}	Germany	600	28.5 / 600 / 620 (4134/1112/1148)	2008[13]
12	Boa 2 Neurath	Germany	2 x 1100	26.0 / 595 / 595 (3771/1103/1103)	2010
13	Nordjylland 3	Denmark	411	29.0 / 582 / 580 (4206/1080/1076)	1998
14	Avedoere 2	Denmark	450	30.0 / 580 /600 (4351/1076/1112)	2002
15	Hemweg 8	The Netherlands	680	26.5 / 540 / 568 (3844/1004/1054)	1994
16	Tachibana-Wan	Japan	1050	25.9 / 600 / 610 (3756/1112/1130)	2000
17	Hitachi-Naka 1	Japan	1000	25.4 / 604 / 602 (3684/1119/1116)	2003
18	Isogo 1	Japan	600	28.0 / 605 / 613 (4061/1121/1135)	2002
19	Changshu	PR China	3 x 600	24.8 / 543 / 571 (3684/1009/1060)	2006
20	Wangqu	PR China	2 x 600	27.5 / 571 / 569 (3989/1060/1056)	2007
21	Waigaoqiao	PR China	2 x 900	27.9 / 542 / 562 (4047/1008/1044)	2004
22	Zouxian IV	PR China	2 x 1000	27.0 / 600 / 600 (3916/1112/1112)	2008
23	Huaneng	PR China	4 x 1000	26.5 / 600 / 600 (3844/1112/1112)	2008

TABLE 4
SELECTED SC/USC POWER PLANTS IN OPERATION OR UNDER CONSTRUCTION

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[13] TARGETED COD

Very interesting fact is that the Boxberg 1 USC (Table 4, Pos. 09) and Tachibana-Wan SC power plant (Table 4, Pos. 16), achieved net (LHV) efficiency of 42.7% (Boxberg) and 43.1% (Tachibana-Wan). Such extremely close efficiency values were achieved with STs at substantial different steam conditions.

According to MHI, only a steam temperature increase from 538/593ºC (1000/1100ºF) to 600/600ºC (1112/1112ºF) improves the net efficiency by about 1.1%. On the other side, according to Siemens engineers, raising both, the steam pressure and temperature from 25.0Mpa/540/560ºC (3625psi/1004/1040ºF) to 27.0MPa/585/600ºC (3915psi/ 1085/1112ºF) increases the net efficiency by about 1.3-1.5%.

So, closeness of the actual efficiency values for the same capacity class turbines with remarkably different steam temperatures, and with regard to similar condenser pressure in the range says that at least one of these STs have noticeable reserves to increase the efficiency.

However, these most impressive efficiencies which have been reached at Boxberg and Tachibana-Wan power plant have been beaten by Siemens at Niederaussem Power Plant (Table 4, Pos. 10). This power plant which is working at more elevated steam conditions, 27.5MPa/580/600ºC (3989psi/1076/1112ºF), reached a net efficiency of 45.2%. An even higher net efficiency is targeted for Westfalen's Unit D, with a single capacity of 350MW designed for steam conditions of 29.0Mpa/600/620ºC (4210psi/1112/1148ºF).

Also higher efficiencies are expected from latest Japanese coal fired USC power plants with improved steam conditions in the range of 30.0Mpa/630/630ºC (4350 psi/1166/1166ºF) in this decade.

Based on the present level of experience as well as depending on the future live steam conditions and other process parameters net (LHV) power plant efficiencies in the range over 50% may be achieved with USC technology in the next decade.

Summary

The coal is the most abundant and widely spread fossil energy resource worldwide and pulverized coal fired power plants currently account for more than 40% of electrical power produced in the world.

In view of the coal long range reserves', increasing importance is to be attached to improve their worldwide utilization.

Probably most of the coal fired power plants to be build worldwide during next decades will be of:-

- Pulverized coal fired SC/USC technology; and/or
- IGCC technology[14]

Expected reduction in specific investment costs combined with low emissions makes these technologies preferable options for future power generation.

The current state-of-art technology USC pulverized coal based power plants are working with net efficiency (heat rate) in the range of 44-46% (7,755-7,420Btu/kWh).

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[14] **References VI**

To achieve an economically optimized pulverized coal-fired power plant, the cycle conditions under which such plant shall operate need to be carefully evaluated taking into account miscellaneous important parameters as the live steam conditions, feed water arrangement as well as number of reheats employed.

Industrial-scale power plants with SC and USC steam conditions are in operation or are under construction in many countries worldwide. These power plants reach net electric efficiencies of over 40%. The specific coal consumption thus decreases considerably.

To open up further efficiency potentials, the electricity supply industries are developing even more advanced power plant concepts using advanced materials for boiler and ST. It will thus be possible in the future to step up the efficiency by 4 to 5%. Beyond 2010, these power plant concepts would allow net efficiency (heat rate) potentials of 48 to 50% (7,110-6,825Btu/kWh).

The development of new alloys for boiler and ST can push the efficiency (heat rate) to 50-52% (6825-6562) in 2020 and further development could offer 52-55% (6,560-6,200Btu/kWh) efficiency (heat rate) in 2050[15].

The assurance of long-term prospects for coal in the industrialized countries constitutes a decisive precondition necessary to develop the advanced technologies there and also apply them in the developing and threshold countries as required by the envisaged sustainable development.

Overall outlook for pulverized coal-fired SC/USC power plant technology is promising and its further growth lies ahead.

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Major Acronyms & Abbreviations:

CFD	Computational Fluid Dynamics
COD	Commercial Operation Date
COP	Cross-Over Pressure
CSD	Computational Fluid Dynamics
DOE	Department of Energy
EU	European Union
EPRI	Electric Power Research Institute
FO	Fuel Oil
FWT	Feed Water Temperature
GE	General Electric
GHG	Green House Gas
HP	High Pressure
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IP	Intermediate Pressure
ISB	Internal Shroud Blading
LHV	Low Heating Value
LNG	Liquefied Natural Gas
LP	Low Pressure
LSB	Last Stage Blade
MHI	Mitsubishi Heavy Industries
NG	Natural Gas
NGI	Natural Gas Intelligence
OPEC	Organization of the Petroleum Exporting Countries
OT	Once-Through
RP	Reheat Pressure
RPP	Reference Power Plant
SC	Supercritical
ST	Steam Turbine
Sm^3	Standard Cubic Meter
USC	Ultra-Supercritical
USC	Ultra-Supercritical