

TECHNOLOGY STATUS REPORT

SUPERCRITICAL STEAM CYCLES FOR POWER GENERATION APPLICATIONS

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Aalborg Unit 3 double-reheat supercritical 285bar/580°C/580°C/580°C 412MW_e coal-fired plant at Vendsysselværket, Denmark

SUMMARY

Current state-of-the-art supercritical steam power generation plant operate at up to 300bar and 600°C, with net efficiencies, firing coal, of around 45% (lower heating value, LHV, basis) depending on coal type and plant location. Much work has been carried out over the last 20 years to develop new steels for these plant, both for the boiler and the steam turbine. A number of new steels are currently being tested which could allow steam temperatures up to 650°C; nickel (Ni)-based alloys are under consideration for higher temperatures.

Steam temperatures and cycle efficiencies have been steadily improving and this trend is expected to continue. State-of-the-art plant are expected to operate at 620°C within the next five years, and at 650-700°C by 2020, with cycle efficiencies perhaps in the range 50-55%.

In addition to work on materials, research and development (R&D) to optimise all aspects of the steam cycle is under way. Such work is aimed at improving plant auxiliaries and cycle layout and optimisation, increasing feedwater temperatures, and reducing flue gas temperatures. The use of vertical furnace-wall tubing may represent a significant imminent advance.

Modern supercritical technology is currently largely restricted to Japan and Western Europe. However, it is now being transferred to other regions. South Korea and China, for example, are starting to use supercritical technology. Developing countries such as these have a considerable demand for new power generation capacity and a substantial market for supercritical steam technology is therefore developing, albeit predominantly with moderate steam conditions. The growing use of supercritical steam cycles is being driven largely by the need to minimise the environmental impact of power generation. In Europe, environmental concerns are particularly strong, with ambitious targets for reducing carbon dioxide (CO₂) emissions agreed in the Kyoto Protocol on Climate Change in 1997. Even in the Far East, environmental requirements are tightening and look set to tighten further. Future supercritical plant sales are difficult to predict, but current estimates suggest a steady rise from ~5GW per annum (pa) now to 25-40GW pa within 20 years.

BENEFITS OF THE TECHNOLOGY

The principal advantages of supercritical steam cycles are:

- reduced fuel costs due to improved thermal efficiency
- CO₂ emissions reduced by about 15%, per unit of electricity generated, when compared with typical existing subcritical plant
- well-proven technology with excellent availability, comparable with that of existing subcritical plant
- very good part-load efficiencies, typically half the drop in efficiency experienced by subcritical plant

- plant costs comparable with subcritical technology and less than other clean coal technologies
- very low emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulates achievable using modern flue gas clean-up equipment.

DEPARTMENT OF TRADE AND INDUSTRY SUPPORT

Since 1990, the Department of Trade and Industry (DTI) has supported six projects associated with supercritical steam cycles for power generation applications, contributing £684,000 to a total cost of £1.72M.

INTRODUCTION

Subcritical steam cycles, which represent the current dominant technology for converting heat from fuel into electricity, operate well below the steam/water critical pressure of 221.2bar. Plant thermal efficiency and, therefore, environmental performance are enhanced by increasing the operating temperature and pressure. The drive for higher efficiency resulted in the development of numerous supercritical designs in the 1950s and 1960s. These early designs were unreliable and expensive, and had poor operational flexibility; this meant most countries (including the UK) chose to retain predominantly subcritical technology. However, development continued, particularly in Europe and Japan, and today supercritical steam is the leading 'clean coal' technology in widespread application. Currently ~10% of orders for new coal-fired power generation plant are for supercritical steam cycles, amounting to ~5GW of new plant.

Supercritical steam cycles are not just applicable to coal-fired plant. Oil- and gas-fired plant are also well proven, with developments under way to extend the technology to fluidised bed combustors (FBCs), and also to heat recovery steam generators (HRSGs) for combined-cycle gas turbine (CCGT) plant. Nevertheless, pulverised fuel (pf) firing, in which the coal is finely ground, is the dominant application of supercritical technology, and is also currently the most technically complex application.

Figure 1 shows a simplified process diagram of a pf plant. The steam cycle (shown) only forms part of the process. Other areas, such as flue gas treatment, are independent of the steam cycle and are discussed later only in regard to their impact on cycle efficiency and marketability.

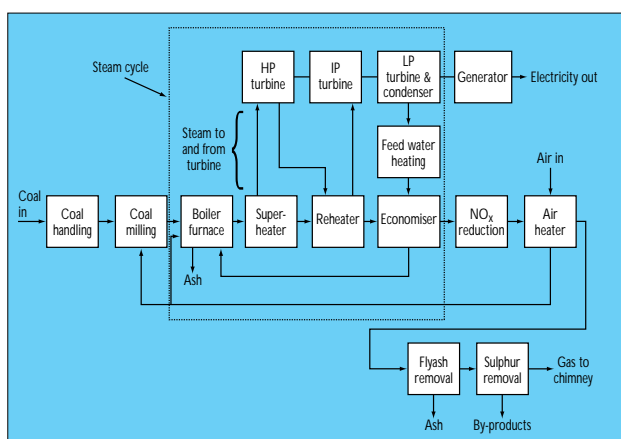


Figure 1. Typical pf plant-process diagram

Subcritical boilers typically take the form of drum boilers in which steam and water from the evaporative part of the cycle (the furnace walls) are separated in the drum. The water is recirculated to the evaporator, with additional feedwater, while the steam passes to the superheater for additional heating. Supercritical-pressure boilers cannot use this drum design, with either forced or natural recirculation of water, because there is no distinct water/steam phase transition above the critical pressure. They must instead be of once-through design.

This implies that, under part-load conditions when the boiler is operating at subcritical pressures, there is at some point in the boiler evaporator section a transition to completely steam flow, ie 'dry out'. Provisions to cope with this condition and restrict the resulting rise in tube-wall temperature are key aspects of supercritical boiler design, and account for the major step change from subcritical drum boilers.

The form of the steam turbine employed with supercritical conditions is the same as that for subcritical cycles, although temperatures throughout the system (including steam inlet, final feedwater and bleed-steam tapplings) are all higher.

CURRENT AND FUTURE STATUS OF SUPERCRITICAL STEAM CYCLE TECHNOLOGY

Steam Cycle Performance

Over the last decade substantial increases in the performance of pf-fired plant have been achieved. Cycle efficiencies of 36% in the late 1960s rose to 40% in about 1985 and 43-44% for plant commissioned from 1990. This trend is illustrated in Figure 2, which shows the efficiency of Danish supercritical units (normalised to standard UK inland conditions) against standard subcritical plant. The double-reheat Ålborg unit, with an efficiency of 45.1%, probably represents the current state-of-the-art. In general, improvements in cycle efficiency have come from improvements in both steam cycle performance and boiler efficiency.

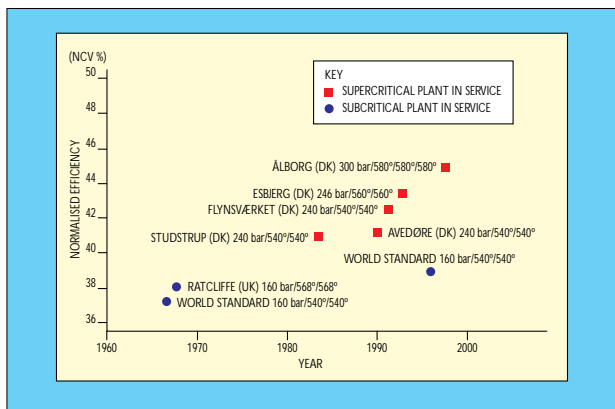


Figure 2. Efficiency (normalised) of Danish pf-fired plant

At a more specific level, improvements have been obtained through:

- increases in main and reheat steam temperatures and main steam pressure, including the transition to supercritical conditions
- changes to the cycle configuration, such as increasing the number of reheat stages and the number of feedheaters, with associated increase in final feedwater temperature
- changes in the boundary conditions of the cycle, principally the temperature and flow of the gas leaving the boiler and the condenser pressure
- reductions in auxiliary power consumption
- improvements in the performance of the individual plant components (coal combustion, turbine efficiency, pump efficiency, condenser performance etc) which in many cases feed into the other areas listed above.

Apart from steam conditions, the cycle efficiency is most sensitive to boiler gas exit temperature, as this is waste heat, and condenser pressure. For a hard coal, a 20°C reduction in boiler gas exit temperature (at the airheater outlet) will improve cycle efficiency by ~1.1% (~0.5 percentage points). The condenser pressure is largely determined by the temperature of the available cooling water. For example, a coastal power station in Denmark with 10°C seawater cooling can achieve 5% (2 percentage points) better efficiency compared with an otherwise identical tower-cooled station in India.

Typical boiler efficiencies for modern pf units fired with high-grade hard coals are now 94-95% (LHV basis), with exceptional cases as high as 96%. Most Danish coal-fired plant are between 94% and 95%. However, the efficiency of the advanced steam conditions, double-reheat unit currently being commissioned at Ålborg is expected to be 95.4%. Here the boiler gas exit temperature will be 105°C, compared to the more usual 120-125°C. Esbjerg is believed to achieve almost 96%.

Boiler efficiencies for lignite-fired units are lower than for hard coal-fired units – a typical modern boiler burning a German lignite is 90-91% efficient (LHV basis). However, the 'lignite' covers a wide range of composition, with moisture varying from >60% to ~20% and ash content from 50% down to ~4%. Consequently, boiler efficiency can be expected to vary by several percentage points depending on the actual fuel composition.

Modern supercritical units have significantly better part-load efficiencies than their subcritical equivalents. Available data suggest reductions in plant efficiency for supercritical units of about 2% at 75% load and 5.5-8% at 50% load. The corresponding values for a standard subcritical unit are 4% at 75% load and 10-11% at 50% load.

Conventional Boilers

Manufacturers and Licences

In the 1920s and 1930s, two once-through boiler technologies were developed and these now dominate the supercritical steam cycle market. However, despite different histories, the Benson design (owned by Siemens AG of Germany) and the Sulzer design (now owned by ABB of Switzerland) look very similar. Both can offer two-pass (Figure 3) and tower (Figure 4) designs and both employ spiral-wound furnace tubing and separator vessels for start-up.

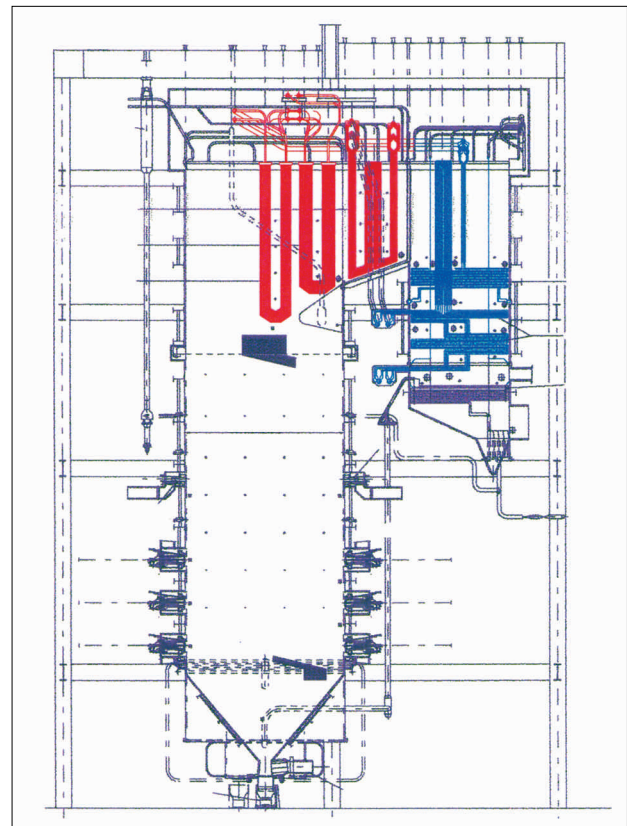


Figure 3. Meri Pori Power Station (supercritical, 550MW_e), Finland (courtesy of MBEL)

Although the licence holders, Siemens, do not themselves manufacture boilers, the Benson licence is the market leader. Detailed design and manufacture is carried out by licensees and sub-licensees, which total about 20. The major manufacturers holding Benson licences include Deutsche-Babcock (Germany), Steinmüller (Germany), AE&E (Austria), BWE (Denmark), Mitsui Babcock Energy Limited (MBEL, UK), Babcock-Hitachi KK (Japan), IHI (Japan), Babcock & Wilcox (USA) and Ansaldo Energia (Italy).

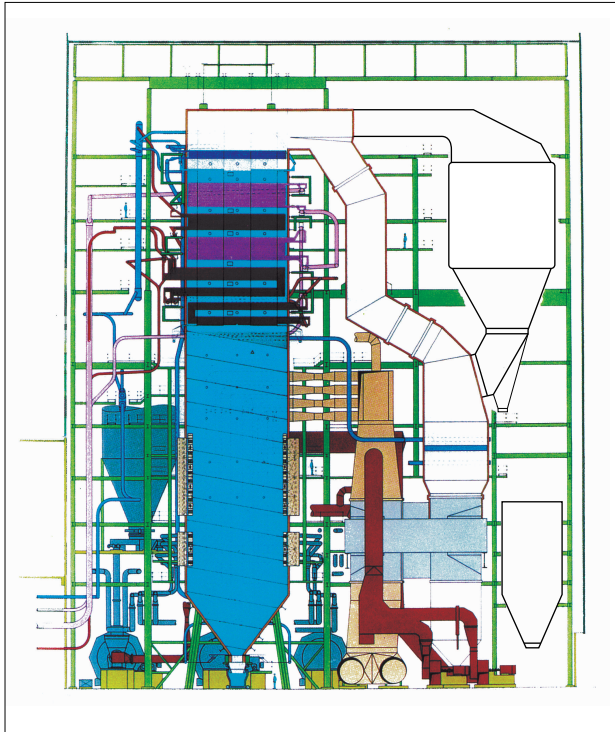


Figure 4. Vestkraft 3 (supercritical, 417MW_e), Esbjerg, Finland (courtesy of ALSTOM Energy Ltd)

ABB now hold the Sulzer licence and are moving away from licensing agreements, preferring to manufacture the plant themselves where possible, or alternatively using local partners in joint ventures. The number of Sulzer licence holders is therefore reduced but still includes Korean Heavy Industries (Korea) and Formosa Heavy Industries (Taiwan). Mitsubishi Heavy Industries (MHI, Japan) and ALSTOM (France) are former licensees and their current designs derive from a Sulzer pedigree.

There is a widespread view that globalisation will result in fewer, larger manufacturers operating. One forecast is that just five major boiler makers will be operating in the global market by 2007, with others operating in smaller niche markets.

Current Status of Boiler Design

Both two-pass (Figure 3) and tower (Figure 4) boiler designs are widespread, with two-pass the market leader. All lignite-fired plant utilise a tower boiler principle. European bituminous coal-fired plant of both types are common, but Japanese and US plant are normally of the two-pass design.

The most popular arrangement of tubing in the combustion zone is that of a spirally-wound membrane wall utilising smooth-bore tubing. This inclined tubing arrangement reduces the number of parallel paths compared to a vertical wall arrangement and therefore increases the mass flow of fluid (steam/water mixture) through each tube. This high mass flow improves heat transfer between the tube metal and the fluid inside, so the tube metal is adequately cooled despite the powerful radiant heat flux from the furnace fireball. Alternative vertical furnace-wall designs are available which use internal ribbing in the tubes to improve heat transfer.

Many manufacturers, and most utilities, are very familiar with the particular features and complexities of the spirally-wound technology and are reluctant to change to a perceived higher-risk vertical tube design in the lower furnace.

Where the heat flux from the furnace is much lower in the upper furnace area, however, the industry standard design is vertical membrane tubing. This is true of both tower and two-pass designs, and the transition to vertical tubing is shown in both Figures 3 and 4.

The superheater stages of two-pass pf-fired plant with advanced steam conditions are similar to those of subcritical designs. However, the increase in pressure or temperature requires either thicker sections or higher-grade components. Thicker components have the penalty of additional cost and weight, higher operating metal temperatures for tubing and reduced flexibility of the plant.

The adoption of new high-strength ferritic steels has recently enabled steam conditions to be raised above 248bar/566°C. Superheater tubes must be designed to operate at temperatures ~35°C above live steam temperatures. For current steam temperatures up to ~580°C, metal temperatures will be ~615°C and low-alloy steel tubes such as T22 may possess adequate creep strength. However, not only do the advanced steam parameters for supercritical plant impose higher stresses and temperatures on the superheater tubes, they also increase the potential rates of both fireside and steamside corrosion. UK Central Electricity Generating Board (CEGB) experience in the 1970s showed that these materials possessed inadequate fireside corrosion resistance with UK coals at 565°C steam temperatures. Medium-chromium (Cr) steels such as X20 can be used at these temperatures or alternatively, for corrosive coals or higher temperatures, more expensive austenitic steels such as T316 and T347 can be used. The current maximum boiler outlet steam temperature is ~580-600°C.

In thick-sectioned components such as steam pipes and headers, ferritic steels, from carbon steel up to 12%Cr X20Cr.Mo.V121 (Mo: molybdenum; V: vanadium), have been used in plant designed for steam conditions of 250bar/560°C. Here the steam lines are normally now manufactured from X20Cr.Mo.V121. Materials with even higher creep strength will be needed for thick-section components under more advanced steam conditions and P91/T91/F91 are suitable for such use up to ~300bar/580-600°C.

The layout and design issues for reheater banks are similar in principle to those of the superheater banks, in particular with reference to materials and temperature limits. However, there is more scope with the reheater to increase temperatures or adopt novel designs because the reheater pressure is much lower and so the tubes are under much less stress. In addition, the reheater is normally situated behind the superheater in a region of cooler gas flow. An additional 20°C is typically achievable in reheater steam temperatures for the same material constraints.

In summary, the current state-of-the-art boiler outlet steam conditions are up to 300bar/580-600°C.

Factors Affecting Boiler Performance

In modern utility boilers, the furnace wall is one of the most critical components limiting the use of more advanced steam conditions. The walls experience the greatest heat flux of all heat-absorbing surfaces because of the intense radiant heat transfer from the fireball. To prevent tube rupture, it is imperative that tube metal temperatures are kept low enough to maintain tube strength for all operating conditions. Since tubes are rigidly welded together to form membrane walls, it is also important that the temperatures across all tubes are as uniform as possible. These criteria set the minimum required water-wall fluid mass flux. They also set the maximum temperature limits. With current materials, the allowable metal temperature at the furnace exit is currently limited to ~480°C. This corresponds to a mean evaporator outlet fluid temperature of ~450°C (normally using 1%Cr.Mo). There are many higher-alloy steels which can tolerate higher furnace-wall temperatures. However, these alloys require more complex welding techniques, in particular, post-weld heat treatment (PWHT).

Unfortunately, increases in final steam temperatures exacerbate the problem by increasing water-wall temperatures. Increases in pressure and the addition of a second reheat circuit also have the same effect. Thus the temperature limit on the furnace water wall prevents the advancement of supercritical steam conditions. With current materials, the furnace wall effectively limits the main steam temperature conditions to ~290bar/580°C. The development of improved materials for the furnace wall that can be welded without PWHT is a key requirement for further advances in steam conditions.

As final superheater and reheater steam temperatures increase, the propensity for tube fireside corrosion increases too. The growth of steamside oxides is also related to the increase in steam temperatures and the design temperature calculations take into account the lower degree of cooling offered by tubing with fully developed steam oxide layers. Corrosion is a key issue for further development.

The elevated temperatures and pressures drive designers to make final superheater headers thicker. Large through-wall temperature differences in thick components can cause very high stresses and limit plant flexibility. Start rates can be as low as 5°C min⁻¹.

The main steam pipework of supercritical plant with high steam temperatures has, to date, been manufactured using austenitic materials and in-service problems have arisen associated with the poor thermal characteristics of these materials. The development of new 'super' ferritic materials such as P91 and NF616 has now overcome the need for austenitic materials for high-temperature steam pipework for applications up to 600°C.

Airheater thermal efficiency limitations can also limit cycle efficiency in advanced plant. Cycle efficiency is enhanced by increasing the extent of feed heating which increases the feedwater temperature to the boiler. If temperature differences across the economiser tube walls, and hence economiser size, are to be maintained, an increase in final feedwater temperature will lead to a rise in airheater gas inlet temperature and, consequently, an increase in the size of the airheater required to achieve a particular boiler final gas temperature. Final feed temperatures of up to 300°C seem to be generally acceptable with current designs.

Areas under Development

Manufacturers are continually trying to improve all aspects of plant design, including plant integration and quicker/cheaper construction techniques as well as the more fundamental design issues discussed above. Three major areas are highlighted below where development is currently focused, but this is by no means an exhaustive list.

Vertical Furnace Tube Designs

Vertical tube furnace-wall designs are being proposed to replace the industry-standard spiral-wound designs. They have clear advantages over the spiral design, namely:

- cheaper and less complex furnace tube design
- easier furnace framing
- cheaper and less complex repair
- lower pressure drop (higher efficiency).

The vertical tubing arrangement in supercritical plant is generally regarded as only practical for large unit sizes (ie >~400-500MW) or where the risk of overheating is reduced by other factors such as with lower-rated furnaces. With the larger number of parallel tubes, the mass flux in the tubes is too low to prevent overheating of smooth tubes and therefore internally-ribbed tubing is utilised.

Of the two design types available, the ABB Sulzer design is better demonstrated, with two advanced units designed by MHI now operating in Japan. The alternative Siemens Benson design is not demonstrated and therefore has more risks associated with it, but offers a lower pressure drop and hence slightly greater efficiency.

Materials

Considerable R&D is under way to develop improved materials. Materials constraints limit the maximum steam cycle performance at the furnace wall exit, the superheater and reheater outlet tubes, and the superheater and reheater outlet headers and pipes. As well as long-term creep properties, weldability and corrosion properties are key issues. In addition, materials research is under way at the cold end of the boiler – the airheater outlet and downstream ductwork. Here, reductions in the boiler exit gas temperature are limited by the need to avoid acid corrosion. As an example of the work in progress, glass fibre-reinforced plastic ductwork has been installed at several German lignite stations (eg Jänschwalde Power Station) and trials are also under way on a teflon tube heat-exchanger downstream of the airheater. Corrosion-resistant airheater elements are under development too.

Combustion and Environmental Issues

Coal combustion and environmental issues represent major areas of R&D, affecting the uptake of clean coal technology. Increasingly stringent environmental requirements have led to a major research effort into, for instance, improving coal combustion, the impact of coal quality, reducing furnace NO_x emissions and back-end flue gas clean-up.

Steam Turbines and Boiler Feed Pumps

Manufacturers

Major manufacturers include ABB Kraftwerke AG (formed from the merger of ASEA and Brown Boveri), ALSTOM, GE, MHI and Siemens AG.

The situation in the UK has changed significantly within the last two years from the perspective of large turbine generator manufacture, with effective changes in ownership of the remaining two manufacturers. C A Parsons was sold to Siemens in 1997 and GEC's sale of shares in GEC-Alsthom led to the formation of ALSTOM.

Manufacturers in America include GE and Westinghouse, both of whom have significant experience with supercritical plant. Siemens has recently bought the power-generating division of Westinghouse, a move which has now been approved by the government regulatory bodies in the USA. Of the remaining manufacturers, Fuji Electric of Japan and BHEL of India manufacture under licence from Siemens. Since MHI of Japan, Hyundai Heavy Industries of Korea and Shanghai Electric Corporation of China all manufacture under licence from Westinghouse, the effect of the Westinghouse take-over by Siemens has potentially far-reaching consequences in terms of turbine manufacturing.

As with boiler manufacturers, the globalisation of the power generation market is driving consolidation within the steam turbine industry. Recent take-overs by Siemens demonstrate that this is already well advanced, more so than in boiler or gas turbine (GT) sectors; this trend is expected to continue.

Current Status of Turbine Design

Steam turbines, including those for advanced steam conditions, are continuously under development by the various manufacturers for full-speed application with shaft speeds of 3000rpm and 3600rpm.

The typical arrangement of a single reheat turbine and associated feed train is shown schematically in Figure 5. Standard turbine modules for single reheat application, including high-pressure (HP) and intermediate-pressure (IP) turbine modules, are now being designed for inlet steam conditions of 240bar/565°C/565°C and 300bar/600°C/600°C respectively, and are anticipated to have electrical outputs in the range up to 1100MW. Typical turbines as manufactured by ABB and Siemens are shown in Figures 6 and 7 respectively.

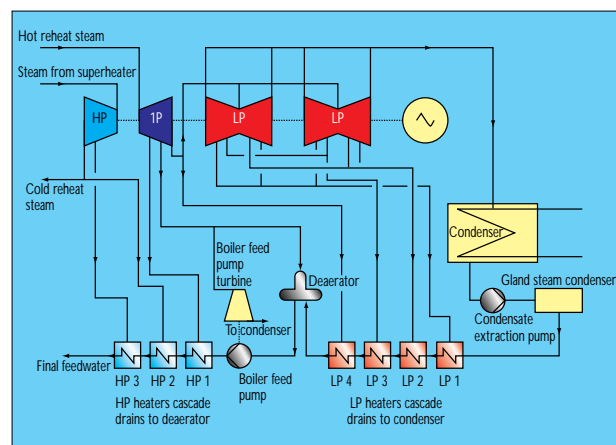


Figure 5. Steam turbine cycle

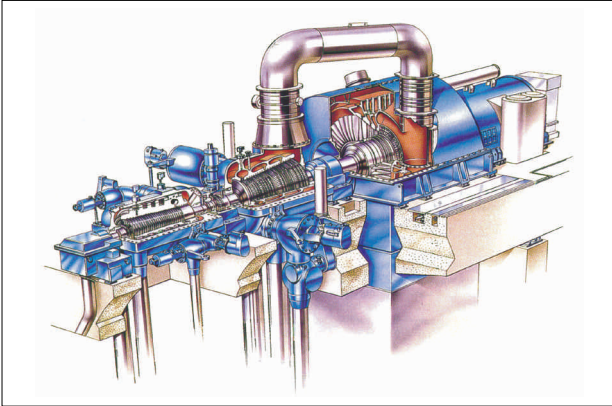


Figure 6. Typical turbine arrangement (courtesy of ABB)

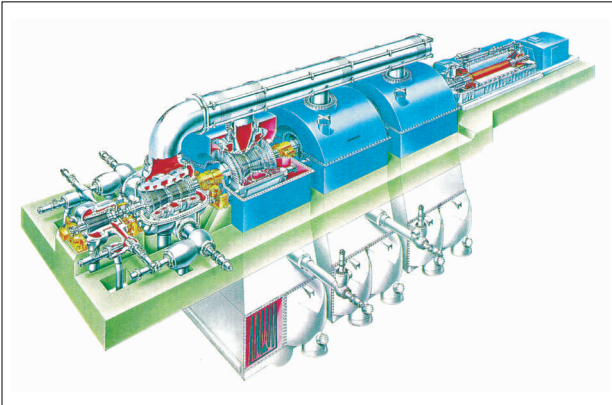


Figure 7. Typical turbine arrangement (courtesy of Siemens)

It is recognised that plant up to ~250MW will be unlikely to achieve the same high efficiencies that the larger output machines are expected to achieve, due to increased blade-path losses in the HP turbines; these plant are expected to remain subcritical.

In addition to the single reheat unit arrangements, designs are available for double reheat applications. In double reheat units the highest-pressure turbine is designated as the VHP turbine and receives the main steam, followed by either a single combined HP/IP turbine, or separate HP and IP turbines, which receive steam from the first- and second-stage reheaters.

Another important factor in the development is the intended plant flexibility. Whilst traditional materials could be utilised for units operating with steam temperatures up to 565°C, the requirement to contain the high pressures would result in large section thicknesses. Manufacturers are therefore utilising some of the 10-12%Cr steel alloys to enable reductions in wall thickness to minimise thermal stresses. The selective use of these materials offers improvements in start-up times, increasing the overall plant utilisation.

The use of double reheat appears to be difficult to justify on economic grounds alone and is not likely to justify significant expenditure on the full development of modular plant.

Steam Valves

Existing basic designs are able to meet the duty of both main and reheat steam valves, and the use of high-Cr ferritic steels currently available permits the design of steam valves for temperatures up to 600°C. Most manufacturers offer combined stop and control valves that are similar to the standard steam chest design that has been deployed successfully for subcritical steam plant.

HP Turbines

The development of existing designs of turbine for application to supercritical conditions has been largely successful using high-Cr ferritic steels. All manufacturers have currently chosen to retain a double-cased design of cylinder rather than move to triple casing to accommodate the higher pressures. The use of a bolted joint is typical, but other designs are employed. A barrel-type design is favoured by Siemens, while ABB utilises a shrink-ring design (Figure 8). Retention of the bolted horizontal split-joint generally provides for easier maintenance than the barrel type.

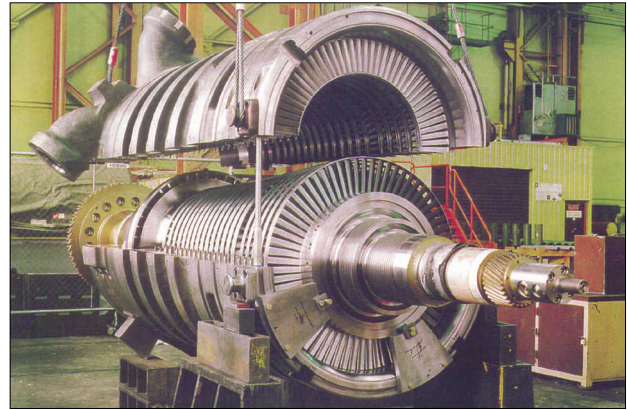


Figure 8. HP turbine at Schkopau (480MW), Germany (courtesy of ABB)

For 565°C applications, the inner casing would generally be cast in conventional 1%Cr.Mo.V steel, but this selection changes to the higher-Cr ferritic steels for 600°C applications. At temperatures >600°C, casing designs would generally be required to utilise Nimonic 80A bolts (instead of 12%Cr steel) at the inner-casing half-joint.

The design of HP rotor depends on the type of blading utilised and is generally of either drum type, in the case of 50%-reaction turbines, or of gashed wheel-type in the case of impulse designs. This moving blade construction is standard and no further development is envisaged in this area. Most manufacturers have retained the use of monobloc forgings, although ABB is able to supply rotors of welded construction which enable a combination of high- and low-Cr steel alloys to match local steam conditions in the turbine.

The use of 1%Cr steel rotors is restricted to use with HP turbine designs incorporating a governing stage as this effectively reduces the temperature of the steam in direct contact with the main section of the rotor body. At higher temperatures, and for those designs without a governing stage, the use of a 12%Cr steel rotor is now required.

IP Turbines

All manufacturers have retained a two-casing construction of the horizontally-split type. The outer casing provides the support for the inner casing together with the blade carriers for the later stages of blading. Most designs rely on bolting to secure the two halves of each cylinder. The only exception to this is the design of casing developed by ABB, which again utilises a shrink-ring design.

For combined HP/IP turbines for double-reheat applications, the arrangement offered depends on the manufacturer and only some have developed opposed-flow steam turbines specifically for supercritical applications. A typical arrangement is shown in Figure 9. Alternative designs have been utilised by other manufacturers for combined turbine designs in subcritical applications and it is anticipated that these may be introduced in supercritical plant.

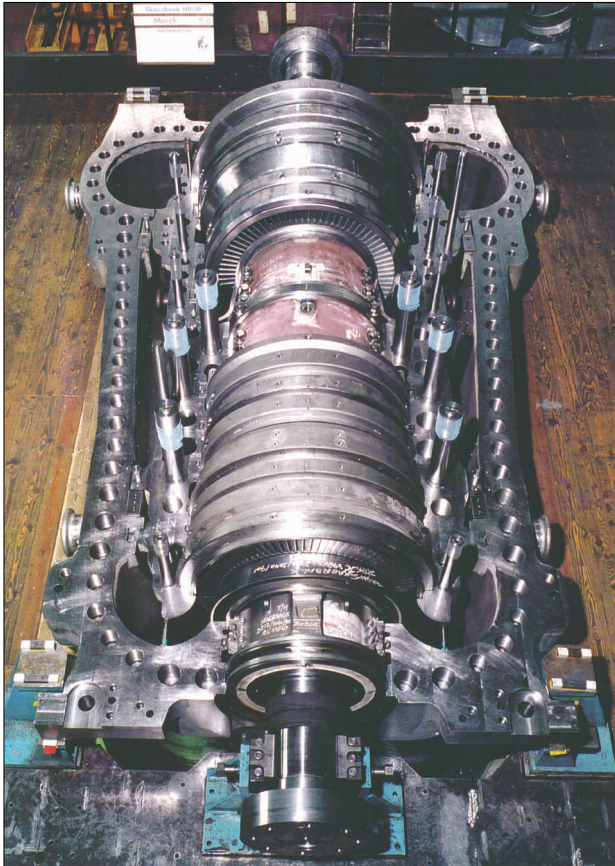


Figure 9. HP/IP turbine at Skærbæk (412MW_e), Denmark (courtesy of ALSTOM Energy)

The IP and combined HP/IP turbines utilised for supercritical plant share many of the design features of existing subcritical designs. Other than improvement in materials, no further developments are considered necessary to achieve significant increases in steam temperatures above 600°C.

LP Turbines

Most low-pressure (LP) turbines may be used for advanced steam condition plant and do not require the use of materials specifically developed for high temperatures. The use of increased main-steam and reheat pressures would, however, be expected to increase the moisture content at the exhaust of the LP turbine. This would increase the rate of erosion on the last-stage blades and may necessitate additional protection for blading and other vulnerable components.

There has also been a general trend to longer last-stage blades and increased exhaust area, thereby enabling a reduction in the number of LP turbine cylinders and consequently reduced cost. This practice generally also increases the propensity for erosion damage on the last-stage rotating blades.

Blading designs have developed significantly since the early 1980s through the use of computational fluid dynamics (CFD) and three-dimensional through-flow computational methods, and this has led to major improvements in efficiency. It is unclear to what extent this trend will continue.

Boiler feedwater pumps (BFPs) (Figure 10) are an essential part of modern power plant, including advanced-cycle pf plant. Failure of these pumps impacts on plant availability.

With the elevated main-steam pressures deployed within advanced-cycle plant, the discharge pressure of the BFP is significantly increased. A consequence is that the pumping power absorbed by the BFP is also increased and it is likely to be the largest single consumer of auxiliary power within the generating station, typically 3-4% of gross power output.

Despite the greater duty head required of supercritical over subcritical pf plant, the existing pump ranges are considered capable of achieving the required duty. Increases in impeller tip speed are generally not necessary, suggesting that no major advancement in technology is required.

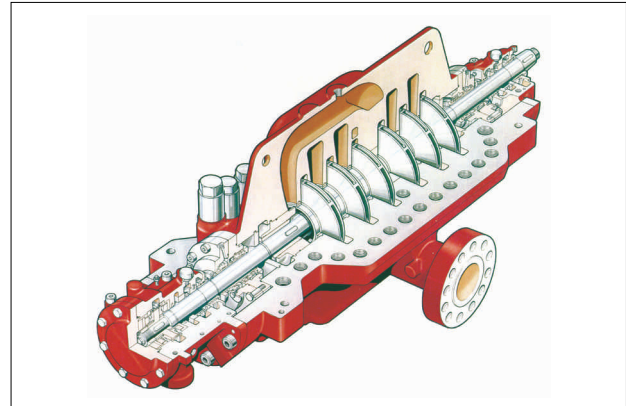


Figure 10. Horizontal split-casing BFP (courtesy of Weir Pumps Ltd)

Turbine Development Trends

Steam conditions of 240bar/565°C/580°C are regarded as standard for advanced steam plant, and new plant with ambitious efficiency targets can achieve 600°C with designs and materials already developed. The main thrust of development is in materials to support higher steam conditions. Without the use of new materials, it is highly unlikely that significant further advances in steam conditions can be achieved.

Ferritic steels with improved creep strength are needed for forged turbine rotors and blades, and for cast valves and casings. Work in the USA (eg by Electrical Power Research Institute, EPRI), Japan (EPDC) and Europe (eg the European Commission's (EC's) Collaboration in Science and Technology, COST, programme) have all set out to develop the steels with much-improved creep strength for temperatures of 600°C and above. The recently-commenced EC-THERMIE Programme-supported '700' project aims to achieve 700°C operation by 2013, in part using Ni-based alloys.

The HP cylinder remains predominantly of double-casing design, but triple- or part triple-casing designs are under active consideration to help with pressure containment and to avoid excessive wall thickness. Heat shields and cooling steam designs are also under development for the hottest components.

Developments are taking place, too, to optimise the feed-heating cycle. The trend to higher final-feed temperatures leads to an increased number of heaters (eg Fynværket has nine heaters including the deaerator) and increased likelihood of a bled-steam tapping being required off the HP cylinder. There is also a move towards header-type HP heaters as the conventional tube-plate design requires thick sections and is vulnerable to cracking at the higher temperatures and pressures.

The location of the BFP within the feedwater heating train itself requires optimisation for each new plant as a compromise occurs between the power consumption required in driving the BFP and the cost of procuring additional HP feedwater heaters.

At present, the use of double reheat appears to be difficult to justify on economic grounds and no general trend towards double reheat has been identified. Although manufacturers are able to offer 'bespoke' designs for specific requirements, single reheat designs are expected to remain the norm.

Retrofit Options

Retrofit opportunities exist for a wide range of clean coal technologies, eg low-NO_x burners, flue gas clean-up, or even repowering with FBCs or gasification cycles where the existing turbine is kept. However, no significant retrofit opportunities have been identified where supercritical plant can be retrofitted onto existing subcritical technology. Work is often undertaken to repair or modify existing units or to deal with design or operating problems, but with no change in steam parameters. The reason for this is that increasing steam pressures or temperatures more than a few % above original design conditions would rapidly lead to creep problems (boilers and turbines); also the swallowing capacity of the turbine and the pressures and temperatures of the entire feed-heater circuit would change.

Future Development

Although other factors (discussed below) are important, the steam conditions and hence the thermal efficiency of advanced supercritical steam cycles are primarily limited by the available materials. The trend towards progressively higher thermal efficiencies can only be achieved if better materials can be identified for a number of critical components.

Most materials development is being conducted under national or international co-ordinated programmes. The main national programmes are in Japan, the USA (funded by the US Department of Energy, USDOE) and Germany (including the MARCKO programme). Japanese manufacturers claim to have already demonstrated materials suitable for 650°C steam temperatures.

Current R&D

Boiler Materials R&D

Furnace wall tubing, T23, developed by Sumitomo Metal Industries and MHI, and 7Cr.Mo.V.Ti.B1010 (Ti: titanium; B: boron), developed by Mannesmann and Valourec, are the most likely materials to be selected for steam conditions up to 625°C/325bar. Short-term creep rupture data suggest that these steels may have equivalent creep properties to T91 steel whilst requiring no post-weld heat treatment. For steam conditions >625°C/325bar stronger materials will be required. Candidate materials currently at the most advanced stage of development are P92, P122 and E911. All three steels offer considerably enhanced creep-rupture properties over more conventional equivalent steels, T91 and X20Cr.Mo.V121, but all require post-weld heat treatment during fabrication.

On the superheater, if the steam temperatures are to be only moderately increased, and the fireside corrosion potential is low, then improved medium-Cr ferritic/martensitic steels such as P91, P92 and P122 could be considered as possible alternatives to X20Cr.Mo.V121. In such circumstances, the steamside oxidation rate assumes increasing importance. Austenitic stainless steels such as TP347H and TP347HFG should possess adequate creep-rupture strength and fireside and steamside corrosion resistance for use in the final superheater tubes operating with steam parameters up to 290bar/580°C. However, it is unlikely that the fireside corrosion resistance of these steels will be sufficient to operate much above 620°C.

More highly-alloyed steels under development, such as NF709, HR3C and HR6W, may allow operation at steam temperatures of 630°C, but again more work is needed.

The recent ASTM/ASME-approved P92 and P122 steels should allow construction of thick-section components and steam lines for pf plant operating with steam parameters up to 325bar/610°C. Similar approval is being sought for E911, the European equivalent to P92. Since this steel has a lower tungsten (W) content than its Japanese counterpart it may be less susceptible to long-term embrittlement in service.

Austenitic steels, such as 1.4910, are receiving consideration for headers in plant operating with steam parameters between 350bar/620°C and 250bar/650°C.

Boiler Design R&D

Considerable research effort into plant damage, including thermal fatigue, has been under way aimed at supporting existing operating plant. This is leading to new designs of, for example, headers and steam chests that are much more resistant to thermal fatigue, and where thermal fatigue can be better predicted. To prevent problems, multiple components can be used to reduce component sizes and hence wall thickness.

Cycle efficiency is improved if superheater and reheater spray flows can be minimised. Improved control techniques and once-through boiler design combine to allow much better control and hence reduced spray flows.

The use of fewer superheater and reheater banks is under active consideration. This reduces capital costs and pressure drops, but can lead to more unequal temperatures. Better controls of firing and sprays, now possible with modern control and instrumentation (C&I) equipment, can mitigate this problem and should allow larger banks than in the past.

Lignite pre-drying has been considered periodically over a number of years, led by Germany. Steinmüller is now installing a large test rig at Niederaußem which promises to improve cycle efficiency by several percentage points.

Again led by Germany, techniques are under development to reduce flue gas exit temperatures to below the acid dew-point temperature. This potentially allows boiler exit gas temperature reductions to about 60°C, the limiting factor being the requirements of FGD processes. To achieve such low gas temperatures, heat exchangers and ductwork that are resistant to acid corrosion are required; these may be made of plastics, Teflon or glass-fibre. Another problem with this approach is that dispersion of cold and corrosive flue gases must be achieved in the atmosphere. The solution increasingly employed is to pass the flue gas into the cooling tower, for dispersion with the natural draft of the tower, to provide an air blanket to prevent the flue gas causing corrosion to the tower walls. This solution is not applicable to, for example, coastal sites where cooling towers are not required.

The use of plate or tubular heat-exchangers for the airheater is another option for improving efficiency. Airheater leakage is reduced considerably and lower average back-end temperatures are possible because the thermal cycling of rotary airheaters is avoided. It also allows feed-heating heat-exchanger tubing to be incorporated into the airheater to improve efficiency across the load range. The penalty is increased capital cost.

Another airheater option, employed at Nordjyllandsværket, Denmark, is to use an additional sector for re-heating recirculated flue gas. This allows better temperature control at low load and avoids the use of a booster fan in hot dusty conditions.

Turbine Materials Development

New alloys based upon 10%Cr.Mo.W.V.Nb.N(B) (W: tungsten; Nb: niobium) are becoming available for turbine rotors and casings for construction of 300-325bar/600-610°C steam turbines. Creep testing to 40,000h, together with large-scale fabrication trials, has so far demonstrated reliable results. Hence, turbine parameters of 600°C/325bar can be considered achievable. Work within COST, to consolidate the properties of these, is intended to allow construction of turbines with steam parameters of 620°C/325bar.

By the addition of cobalt to 12%Cr.W steel (ie NF12 and HR1200), Japan expects to be able to manufacture steam turbines capable of handling final steam conditions of 650°C/350bar.

A number of design changes are also being developed to allow higher temperatures and pressures to be used:

- partial triple-casing on turbines or use of inlet guide vanes to reduce the peak pressures seen by the HP cylinder
- steam inlets and valves welded rather than flanged to give reduced leakage and fewer maintenance problems
- use of heat shields and cooling steam in the IP turbine inlet
- new blade coatings to reduce solid particle erosion where high-velocity inlets are used to minimise pressure effects.

Turbine and Cycle Development

Advances in the steam turbine and overall cycle optimisation are generally incremental in nature and are taking place across the board. Some of the highlights are:

- improved blading profiles making use of modern CFD techniques
- higher final feed temperatures and bled-steam temperatures
- bled-steam tapping off the HP cylinder
- improved efficiency of auxiliaries
- lower condenser pressures using larger condensers and larger LP exhaust areas – this requires site-specific cost optimisation for each project
- a trend to larger unit sizes improving turbine efficiencies
- increasing automation and levels of control
- optimising plant layout, eg to shorten pipe runs and ductwork.

Manufacturers are also increasingly moving towards modular designs using standard pre-engineered components wherever possible. Where it is possible to use turbine cylinders, pumps and feed heaters that have been pre-engineered, the design costs and construction time are reduced. Other developments are also under way to reduce construction times.

R&D Needs

Much work has been carried out over the past 20 years to develop new steels for supercritical plant applications. The most significant advances appear to have been made in Japan. Japanese steel-makers claim to have already developed materials which will allow the manufacture of plant capable of operating up to 650°C.

Steels with improved mechanical properties are now becoming available in Europe. These have allowed a progressive increase in main steam temperatures, such that power plant with final steam temperatures of 600°C can now be considered commercially available. Main steam temperatures of 625°C should also be realisable in the near term. However, further work will be required to realise main steam temperatures up to 650°C, covering all the main areas from furnace wall tubing through superheater and reheater tubing and pipework to the turbine inlet.

Creep-rupture data reported in the published literature for most developmental steels extend to ~45,000h, with creep-rupture strength for longer times being derived by extrapolation. Data obtained from much longer exposures will be required since modern plant are generally designed for 200,000h. In addition, the 9-12%Cr steels continue to display a ~20% reduction in strength in the Type IV weld-cracking zone. Either this will need to be accounted for in design, or further work will be required in an attempt to minimise the problem.

Of perhaps greater concern, most of the fireside corrosion data provided by Japanese steel-makers are based on 100h exposure of the trial material to an idealised molten salt mixture in laboratory studies. Whilst these data may be of value for ranking purposes, much more realistic fireside corrosion data, obtained from much longer exposures to relevant environments, will be required. More attention needs to be paid to fireside corrosion of candidate boiler tube steels, particularly the effects of fuel quality on corrosion rates – these steels still need realistic exposure to high-temperature flue gases in a variety of operating plant to evaluate their long-term performance.

Similarly, little attention appears to have been paid to the steamside oxidation resistance of most of the steels. Silicon (Si) has been shown to have an important influence on steamside oxidation rates for 9-12%Cr steels. However, increasing the Si content of the steel >0.4% is found to be detrimental to toughness. Given that oxidation rates will inevitably increase with increasing temperature, more work needs to be done on determining the best means to limit the steamside oxidation rates on all components in the system.

In addition to the materials issues highlighted above, there are opportunities for progressive improvements in all aspects of plant design and construction including plant auxiliaries, particularly mills and airheaters.

There is a need for a demonstration plant of the Benson vertical furnace wall design. If successful, this would represent a significant step forward in terms of reducing boiler plant cost and feed pump power consumption.

As well as hardware improvements, advanced control techniques should be developed to optimise plant operation and maintenance. These include intelligent control systems to, for example:

- maintain uniform temperatures across the boiler by control of burner parameters
- minimise carbon-in-ash or NO_x formation in the same way
- better match load and firing during load changes, to avoid temperature excursions and improve ramp rates
- improve reliability and repeatability of cycling procedures
- condition-monitor both boiler and turbine components
- forecast damage accumulation and allow targeted preventative maintenance.

Trends in Technology

Predicting trends in technology development is notoriously difficult. Improvements to power plant have been very slow. The first advanced supercritical demonstration plant (Eddystone, USA) was designed in the late 1950s with a maximum steam temperature of 650°C, but, 40 years on, such steam conditions are not considered commercially demonstrated. Throughout the 1970s and 1980s steam temperatures were anchored firmly in the 540-566°C range.

In recent years, however, growing environmental pressures have forced a change. New materials have been under development and the 1990s have seen an unabated trend to increased steam conditions (Figure 11). It is uncertain now whether this trend will continue and when it might tail off.

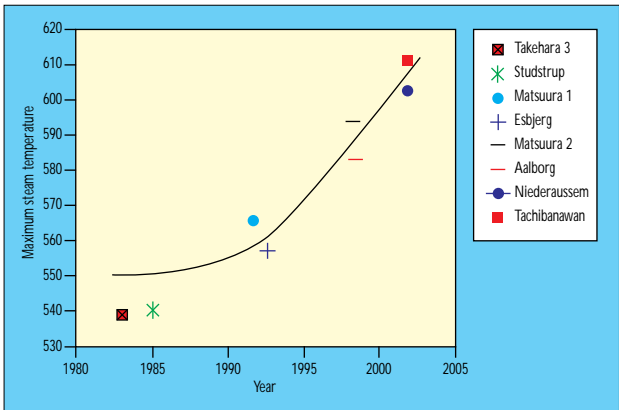


Figure 11. Maximum steam temperatures of leading supercritical units

In general, the power generation industry appears to be 'bullish'. Japan now has Misumi-1 nearing completion at 600°C/600°C and is starting construction of Tachibanawan at 600°C/610°C. In Europe, the Danish utility ELSAM is convinced that all materials now available would allow construction of a double reheat unit with 325bar/610°C/630°C/630°C steam conditions and an efficiency of almost 50% (using Danish seawater cooling).

All main European manufacturers are involved in the EC-THERMIE '700' project, which is acting as the benchmark for R&D and forecasts; ABB aims to deliver 700°C plant by about 2010.

The most advanced plant ordered in Europe is the Niederaußem lignite plant in Germany with steam conditions 260bar/580°C/600°C. Technical efficiency is forecast at around 43%. Steinmüller claims its lignite-drying process would add an additional 2-4 percentage points.

Siemens is not so optimistic, suggesting that, for inland European conditions, 50% will only just be achieved using Ni-based alloys and 700°C steam temperatures. Figure 12, based on information supplied by Siemens, shows the areas where efficiency improvements are likely to come from. Although 600°C is already realisable (and Siemens is providing the turbine for Niederaußem), Siemens forecasts 620°C as the limit of that realisable in the next ten years.

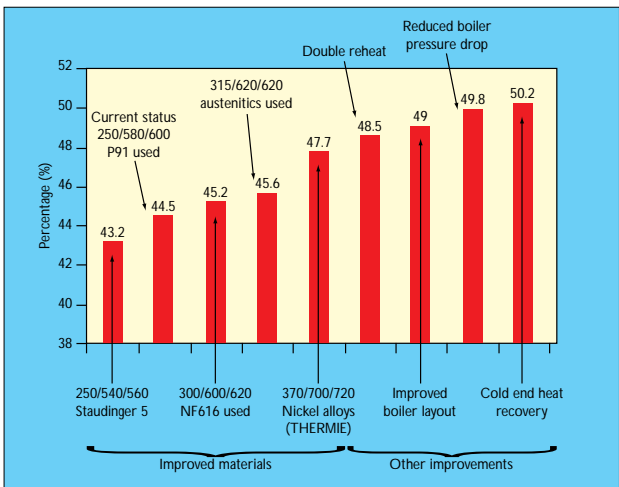


Figure 12. Potential efficiency improvements (based on a 700MW bituminous coal-fired plant, with a 40mbar condenser pressure)

In the short term (<5 years), new 600°C units will be demonstrated in Europe and Japan. Efficiency improvements to lignite plant are narrowing the efficiency gap between lignite and bituminous coal plant, but at a cost. If environmental pressures become tougher, new features to allow cooler boiler exit temperatures will also be applied to bituminous coal plant. Plant with steam conditions >620°C are unlikely except perhaps in Japan.

There will continue to be incremental improvements in efficiency. The current state-of-the-art for inland European sites is about 45% (LHV basis) and this is likely to increase by ~1%.

In the medium term (5-10 years), newer materials will be adopted in demonstration plant. The speed at which this occurs depends on the research effort and the strength of the environmental/commercial drivers. However, with the use of austenitic steels, temperatures up to 650°C should be achievable. Whether such a plant will be economic is as yet unclear.

Improvements are likely to continue from improved control systems, more efficient auxiliaries and better design optimisation. ABB suggests a growth in efficiency of about 2-3 percentage points over the next ten years. This estimate is consistent with current R&D as well as with historic trends (state-of-the-art efficiency has risen by ~7-8 percentage points over the last 30 years).

In the longer term (10-20 years), trends become more difficult to predict. The EC-THERMIE '700' project, if successful, will result in a 700°C unit demonstrated in about 2013. Forecasts of efficiency for this technology range from slightly over 50% to 52-55%. This would represent something of a step change by comparison with previous development.

The timetable for demonstration of materials required for the EC-THERMIE '700' project is ambitious, even though the project represents a major research effort. The results of all activities are uncertain, and there must be doubt as to whether a reliable demonstration plant can be delivered. Also, Ni-based alloys required for 700°C plant are expensive, ~10 times the cost of austenitic steels and ~20 times that of advanced ferritic steels.

Commercial state-of-the-art plant 15-20 years hence are therefore most likely to be 650°C units, from a mixture of ferritic and austenitic steels, operating at around 50% efficiency (European inland conditions). 700°C and 52-55% efficiency probably represents the upper limit.

These efficiency improvements are likely to come from a range of factors, eg lower flue gas exit temperatures, more efficient auxiliaries, better coal combustion, higher feedwater temperatures, and lower pressure drops through the system. The efficiency improvement simply due to the increased final steam conditions is expected to be less than half of the total.

Alternative Boiler Technology

Current Status

In principle, supercritical steam cycles can be used for any technology using a steam cycle to generate electricity. Supercritical plant can therefore be incorporated into:

- gasification cycles
- FBCs
- any process involving an HRSG to power a turbine generator.

However, in order to be commercially viable, supercritical cycles need to be a certain size, and also to be able to generate high-temperature steam. For all the above cycles, one or both of these factors have been missing to date, so no supercritical version has been constructed.

However, as FBCs and CCGTs advance, units are becoming larger, and HRSG temperatures are rising. Supercritical versions are likely to become commercially available within the next 5-15 years and currently form a focus for R&D. Although a supercritical steam cycle within a coal gasification combined-cycle process remains a future target, demonstration plant for FBCs and for CCGT plant are already operating or under construction.

Research and Development

FBC Plant

Circulating FBC (CFBC) plant are claimed to have certain inherent advantages for the application of supercritical conditions. These are:

- furnace wall heat flux is generally lower than in a pf-fired boiler
- wall temperatures can be reduced by the use of an external heat-exchange bed
- the walls are maintained clean of ash deposits
- the heat flux profile is greatest at the bottom of the furnace, where particle concentration is greatest, and decreases with height.

As with conventional boilers, internally-ribbed tubes are expected to be used, either throughout the combustor or as part of the combustor walls. Foster Wheeler's CFBC would utilise the relatively new Compact design, where the particle separator is incorporated into the main combustor vessel in a square configuration.

Electricité de France (EdF) is developing designs for a supercritical CFBC at the 600MW_e scale, with steam conditions of 270bar/600°C/600°C and final feedwater temperature of 290°C.

A 350MW_e coal-fired pressurised FBC (PFBC) unit with a supercritical steam cycle is under construction at Karita in Japan for the Kyushu Electric Power Co. This is an ABB Carbon design, which is by far the dominant commercial form of PFBC at present. Steam conditions are 246bar/569°C/568°C. All evaporation, superheating and re-heating is carried out in tube bundles submerged in the bubbling fluidised bed.

ABB Carbon has indicated that, although a supercritical steam cycle helps to maximise plant efficiency, its own development activities are targeted more at improving reliability and reducing capital costs, eg by increased modularisation and increasing the output of standard combustors. In particular, its previously rated 70-80MW_e and 350MW_e combustors are being uprated to 100MW_e and 425MW_e respectively.

HRSGs for CCGT Applications

In a CCGT, the steam cycle is determined by the way the HRSG extracts the heat from the GT exhaust gas. The development of HRSG plant is therefore strongly linked to advances in GT design. As a result of the limitation on steam conditions dictated by GT exhaust temperatures, the use of once-through HRSGs has not yet been widely adopted.

One full-scale once-through demonstration HRSG is currently under construction by Deutsche Babcock at the Cottam Development Centre, UK. This Benson design is subcritical with superheater steam conditions of 580°C and 160bar. Other small-scale trials are also in progress. Indications are that HRSGs will progressively move to once-through technology and then to supercritical pressures as GTs become larger and exhaust temperatures rise.

FACTORS AFFECTING THE MARKET

The key commercial and technical factors influencing the market for supercritical steam cycles for coal power generation include costs, availability, environmental performance, thermal performance and competition.

Costs

Capital costs of supercritical pf quoted in the literature range widely. Kjær (1996) quotes US\$1400 kW⁻¹ for a 400MW_e high-specification plant in Europe, while the World Bank (1998) quotes US\$850-1050 kW⁻¹ for moderate supercritical plant and US\$1000-1200 kW⁻¹ for advanced plant. Alternatively, Paffenbarger (1998) quotes US\$772 kW⁻¹ for a 2 x 600MW station in China. The general consensus is that power plant costs have fallen rapidly in recent years and that prices towards the lower end of this range represent the likely costs of future plant. Probably the best estimate available is US\$896 kW⁻¹.

There is a general consensus that supercritical steam cycles cost slightly (3-10%) more than subcritical versions. However, site-specific factors tend to dominate. Paffenbarger (1998) quotes overnight capital costs for 20 sites around the world, listing the average price of five supercritical sites at US\$1160 kW⁻¹, whilst the average price for 15 subcritical units is given at US\$1340 kW⁻¹.

It is worth noting that the EPC price may be substantially less than the total capital cost of developing a project. Land, taxes, project management, transmission lines to an existing grid system, other infrastructure changes and financing can add >40% onto a basic EPC price. A government-sponsored project with low cost of capital is likely to be significantly cheaper in this respect than where an Independent Power Producer (IPP) is involved.

Operating costs are dominated by the fuel cost, which is cheaper for supercritical cycles than for subcritical due to the better efficiency. This is a simple function of fuel price and unit efficiency and can more than offset the slightly higher capital cost of supercritical technology.

Availability

The availability of modern supercritical designs is expected to be very similar to those of subcritical plant, unless a very advanced or experimental design is chosen.

Typical average availability is close to 85%. However, with appropriate commercial drivers in place, the maximum achievable is probably significantly higher than this, perhaps >90%. The average availability of Denmark's five supercritical units from 1993-95 was ~89%, despite commissioning problems at Esbjerg 3.

Environmental Performance

The growing use of supercritical steam cycles is partly driven by the need to improve plant efficiency and so reduce fuel costs. However, it is also increasingly being driven by the need to minimise the environmental impact. Improvements in coal-fired plant are now being driven largely by environmental pressures, particularly the CO₂ targets set by the Kyoto Protocol on Climate Change in 1997. The signatories to this convention (which include most of the developed world) have committed themselves to reducing CO₂ emissions by 5% by about 2010 compared with 1990 levels. As emissions have risen since 1990, this represents a severe target and is bound to impact on the power industry which is a major source of CO₂ emissions.

The other major emissions, SO_x, NO_x and particulates, can all be controlled using various flue gas treatments. Modern equipment can achieve very low emissions albeit at high cost. Emission levels achievable with coal-fired plant are set out in Table 1.

Emission (mg Nm ⁻³ @ 6% oxygen, dry volume basis)	Current EU limit	Best achievable*	Technology
Particulates	50	25 15 <10	ESPs bag filters with FGD downstream
SO _x	400	100	Limestone gypsum FGD
NO _x	650	100	Low-NO _x burners and SCR

*Exact figure depends on coal quality

ESPs: electrostatic precipitators

SCR: selective catalytic reduction

Table 1. Gaseous emissions using best available established technology on coal-fired plant

Emissions-reduction technology represents a major area of research for coal-fired plant applying equally to subcritical and supercritical steam cycles. Flue gas clean-up technology is constantly under development to improve performance, reduce costs and extend the range of coals tolerated. Low-NO_x burners, particularly, offer a cost-effective means of reducing NO_x emissions and reduce the need for more expensive flue-gas equipment.

Under normal circumstances, all solid residues from coal firing can also be recycled, hence avoiding the need for landfill. Ash products (fly ash and bottom ash) and gypsum from FGD can all be used in different ways by the construction industry. In common with subcritical units, the only difficulties arise if combustion problems reduce the ash quality or if the market for the product becomes saturated.

Thermal Performance

The main impact of the supercritical cycle is to increase the overall plant thermal efficiency, thereby reducing the fuel consumption per unit of electricity generated. As well as reducing fuel costs, this is a highly practical way of reducing CO₂ emissions in coal-fired plant. Replacing a typical existing subcritical coal-fired plant of 38% efficiency with a state-of-the-art advanced supercritical design of ~45% efficiency results in a ~15% reduction in CO₂ emitted per kWh electricity generated. Similarly, all other emissions, eg NO_x and SO_x, are reduced pro rata with the fuel consumption.

Because of growing environmental concerns, the thermal efficiency of the supercritical process is one of its main selling points. If it is to compete effectively in the market in the long term, it has to remain at least as efficient as any competitor technology. Continued improvement in efficiency is an important response to the market drivers.

Competitor Technologies

For the coal power generation market, supercritical cycles compete with well-proven subcritical technology, and with FBCs and integrated gasification combined cycle (IGCC) plant.

FBCs are increasingly proven in the market place up to ~350MW units, with 500MW units forecast within the next ten years. FBCs have a strong niche market burning difficult fuels, as anything from washery wastes and anthracite to municipal waste can be combusted. However, with good fuels, supercritical pf has better efficiency than atmospheric FBC. Pressurised FBCs (in which the flue gas passes through a GT) have comparable efficiency but are less well proven.

IGCC is at the demonstration stage with about half a dozen plant worldwide. IGCC offers power generation as efficient as modern supercritical pf, but with lower emissions. However, the technology still has three significant problems to overcome before becoming fully commercial – it is more expensive than its rivals, reliability is poor, and the operating flexibility of the plant has yet to be proven. If these problems can be overcome, IGCC should take up a significant market share.

However, the main market threat to supercritical pf comes from non coal-based technologies. Gas firing, nuclear, hydro and wind schemes, and even oil firing, all result in lower CO₂ emissions per unit of electricity generated. In recent years coal has lost a substantial market share to gas-fired plant. CCGTs are cheaper to build and operate than equivalent pf plant, have much higher efficiencies (~60% on modern plant) and lower emissions. These technologies all threaten to displace coal-fired generation.

Other Factors

Globalisation of the power generation market is a significant factor affecting the development of supercritical power. There is a trend towards consolidation, exemplified by the purchases by Siemens of Parsons and Westinghouse, as manufacturers seek to operate as multinationals.

One factor affecting choice of technology is the type of fuel available. This is likely to maintain coal as pre-eminent in the Far East since other fuels are limited. There is little or no loss of fuel flexibility in moving from subcritical to supercritical steam cycles. Particular coals may still present particular problems (eg fireside corrosion is enhanced by higher metal temperatures) but plant can be designed to cope with most coals.

For poor-quality fuels, FBCs are likely to become an increasingly effective competitor as combustion and good environmental performance are both easier.

The operational flexibility of coal-fired supercritical plant is also a strong factor in their favour. There is no loss of flexibility moving from subcritical to moderate supercritical conditions – indeed the once-through boiler design is intrinsically more flexible in some respects than drum designs. If very advanced conditions are used, components become thicker and some flexibility is lost. However, in general, supercritical plant are capable of frequency response, regular cycling and load-following with ramp rates in the order of 3% min⁻¹.

Coal-firing has the strategic advantage that coal can be transported long distances and stored in large quantities. Thus it offers excellent security of supply.

MARKET TRENDS

Forecasts for electricity demand indicate a steady growth over the coming decades. For example, the Energy Information Administration (EIA) forecasts growth averaging 2.7% pa. Figure 13 shows the breakdown by region to 2020 (EIA 1998). Strongest growth is forecast in China (6.5%) and Asia (5.3%).

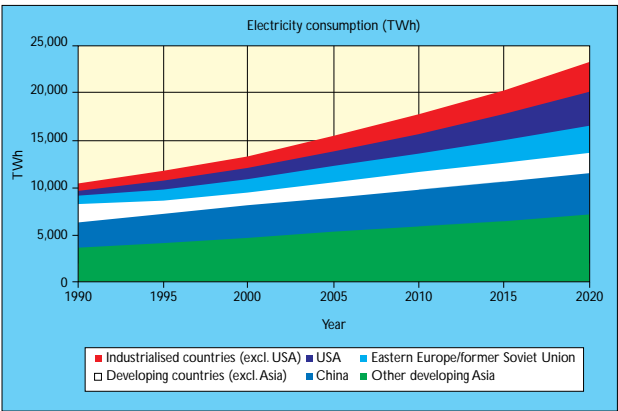


Figure 13. Electricity consumption projection to 2020 by region (EIA 1998)

This expectation of steadily increasing electricity demand is reflected in forecasts of demand for new power plant. About 100GW of new power plant (all fuels) was ordered worldwide in 1997, and annual growth is estimated at 2-3% for the foreseeable future.

More difficult to predict is the market share for coal-fired plant and, in particular, supercritical plant (which will be predominantly coal-fired). Coal-fired plant currently account for about half the market, amounting to some 50GW each year. Forecasts vary, but coal is generally expected to hold its share of the market up to 2020. One forecast (World Energy Council, WEC 1998) is shown in Figure 14. An independent forecast suggests an increase of 40GW pa in demand for coal plant by 2015 due to Asian demand alone.

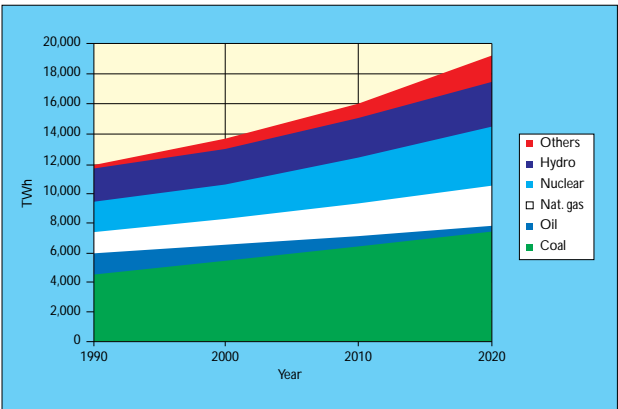


Figure 14. Global electricity production by fuel to 2020

The future market for coal-fired power generation therefore appears to be ~50-80GW pa at ~2020, with any loss of coal market share at least offset by overall market growth. However, demand for coal-fired power will switch to developing countries, particularly China, India and the Asia/Pacific region.

Forecasts beyond 2020 are highly speculative. Scenarios diverge considerably depending on the influence of environmental concerns, forecast technological advances and the fate of nuclear power. However, many show coal-fired power generation starting to decline, in which case 2020 may represent the high point of coal-fired power.

Annual demand for supercritical power plant since 1982 is shown in Figure 15, which presents a three-year rolling average to remove shorter-term fluctuations. The supercritical share of the coal-fired power market has historically averaged about 20%. It reached an early peak in the late 1960s with a major building programme in the USA, but then fell back. In the 1980s the market share dipped to <10%, but in the past five years has begun to rise again.

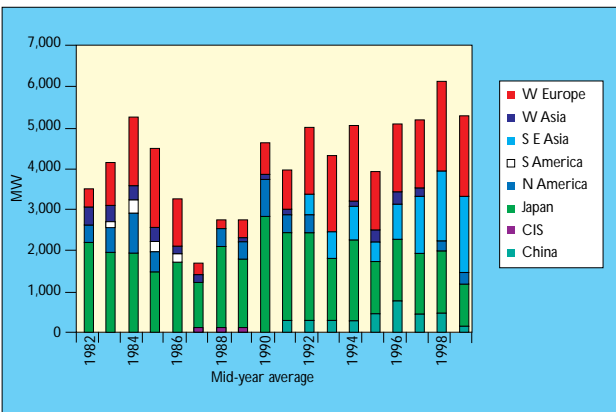


Figure 15. Supercritical plant commissioned since 1982 – three-year rolling average

Figure 15 also shows the regional demand for supercritical plant. Western Europe and Japan have been the main markets. During the 1990s, demand in Korea (South East Asia) and China has replaced that lost in Japan.

Enquiries for new projects are now predominantly supercritical, except for India. Even there, however, a supercritical project is under development. Recent economic problems in Asia are likely to delay market growth. ABB anticipates that the share of supercritical in the coal-fired power market may increase to 50% by 2015.

To summarise, the market for new coal-fired power plant is forecast as relatively stable and to reach 50-80GW pa by 2020, with the main demand for new plant in South East Asia (including China and India). Demand for supercritical plant is currently running at just over 5GW pa. However, with market penetration beginning to be achieved in South East Asia, this is set to increase. Most new coal-fired plant in Europe and Japan are likely to be supercritical. In the short term (0-5 years) the market share for supercritical is likely to grow to ~20% of coal-fired plant. In the medium term (5-10 years) good penetration of the South East Asian market outside India should allow further growth. In the longer term (10-20 years) market penetration should also be achieved in India, so that by 2020 at least 50% of new coal plant are expected to be supercritical, amounting to 25-40GW pa.

CONCLUSIONS

- The current state-of-the-art for coal-fired supercritical steam cycles is ~600°C/300bar maximum steam conditions, with a net thermal efficiency of about 45% (LHV, based on UK inland conditions). 620°C plant are expected within five years while, in the longer term (10-20 years), 650-700°C is expected, with resulting cycle efficiencies in the range 50-55%.
- Materials limitations are the major factors limiting further development, with key constraints at the furnace wall, superheater and reheater outlets, and the first stages of the HP and IP turbines. Considerable materials R&D is under way in Europe, Japan and the USA.
- Other developments are under way, mostly by individual manufacturers to optimise cycle design and improve individual components, which are resulting in incremental improvements across the plant.
- Identified R&D needs include extensive materials research, particularly into the welding and corrosion properties of candidate high-temperature materials, and demonstration of a Benson vertical furnace tube.
- No significant opportunities for retrofit of supercritical technology to existing (predominantly subcritical) plant have been identified.
- FBCs using supercritical steam cycles are now being developed. For example, a 350MW PFBC is under construction in Japan.
- The indications are that HRSGs will progressively move to once-through technology and then to supercritical pressures as GTs become larger and exhaust temperatures rise. The first full-scale subcritical demonstration Benson design HRSG is nearing completion in the UK.
- Supercritical technology is expected to progressively displace subcritical designs due to its better environmental performance and lower associated fuel costs. Asia is expected to generate the most significant demand. Current estimates suggest a steady rise in new supercritical plant from 5GW pa now to perhaps 25-40GW pa in 20 years time.

ACKNOWLEDGEMENTS

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