Development of a PF Fired High Efficiency Power Plant (AD700)

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Abstract

European efforts to start substantial improvements of the performance of well established supercritical coal-fired power technology named the AD700 project began in 1998. Major targets were development of austenitic materials and nickel-based superalloys for the hottest sections of boilers, steam lines and turbines. Other targets were development of boiler and turbine designs for the more advanced conditions and finally economic viability of the AD700 technology has been investigated. The project has been very successful and 40 partners from the European power industry have worked together in several projects cofunded by the European Commission for nearly years. Procurement of mature and commercially optimised AD700 plant could take place around 2015.

The investigated nickel-based materials have shown very high creep strengths but they have also shown to be very hard to manufacture, and more efforts to define new machining lines are being started. Ongoing tests indicate that the developed austenitic material will fulfil its creep strength target and is now ready for commercialisation.

Development works on boiler and turbine designs for the advanced steam conditions have also been successfully completed but they also clearly indicate that further development work on improved ferritic steel for furnace walls is important.

Conventional development of the steam cycles is based on new improved materials, which open for higher steam temperatures and efficiencies whereas other thermodynamic tools are only slowly being accepted. However, in the present paper a proposal for steam cycle improvements not based on higher steam temperatures is presented. The improved cycle is named the Master Cycle (MC) and it is based on a revision of the double reheat steam cycle where the bleeds of the IP turbines have been moved to a feed pump turbine bleeding on the first cold reheat line. Elsam has established protection of a patent for the MC in a number of countries.

At constant main and reheat steam temperatures, the MC offers solid heat rate improvements of ~3.5% compared with single reheat cycles and a seawater-cooled plant based on the Master Cycle could reach a net efficiency of 50%. This would mean robust improvement of competitiveness, less CO_2 per MWh being generated and a more sustainable use of the coal resources. In the future, the net efficiency will continue to increase and a sea-water-cooled 800 MW AD700 power plant to start commercial operation around 2020 might reach a net efficiency around 55% based on the MC. This is a perfect match to the future demand for achievable zero emission power plant.

1 Introduction

Coal reserves are significantly more abundant and much more widely and evenly dispersed than other fossil fuels. Coal is the invisible man powering 40% of the global electricity and at current consumption rates over 160 year’s worth is available. The European Commission has recognised the importance of coal in improving Europe’s security of energy supply and in the coming 7th Framework Programme (FP7) a role for coal has been found, which is well in line with former working programmes. But future coal-based power plant must demonstrate the highest possible efficiency and be foreseen for CO_2 capture.

The 1990s was a green decade with strong focus on environmental issues and sustainability and coal was banished as a strong CO_2 emitter. Therefore, in 1994 a large group of European power generators and equipment manufacturers started to establish a joint European R&D project named “The Advanced Pulverised (700 °C) PF Power Plant” or shortly the AD700 power plant which should convert coal to power with an efficiency of > 50% (50%+). The group wanted to create a strategic and technological platform, which should make the public [politicians, media, non-governmental organisations (NGO’s), etc.] aware of how an advanced use of coal like the AD700 technology can contribute to large reductions of CO_2 emissions from coal-based power plant in Europe and world wide and at the same time enhance European security of energy supply by keeping coal in the portfolio of fuels for European power generators.

The technological target of the AD700 project was a phased development and demonstration of an advanced ultrasuper critical (USC), pulverised coal-fired (PF) power plant technology, operating at net efficiencies of 50%+ while remaining operationally flexible and competitive in the power pools. Two main items were addressed:

- Development of new high temperature materials to expend the limits for steam parameters.
- Thermodynamic improvements of cycle and component designs to reduce the efficiency gap between the ideal reversible Carnot cycle and the real existing water/steam cycles.

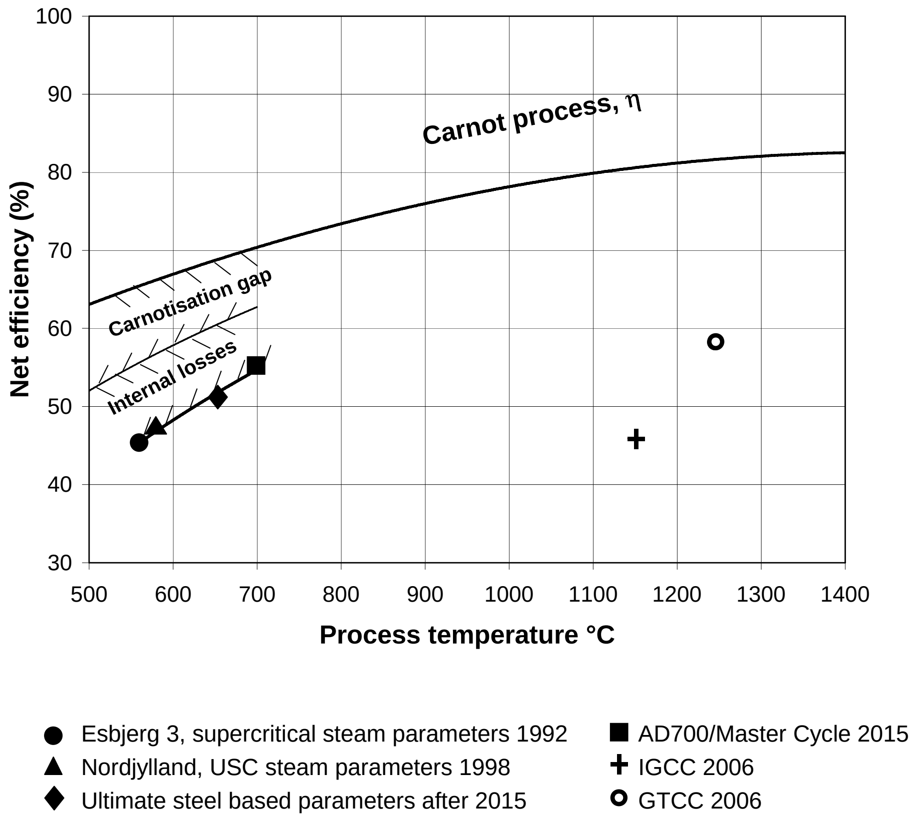

Figure 1 Efficiencies of seawater-cooled power plant fired by coal or gas

The two development activities are illustrated in Figure 1, which shows the Carnot cycle efficiency versus maximum process temperature and some examples of contemporary high efficiency power plant. The figure shows how higher process temperatures (established through better materials) drive the Carnot cycle and the existing cycle efficiencies upward along the temperature axis. The present proposals for the AD700 technology mainly focus on developments along the temperature axis.

Furthermore, Figure 1 shows how the lack of completeness of the existing water/steam cycles and their main components creates an efficiency gap between the Carnot cycle and the real existing water/steam cycles. The efficiency gap is made up of internal losses and a gap, which we have named the Carnotisation gap to illustrate lack of completeness of the water/steam cycle itself. Figure 1 also shows that even after the first AD700 plant starts there still seems to be a large potential for efficiency improvements of ~15%-points, which can be exploited through the establishment of the second development track to reduce internal losses (through improved turbine blade and sealing technologies, higher boiler efficiencies, less auxiliary power, etc.) and enhance carnotisation of the water/ steam cycles by higher steam pressures, higher feed water temperatures, double reheat, less pressure loss, etc.

Surging energy prices have given coal a strong impetus in the European power market. Fortunately, this impetus has come at a time when new and improved steels for all crucial sections of boiler, steam lines and turbine have been qualified in time for a number of new European 650-1100 MW power plants with USC steam parameters.

Most of these installations are built at inland locations with a wet cooling tower and achieve net efficiencies of ~46%. If they had been built at coastal locations in Northern Europe and based on the Master Cycle to be described at the end of the present paper, net efficiency would be ~50% (these plants are not shown in Figure 1).

The remaining sections of this paper will focus on AD700 history and outlook, considering materials for the AD700 technology and finally will offer an example of a revised water/steam cycle in which carnotisation is improved.

2 AD700

Maximum steam temperatures of the AD700 project would be around 700 °C, which means that development and demonstration of new high temperature materials, and boiler and turbine designs were crucial to the success of the project. Four major phases have been foreseen:

I. Material development and demonstration
II. Fabricability of materials
III. Component demonstration
IV. Construction and operation of a full scale AD700 power plant

The whole project would last for ~20 years from the idea was launched in the mid 1990s until it would be commercially mature around 2015. From the beginning it has been very important for the ~40 partners to obtain political acceptance of the project by the European Commission through financial engagement. The work of phases 1 and 2 was split among boiler, turbine and process groups; the boiler and turbine groups mainly worked on development and demonstration of new materials and the impact of advanced steam parameters on boiler and turbine design. The third group was a balance of project group named the process group, which took care of those issues not dealt with by the boiler and turbine groups and in particular investigated the economic viability of the AD700 technology.

Phase 1 of the AD700 project started in 1998 and ended in 2004. It was carried out within the Commission’s 4th framework programme under the contract SF/01001/97/DK [1]. DG TREN and the Swiss and British governments were financial cosponsors.

One of the main issues was identification and selection of appropriate materials and testing of these as described later. Parallel to that, the optimum thermodynamic cycle should be defined and corresponding designs should be developed for boiler and turbine. Thorough studies of fuel options, slagging and fouling, and emission control were carried out to find the right design parameters for the boiler. The possibility for cofiring with biomass was also studied.

As the nickel-based alloys are extremely expensive, the concept of compact design was studied. The aim of this is to limit the amount of these materials – e.g. by making the steam lines as short as possible. The outcome of phase 1 demonstrated that an AD700 plant is technically feasible and it will have a competitive advantage over the current internationally accepted generation of coal-fired power plants.

The second phase of the AD700 project started in 2002 and will end in 2006. It was carried out within the Commission's 5th Framework Programme under the contract ENK5-CT2001-00511 [2]. DG RTD and the Swiss government was a financial co-sponsor.

One of the main tasks in this phase has been to design, manufacture and test various components. For the boiler an evaporator panel, a superheater panel and welding of thick walled pipes were considered. A very thorough study was made of the horizontal boiler identified in phase 1 as a solution which would allow a very compact design. The study shows that this design also has potential for reduction of the boiler price in general.

For the turbine, a turbine inlet valve, forged rotor, welded rotor, moving blades, stationary blades, bolting and welding of pressure containment parts were considered. Also innovative designs with the aim of reduced need for the nickel-based alloys have been studied.

Considerable effort has been made to establish business plans for a full-scale demonstration plant (phase 4). The studies included a detailed risk assessment and a new check on the feasibility taking the latest material strength values and prices in consideration. The technology is still feasible even when a moderate price for CO_2 quotas is used.

Another target was to establish plans for a component test facility which would allow testing of components on a larger scale and for a prolonged period.

Several plans have been on the table and one included the high pressure part of a full scale 400 MW turbine to be built in connection with Elsam's 580 °C double reheat plant Skaerbaek 3. However, as the EU's framework programme 6 did not allow support for fossil fuels, it was not possible to finance it (budget was 150 M€). Instead plans were made for a less ambitious CTF mainly testing boiler components (phase 3).

Phase 3 of the AD700 project covers the component demonstration programme and it started in July 2004 with a component test facility (CTF) at the Scholven power station in Gelsenkirchen. The acronym of the project is COMTES700 and the Commission's Research Fund for Coal and Steel is co-sponsor together with a group of major European power generators named the Emax group.

The facility includes test of an evaporator and a superheater panel mounted in the boiler of Scholven F together with the necessary steam line and valves. It also includes a high pressure bypass valve, a safety valve and a turbine inlet valve (budget 25 M€). The CTF went in operation in August 2005 and will be in operation until mid 2009 followed by six months of materials investigations.

If the outcome of phase 3 is positive, phase 4 of the AD700 project could start around 2010 with the construction of a 400 MW Full-Scale Demonstration Plant (FSDP) somewhere in Europe. Some 3.5 years would be needed for construction and commissioning and afterwards two years of operation would be needed to pick up operational experiences. If everything goes well, the AD700 technology would be commercially ready around 2015.

If a FSDP is to be ordered in 2010, a planning period of two years to prepare bid specifications and to negotiate with the bidders should be foreseen. Therefore considerations concerning participation and creation of an owner's consortium with all its agreements would have to begin in 2007.

The FSDP is a big investment so it is foreseen that a consortium of power generators would be created to share the risk of construction and operation of the FSDP in co-operation with the European Commission. At present it seems that the Commission's 7th Framework Programme (FP 7) would be an excellent instrument to provide the essential political support for the FSDP but it is important to note that support from FP 7 would foresee demonstration of CO_2 capture in combination with the FSDP.

3 Materials

The realisation of the AD700 power plant called for development and qualification of appropriate materials including nickel-based superalloys for the most severely exposed components. In phase 1, ambitious targets regarding the creep rupture strength were set up for the development of ferritic, austenitic and nickel-based materials to meet the AD700 requirements. Besides creep rupture strength, these materials should also meet other requirements such as flue gas corrosion resistance, steam oxidation resistance, resistance to thermo-mechanical cycling and of course the ability to be manufactured and welded in thick section.

3.1 Materials for furnace walls

Three newly developed steels were selected as candidate materials for furnace panels. The highly alloyed 12%Cr tube steel HCM12 and the low alloyed 2.5%Cr tube steel HCM2S, both developed by Sumitomo Metal Industries and Mitsubishi Heavy Industries, and the Mannesmann developed 2.5%Cr tube steel 7CrMoVTiB1010.

HCM12 was chosen due to its excellent creep strength and oxidation and corrosion resistance. Furthermore, owing to its duplex microstructure of approximately 30% d-ferrite and 70% tempered martensite, it is possible to weld this steel without preheat and post-weld heat treatment (PWHT) [3]. The two low alloyed 2½%Cr tube steels HCM2S and 7CrMoVTiB1010 had sufficient high temperature strength and also a metallurgy which makes it possible to omit PWHT [4], [5]. The chemical composition and mechanical properties for all three steels are given in table 1 and figure 2 respectively.

Testing of HCM12, HCM2S and 7CrMoVTiB1010 is in progress in Europe to establish practical experience with the handling of these steels. In the furnace panels of an existing subcritical once-through boiler, test sections of all three steels have been installed, and service under cycling conditions has been tested for several years. For the HCM2S and 7CrMoVTiB1010 tube materials, no problems have been encountered during the production of the test panels or during operation at steam temperatures up to 500 °C. Test panels of HCM12 have been service exposed with steam temperatures up to 530 °C under cycling conditions.

Within the AD700 project phase 3 both 7CrMoVTiB10 10 and HCM12 are being tested in the CTF evaporator panel at Scholven power station in Gelsenkirchen.

Unfortunately, it was later realised that a major reduction in long-term creep rupture strength at temperatures above 550 °C must be foreseen for many of the 10–12%Cr steels, including HCM12. Systematic microstructure investigations of different 10–12%Cr steels showing sigmoidal creep behaviour have demonstrated that precipitation of the complex Z-phase nitride [Cr(V,Nb)N] takes place in the steels at the expense of the strengthening MX carbonitrides, which dissolve [6]. This mechanism is responsible for the reduction in creep strength, and it seems that high Cr steels are more prone to Z-phase formation than low Cr steels.

The presence of Z-phase with its detrimental effect on the long-term microstructural stability of the new generation of 9–12%Cr steels constitutes a serious challenge for the development of a cost effective AD700 power plant. New routes for the development of iron-based materials for furnace walls must be sought, otherwise the only alternative would be to use nickel-based superalloys like alloy 617 for the hottest part of the furnace wall. The fact that alloy 617 tubes cost roughly 10 times more than HCM12 and call for a far more expensive fabrication means that the whole boiler economy must be carefully considered before such a choice of material is taken.

3.2 Materials for superheater tubes

For superheater tubing, the aim is to develop an improved austenitic tube material with sufficient strength and flue gas corrosion resistance to operate at steam temperatures around 650 °C, and to develop a nickel-based superalloy to fill the gap up to 700 °C steam temperature. Intensive development work is continuing in the AD700 project to demonstrate a suitable austenitic tube material with 100,000 h rupture strength of ~100 MPa at 700 °C and a nickel-based tube material with 100,000 h rupture strength of 100 MPa at 750 °C - both materials have to demonstrate a flue gas corrosion resistance better than 2 mm metal loss during an exposure of 200,000 h.

Table 1 Nominal chemical composition, wt%

	C	Cr	Mo	W	Others
HCM2S	0.06	2.25	0.3	1.6	V, Nb, N, B
7CrMoTiB10 10	0.07	2.4	0.3		V, Ti, N, B
MCH12	0.1	12	1	1	V, Nb

Table 2 Nominal chemical composition, wt%

	C	Cr	Ni	W	Cu	Nb	Others
Alloy 174	0.08	22	25	3.5	3	0.5	Co, N
NF709	0.08	20	25	-	-	0.25	Mo, Ti, N
Super 304H	0.10	18	9	-	3	0.45	N

For the development of a new austenitic stainless steel, 30 trial melts were manufactured based on different alloy design principles. After two screening tests of up to 15.000 h of testing, the alloy 174 showed the best overall material properties and was selected to be tested further as an AD700 candidate material. The chemical composition and creep properties are shown together with some of the best commercial austenitic superheater tube alloys in table 2 and figure 2.

In figure 2 the improvement in creep rupture strength as compared to the other austenitic materials is obvious and continuing steam oxidation and flue gas corrosion tests demonstrate properties comparable with or slightly better than those obtained for a large variety of 22-25% Cr austenitic superheater steels. So far all targets are fulfilled.

Long-term creep rupture properties for base material as well as cross-weld specimens and microstructural stability test are continuing and will complete the characterisation of this super austenite which will be launched in the market by Sandvik under the name Sanicro 25.

Regarding candidate materials for the nickel-based tubing, a literature survey concluded that the existing alloy NIMONIC® alloy 263 had adequate strength to meet the creep requirement, but the literature survey also showed that its corrosion resistance might be inadequate. Therefore, >30 trial compositions based on alloy 263 were produced. Improvement of the coal ash corrosion resistance of the alloy was developed in a series of coal ash corrosion tests at different temperatures employing samples with a systematic variation in alloy constituents.

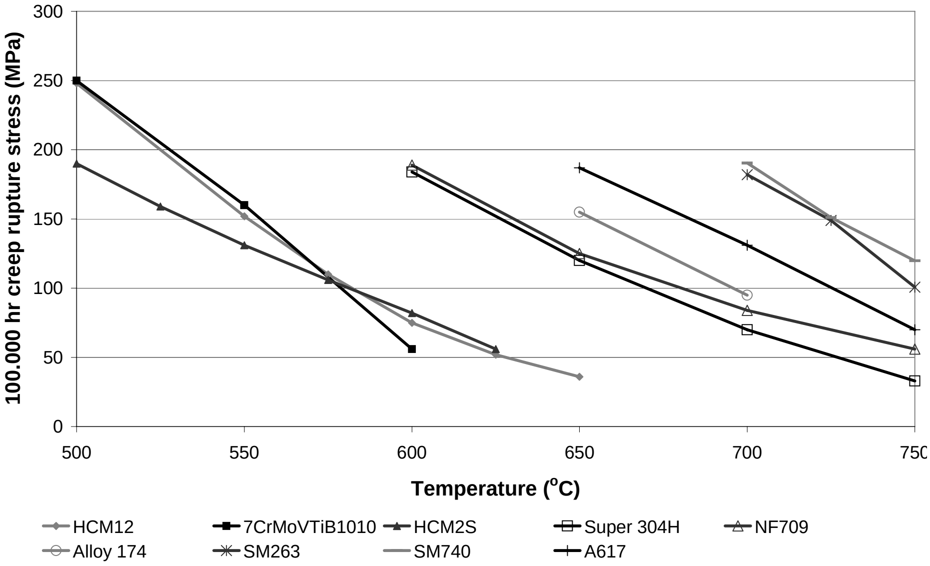

Figure 2 Creep rupture strength of candidate materials for the AD700 power plant

The resultant optimised chemical composition which was selected is given in table 3, together with two other nickel-based candidate materials. The new alloy INCONEL® alloy 740 is a nickel-chromium-cobalt alloy which is age hardenable by γ prime precipitation but also benefits from solid solution hardening.

Table 3 Nominal chemical composition, wt%

	C	Ni	Cr	Mo	Co	Al	Ti	Nb	Mn	Fe	Si
Alloy 740	0.03	Bal	25.0	0.5	20.0	0.9	1.8	2.0	0.3	0.7	0.5
Alloy 617	0.07	Bal	21.5	9.0	11.5	1.0	0.35	-	0.25	1.0	0.25
Alloy 263	0.06	Bal	20.0	5.8	20.0	0.5	2.1	-	0.3	0.35	0.2

A large creep test matrix is presently underway for both alloy 263 and alloy 740 covering two major test temperatures, 725 and 775 °C, with some shorter term tests at 700, 750 and 800 ºC. Test durations up to 65,000 h are being targeted. From the results obtained so far estimations on the 100,000 h creep rupture strength are depicted in Figure 2 based on 20,000 h data.

In the frame of Emax, fabrication trials of superheater sections partly made of Sanicro 25 and alloy INCONEL® alloy 740 leading to in-plant exposure testing have been finished successfully. In-plant tests taking these superheater tube materials to temperatures above 700 °C began in September 2004 at the power plant Esbjergværket [7] and in July 2005 at the power plant Scholven.

3.3 Thick section components and steam piping

For thick section boiler components and steam lines there are two goals for the materials development. In order to lower the cost of an AD700 power plant, it would be desirable to expand the present temperature range for the ferritic/martensitic 9-12% Cr steels up to

~650 °C; above 650 °C, a nickel-based superalloy with 100,000 h rupture strength of 150 MPa at 700 °C is needed to allow construction of outlet headers and main steam lines with acceptable wall thicknesses.

The task of improving the 9-12%Cr steels on top of the impressive developments in the last two decades has proved to be very difficult. In the last five years, worldwide research has resulted in a large number of new alloys being announced, and from short-term tests they seemed very promising. However, in long-term tests the steels show sigmoidal creep behaviour and so far no ferritic alloy has demonstrated long-term creep strength better than steel P92. In AD700 attempts were also made to improve the creep rupture strength of 9-12%Cr steels. Of the seven melts manufactured six turned out to be weaker than P92 and only one melt, a 9%Cr5Co2WVNbN, showed creep rupture strength similar to P92. In parallel, tests were made on steel NF12. Short-term data demonstrated a major improvement, but longer term data showed a dramatic drop in strength also for this steel. These dramatic decreases in strength have all been ascribed to the precipitation of Z-phase as described above for the furnace wall material HCM12.

Alloy 263 or an improved version of alloy 617 may meet the demands for outlet headers and steam lines at 700 °C steam temperature. In the AD700 context, focus was put on alloy 263 as its strength would enable constructions with smaller wall thicknesses which in turn would lead to a reduction in costs when building an AD700 power plant.

A vital demonstration of the viability of this alloy in the context of the AD700 programme was achieved with the manufacture of a thick section pipe. A two-ton ingot has been produced in alloy 263 and this has been put through the normal pipe production route to produce 4.5 m steam pipe with dimensions 310 mm o.d. x 66 mm wall thickness. Welding trials have been successfully performed and long-term creep rupture data for base material as well as cross-weld specimens and microstructural stability test are continuing and will complete the characterisation of this nickel alloy. Furthermore, long-term creep tests on commercially available 15 mm diameter bar are continuing. All creep rupture data obtained so far suggest that the alloy will easily meet the creep criteria. More thick section pipes have been produced to enable a full qualification of alloy 263 to be used with all its strength potential for steam pipe application.

3.4 Materials for the turbine

As for the boiler and for the steam lines it has been necessary to qualify materials for the hottest part of the turbine, e.g. inlet valves inlet part of the HP- and IP-turbine, first rows of blades and bolts. A special group within AD700 has been working with this qualification. Materials were selected from the large variety of nickel-based alloys well known from the gas turbine industry. The task was to qualify these materials to be used in a temperature and pressure regime and environment different from what is known from the gas turbines.

During the first six years materials for turbine castings and forgings bar material were selected and qualified for the construction of a high temperature steam turbine. In table 4 the nominal chemical compositions of these materials are given.

Table 4 Nominal chemical composition, wt%

	Ni	Cr	Mo	Co	Al	Ti	Nb	Mn	Fe	Si	B
Alloy 617	Bal	21.5	9.0	11.5	1.0	0.35	-	0.25	1.0	0.2	
Alloy 625	Bal	22.0	9.0	-	0.2	0.2	3.5	-	-	-	
Alloy 718	Bal	19.0	3.0	-	0.5	1.0	5.0	-	18.0	-	
Alloy 263	Bal	20.0	5.8	20.0	0.5	2.1	-	0.30	0.35	0.2	
Waspalloy	Bal	20.0	4.0	14.0	1.4	3.0	3.5	-	-	-	0.005
N 105	Bal	15.0	4.0	20.0	4.5	1.2	3.5	-	-	-	0.005

Alloy 617 and 625 are foreseen to be used for turbine castings and forgings, whereas alloy 718 and 263 will only be considered for forgings. Waspalloy and N 105 are to used for bar material applications like blades and bolts. Test components of valve bodies and steam chest of materials alloy 617 and 625 and full scale rotor forgings of materials alloy 617, 625, 718 and 263 have been produced. As the use of a welded rotor construction is foreseen in future AD700 power plants heavy section rotor weldings have been demonstrated. Mechanical testing on samples taken from all these product including the weldments are in progress [8].

In COMTES700 a full scale turbine inlet valve is part of the component test facility.

4 Master Cycle

The improvements of steel as described above also meant remarkable progress concerning main and reheat steam temperatures which increased from the 540-560 °C range to the 600-610 °C and they will continue to increase as AD700 technology becomes commercially mature within ten years. Basically higher steam temperatures also mean higher efficiencies but a more detailed analysis of the water/steam cycle shows that superheating of the bleed steam for the regenerative feed-water heaters also continues to increase, which is thermodynamically disadvantageous. Therefore, in modern water/steam cycles the efficiency gain through higher main and in particular reheat steam temperatures disappears for that part of the reheat steam that is later on used as strongly superheated (above ~250 K) bleed steam for the feed-water heaters.

In this section it will be shown how the conventional water/steam cycle can be improved by a slight change, which reduces super heat of the bleed steam. The improved cycle was invented by Elsam and is named the Master Cycle (MC). Patent protection has been established in Australia, Europe, Canada, India, South Africa and the USA**.** Using the wording of the section "Introduction", it might be said that the carnotisation gap of a conventional cycle is further reduced with the MC. The MC works on both single and double reheat cycles and on both USC and AD700 steam parameters but - independently of steam parameters - it works most effectively on double reheat cycles.

The major change of the MC is the removal of the steam bleeds for the regenerative feed water heaters from the IP turbine(s) to a separate turbine named the tuning turbine or the T-turbine. With the T-turbine installed, both the reheat and regenerative feed water preheating processes are decoupled and can be optimised (tuned) independently. Tables 5 and 6 show the superheat of the four top bleeds of a number of single and double reheat cycles. The tables clearly show that in particular the first bleeds (marked with a *) after re-heating are very hot for the conventional cycles and table 6 also shows how effectively the MC reduces the superheat of the bleed steam of the double reheat cycles.

Figure 3 illustrates the principles of the Master Cycle with double reheat.

Table 6. Super heat of the four top bleeds of three double reheat cycles including the Master Cycle

Heater	Top heater		Top heater – 1		Top heater – 2		Top heater – 3	
	p_{Bleed}	Super heat	p_{Bleed}	Super heat	p_{Bleed}	Super heat	p_{Bleed}	Super heat
Steam parameters	bar	K	bar	K	bar	K	bar	K
285 bar/580/580/580/ 300 °C	78.1	77	* 41.6	* 232	20.66	166	* 13.8	* 337
285 bar/580/580/580/ 300 °C, MC	77.5	75	40.8	35	19.9	Wet	11.0	Wet
375 bar/700/20/720/ 350 °C	123.0	172	* 78.8	* 354	29.8	250	* 17.7	* 432
375 bar/700/720/720/ 350 °C, MC	132	179	85.4	144	32.2	70	17.2	28

* The first bleeds

The T-turbine is a separate turbine bleeding on the first cold reheat line downstream of the check valves and as steam for the T-turbine starts expansion from relatively cold

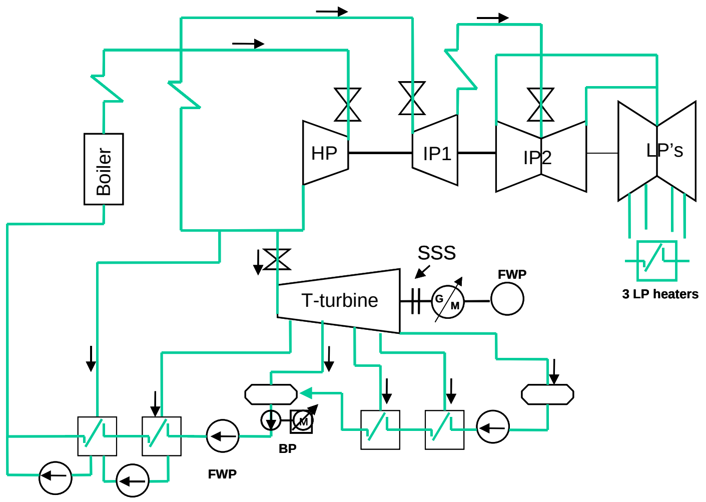

Figure 3 Principles of the Master Cycle with double reheat

conditions, the super heat is rapidly reduced. This also means that bleed steam from the T-turbine is very cold and the final bleeds of the T-turbine steam might even be slightly wet.

As steam is being extracted constantly along the steam path of the T-turbine, the volume low only increases slowly and the T-turbine needs to rotate at ~5000 rpm to achieve good stage efficiencies. After the T-turbine, the steam exhausts into a regenerative heater, so no expensive T-turbine condenser is needed. The T-turbine also drives a 100% feed pump and a generator, both running at the same speed as the turbine. The generator balances the power being generated and it could be added to the main transformer through separate primary coils. During start and stop, the T-turbine stops by opening the SSS clutch and the generator switches into motor operating mode to drive the feed pump. This also means that no separate start up pump is needed.

Good efficiency of all stages of the T-turbine is paramount to the success of the MC, which means that design of the T-turbine becomes easier as plant output increases. Therefore, the continuing trend to increase the output of coal-fired plant to the 800 - 1000 MW range is very beneficial for the MC.

IP turbine design becomes simpler and cheaper with the MC as all bleeds disappear and the extraction lines with their check and shut-off valves also can be designed for much lower temperatures and cheaper materials. More bleed steam is needed as superheat of the T-turbine bleeds is reduced, which also means that more main steam is needed to improve cooling of the furnace walls and efficiency of the HP turbine through longer blades.

Removal of bleed steam from the IP-turbines to the T-turbine also means that steam flow through the reheaters of the MC is reduced by some 20-25% creating large reductions and savings of reheat steam lines and reheater surface in the boiler. Preliminary investigations indicate that the MC boiler price would come close to the price of a conventional single reheat boiler.

Cycle studies of the MC show that in total there is a heat rate gain (in kJ/kWh) around 3.5% for the MC compared with a conventional single reheat cycle and a seawater-cooled power station based on the MC could reach a net efficiency of 50%. Further, MC decoupling of the reheat and regenerative feed water preheating systems offers more freedom to optimise these systems, which is very advantageous for the cycle designer in his efforts to reduce investment cost.

It may be concluded that the MC seems to bring a competitive advantage of ~3.5% on specific heat rate compared with a conventional single reheat cycle and the net present value of coal savings and CO_2 reductions is worth about 70 M€ for an 800 MW plant. These savings can be achieved at roughly constant investment cost.

Finally, in conventional cycles a minimum heat rate always appears as final feed water temperature increases but with the MC the situation seems different and thermodynamically more advantageous as the heat rate continues to fall. No conclusion on this phenomenon, which improves carnotisation of the cycle, exists at present but further investigations are being started.

5 Conclusions and outlook

Since the erratic price increases of primary energy started a few years ago and the gas supply crisis this year, coal has made a strong comeback in the European power market. Fortunately, the comeback appears at a time when new and improved steels for all crucial sections of boilers, steam lines and turbines have already been qualified in time for a number of new 650-1100 MW power plant with USC steam parameters.

Furthermore, improved nickel-based materials are being developed and qualified and they will be the basis for a new generation of advanced power plant operating at rated steam temperatures of 700 °C. Construction of an advanced 400 MW AD700 power plant could start around 2010 and be ready for operation around 2012.

Based on new steels, the net efficiency of contemporary power plant technology demonstrates robust improvement meaning improved competitiveness, less CO_2 per MWh being generated and a more sustainable use of the coal resources. In the future, the net efficiency will continue to increase and a seawater-cooled 800 MW AD700 power plant to start commercial operation around 2020 might reach a net efficiency around 55% based on the MC. The MC was invented by Elsam and is a slight modification of the double reheat cycle offering 3.5% improvement of heat rate compared with a single reheat cycle. Patent protection has been established in a number of countries.

However, pressure on energy resources and demand for zero emission power plant will continue and even grow in future, so there is indeed a need for more effective and sustainable power station. AD700 is a relevant answer to these requests. A coal-fired boiler allows co-firing with biomass and fractions of waste which reduces the CO_2-emission. The ultimate efficiency makes it economically feasible to install CO_2-capture after such a plant.

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