Status of advanced ultra-supercritical pulverised coal technology

Kyle Nicol

CCC/229 ISBN 978-92-9029-549-5

December 2013

Abstract

In pulverised coal combustion (PCC) power plant, increasing the maximum temperature of the steam cycle increases the electrical efficiency, which in turn lowers both coal consumption and flue gas emissions. However, the maximum steam temperature is limited by materials that can operate at these conditions for practical service lifetimes without failure. The EU, USA, Japan, India and China all have material research programmes aiming for the next generation of increased steam temperatures and efficiency, known as advanced ultra-supercritical (AUSC) or 700°C technology. This report reviews developments and status of these major material research programmes.

Acronyms and abbreviations

AD700	Advanced 700°C
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AUSC	advanced ultra-supercritical
BHEL	Bharat Heavy Electrical (India)
CCHLPA	cross compound at high/low position arrangement
CCS	carbon capture and storage
CISRI	China Iron and Steel Research Institute Group (China)
COST	CO-operation in the field of Science and Technology
CTF	component test facility
DMW	dissimilar metal welds
EC	European Commission
EN	European Standard
EPDC	Electrical Power Development Centre (Japan)
ETR	Esbjerg test rig
FP	Framework Programme
FSDP	full-scale demonstration plant
GMAW	gas shielded metal arc welding
GTAW	gas tungsten arc welding
HAZ	heat affected zone
HHV	higher heating value
HP	high pressure
HPE	Hitachi Power Europe
HWT	hochtemperatur werkstoff teststrecke (high temperature material test track)
IEA	International Energy Agency
IGCAR	Indira Gandhi Centre for Atomic Research (India)
IP	intermediate pressure
LHV	lower heating value
LP	low pressure
NEA	National Energy Administration (China)
NIMS	National Institute for Materials Science (Japan)
NTPC	National Thermal Power Corporation
PCC	pulverised coal combustion
PWHT	post weld heat treatment
P&ID	piping and instrumentation diagram
RFCS	research fund for coal and steel
RMB	renminbi
SAW	submerged arc welding
SMAW	shielded metal arc welding
TCV	turbine control valve
TIG	tungsten inert gas welding
TMAX	maximum temperature
TMIN	minimum temperature
USC	ultra-supercritical

Contents

1 Introduction

Pulverised coal combustion (PCC) power plant dominates the power industry and will continue to do so for the foreseeable future. The ageing global fleet of PCC plant and rising demand for electricity mean that new PCC plant are required. Increasing PCC plant electrical efficiency guarantees lower coal consumption, resulting in reduced fuel costs and helps to sustain valuable coal resources. A higher electrical efficiency also lowers the amount of flue gas to be treated in the flue gas cleaning systems, and lowers the carbon tax. A higher electrical efficiency will also assist the deployment of CCS (carbon capture and storage). This is because higher electrical efficiency improves the economic viability of CCS in two ways. Firstly, there is less carbon dioxide produced for a given power rating, resulting in a smaller CCS process and associated auxiliary load. Secondly, as more electricity is available for the grid, the CCS auxiliary load has less of an adverse effect on plant economics.

One of the most effective ways to increase the electrical efficiency of PCC plant is to increase the steam parameters. The maximum steam parameters are limited by materials that can operate at these conditions for a practical service lifetime without failure. Historically, the steam parameters have increased with the development of improved steels. The first generation of PCC plant operated at subcritical steam parameters, achieved with low alloy CMn and Mo ferritic steels. The next generation was supercritical (SC) steam parameters, achieved with low alloy CrMo steels and 9–12% chromium martensitic steels. Ultra-supercritical (USC) steam parameters followed with improved martensitic 9–12% chromium steels (such as grade 92) and austenitic steels (such as HR3C and Sanicro 25). State-of-the-art USC technology has reached a superheater temperature of 604ºC and electrical efficiencies of 47% (net, LHV, hard coal). The new target is advanced ultra-supercritical (AUSC) steam parameters reaching superheater temperature of 700ºC with electrical efficiency estimated at 50% (net, LHV, hard coal). However, AUSC steam parameters will require the use of nickel alloys in high temperature components.

Table 1 defines the steam parameters in each generation of PCC plant steam cycles. These values are not internationally defined but are adopted in this report. The associated electrical efficiency and coal consumption range with the materials required to achieve the steam parameters are given.

High temperature components range in shape and size, from long thin-section superheater tubes to large thick-section valves. Each component is manufactured from parent materials and welded together using filler material. Parent materials are extrusion, cast and forged into shape. Material properties depend on the material microstructure which is a result of multiple variables in the manufacturing process. As a result there are many materials available. High temperature components then have to withstand certain types of stresses and chemical attack for up to forty years in service.

Table 1 Steam parameters in PCC plant steam cycles (IEA, 2012)

	Superheater temperature and pressure	Material in high temperature components	Efficiency, LHV (net), hard coal, %	Coal consumption, gCOAL/kWh
Subcritical	⩽540°C and <22.1 MPa	Low alloy CMn and Mo ferretic steels	<35	⩾380
SC	540–580°C and 22.1–25 MPa	Low alloy CrMo steels and 9–12% Cr martensitic steel	35–40	380–340
USC	580–620°C and 22–25 MPa	Improved 9–12% Cr martensitic steels and austenitic steels	40–45	340–320
AUSC	700–725°C and 25–35 MPa	Advanced 10–12% Cr steels and nickel alloys	45–52	320–290

Superheater manufacture involves extruding several materials into long thin-section tubes, which are welded together with shallow welds. Superheaters are exposed to fireside corrosion, steamside oxidation, static loads and fluctuating thermal gradients, which cause creep and fatigue damage respectively. A contrasting example is a steam turbine valve. Parent materials are forged or cast into thick-section shapes and welded together with deep welds. Steam turbine valves require high resistance to steamside oxidation and fatigue damage.

Developing AUSC technology will require an extensive and complex materials research programme, lasting over ten years at a substantial cost with high technical risk. Major industries have acknowledged that it is not possible to develop AUSC technology alone. Consortia of utilities, manufacturers, research establishments are required to combine their individual strengths and resources in order to solve the technical issues to expedite AUSC technology.

Furthermore, developing AUSC technology is economically risky for investors. In some cases financial support has been provided by government bodies in order to mitigate the financial risk. There are such material research programmes in the USA, EU, Russia, Japan, China and India. This report reviews developments and status of the major material research programmes for AUSC) pulverised coal technology.

Osgerby (2007) estimates that, for a specific component fabricated from new materials, a typical high temperature materials research programme takes roughly twelve years. The programme will consist of the following stages:

- **Investigation of trial materials (two years)**: Includes creep rupture testing to at least 10,000 hours;
- **Prototype component manufacture from the best trial material (oneyear)**: This stage is essential to demonstrate that the material can be manufactured and welded into large-scale components without problems arising from microstructure change (such as excessive chemical segregation or grain size control). A thorough inspection routine of large-scale components must be demonstrated;
- **Characterisation of the prototype (four years)**: This typically includes long-term creep rupture testing from at least 30,000 to 100,000 hours (roughly 3½–11 years), low cycle fatigue testing and cycle hold testing. Other investigations that may be carried out include the influence of long-term ageing on tensile and impact strength, fracture toughness and cracking properties. Steamside oxidation and fireside corrosion rates must be assessed;
- **Commercial component (1 year)**: Launch as commercial material and gain first purchase order;
- **Test commercial products to establish scatter band of properties (four years)**: Variations in component properties are typically of the order of ±20%. Knowledge of this scatter band and the position of the first prototype within it are required to exploit fully the properties demonstrated in a single prototype.

2 Materials in PCC plant

This chapter provides background information on the use of high temperature materials in pulverised coal technology. Section 2.1 explains how increasing superheater steam temperature results in increased electrical efficiency. Section 2.2 explains how high temperature materials are damaged in PCC plant. Section 2.3 and Section 2.4 list the candidate materials that are required for AUSC technology and explain the materials standards involved. Sections 2.5 and 2.6 briefly explain the welding process and concept of coatings respectively. Section 2.7 describes economics involved in AUSC technology.

2.1 Carnot cycle

PCC plant transfer heat energy from the boiler to the steam turbine via the steam cycle. The steam cycle operates under the thermodynamic principle of the Carnot cycle (specifically the Rankine cycle when water is used as the working fluid). The Carnot cycle efficiency is proportional to the equation T_{MAX}–T_{MIN})/T_{MAX}, where T_{MAX} is the maximum temperature and T_{MIN} is the minimum temperature, both measured in kelvin. Therefore, to improve the Carnot cycle efficiency the difference between T_{MIN} and T_{MAX} must be increased (Modern Power Systems, 2008; Nalbandian, 2008). Increasing both the superheater and reheater temperatures by 20°C equates to an increase of roughly 1% point in net efficiency (National Coal Council, 2007).

T_{MAX} is found in the superheater, main steam pipework and valves, and the high pressure (HP) turbine. T_{MAX} is limited by materials that can operate in these components at these temperatures for a practical length of time without failure.

T_{MIN} is dependent on the cooling water source, which can be river water or sea water. The amount of cooling available depends on the temperature of the cooling water which varies geographically. A PCC plant in Scandinavia that is cooled by sea water from the Baltic Sea will have greater cooling capacity compared to air cooled plant in the Karoo region of South Africa. In Europe, a PCC plant with sea water cooling has 1.5–2% points additional electrical efficiency than the same PCC plant located inland using river water cooling (recirculated in cooling towers) (VGB, 2012b). Thus, the minimum temperature is constrained geographically.

Increasing T_{MAX} reduces losses to what is known as the Carnotisation gap. The Carnotisation gap is loss in efficiency due to thermodynamic incompleteness of the Carnot cycle. The Carnotisation gap is large at low temperatures. For example, 10% of electrical efficiency is lost to the Carnotisation gap when T_{MAX} is 600°C, and can be reduced significantly when T_{MAX} exceeds 900°C. This concept is represented graphically in Figure 1 as a plot of T_{MAX} (°C) and related carbon dioxide emissions (gCO_2/kWh) with efficiency – the numbers used are an average of the global values.

Other aspects of the electrical efficiency of PCC plant include the heating value of the coal-fired, auxiliary load and internal losses, andwhether it is single or double reheat and the method of performance measurement. It is also important that efficiency is calculated on the same heating value basis, which is generally the lower heating value (LHV). Efficiency measured on a higher heating value (HHV) basis can be nearly 2% points lower than a LHV basis for bituminous coals (10–12% moisture content) and 6% points lower for many lignite coals (Henderson, 2013). Figure 1 shows some state-of-the-art PCC plant operating in 2013. Although reheat temperatures are higher than $T_{MAX,}$ the steam has significantly lower pressure and therefore much less energy. Figure 1 illustrates the efficiency gain of a double reheat PCC plant.

Increasing efficiency by increasing the maximum steam pressure is not as beneficial as increasing

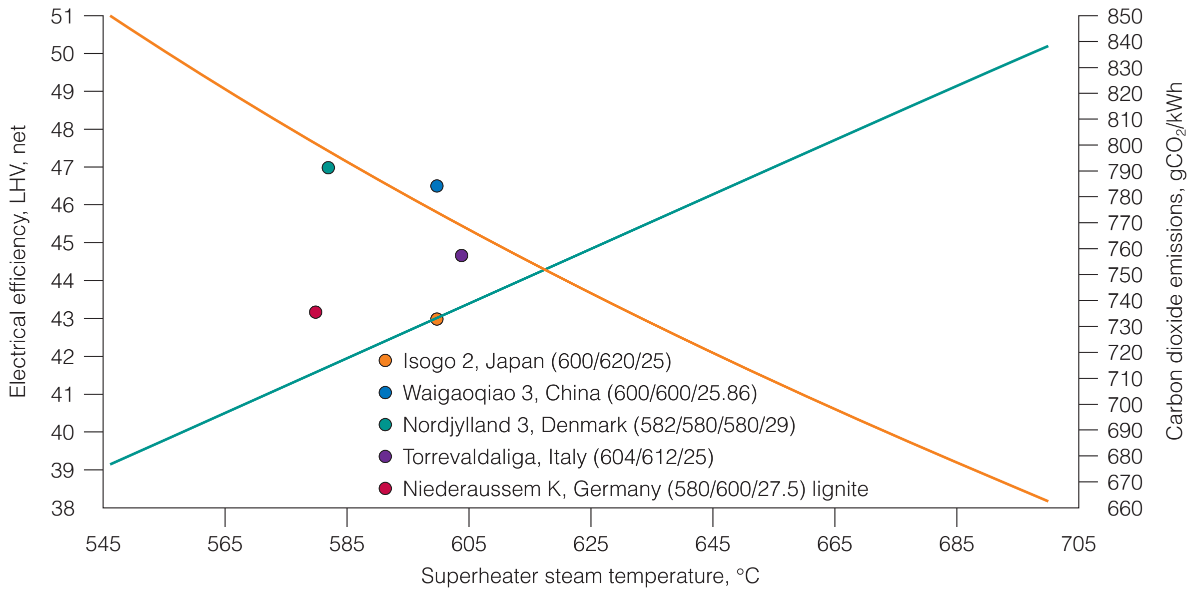

Figure 1 Relationship between steam temperature and electrical efficiency (IEA Clean Coal Centre, 2012; IEA, 2012, VGB 2012; Mao, 2012; Gibbons, 2013)

T_{MAX} for two reasons. Firstly, increasing T_{MAX} from 600°C to 700°C will result in an efficiency rise of 2.2%, whereas increasing the pressure from 25 MPa to 35 MPa results in an efficiency rise of 0.8% (Mao, 2012). Secondly, higher maximum pressures require thicker-section components. This limits the rate of heat transfer, leading to longer load change times, which are detrimental for cyclic operation.

Net efficiency loss to auxiliary load and internal losses together are known as the component gap. The component gap can no longer be significantly improved as it has reached a point of diminishing returns; this loss accounts for approximately 10% net efficiency when T_{MAX} is 600°C (Modern Power Systems, 2008).

To summarise, as T_{MIN} is constrained geographically and the component gap is largely closed, the single most effective way to increase the net electrical efficiency of PCC plant is to increase T_{MAX}.

2.2 Damage mechanisms

Materials last for a finite time in an operating PCC plant. Materials are gradually degraded by chemical attack, in the form of fireside corrosion and steamside oxidation, which lowers the material strength. At the same time these materials are exposed to mechanical stresses, induced by physical loads or thermal gradients, which deform the material. Ultimately, the combination of chemical attack and mechanical stresses on materials in service will result in material failure. The following sub-sections will expand on chemical attack and stress.

2.2.1 Chemical attack

Steamside oxidation is the oxidation of metal surfaces exposed to the steam in the steam loop; this will be most prevalent in higher temperature locations, such as pipes, tubes, valves and steam turbines. Steamside oxidation consists of three stages. Firstly, oxide scale builds up causing materials to overheat, which decreases material strength. Secondly, the oxide scale eventually exfoliates, gradually reducing the materials cross-sectional area, which again decreases material strength. Finally, the oxide scale fragments and erodes the entire steam loop, further decreasing strength. In short, steamside

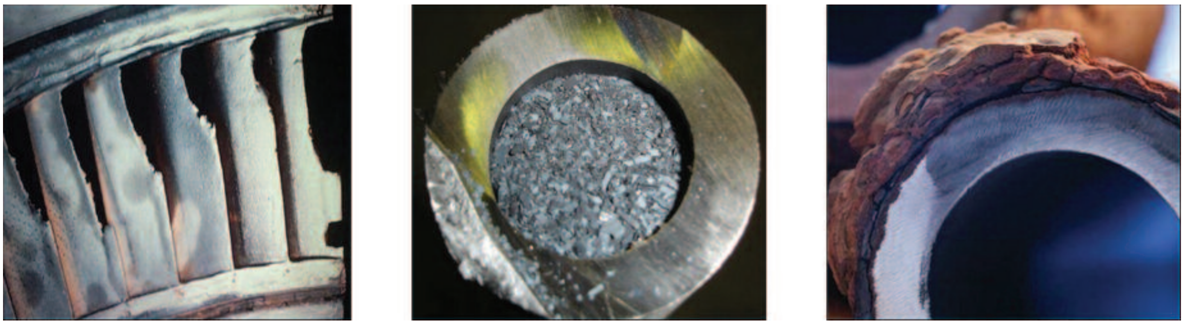

Figure 2 Steamside oxidation, erosion and fireside corrosion (Mao, 2012,Stein-Brzozowska, 2012)

oxidation will lower steam turbine efficiency and decrease material strength and may lead to pipe blockages, *see* left picture and middle picture in Figure 2 (Viswanathan, 2008a).

Fireside corrosion (or hot corrosion) is a term used to describe the chemical attack of metal surface in boilers by flue gases and molten coal ash containing elements such as sodium, sulphur and chlorine. The pipework, valves and turbines are not exposed to fireside corrosion. The accumulation of corrosion by-products on metal surfaces, *see* far right picture in Figure 2, has two effects. Firstly, heat transfer rates are decreased resulting in reduced thermal efficiency. Secondly, material strength is reduced through overheating and the gradual reduction of cross-sectional area. Fireside corrosion occurs in the high temperature gas phase, high temperature gas and liquid phase and low temperature liquid phase as explained below (Moreea-Taha, 2002):

- **High temperature gas phase:** At high temperature, sulphur (sulphur dioxide and hydrogen sulphide) and chlorine species (in the form hydrogen chloride and chlorine) can corrode materials by reduction or oxidation mechanisms. Common products of corrosion are sulphates, sulphides and chlorides. High temperature gas phase corrosion involving chlorine is called chlorination and with sulphur it is sulphidation.
- **High temperature gas and liquid phase**: Various salts formed during combustion condense on materials as a liquid film. New salts are then formed from reaction with other salts and with various elements from metal surfaces. Some of these new salts can then evaporate, depleting materials of certain elements, which potentially leads to secondary corrosion mechanisms. The corrosion rate depends on the affinity of the alloying elements to salts.
- **Low temperature liquid phase**: Low temperature corrosion may result from the condensation of sulphuric acid, sulphurous acid and hydrogen chloride in the colder areas of the boiler. The resulting corrosion is usually manifested as pitting.

Refuse derived fuel and biomass can be cofired with coal, which can alter fireside corrosion mechanisms. This is one reason why material research programmes are not identical. Another reason is that many types of coal are fired which could have different fireside corrosion mechanisms. For example, research in the USA assesses fireside corrosion effects on materials when firing indigenous high sulphur coals (Viswanathan, 2008b; Gazzino, 2012).

Chemical attack can be quantified in laboratory-scale tests that simulate the condition found in full-scale application, more accurate quantification can be obtained via tests in large-scale component test facilities.

2.2.2 Stress

Materials in PCC plant are exposed to mechanical and thermal stresses. Mechanical stresses are caused by pressures and physical loading. Thermal stresses are induced by temperature gradients. Stresses result in two kinds of damage mechanisms, creep and fatigue.

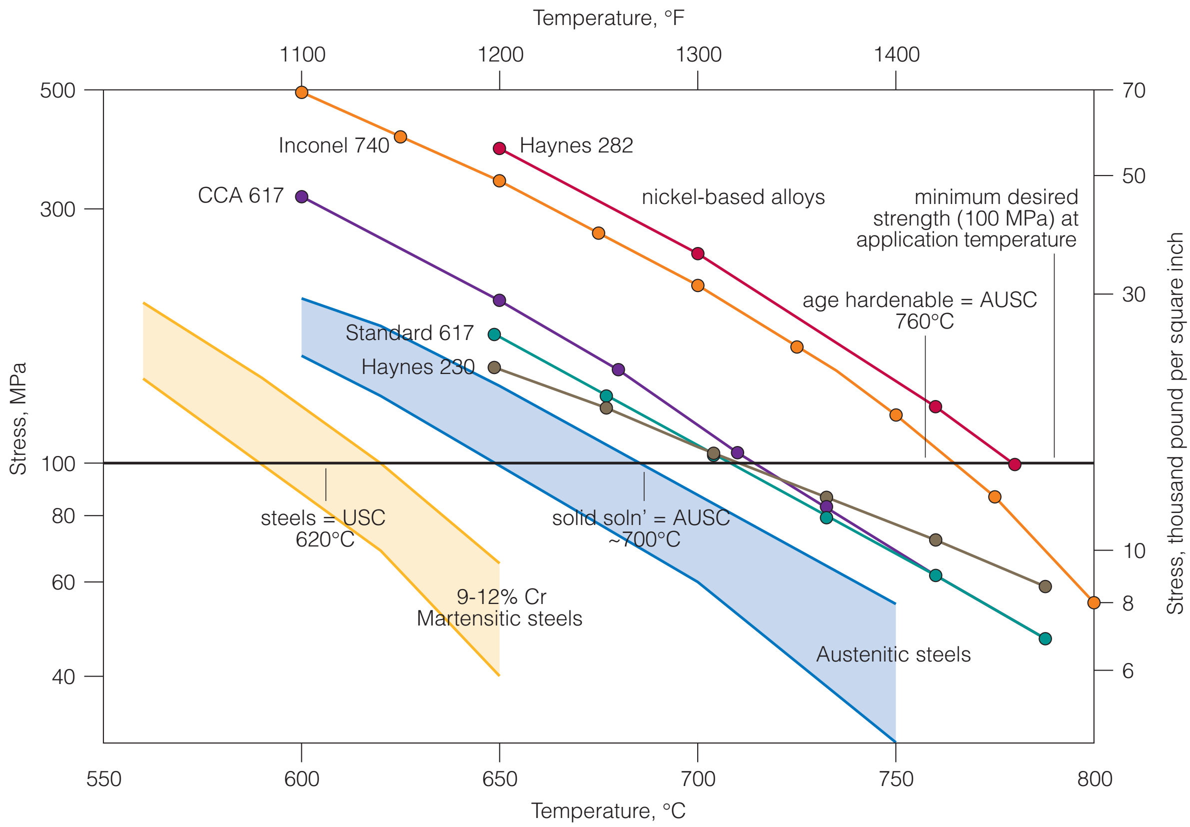

Figure 3 100,000 hour creep rupture tests (Romanosky, 2012)

Creep is time-dependent deformation of material with time due to constant stress. Creep damage is seen as strain in the material, internal damage, cavitation and cracks on the metal surface and will terminate in rupture. Creep damage is measured as a percentage material affected that has occurred within the projected life of the material. Turbine blades have to withstand creep damage, as contact with turbine casing would result in catastrophic failure. Fatigue is caused by cyclic stresses and can result in internal cracking. Generally, cyclic stresses have increased with more vigorous cyclic operation in PCC plant over the last two decades (due to market forces and the use of renewable energy). Creep-fatigue is the combined interaction of creep and fatigue. Ultimately, a complex interaction between chemical attack, thermal and mechanical stresses will cause material failure (Viswanathan, 2008a; Kranzmann and others, 2012; Starkey, 2013).

In PCC plant, creep damage is affected by varying stresses – the number of possible stress-temperature-time combinations is infinite. Creep rupture tests are used to determine the time taken of a material to rupture under a fixed static tensile load (0–500 MPa) at a constant certain temperature (500–800°C). Short-term creep rupture tests are in the region of 10,000 hours (14 months) long-term creep rupture tests are 100,000 hours long (11½ years). Data can be plotted as a log of stress against a log of time to which a best fit curve for a certain temperature is obtained. This best fit curve for a certain temperature can be extrapolated to predict stress to failure for longer times. An alternative way of plotting these results is with a log of stress against temperature for a certain time to rupture (such as 100,000 hours). Again, a best fit curve for a certain time to rupture can be drawn, extrapolated and used to predict temperature to failure at a certain stress (NDT Resource Center, 2013). Figure 3 shows results from creep rupture tests at 100,000 hours for different materials. In these tests, PCC plant materials have to be able to withstand at least 100 MPa for 100,000 hours at the required temperature. This requirement rules out the use of steels above 700°C, only nickel alloys have sufficient creep rupture strength (Romanosky, 2012).

2.3 Candidate materials

The candidate alloys for AUSC technology are nickel alloys and new high temperature steels – they are described below. It is important to note the temperature of thin-section components, such as the superheater and reheater, will exceed that of the steam. To obtain 700°C T_{MAX}, materials in some components, such as the superheater, will reach 740°C and the adjacent flue gas will approach 770°C (Maile, 2012). Throughout this report the steam temperature will be used, not the metal temperature.

Nickel alloys have high creep resistance, fireside corrosion resistance and weldability above 630°C. However, nickel alloys have low thermal conductivity, they cannot be easily cast or forged large enough for full-scale rotors or thick-section components, and some nickel alloys have limited steamside oxidation resistance. For candidate nickel alloys for application in PCC plant, there is no long-term creep resistance data on parent alloy or welds, because these nickel alloys have only previously been applied in applications where short-term creep resistance is required (1000 hours).

As nickel alloys are expensive, their use is minimised by only using them in the hottest components of the boiler and steam turbine. Lower cost materials are used where possible to maintain economic favourability – research on advancing steels for use to 650°C is under way. Additionally, alternative plant configuration to shorten the nickel alloy pipework is an attractive prospect.

Austenitic steels can be used at temperatures up to 700°C but are limited to superheater and reheater applications. However, new austenitic steels use aluminium to form a protective alumina oxide for improved oxidation resistance up to 900°C and are estimated to have creep rupture strength of over 100 MPa for 100,000 hours at 660°C. It is said that these alloys could have lower thermal expansion coefficients than traditional austenitic steels (Gibbons, 2013).

Martensitic steels are now well understood, and interesting concepts in Europe and Japan to increase creep and steamside oxidation resistance are being researched. These concepts include Z-phase strengthening, boron modification (examples include MARN, MARBN, BH and TAF steels), fine tuning the composition with the carbon to nitrogen ratio, optimised heat treatment, niobium free steels, chromium limitation of steels and low carbon steels. Unfortunately, attempts to increase steamside oxidation resistance whilst maintaining creep resistance have not yet been found (Subanovic and Schneider, 2012; Kuhn and others, 2012; Gibbons, 2013).

Low alloy ferritic steel has been seen as obsolete for the last 30 years. However research has seen a paradigm shift towards the development of fully ferritic >15% chromium steels (without martensitic transformation) as they have sufficient steamside oxidation resistance up to 650°C and do not require expensive post weld heat treatment (PWHT). Another way to improve strength could be found through precipitation of intermetallic phase (Kuhn and other, 2012).

2.4 Material standards

New materials have to pass applicable material regulation tests before they can enter commercial service. The tests vary depending on the material standards authority. For example in the EU, materials used under pressure must meet the requirements of the Pressure Equipment Directive and are given an EN designation. In the USA, materials must meet the boiler and pressure vessel code (BPVC) set by American Society of Mechanical Engineers (ASME) and are given an ASME designation. Additionally, materials in the USA can also be given a designation by the American Society for Testing and Materials (ASTM). There are numerous other materials standards and there can be more than one standard per country. To further complicate matters, materials have company designation and names consisting of basic chemical composition.

Future PCC plant in Europe will need to meet requirements of vigorous cyclic operation – this includes a lower minimum load, higher load gradients, increased number of starts, lower minimum downtime and lower minimum start-up time.

Table 2 details the materials mentioned in this report. To avoid misunderstanding, this report will use the names for materials given by the authors. Generally, the ASTM grade is used, such as grade 22, which in Europe is designated 2.25 CrMoV and again different in Japan. Grade 22 is known as T22 in the tube standard SA199, P22 in the pipe standard SA335, F22 in the forging standard SA182 and 22 classes 1 and 2 in the plate standard SA387. There are subtle differences between the materials and it is conventional to distinguish them (Starkey, 2013).

2.5 Welding

The following types of welding procedures are used for high temperature materials in PCC plant components:

- gas shielded metal arc welding (GMAW), also referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG);
- submerged arc welding (SAW);
- shielded metal arc welding (SMAW);
- tungsten inert gas welding (TIG) or gas tungsten arc welding (GTAW).

Table 2 List of AUSC candidate materials with designation and chemical composition

Europe (EN)	USA (ASTM)	Company designation	Known by	Material type	References
CrWVMoNb9-6	T23/P23	HCM2S (P23)	T23/P23	Ferritic steel	Hagen and Bendick, 2013
7CrMoVTiB10-10	T24/P24	N/A	T24/P24	Ferritic steel	Hagen and Bendick, 2013
N/A	N/A	SAVE12	SAVE12	Ferritic steel	Holcomb, 2012
X10CrMoVNb9-1	T91/P91	N/A	T91/P91	Martensitic steel	Hagen and Bendick, 2013
X10CrWMoVNb9-2	T92/P92	NF616 (P92)	T92/P92	Martensitic steel	Hagen and Bendick, 2013
X6CrNiNbN 25-20	A213 - TP310HCbN	HR3C	HR3C	Austenitic steel	Nippon Steel and Sumitomo Metal, 2013
X10CrNiCuNb 18-9-3	A213	Super304H	Super304H	Austenitic steel	Nippon Steel and Sumitomo Metal, 2013
N/A	A213 - TP31MoCbN	NF709	NF709	Austenitic steel	Nippon Steel and Sumitomo Metal, 2013
X7NiCrWCuCo NbNB25-23-3-3-2	A213 - A312	Sanicro 25	Sanicro 25	Austenitic steel	Holcomb, 2012
N/A	B167	HR6W	HR6W	Nickel alloy	Nippon Steel and Sumitomo Metal, 2013
N/A	N/A	Haynes 230	Haynes 230	Nickel alloy	Holcomb, 2012
N/A	N/A	Inconel 740	Inconel 740	Nickel alloy	McCoy and others, 2013
N/A	N/A	Inconel 617	Inconel 617	Nickel alloy	McCoy and others, 2013

Known by	Chemical composition, mass %								
	C	Si	Mn	Al	Cu	Cr	Ni	Mo	W
T23/P23	0.04–0.10	<0.5	0.10–0.60	<0.03		1.9–2.6		0.05–0.30	1.45–1.75
T24/P24	0.05–0.10	0.15–0.45	0.3–0.7	<0.02		2.2–2.6		0.9–1.1	
SAVE12	0.01	0.3	0.2			11			3
T91/P91	0.08–0.12	0.2–0.5	0.3–0.6	<0.04		8–9.5	<0.4	0.85–1.05	
T92/P92	0.07–0.13	<0.5	0.3–0.6	<0.04		8.5–9.5	<0.4	0.3–0.6	1.5–2.0
HR3C	0.04–0.10	1–1.5	<2			24–26	19–22		
Super304H	0.07–0.13	0.3	1	0.03	3.5	19	10.5		
NF709	0.05	1	2			20	11		2.6
Sanicro 25	0.1	<0.4	<0.6		2.0–3.5	21.5–23.5	23.5–26.6		2.0–4.0
HR6W	0.1	1	1.5			24.5	22		8
Haynes 230	0.1			0.35		22	Bal	2	14
Inconel 740	0.03	0.5		0.9		25	Bal	0.5	
Inconel 617	0.08	0.1		1.2		22	Bal	9	

	Ti	V	Nb	B	N	P	S	Fe	Co	Ta	Nd
T23/P23		0.2–0.3	0.02–0.08	0.0005–0.006	<0.03			Bal			
T24/P24	0.05–0.10	0.2–0.3		0.0015–0.007	<0.01			Bal			
SAVE12		0.2	0.07		0.04			Bal	3	0.07	0.04
T91/P91		0.18–0.25	0.06–0.1		0.03–0.07			Bal			
T92/P92		0.15–0.25	0.04–0.09	0.001–0.006	0.030–0.070			Bal			
HR3C			0.2–0.6		0.15	<0.045	<0.03	Bal			
Super304H			0.6	0.01	0.12	0.04	0.01	Bal			
NF709		0.5	0.5		0.25	0.04	0.03	Bal			
Sanicro 25			0.3–0.6		0.15–0.3	<0.03	<0.015	1.0–2.0			
HR6W	0.2		0.35		0.35	0.03	0.015	27			
Haynes 230				<0.015				<3	5		
Inconel 740	1.8		2					0.7	20		
Inconel 617	0.4								12		

Welding can introduce internal stresses and undesirable changes to the microstructure in the heat affected zone (HAZ) of the parent material. Post weld heat treatment can be used reduce these internal stresses and prevent permanent microstructure changes caused by welding. The ratio of creep rupture strength of the welded joint to the strength of the base metal is called the weld strength factor (WSF). In general, boilers require a WSF of 0.8–0.85 over 100,000 hours; nickel alloys in AUSC technology may suffice with a lower WSF.

Dissimilar metal welds (DMW) are welds between two materials with different thermal coefficients of expansion. Thermal stress can cause DMW to crack and potentially rupture. The risk of cracking is greater for thicker-section components. This is one of the reasons why austenitic steel is limited to superheater and reheater applications. The application of nickel alloys with steels in PCC plant may increase the risk of cracking at DMW (Stultz and Kitto 2005; Viswanathan, 2008a).

2.6 Coatings

Historically steels have been modified to improve resistance to chemical attack, however further modification has proven difficult. Fortunately there is an alternative route to improve resistance to chemical attack through the use of coatings (carbide/metallic spraying). Coatings can be applied on the inside diameter surface for protection against steamside oxidation or on the outer diameter (OD) surface to combat the effects of fireside corrosion. If used, the reduced need for inherent resistance to chemical attack of materials will allow the use of lower cost materials and a radical change in component design and manufacturing process would be required, depending on the method of coating application (Osgerby, 2007). Coating metals requires strict process control otherwise the coating may not adhere. Coatings are not currently used in PCC plant and boiler manufactures have avoided coatings as they have failed to work in practice (Holmström 2012).

2.7 Economics of AUSC technology

The economic viability of AUSC technology depends on the efficiency, the capital cost (which is increased through the use of nickel alloys), coal price and carbon tax. Although the capital cost is greater, the operation, maintenance and fuel costs are reduced. Generally, AUSC steam parameters start with superheater steam at 700°C as this is where use of nickel alloys is estimated to become economically favourable and technically viable.

The capital cost of nickel alloys depends on the price of raw materials and manufacturing. The raw material cost represents roughly a third of the nickel alloy component cost – this cost depends on variable trade price of nickel and other expensive alloying elements such as cobalt and molybdenum. The manufacturing cost of nickel alloys represents roughly two thirds of the nickel alloy component cost – this is dependent on the amount of skilled labour available and manufacturing capacity. Advanced steels generally cost the same as the alloying element, and manufacturing techniques are similar.

Mao (2012) states that at current prices, and assuming a single reheat PCC plant, the cost of the main and reheat piping in Inconel 617 will be forty-three times more expensive as using P92. Gierschner and others (2012) say that components manufactured from nickel alloys are at least ten times more expensive than ferritic steel and five times more expensive than martensitic steel.

3 European Union

The European Union (EU) has a deregulated power market, tight emission standards and has subsidises renewable energy. Much of the readily available coal has been mined and the extraction of gas from shale formations could potentially become a significant energy source. For these reasons, electricity from renewable sources and gas has increased and new build PCC plant in Europe are only required with the closure old PCC plant or nuclear power. Historically however, Europe has been at the forefront of coal technology and still operates some of the most efficient and environmentally clean PCC plant globally.

High temperature materials used in state-of the-art USC PCC plant have been developed largely in Europe and research continues. Figure 4 shows a Gantt chart of the high temperature material research programmes in Europe accurate to 2013 with plans to 2026. The steel research programme COST is highlighted in green and ended in 2008. The first high temperature materials research programme AD700 started in 1998 and finished in 2011 is highlighted in red. AD700 continued in 2011 under the names of COMTES+ (HWT II and ENCIO), NextGenPower and MACPLUS, they are planned to finish in by 2017 and are highlighted in blue. Smaller projects, mostly based in Germany, are highlighted in purple. The following sections of this chapter will first explain the co-ordination and funding initiatives and then expand on the material research programmes and projects.

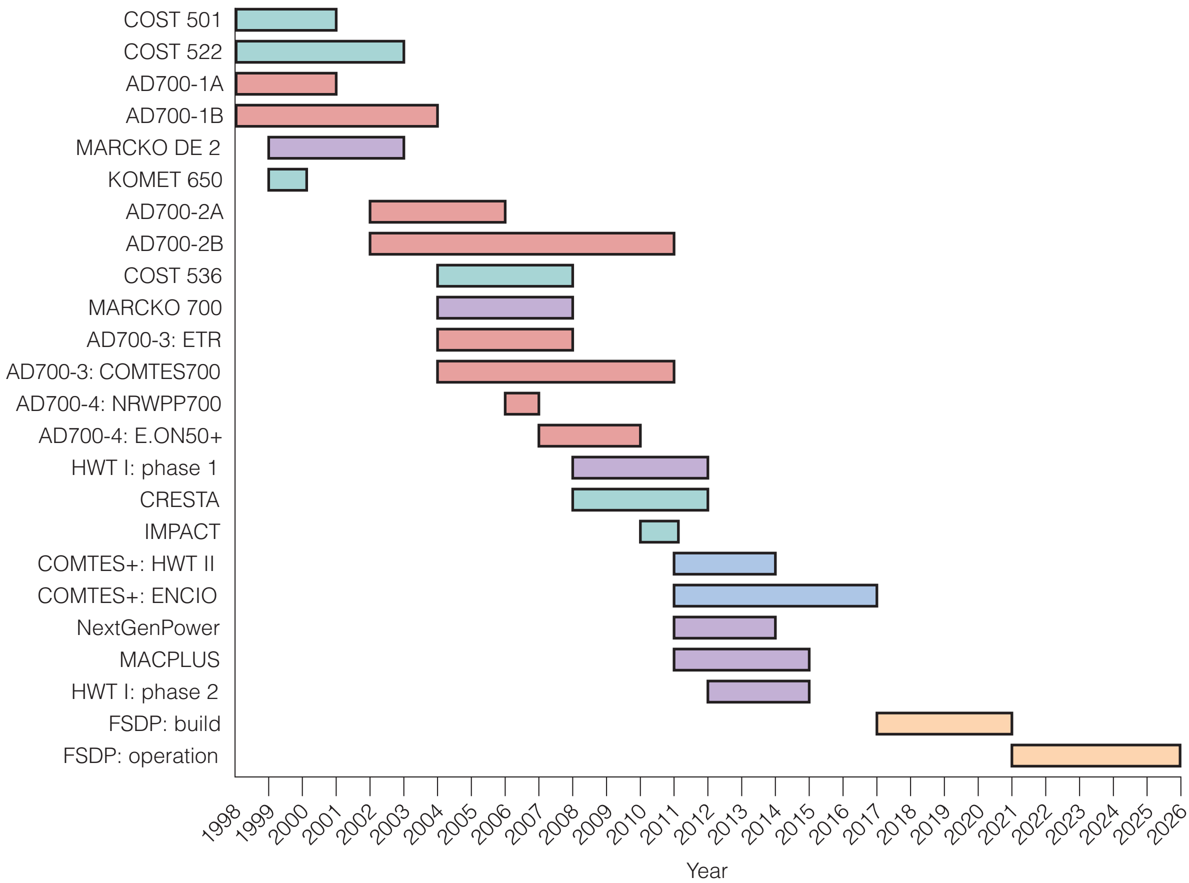

Figure 4 Gantt chart of the European research programme

3.1 Financing and co-ordination initiatives

High temperature materials research projects in Europe are co-ordinated and sometimes partly financed by the European E_{MAX} initiative or German COORETEC initiative explained below. VGB play a key role in setting up and co-ordinating many programmes and projects. Many national governments across Europe support projects financially.

3.1.1 E_{MAX}

Major European utilities have set up the 'E_{MAX} initiative' which is co-ordinated by VGB. The E_{MAX} initiative aims to develop advanced PCC plant with optimised efficiency, economy and environmental sustainability. Members of this consortium are EDF (France), Electrabel (Belgium), Elsam (Denmark), EnBW (Germany), PPC (Greece), RWE (Germany) and Vattenfall (Sweden/Germany). The E_{MAX} initiative organises and directs high temperature material research programmes, such as COST, AD700, COORETEC, which will be explained subsequently. Each project consists of a consortium of participants, including component manufacturers, major utilities and research establishments across Europe. The participants are carefully selected to meet the needs of the programme in terms of competencies and knowledge of one or more aspects of the supply chain. Most projects are in part funded by the European Commission.

3.1.2 COORETEC

Established by the German Federal Ministry of Economics and Technology in 2004, the CO_2 Reduction Technologies (COORETEC) initiative is a funding framework to advance fossil fuelled power plant. COORETEC is currently providing funding for AUSC technology in Working Group 2: Coal-fired steam power plants with maximum efficiencies (COORETEC, 2013).

3.1.3 Horizon 2020

Horizon 2020 is an €80 billion research and innovation funding programme planned by the European Commission lasting from 2014 until 2020. Roughly €5.8 billion would be for secure, clean and efficient energy. It will follow on and extend from FP7 (Wilde, 2012).

3.2 COST

The European CO-operation in the field of Science and Technology (COST) programme aimed to developed new steels that have slightly improved performance on materials grade 91 and grade 92. From 1980 to 2008, COST 501, COST 522 and COST 536 developed some new steels, such as grade 911 for 625°C piping and tubing and alloys FB2 and CB2 for 610°C rotors.

3.3 KOMET 650

KOMET 650, also known as 'Power station options: developments in materials and measurement techniques and tests under operating parameters at 650°C', was a wholly German joint research programme that started the research on using steels in PCC plant with higher steam temperatures of 650°C and a correlating efficiency of >47%. KOMET650 ran from 1999 to 2008, and there were fifteen individual projects in the areas of materials, measurement techniques and modelling. Small-scale tests were undertaken in the laboratory. Large-scale test were conducted at four steam loops placed in Westfalen PCC plant. Each steam loop tested ten different materials at temperatures up to 650°C and pressures up to 19 MPa. The total cost of the project was €10 million, which was funded through COORETEC. KOMET650 was made up of twelve companies which published four reports, the findings are summarised in the following sections.

Investigations of the operational behaviour of boiler materials and their welded joints at temperatures up to 650°C: This report details the findings from the four steam loops that were placed in Westfalen PCC plant. The steam loops tested numerous materials for use in superheaters. The investigations found the following practical material limits with respect to steam temperature: <550°C for martensitic grades E911 and NF 616, <570°C for austenitic grades 1.4910, 1.4941, Esshête 1250 and Super 304 H, <600°C for austenitic grade TP347HFG, <620 °C for austenitic grade NF709, <630°C for austenitic grade AC66 and >630°C for nickel alloy Inconel 617 (VGBa, 2012).

Findings on the operational behaviour of the pipe materials used, and assessment of the overall design in the light of the current regulations: The object was to determine material and component behaviour at elbows in various heat-resistant materials and their welded joints, and then to examine the design and measurement principles under realistic operating conditions for steam pipes in the temperature range to 650°C. A steam pipe was fabricated from a selection of martensitic and nickel alloys, with elbow, DMW and similar welds. The pipe was installed in the Westfalen PCC plant and tested for eight years (22,170 hours). This study concluded that it is still relevant to test the creep deformation for the 9% chromium steels using the 'replication method' surface microstructure testing. Realistic estimates of pipeline life can be obtained only on the basis of pipeline monitoring. A pipeline monitoring process should at least ensure that the average relaxation level can be estimated and that the mounting components, such as hangers and springs, can be checked.

Investigation of materials for use in steam turbines at temperatures up to 650°C: A bypass of steam taken from the test pipe section installed in Westfalen PCC plant was directed onto test pieces installed in two modules, one at 620°C and the other at 650°C. After a year of operation the test pieces were removed and examined using metallographic and scanning electron microscope. The study concluded that steels, especially ferritic and martensitic steels, have a linear growth rate of oxidation and subsequent spallation. As the temperature rises the oxide layer becomes too thick for operation; this is known as the practical limit. The practical limit for 9–12% chromium martensitic steels is <600°C and for austenitic steels is <620°C. However, initial results have shown that surface treatments, such as coatings, could possibly increase the practical limit of steels.

Operational experience with control valves in the high temperature range: This project investigated whether the tried and tested materials and fabrication methods for valves operating at 610°C could be used at 650°C. Thermal shock is a problem for valves as they are made up of components that vary in design, fabrication method and material – the valve body is a large thick-section component. Two valves were installed in parallel on a bypass of the testing loop of Westfalen PCC plant. Numerous experimental and mathematical investigations into the long-term resilience and operating safety of control valves showed that reliable and safe valves can be produced for steam parameters of 650°C and 18 MPa using material 1.4905 for the valve spindle, material 2.8877 for the piston rings, control and throttle elements.

KOMET650 concluded that, of the materials tested, steels have a practical limit of 630°C, whereas nickel alloys are suitable for temperatures above 630°C. KOMET650 provided information that will facilitate the development and operation of AUSC technology (VGB, 2012a).

3.4 AD700-1

COST and KOMET650 concluded that steels have a practical limit of 630°C and that nickel alloys are suitable above 630°C. These conclusions prompted the European utilities and component manufacturers to start the Advanced 700°C (AD700) Material Research Programme in 1998. AD700 aimed to achieve 700°C and 37.5 MPa superheater steam parameters using new nickel alloys (Modern Power Systems, 2008). Initially, the AD700 programme was divided into four phases over a period of 20 years from 1998 to 2018. Figure 5 shows a Gantt chart of the AD700 project plan from the early 2000s, before problems encountered in phase 3 of the AD700 programme forced a change in plan from 2010 (VGB, 2013b).

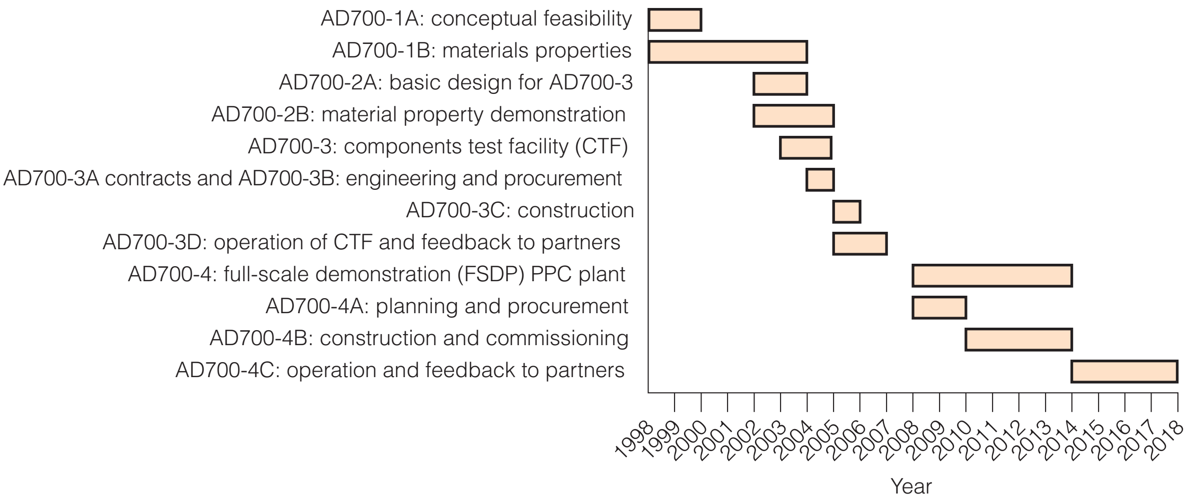

Figure 5 Initial Gantt chart of the European research programme (VGB, 2013b; COMTES700, 2013)

Phase 1 of AD700 consisted of 40 partners and was co-ordinated by Elsam Engineering (now DONG Energy). The European Commission (EC) financed 40% of AD700, under Framework Programme (FP) 4: THERMIE 2, the Swiss and UK governments. The aims of phase 1 were to confirm the technical and economic feasibility of the concept (part A), investigate material property requirements and then plan a material development programme (part B) (VGB, 2013b; COMTES700, 2013).

Part A of phase 1 finished in December 2001. Single steam cycles with parameters 700/720/35 reaching 50.7% and double reheat steam cycles with parameters 700/720/35 reaching 52% on coastal sites. Part A also developed new concepts for power plant configuration to minimise the use of expensive materials. PCC plant superheaters only have 150 metres of pipework and double reheat plant can have 450 metres of pipework. To shorten this pipework, Siemens have developed a horizontal boiler, known as the compact design, which, for a 550 MW unit is 32 metres shorter than a two-pass boiler or 60 metres shorter than a tower boiler and the steam turbine plinth is raised to 30 metres, as opposed to the standard 16 metres. The compact boiler reduces the amount of expensive high temperature pipework by 80% (Scott, 2001). Another arrangement is to have the boiler and steam turbine inline (Modern Power Systems, 2008). Alstom and Hitachi Power Europe (HPE) have also designed AUSC boilers. Part B finished in 2004 – the material testing proposed Sanicro 25 and Inconel 740 as the nickel alloys for use in AUSC technology (Jedamzik, 2012).

3.5 AD700-2

Phase 2 started in 2002 and ended in 2007. AD700-2 included over thirty participants, and was funded in part by the EC under FP5 (50% of total) and the Swiss government. Phase 2 was also co-ordinated by Elsam Engineering. AD700-2 completed the preparatory work for a component test facility in phase 3. Large-scale components were designed for the chosen host plant. AD700-2 chose candidate materials for component testing in phase 3. Part of the characterisation which finished in 2011 included long-term creep tests of martensitic steel (P92, H1F28, NF12), austenitic steel (Alloy 174, SAVE 25) and nickel alloys (Alloy 4020, Inconel 740, Nimonic 263) (VGB, 2012b; VGB, 2013b; Jedamzik, 2012).

3.6 AD700-3

The aim of AD700-3 was to demonstrate the novel manufacturing concepts and performance of new materials in operational boilers of large-scale components. Large-scale demonstration is required to minimise the technical risk involved in building and operating a full-scale demonstration plant. The aims were to design, manufacture, construct and operate test facilities. AD700-3 was split into the following steps, A: contracts; B engineering and procurement; C construction; D operation of test facilities and feedback to partners.

Phase 3 was split into three sub-projects, the COMponent TESt facility for 700°C (COMTES700), the turbine control valve (TCV) project and the Esbjerg Test Rig (ETR). It was not possible to fund AD700-3 directly under the EC under FP6. COMTES700 received €6 million from the EC through the Research Fund for Coal and Steel (RFCS) and €9 million by the E_{MAX} initiative. The TCV and ETR projects were funded by the E_{MAX} initiative (Wilde, 2012; Modern Power Systems, 2008).

3.6.1 COMTES 700

COMTES700 installed a component test facility (CTF) at E.ON's Scholven PCC plant in Gelsenkirchen (Germany). The CTF consists mainly of a slip stream steam line which runs parallel to the main steam line and has an optional bypass to the reheat. Steam is further superheated through an evaporator and superheater to 705°C and 22.6 MPa flowing at 12 kg/s, which passes into a header, a pipe and a HP bypass valve and a HP turbine control valve (TCV). Some of these boiler components are shown in Figure 6. Finally, the steam is spray cooled and added to the main steam again. Figure 7 shows a piping and instrumentation diagram (P&ID) of the CTF. Although the maximum steam pressure proposed for AUSC plant designs are higher at 35 MPa, the steam loop could not exceed the 22 MPa limit of the steam turbine. The components were fabricated from the following alloys T24, HCM12, TP310N, HR3C, Alloy174, Alloy 617, Alloy 617m and Inconel 740. The components were monitored and inspected over the test duration.

VGB co-ordinated the project, the manufacturers were Alstom, HPE, Burmeister & Wain and Siemens. Other partners were E.ON, EDF, Electrabel, EnBW, ENEL, Dong Energy, PPC, RWE, Vattenfall. The total cost was €15.2 million which included a €6.08 million contribution from the RFCS and €8.66 million from the E_{MAX} power plant initiative and €0.46 million from the suppliers.

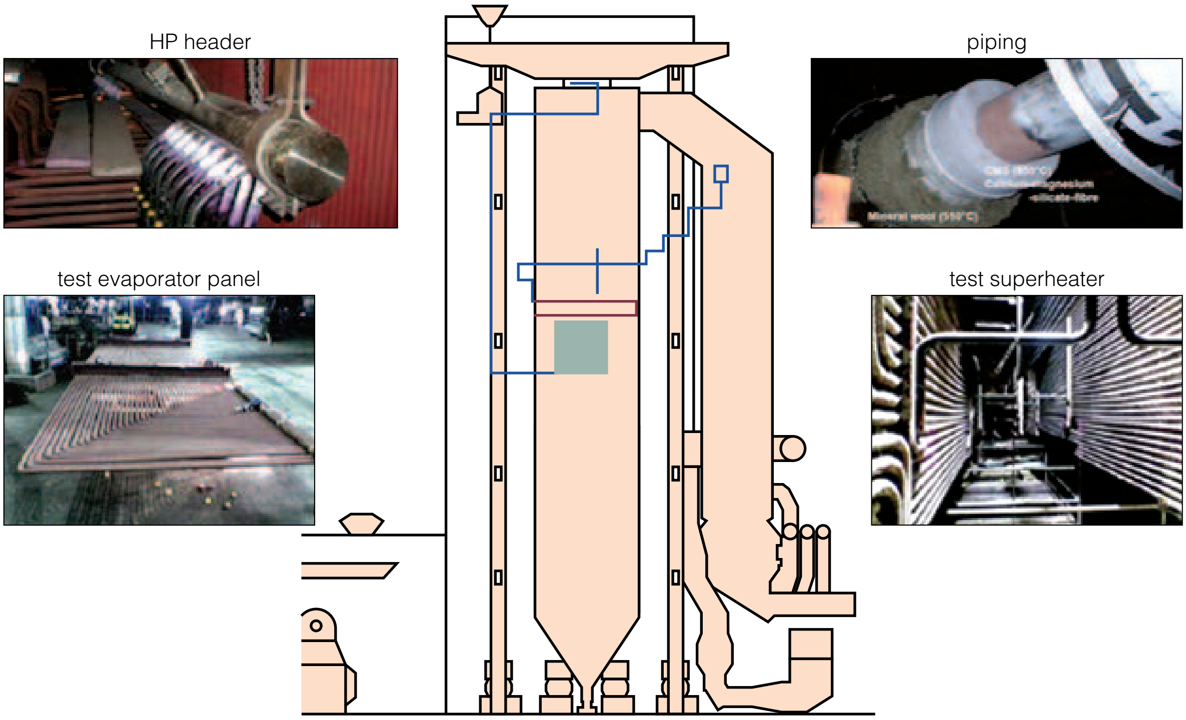

Figure 6 Boiler components in the CTF (Marion, 2012)

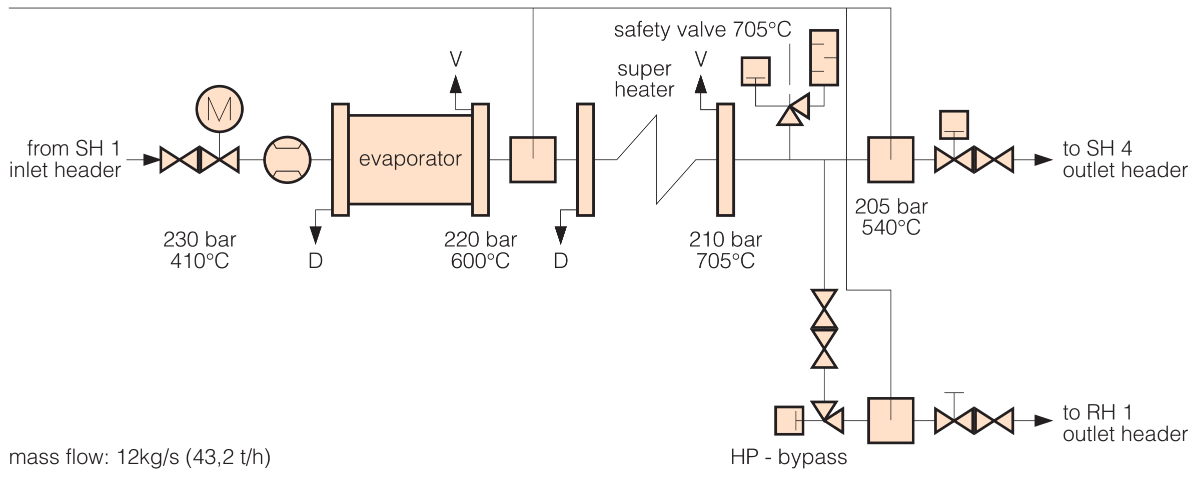

Figure 7 P&ID of the European CTF (COMTES700, 2013)

Testing at the commercially operating Scholven PCC plant provided the first opportunity to investigate the effects of high temperature gradients on nickel alloys. Between 2004 and 2009 the CTF tested extensively the component creep and fatigue properties for 24,000 hours at 700ºC.

Repair welds of thick-section (50 mm) Alloy 617B steam pipe posed major s; cracks appeared in the HAZ along the grain boundaries. These cracks were caused by a phenomenon called stress relaxation cracking (SRC). To prevent SRC of the repair welds the welding procedure was altered, however SRC persisted. Investigation has shown that Alloy 617B hardens with time due to precipitate formation around the grain boundaries. SRC can be avoided with optimised welding procedures and PWHT. Alloy 617B was exposed to PWHT at 980°C for 3 hours to avoid SRC (Gierschner and others, 2012).

The Alloy 617B valve body was tested at the following steam parameters, 705°C and 21 MPa at a flow rate of 12 kg/s for 22,400 hours between 2005 and 2009. Investigation after 2009 revealed that the HP bypass valve, although still functional, had developed cracks in the valve body. The causes of these cracks have been explained by notch effects coupled with high thermal gradients. The location and extent of the cracking is shown in Figure 8. These types of cracks can be avoided by minimising notch effects through a revised valve body design and protection against thermal shock, by preheating and valve insulation (Jedamzik, 2012; VGB, 2013b; Gierschner and others, 2012).

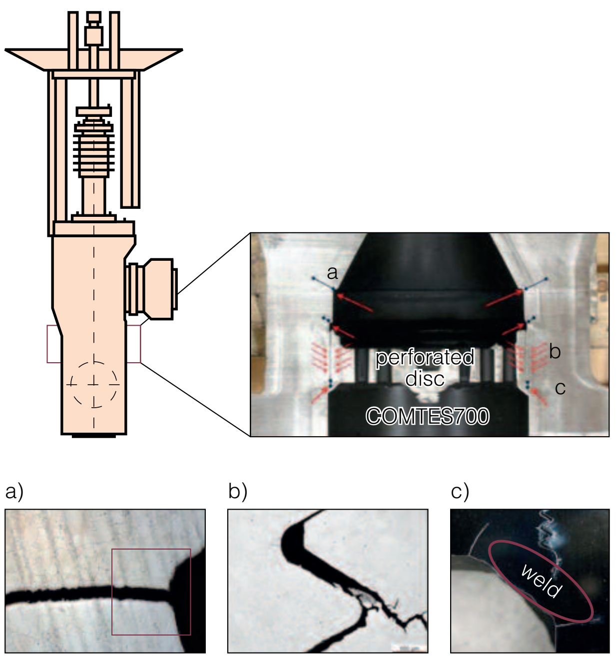

Figure 8 Cracking of an HP bypass valve
(Gierschner and others, 2012)

By 2009, valuable operational experience had been gained on the following main topics:

- manufacturing, bending and welding of the new materials;
- determination and evaluation of residual service life;
- control and examination of the new components under operational behaviour;
- testing of nickel alloys under operational behaviour;
- data collection for the use of ribbed pipes;

- operational behaviour of components in high temperatures;
- flue gas corrosion and steam oxidation behaviour of the materials.

The results were evaluated by a special working group. This led to improved component design, updated boiler codes (design of components from verified alloys), problem identification and further research requirements (Marion, 2012; Gierschner and others, 2012; Wilde, 2012; Jedamzik, 2012; COMTES700, 2013; VGB, 2012b).

3.6.2 TCV

The CTF included testing a HP turbine control valve (TCV) which was manufactured by Alstom and Siemens (Siemens design with Alstom-specific components). TCVs are made up of components that vary in shape, size, material, and fabrication process, some components are welded together. These complexities makes TCVs sensitive to thermal stresses and are susceptible to fatigue damage. HP TCVs are a critical component in the steam turbine with regard to safety and optimal performance of the steam turbine and they are exposed to the highest steam parameters and largest thermal gradients of any component from the steam turbine. Therefore testing a HP TCV in the CTF will be representative of other steam turbine components.

3.6.3 ETR

Managed by the E_{MAX} group of European utility companies, the Esbjerg test rig (ETR) consisted of a single loop of superheater tubes placed in a boiler of Esbjerg PCC plant (this was the fourth steam loop to be installed). The steam cycle was arranged so that the ETR operated up to maximum steam parameters of 720°C and 27 MPa. The steam loop was manufactured by Alstom Power Boilers (Stuttgart) and operated from 2004 to 2008. The resistance to fireside corrosion and steamside oxidation of the following materials were assessed, TP347HFG, S304Hcu, TP310N, HR3C, Sanicro 25, HR6W and Inconel 740 (VGB, 2013b).

3.7 AD700-4

Between 1998 and 2008, the European Commission invested approximately €1 billion into AUSC technology. AD700 phases 1, 2 and 3 demonstrated material properties, component design manufacturing capability for AUSC technology.

The next phase was to pre-engineer the full-scale demonstration plant (FSDP) in order to asses economic and technical viability of AUSC technology, from which the utilities would make a decision whether to go ahead with the build. The first three phases produced a notable research spin-off technology called the Master Cycle; this is a modification of the regenerative feedwater preheating system, adding an extra 1.5% points to the net efficiency (Modern Power Systems, 2008).

3.7.1 NRWPP700

The pre-engineering study, called the North Rhine-Westphalia Power Plant at 700°C (NRWPP700), began in October 2006 and ended in 2008. The consortium included a group of twenty operators, manufacturers and suppliers involved in the AD700 programme; the project co-ordinator was VGB. Over 70% of the funding came from the partners and the rest from regional funds from Brussels via the government of North Rhine-Westphalia. NRWPP700 was completed in three stages.

Stage 1 – Demonstration plant planning (500 MW, bituminous coal): This study determined the

Table 3 Candidate materials for the European FSDP (VGB, 2012b)

Components		Candidate alloys
Header inlet	Superheater 1, 2, 3 and 4	P92, P92, Alloy 617 and Alloy 617m
	Reheater 1.1 and 1.2	13CrMo4-5 and Alloy 617m
Header outlet	Superheater 1, 2, 3 and 4	P92, Alloy 617, Alloy 617m and Alloy 263
	Reheater 1.1 and 1.2	Alloy 617m
Pipes	Superheater 1	T92
	Superheater 2	Alloy 617m, Alloy 174
	Superheater 3	Alloy 617m, Alloy 174, HR3C
	Superheater 4	Inconel 740
	Reheater 1.1	Alloy 617m, HR3C, S304, T91, 10°CrMo9.10
	Reheater 1.2	Alloy 617m
Casing	Outer casing	Cast steel (9-10% Cr)
	Inner casing	Alloy 625 (cast), welded with 9-10% martensitic steel
Valve	Casing	Alloy 625 (cast)
	Weld-on ends	Alloy 617m
Rotor	HP and IP	Alloy 617 welded with 2% chromium, 10% chromium steel
Blades	HP and IP	Martensitic steel, Nimonic80, Waspalloy

technical and economic feasibility of a demonstration unit fired by bituminous coal. On the boiler side, three tower boiler concepts from Alstom, HPE, and Burmeister and Wain Energy were assessed. It was decided to opt for a HP boiler with steam parameters of 705/720/36.5 reaching over electrical efficiency (net, LHV). The steam turbine examined generated a total of 550 MWe at the shaft or 500 MWe net taking into account auxiliary load. A smaller unit size was chosen as it minimises risk to investors. In 2012, the capital cost for this demonstration unit fired by bituminous coal was €1.7 billion (>3000 €/kW). The following additional research projects were carried out in the scope of NRWPP700:

- production of a casing fabricated from Alloy 617m for a HP bypass valve;
- processing and relaxation of new nickel alloys under modified cyclic load;
- investigation of development possibilities for high-temperature sensors;
- components designed for high temperatures;
- non-destructive investigations of different welds to produce steam turbine rotors fabricated from nickel alloys;
- manufacture of a HP pipe extruded Alloy 617 in the extrusion process;
- qualification of Inconel 740 for the steam generator superheater;
- qualification of Alloy 617m for thick-section superheater pipes;
- increased thermodynamic investigations regarding the Master Cycle;
- HP pipe extruded from Alloy 617 (separately funded).

The candidate alloys are shown in Table 3. It is important to note that Alloy 263, Inconel 740 and Alloy 174 are still in the development stage. The membrane wall is superheater 1 in this design.

Stage 2 – Commercial plant planning (1000 MWe, bituminous coal): This stage transferred the technical and economic findings of stage 1 to a commercial 1000 MWe unit to test for economic feasibility against a 1000 MWe USC plant. It was proved technically possible to scale up the boiler and steam turbine. Additionally, the economics for such a unit were calculated. For highest steam turbine efficiency a conventional configuration was chosen, consisting of a single flow HP turbine, a double flow IP turbine and two double flow LP turbines. To calculate the maximum efficiency of a 1100 MW unit, all parameters and components have been pushed to their physical, practical and economical limits. Using an inland state-of-the-art USC plant (600/610/28) with 45% efficieny (normal operating conditions including start-up and shut-down losses) as a starting point, the following efficiency improvements have been estimated for a new AUSC PCC plant:

- +2.2% points were added for steam temperature increase to 705/720;
- +0.8% for main superheater steam increase to 35 MPa;
- +0.2% for increase of boiler inlet temperature;
- +0.7% for sea water cooling;
- +1.2% for decreasing flue gases in stack to 65°C (+0.4% on new boiler, +0.4% for low temperature heat displacement +0.4% for high temperature heat displacement);
- +0.1% for other incremental improvements.

The total increase is +5.2% points, resulting in 50.2% efficiency, of which 3.2% points is gained from the increase to AUSC steam parameters. The NRWPP700 concept is CCS ready – it is estimated that the addition of CCS will reduce net efficiency by 8–12 % points. Economies of scale reduce the specific capital cost to 2000 €/kW with a 1100 MW commercial unit. In comparison, a modern supercritical PCC plant built in the developed world in 2012 would cost <1200 €/kW.

More detailed planning work and the reduction of fabrication costs could significantly lower capital expenditure. Stage 2 identified the need for the following additional research projects:

- short-term and long-term properties of nickel alloys;
- production and manufacturing of nickel alloys;
- developing an improved version of P92 (this would dramatically lower the amount of nickel alloy used);
- further qualifying works on austenitic material Sanicro 25;

Stage 3 – Commercial plant planning (1000 MWe, lignite coal with pre-drying): This stage transferred the technical and economic findings of stage 2 to a commercial lignite-fired 1000 MWe unit test for economic feasibility against a 1000 MWe USC plant. A lignite-fired PCC plant running at 650°C, 675°C and 705°C with lignite pre-drying was assessed reaching efficiencies of 51.6%, 52.06% and 52.63% respectively (net, LHV). Work from stage 2 was used for this assessment. However differences in temperatures, pressures and dimensions required some redesigning (VGB, 2012b; 2013b; Modern Power Systems, 2008).

The reverse approach would have been to pre-engineer a commercial (1000 MWe) unit and subsequently down-scale to a demonstration size unit (500 MWe). However, the reverse approach was rejected as no detailed findings of the demonstration plant size would be available for submission in time for funding from EC though FP7.

3.7.2 E.ON 50+

Building a FSDP involves procurement (site, components and contractors), construction of components, plant erection and finally plant commissioning. The first task of pre-engineering was NRWPP700, described in Section 3.7.1, after which E.ON were to take over the FSDP build in a project called E.ON 50+. In 2008 it was decided that a 500 MW FSDP would be built at Wilhelmshaven (Germany). The electricity produced from a demonstration unit is likely to be more expensive than the projected market value, as the unit is smaller and it is a prototype. Commercial AUSC PCC units are likely to be built in the 1000–1100 MW range, to utilise economies of scale. In 2010, the FSDP was postponed due to technical problems (such as cracking of thick-section components). However, research continues in order to solve these technical problems, and knowledge from all former and current projects will be consolidated in the FSDP which is planned to be built from 2017 to 2021 and operated from 2021 to 2026 (COORETEC, 2013; Gibbons 2013).

3.8 MARCKO DE2

The project 'Material realisation low for a CO_2 power plant' or MARCKO DE2 started in April 1999 and ended in March 2003. Managed by VGB, MARCKO DE2 helped qualify Alloy 617 for outlet headers and superheater tubes in AUSC boilers. Alstom Power Boilers in Stuttgart successfully fabricated a steam header from Alloy 617m via GTAW and SAW procedures. It was funded by the German government through COORETEC and the Research Association of the Working Group of the Iron and Metal Processing Industry (VGB, 2013b; Wilde, 2012).

GTAW narrow gap orbital welding has been shown to be the weld procedure of choice for martensitic steels and nickel alloy tube to tube welds in PCC plant. The process is fully automated and produces efficient and reliable welds. Less filler material is required due to efficient use and the narrow gaps reduce the amount required. The automated process is quicker than the manual process. Automated welding is reproducible and ensures a constant level of quality. Grab and Stahl (2012) detail TIG narrow gap welding and PWHT.

3.9 MARCKO 700

Figure 9 Testing of a membrane wall by Hitachi Power Europe (Jedamzik, 2012)

The series of MARCKO projects continued with the project called 'Material Qualification for the 700/720°C Power Plant' (MARCKO 700). MARCKO 700 started in August 2004 and ended in June 2008. Headed by Professor Karl Maile of the Stuttgart Materials Testing Institute, MARCKO 700 helped qualify materials T24, 12CrCoMo and Alloy 617 for use in tubes and components, and T91, T92 and VM12 for use in membrane walls. MARCKO 700 started long-term creep rupture tests of components and welds, as shown in Figure 9. Funded was provided by the German government through COORETEC and the Research Association of the Working Group of the Iron and Metal Processing Industry (Maile, 2012; VGB, 2013b).

3.10 HWT I

The project Hochtemperatur Werkstoff Teststrecke (HWT I) or high temperature material test track is titled 'Investigation of the long-term service behaviour of tubes for the future high-efficiency power plant'. HWT I has installed four test loops in a commercial boiler, unit 6 at GKM PCC plant near Mannheim (Germany). This boiler has a peak temperature of 1260°C and the test loop will produce steam at 725°C and 16 MPa at a flow rate of 0.32 kg/s. Forty-three different alloys are used; there are three martensitic steels and nine austenitic steels in the first loop, eleven austenitic and three nickel alloys in the second loop, three austenitic and seven nickel in the third loop and finally seven nickel alloys in the last loop. All aspects of fireside corrosion, steamside oxidation, DMW and similar welds with various fabrication methods and designs will be assessed. Additionally, there are two external loops undergoing creep rupture tests with live steam at 630°C and 725°C testing ten austenitic steels and nickel alloys. HWT I started in 2008 and will end in 2015.

Information gathered from the privately funded HWT I project will be used to qualify new superheater materials. Organisations involved include MPA University of Stuttgart, eight manufacturers, two inspection authorities and four utility companies (Jiang, 2012; Maile and Metzger, 2012).

3.11 Post AD700

Collectively, the AD700 programme and the KOMET and MARCKO projects have successfully demonstrated manufacturability of critical components from nickel alloys and assessed their behaviour at higher steam parameters with some excellent results. However, the cracking of thick-section nickel alloys must be overcome, manufacturing costs reduced, fireside corrosion under biomass and waste cofiring assessed, performance under static operation to severe cyclic operation guaranteed and 650°C steels developed to significantly improve the economics of AUSC technology. The issues are being tackled in AD700 which continues under the names of COMTES+ (ENCIO and HWTII), NextGenPower and MACPLUS.

3.12 COMTES+

In 2011, COMTES+ was set up by VGB to further qualify candidate AUSC materials in two called ENCIO and HWT II. COMTES+ will reuse components from COMTES700. Results from COMTES+ are expected by 2017 and should generate all the knowledge necessary to design, build and operate a FSDP. Together these projects have a budget of approximately €70 million, partly funded by the EC under FP7 (Gierschner and others, 2012; Maile and Metzger, 2012).

3.12.1 HWT II

Hochtemperatur Werkstoff Teststrecke (HWT) II primarily investigates the operation and failure behaviour of thick-section components under base load and cyclic operation. The work will be completed in a test loop at GKM PCC plant (Germany). HWT II started in January 2011 and is planned to end by December 2014. There are 28 European partners and it is funded by industry (generating companies, equipment and material suppliers and inspection authorities involved) and the German government through COORETEC with a budget of €17.6 million.

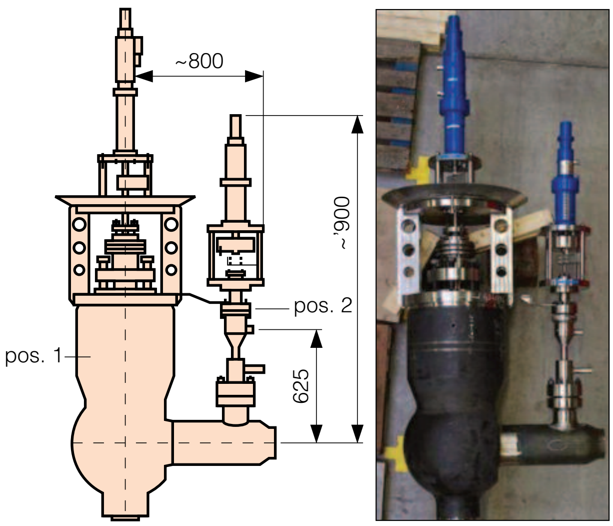

Figure 10 HP bypass valve tested in HWT II (Gierschner and others, 2012)

Steam extracted from unit 6 at 530°C is heated to 725°C in superheaters fabricated from materials P92, DMV310, A263, A740 and A617B. The superheater pipes A740 and A617B are welded to a header fabricated from A617B and A263 respectively. A bypass valve is installed after the header to release steam out of the test loop in case of an emergency. The HP bypass supplied by HORA, which was originally manufactured for the E.ON 50+ demonstration plant, is shown in Figure 10. To avoid cracking of the HP bypass valve, the valve has been redesigned and PWHT is used. The valve is of 'flow to open design', the valve body is forged from Alloy 617B and weighs 2.6 tonnes and allows 2.75 kg/s of steam flow. The bypass piping includes a pressure reducing and de-superheating system

(PRDS), which is a process where the temperature of the superheated steam temperature is reduced, using valves and water injection. From the bypass valve the steam at 725°C passes through a bent pipe extruded from A617B or A263 with an outside diameter of 200 mm and a wall thickness of 50 mm. The steam can then be cooled by water injection and a steam cooler to at least 307°C and 2 MPa, to simulate start-up and shut-down procedures and definitive cycling conditions. Two steam control valves from Bopp & Reuter and Welland & Tuxhorn will be used to do this. The steam then passes through a straight pipe extruded from A617B or A263 with an outside diameter of 219.1 mm and a wall thickness of 50 mm. After the pipe the steam is passed through two control valves. Finally, the steam at less than 400°C then goes into the reheater tubing. Operation of the test loop started in October 2012 (Gierschner and others, 2012; Grab and Stahl, 2012: Maile and Metzger, 2012; VGB, 2013b).

3.12.2 ENCIO

The European Network for Component Integration and Optimisation (ENCIO) project started in 2011 and is expected to finish in 2017. The aim of ENCIO project is to demonstrate and qualify fabrication, welding, behaviour, erection and repair concepts for up to 140 mm thick-section nickel alloy components for a long lifetime. The work will be completed using test loops in a new test facility operating at 700°C, 17.7 MPa and 5 kg/s flow rate of steam. The total budget of ENCIO is €24 million – this includes €10 million provided from the RFCS and €14 million of industrial funds. The project is co-ordinated by VGB and involves twenty-three other European partners. The leading partners are Centro Sviluppo Materiali, ENEL and Hitachi Power Europe (Gierschner and others, 2012; Wilde, 2012). The host plant is Andrea Palladio Fusina PCC plant (Venice, Italy), which is owned and operated by ENEL. The steam cycle is arranged so that steam at 705°C is sent to the four independently operated test loops. Figure 11 shows the test loop arrangement of ENCIO which will investigate the following items (Jedamzik, 2012; Gazzino, 2012):

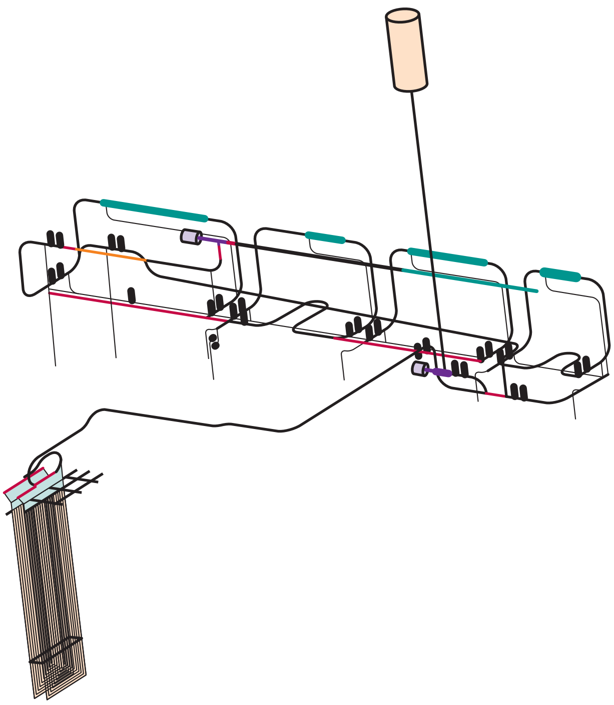

Figure 11 ENCIO test loop arrangement (Jedamzik, 2012)

- **Test loop 1**: Development of a pipe repair concept for aged materials: This loop simulates a pipe repair situation. This task involves basic investigations to characterise the aged materials followed by repair welds which are used to optimise welding procedure specifications (TIG welding with PWHT).
- **Test loop 2**: Lifetime monitoring for components at 700°C and hot iso-static pressing (HIP) of components. This loop will be used for online monitoring and measuring the creep behaviour of Alloy 617B in order to develop a monitoring concept for nickel alloy pipes. This loop will be used to test components, such as T-pieces, valve bodies and turbine components, that have been fabricated using hot iso-static pressing (HIP). HIP is a commercial manufacturing process where materials are placed in an inert atmosphere in a pressure containment vessel for a certain amount of time. The material undergoes plastic deformation, creep and diffusion bonding which eliminates internal voids and micro-porosity and this increase the density of material, which improves the materials properties, such as workability and fatigue resistance.

- **Test loop 3**: New materials for thick-section components: This loop explores possible improvements in weldability of Alloy 617 by means of improved melting processes to reduce the amount of impurities within the ingot.
- **Test loop 4**: Testing of turbine cast components and welds: This loop aims to prove full-scale welds between thick-section Alloy 617 OCC and Alloy 625 cast (this weld is found in the steam turbine).

3.13 NextGenPower

NextGenPower (SP0) is a project that aims to demonstrate the fabrication and utilisation of nickel alloys and material coatings for use in boiler, pipework and steam turbines in AUSC PCC plant. The NextGenPower project began in May 2010 and will end in April 2014. The project has a budget of €10.3 million, over half of which is from the European Commission. Partners of NextGenPower include VTT technical research centre of Finland, DMV KEMA, E.ON Benelux, Doosan Power Systems, Monitor Coatings, Goodwin Steel Castings, Cranfield University, Aubert & Duvel, Saarschiede, Technical University Darmstadt, Skoda and VUZ welding repair institute. NextGenPower is managed and co-ordinated by DNV KEMA. The following bullet points explain how the project is divided (Stam, 2012).

- **SP1 Boiler and pipework (Doosan and Babcock)**: Using coated steels in the boiler and heat exchangers could be a cheaper alternative than using nickel alloys. This project will assess the application method, welding compatibility (thus ability to be repaired or replaced) and performance of steel coatings in fireside and steamside corrosion. Mechanical tests are proposed to quantify the life expectancy of coated steels. These tests include creep, low cycle fatigue, low cycle fatigue with dwell, notched relaxation, cyclic notched tests, slow strain rate tensile tests, fracture toughness and hardness. Tests will be conducted selectively upon parent metal, weld metal, cross weld, longitudinal weld and service simulated material. Projects include:
  - WP1.1 Fireside corrosion of membrane walls and superheaters (DNV KEMA);
  - WP1.2 Steamside oxidation in boiler (Cranfield University);
  - WP1.3 Creep and fatigue of tubes, pipework, steam turbine (Doosan and Babcock);
- **SP2 Steam turbine (Skoda)**: This project will demonstrate the capability to cast, forge and weld nickel alloys for rotors, casings and valve chests. A programme of mechanical tests will be carried out to verify component properties. Non-destructive inspection techniques will be optimised and qualified. For nickel alloys steamside oxidation is negligible and the mechanical properties can be modelled on the basis of the material composition. Projects include:
  - WP2.1 Casting (Goodwin Casting);
  - WP2.2 Rotor Welding (Skoda);
  - WP2.3 Forging (SSF);
- **SP3 Integration (DNV KEMA)**: The main objective of SP3 is to integrate the work done in SP1 and SP2 and to make sure that at a later stage results can be integrated into the power plant. Projects include:
  - WP3.1 Operating conditions and environments (DNV KEMA);
  - WP3.2 Integration in power plants (DNV KEMA);
  - WP3.3 Modelling and case studies (Cranfield University);
- **SP4 Dissemination** (DNV KEMA).

3.14 MACPLUS

MACPLUS is an acronym for ‘material component performance driven solutions for long-term efficiency increase in ultra-supercritical’ power plants. MACPLUS will assess six aspects (*see below*) of AUSC technology via laboratory testing, industrial-scale test loops and computer models. MACPLUS started in January 2011 and will finish in June 2015. MACPLUS is carried out by a consortium of twenty-four partners and seven sub-contractors from ten European countries. The total budget is €18.2 million, of which €10.7 million is provided from the EC under FP7. MACPLUS is split into the following projects (Zanin, 2013; MACPLUS, 2013):

- **WP1** (Foster Wheeler Energia) will investigate new refractory materials.
- **WP2** (Technical University of Graz) will investigate new ferritic and martensitic steels (MARBN and FB2 mod) for use in headers and pipework to avoid premature Type IV cracking of welds.
- **WP3** (Centro Sviluppo Materiali) aims to understand the operational behaviour of austenitic steels and nickel alloys in superheaters using laboratory specimens and materials from previous test loops, such as the AD700-3. Material modifications via fabrication and composition will be assessed along with long-term behaviour extrapolation via modelling. A superheater tube and welded joints of thick-section pipes fabricated from modified nickel alloy will be fabricated and tested to demonstrate improved performance.
- **WP4** (Doosan Power Systems) will assess fabrication and application processes of multi-layer and multi-material boiler tubes for application in aggressive fireside conditions.
- **WP5** (Alstom) will assess high temperature components in a steam turbine using latest generation high alloy steels for use at 620–670°C and nickel alloys at 670–720°C. This will be completed via metallurgical-thermo-mechanical modelling and manufacturing.
- **WP6** (E.ON New Build & Technology) aims to develop advanced design and testing criteria for high temperature components development, integration and standardisation into AUSC PCC plant. This work will build on existing testing methods in order to identify future development needs.
- **WP7** (Centro Sviluppo Materiali) is simply the co-ordination and dissemination of projects WP1–6.

3.15 IMPACT

Based in the UK, the ‘Innovative Materials Design and Monitoring of Power Plant to Accommodate Carbon Capture’ (IMPACT) project is a joint venture between E.ON New Build & Technology (plant user), Doosan Power Systems (boiler and welding), Alstom (turbine and components), Goodwin Steel Castings (cast component supplier), National Physical Laboratory (monitoring technology) and Loughborough University (microstructural characterisation and modelling). The total budget is £1.8 million, partly government funded through the Technology Strategy Board, and runs from 2010 to 2013. There are three objectives within the project:

1. Develop of advanced welded MARBN steels for power plant;
2. Improve the design for welded components to reduce premature cracking;
3. Improve the strain and materials monitoring to allow high temperature operation.

The proportion of boron in steels has been previously altered with inconsistent results. Fujio Abe of National Institute for Materials Science (NIMS) of Japan found that alloying boron with nitrogen in certain amounts achieves high creep rupture resistance; MARBN steel (MARtensite plus boron plus nitrogen) was discovered. The IMPACT project has optimised the composition of MARBN steel and short-term tests have shown that MARBN has 20–40% higher creep rupture resistance than P92 at temperatures up to 675°C. Heat treatment at 1200°C further increases the creep rupture resistance by 10–15%. Potentially, MARBN has 55% higher creep rupture resistance than P92. However, MARBN steel shows a substantial weld strength reduction and is susceptible to cracking in the HAZ. The proportions of the alloying elements in MARBN need not be exact – a wide range is acceptable for similar properties. In May 2012, Goodwin Steel Castings (UK) produced an eight tonne melt of MARBN, from which ingots and castings were fabricated and welded. These components are now in long-term tests (Allen and others, 2013).

3.16 KMM-VIN WG2

The European Virtual Institute on Knowledge-based Multifunctional Materials (KMM-VIN) was established in 2007 and aims to foster the creation of a powerful platform for research and development and industrial application of advanced materials. In 2012, KMM-VIN integrated the members and plans from the cancelled COST 556 EMEP project along with old KMM-VIN members interested in different materials for energy applications into its agenda to form Working Group 2: Materials for Energy (WG2). KMM-VIN WG2) is an unfunded collaboration seeking to promote and co-ordinate research into advanced steels. Individual project are funded by private sources, national governments or the EC.

KMM-VIN WG2 is made up of 72 research establishments and 25 companies across Europe. The AUSC technology projects facilitated by KMM-VIN WG2 co-ordination effort are detailed subsequently (KMM-VIN, 2013).

3.16.1 EBW

Technical University of Graz and Voest-alpine Giesserei Traisen are researching DMW using electron beam welding (EBW). EBW has no filler material, shorter welding time, less machining time for joint preparation and smaller fusion zone. Nickel alloy 625 has been welded to 9% chromium steel CB2 using EBW, no defects have been found and testing has shown good mechanical properties. Creep rupture tests are planned.

3.16.2 MARBN

Working with the IMPACT project, Technical University of Graz and Technical University of Chemnitz are characterising MARBN steel and the corresponding welding process.

3.16.3 Z Ultra

Z Ultra is short for 'Z-phase strengthened steels for ultra-supercritical power plants'. Z Ultra started in February 2013 and is partially funded by the EC under FP7. Z Ultra was developed independently of KMM-VIN WG2. Z Ultra aims to improve the creep rupture strength of martensitic 12% chromium steels by increasing the amount of Z phase precipitates for operation with 650ºC steam. Numerous steels, filler materials and welding processes are being assessed. Atomic scale microstructural investigations are employed to save time. Microstructure modelling will also be established to hasten research, improve understanding, and provide design tools and lifetime estimation methods for the operation of future power plants. The project co-ordinator is Fraunhofer IWM (Germany) and involves ten partners, some non-EU.

3.17 Rafako

Rafako (Poland) have undertaken a research project that aims to calculate the highest possible steam parameters using commercially available materials. These materials must meet the applicable European standards and therefore represent a boiler that is commercially available. Firstly, the critical boiler components were identified. Secondly, the global steel market was analysed. Thirdly, the most suitable materials were selected for critical components. Finally, the highest possible steam parameters for the selected materials were calculated, regarding strength only, using the TRD-EN programme to achieve a 200,000 hour operating time. Corrosion and oxidation have been assumed not to become a problem within the 200,000 hour operating time. Some elements were recalculated by the ANSYS programme (finite elements method). The result is a boiler with steam parameters of 653/672/30, achieving 48% efficiency (LHV, net, coal heating value of 25MJ/kg, 94% boiler efficiency, 4.5 kPa condenser pressure). The materials needed would include only 15% austenitic steel and 5% nickel based alloy. A problem with this study however is that there is no commercially available steam turbine that can operate at these steam parameters (Cieszynski and Kaczorowski, 2012).

3.18 Summary

High temperature material research programmes in Europe are steered largely by a consortium of large utilities under the name of the E_{MAX} initiative. Funding for the majority of projects has come from the European Commission and German government (mostly through COORETEC) and to a lesser extent the UK and Swiss governments; some projects have been financed purely by utilities.

Starting in 1998, the AD700 programme in Europe involve up to forty partners and aimed to develop AUSC technology at 700°C and 37.5MPa. The entire project, including operation and evaluation of a full-scale demonstration plant (FSDP) was initially planned for completion in 2018. A pre-engineering study of a full-scale demonstration project (FSDP) called the North Rhine-Westphalia Power Plant at 700°C project was completed in 2009 and concluded that the FSDP would have a net efficiency of 50.2% (LHV, hard coal). After four years of operating and subsequent evaluation of components from component test facilities (CTF) in AD700 phase 3 (COMTES700, TCV and ETR projects), cracks were found in thick-section components which ultimately postponed construction of the FSDP. The AD700 programme continues until 2017 under the names of COMTES+, with the HWT II project in Germany and ENCIO project in Italy, NexGenPower and MACPLUS which aim to solve problems with, improve and develop new materials, assess the effect of biomass and waste cofiring on materials and reduce manufacturing costs.

During the AD700 programme, MARCKO DE2 helped qualify Alloy 617 for outlet headers and superheater tubes. MARCKO 700 helped qualify materials T24, 12CrCoMo and Alloy 617 for use in tubes and components, and T91, T92 and VM12 for use in membrane walls. HWT I is in the process of qualifying numerous materials and welds for superheaters. The government funded steel research programme COST was cancelled in 2011 but continued as KMM-VIN WG2, an unfunded collaboration seeking to promote and co-ordinate research into advanced steels. The importance of 650°C steels if further demonstrated by the CRESTA and IMPACT projects.

There are plans in Europe to build a FSDP (500 MW at 705/720/35) in 2017-21, with operation and feedback in 2021-26. The numerous high temperature material research programmes and projects in Europe have produced notable research spin-offs for use in USC plant, such as improved steels, boilers and steam cycle designs.

4 USA

The USA has one of the largest coal reserves in the world and has helped pioneer the use of new high temperature materials in PCC plant. The fleet of PCC plant is approaching the end of its design life and new power plant need to be built. However, the recent advent of shale gas extraction has dramatically lowered gas prices.

The programme on 'Advanced Ultra-supercritical Power Plant Materials' in the USA started in 2001. The research programme is financially supported by the US Department of Energy and Ohio Office of Coal Development, and is split into two consortia, the major US boiler manufacturers (Alstom, Babcock & Wilcox, Foster Wheeler, Riley Power, GE Energy) and US steam turbine manufacturers (Alstom, GE energy, Siemens). The national laboratories, Oak Ridge National Laboratory and the National Energy Technology Laboratory support both consortia. The research programme is managed by the Energy Industries of Ohio with the Electrical Power Research Institute serving as the programme technical lead.

The boiler side of the programme is split into two phases. Phase one has been split into eight tasks. Phase two extends and enhances on tasks in phase one. The boiler side of the programme will assess alloys in air fired and pure oxygen fired boilers (also known as oxyfuel combustion/oxy-combustion/oxyfuel), cyclic operation, material coatings and the effects on fireside corrosion of firing high sulphur coals indigenous to the USA. The steam turbine side of the programme is split into two phases, phase one has selected candidate materials and phase two will test these materials in six tasks (Romanosky, 2012; Marion, 2012; Shingledecker, 2012). Figure 12 is a Gantt chart which shows the US material research programme (Romanosky, 2012; Phillips, 2011).

The National Energy Technology Laboratory are aiming for 760ºC (1400ºF) maximum temperature and 35 MPa (5000 psi) maximum pressure, with efficiencies of 45–47% (net, HHV) and a corresponding drop in carbon dioxide emissions of 15–22% (Romanosky, 2012). Alstom have estimated an increase of efficiency of 7 percentage points when going from USC to AUSC steam parameters (Marion, 2012). Alstom argue that 760ºC maximum temperatures should be reached as opposed to 700ºC for three reasons. Firstly, nickel alloys can reach this temperature. Secondly, the cost of precipitation strengthened nickel alloy needed for 760ºC is the same as solution strengthened alloy for 700ºC. Finally, conventional PCC plant configuration can exploit temperatures of 760ºC (Marion, 2012).

4.1 Boiler

Figure 13 shows the tasks of the boiler project. The following sections describe each of the tasks and assess their current status.

4.1.1 Task 1: Conceptual design

Alstom have completed designs for a 550 MW and 1100 MW tower AUSC boiler and steam turbine set based on proven conventional configuration and experience. In late 2012, Alstom were designing a 1000 MW two-pass AUSC boiler and were assessing the possibility of placing the HP turbine higher to shorten the superheater steam pipe with an 1100 MW boiler; the intermediate pressure (IP) and HP turbines would remain at ground level (Marion, 2012).

Babcock & Wilcox have a modified AUSC tower boiler design which is based on proven USC boilers. The modified tower design combines features of both tower boiler and two-pass designs; advantages

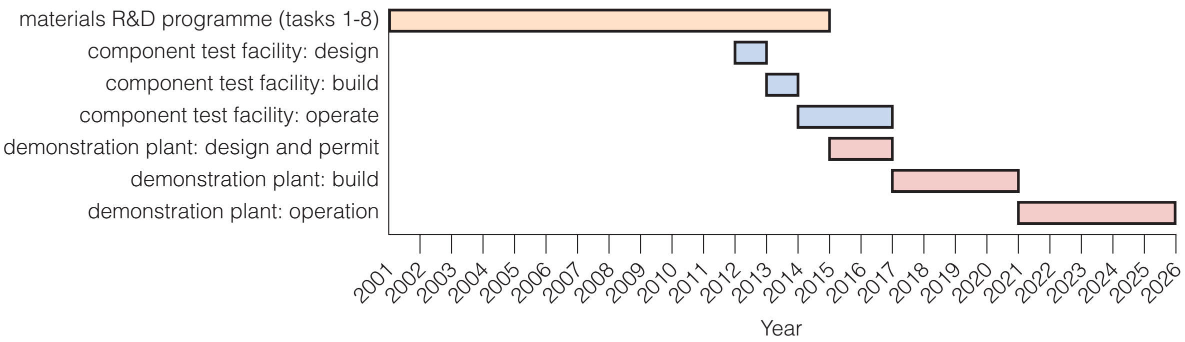

Figure 12 Gantt chart of the US research programme (Phillips, 2011)

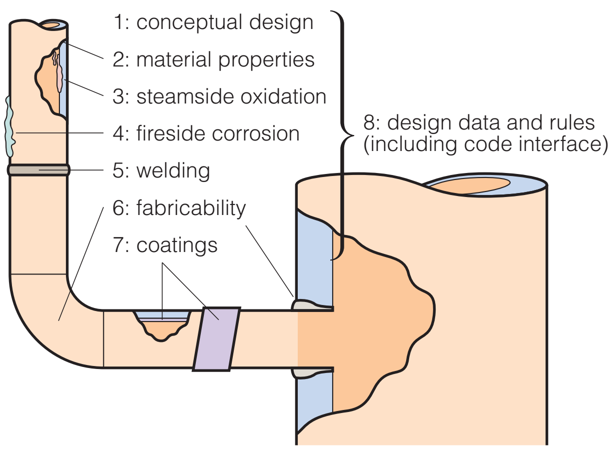

Figure 13 Boiler tasks (Romanosky, 2012)

include minimised steamside oxidation and fireside corrosion, improved reheat control, lower overall height, and shorter pipework. Babcock & Wilcox state that they have a boiler ready for main and reheat temperatures of 700ºC and 730ºC respectively. Babcock & Wilcox are working with steam turbine manufacturer Toshiba on alternative steam cycles to minimise piping length, for air fired and oxyfuel boilers with and without the addition of CCS. Factors under consideration include single or double reheat, boiler capacity, steam turbine configuration, base load and cyclic operation (starting conditions, turndown cycling, feedwater pump drive, sliding pressure, pure or throttle reserve, pressure 'shelf' at minimum load, rate of load change) and the application of carbon capture (condensate heat exchangers for oxy-combustion heat recovery and turbine steam extraction for post-combustion solvent regeneration). Babcock & Wilcox are confident they will be able to manufacture a boiler capable of handling steam at 760ºC (McCauley, 2012). When all the necessary information has been collected through tasks two to seven (detailed in Figure 13), including material costs, task one will be revisited in order to optimise the boiler design.

4.1.2 Task 1: Economic analysis

For more attractive economics, the material research programme in the USA uses higher strength materials to achieve temperatures higher than 700ºC. An example of this concept can be demonstrated with a comparison between pipework manufactured of materials Alloy 617 and Inconel 740H. A single reheat 750 MW boiler running at the following steam parameters 704/704°C and 732/760°C was used as a reference. The capital cost of the Inconel 740H pipework was estimated to be 55–110 $/kg, Alloy 617 is considered to have an equivalent cost. The delivered cost for Inconel 740H is 55 $/kg and the delivered cost for alloy 617 is 110 $/kg. Welding Inconel 740H is estimated to be less than half the cost of welding Alloy 617. The combined effect of these results demonstrates that the utilisation of 740H in place Alloy 617 in AUSC pipework will result in a significant cost savings with regard to both capital and maintenance (Shingledecker, 2012).

Using historic prices for nickel, all studies show that the cost of electricity (COE) from AUSC technology is more expensive by 1.5–13% than USC technology, unless there is a carbon tax. If CCS were deployed, the cost of electricity from AUSC technology would be cheaper than USC, for both air and oxygen fired combustion. Figure 14 shows an economic study completed by Alstom and Electric

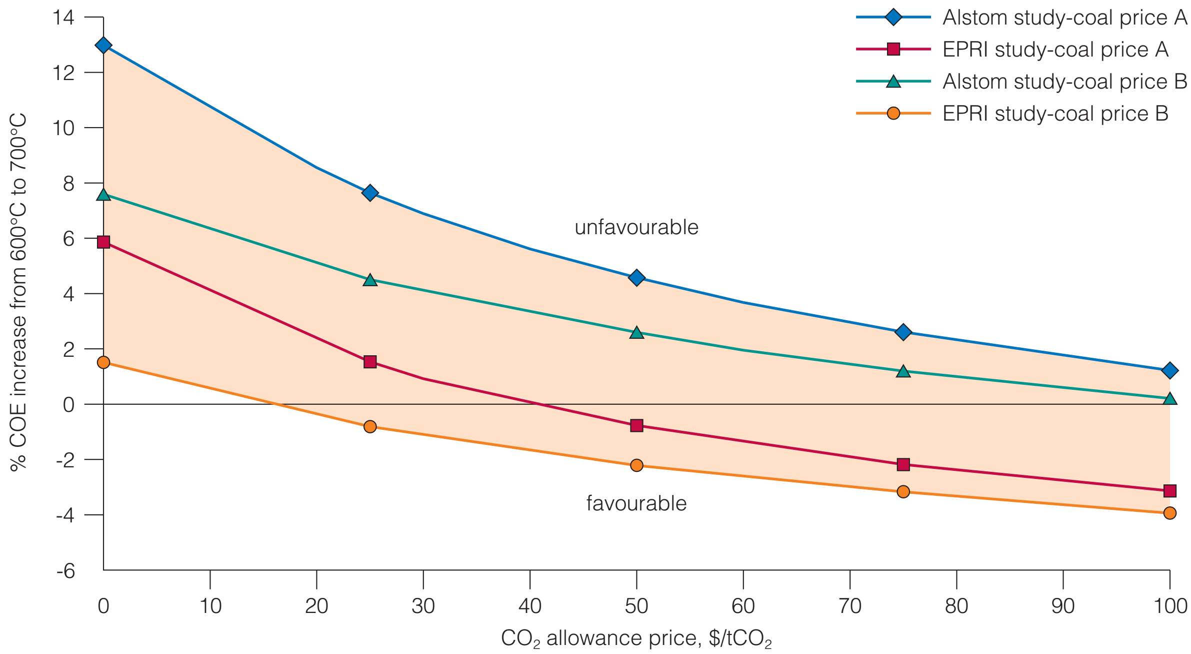

Figure 14 Economics of AUSC technology (Marion, 2012)

Power Research Institute. The x-axis shows the price of a carbon dioxide tax ($/t) and the y-axis shows percentage increase in COE as temperatures rise from 600ºC to 700ºC. Any point below the colured area shows favourable economics, any point above the coloured area shows unfavourable economics. The coloured area takes into account the estimated capital cost of AUSC technology, any point in this region could be economically favourable or unfavourable (Marion, 2012).

4.1.3 Task 2: Mechanical properties

Mechanical testing is extensive and is split among the US boiler manufacturers and national laboratories. All data from mechanical testing are accumulated in a long-term material property database. Babcock & Wilcox are using finite element software (3D-FEA) to analyse stresses of thick-section components (McCauley, 2012). Mechanical testing has found that Inconel 740H has a higher allowable stress than other code-approved nickel alloys, such as Alloy 617 and Alloy 230. Therefore Inconel 740H requires thinner walls for a given stress than weaker alloys, which reduces the quantity of material usage, the amount of welding required and puts less load on the structural supports, thus reducing time, cost and risk. Additionally, thinner pipes are less susceptible to cracking with cyclic operation and Inconel 740H has a large forging window (its low flow stress allows for long extrusions of pipes/tubes with a range of widths). Candidate materials have been selected through basic mechanical tests, including creep rupture testing to 10,000 hours. Full-scale pressurised creep tests on candidate alloys are now being performed on heat treated cold-bent tubes. This will help determine whether cold strain affects creep rupture strength. This data will be used as the basis to set rational cold-work limits for the guidelines in the ASME BPVC (Viswanathan, 2008a).

4.1.4 Task 3: Steamside oxidation

Initially materials, coated and non-coated, were screened by laboratory tests. Long-term testing is under way in order to improve the understanding of long-term oxidation kinetics and exfoliation. In 2012, Babcock & Wilcox were performing steamside oxidation tests of pieces, including coated test pieces, at 620°C, 650ºC, 750ºC and 800ºC to 10,000 hours. Results to date have concluded the following (McCauley, 2012):

- austenitic steels show good resistance to oxidation and exfoliation up to 700ºC;

- several outstanding ferritic and austenitic steels were identified;
- nickel alloys show the least oxidation and absence of exfoliation;
- parabolic kinetics have been exhibited, allowing the prediction of oxidation rates.

4.1.5 Task 4: Fireside corrosion

Task 4 will evaluate the long-term corrosion resistance of materials, cladding and coatings under a variety of fireside conditions. Initially alloys were screened in laboratory tests that simulate membrane wall, superheater and reheater conditions using a range of coals at different temperatures for 1000 hours. The candidate materials have since been tested in steam loops in commercial size boilers. Figure 15 shows a steam loop installed at the Niles PCC plant (USA), which fires high sulphur coal. AUSC steam parameters are achieved by throttling up the steam flow to achieve 760ºC. The steam loop replicates a superheater, reheater and membrane wall components. Tubes are monitored during planned outages by means of inside and outside diameter measurements for corrosion and oxidation wastage, and photographs are taken to record the surface condition. Steam loop field testing will validate laboratory corrosion and oxidation testing and provide knowledge on the reliability of component fabrication. The conditions at the membrane walls are similar to those at the superheater tubes and therefore testing of membrane wall materials in the steam loops have not been undertaken.

Figure 15 Steam loop at Niles PCC plant (Viswanathan, 2008b)

Results from the steam loop at Niles PCC plant show that 9–12% chromium martensitic steels may not have sufficient fireside corrosion resistance when firing high sulphur coals – weld overlays and coatings may be required (Viswanathan, 2008b). Alloys for oxy-combustion are being tested at the laboratory stage only and work is ongoing. To date, no major difference has been found in boiler materials required for oxygen-fired boilers to those for air-fired boilers.

Figure 16 Second steam loop (Romanosky, 2012)

In 2012 an additional steam loop manufactured from candidate materials, shown in Figure 16, was placed in another commercial boiler. The field tests will run for 12–18 months operating with steam up to 760ºC firing high sulphur coals, and will include the use of air cooled probes. Materials tested are Super304H, HR3C, HR6W, Haynes 230, Haynes 230 with an Amstar thermal spray, Inconel 617, Inconel 617 with EN33 laser cladding, Inconel 617 with EN622 laser cladding, Haynes 282, and Inconel 740.

Results show that resistance to fireside corrosion for nickel alloys is a function of chromium level; it decreases rapidly as chromium increases from 22% to 27% and then levels out. Inconel 740 showed greater fireside corrosion resistance than Haynes 230 and CCA617. Results have shown parabolic kinetics, allowing prediction of corrosions rates. Material testing in oxyfuel environments has shown less fireside corrosion attack than for the air-fired boilers. Overlays and coatings will be necessary on membrane walls in units burning high sulphur coals as the 9-12% chromium martensitic steels do not have adequate fireside corrosion resistance (McCauley, 2012). External and internal coatings with application methods have been identified (Romanosky, 2012).

4.1.6 Task 5: Welding

For a number of materials, including Haynes 230, the weld metal is the weakest link. The weld usually fails at a shorter time interval or lower stress level than the parent alloy. Welding procedure, filler material chemistry and PWHT are under investigation to improve weld strength (Viswanathan, 2008a). Welding of tubes is a well understood and developed process; however welding of thick-section plates is difficult and require GMAW (Viswanathan, 2008b). Babcock & Wilcox are researching weld life cycle, this will allow simultaneous testing of various material conditions at a given temperature, including: stress-relieved, as-welded, effect of filler metal, and stress. Continuing work includes DMW, weld metal chemistry and effects on weld strength reduction factor. Babcock & Wilcox have had success with the following welds (McCauley, 2012):

- welding of tubes, pipes and thick-section of Inconel 740;
- welding of thick-section stainless steels and Alloy 282;
- welding of small diameter alloys and narrow groove welding;
- circumferential pipe weld for thick-sections (75 mm) made of Inconel 740H;
- butt welding procedures using 5–7.6 cm (2–3 inch) thick-section components qualified. Alloys include Haynes 230 via pulsed GMAW using matching filler and Inconel 740 via hot wire GTAW using matching filler.

By late 2012, the programme had developed and qualified successful and repeatable welds for numerous alloy combinations, sizes and configurations. Ongoing work includes improving weld performance and simulating weld repair activities for nickel alloy boiler components (Shingledecker, 2012).

4.1.7 Task 6: Fabricability

The programme has subjected alloys to common fabrication processes and produced prototype assemblies. The fabrication methods for machining, bending and swaging are being qualified. Figure 17 shows a mock-up section of the header, which demonstrates the fabrication capabilities achieved (Viswanathan, 2008b):

- **Forming**: Press forming of headers and piping, bending of plates (CCA617), bending of tubing, swaging of tube ends.
- **Machining**: Weld grooves for header and pipe; longitudinal and circumferential seams; socket weld grooves for tube to header joints; held grooves for tube circumferential seam.
- **Welding**: SAW for headers and longitudinal and circumferential pipe seams, SMAW and GTAW for tube to header socket joints, tube to tube joints and DMW (for example between CCA 617 and Super304H and T91 tubing).

Babcock & Wilcox have fabricated full-scale membrane wall panels from T23 and T92 and have trialled PWHT field repairs. The following fabrications methods have been successful: hot bending trials, machining trials, and tube swaging trials. Controlled cold strain, recrystallisation and precipitation studies have been completed for all candidate materials showing successful results (Inconel 740, Alloy 230, CCA617, S304H, HR6W and SAVE12) (McCauley, 2012).

Figure 18 shows a pipe fabricated from Inconel 740H after extrusion at Wyman-Gordon's 35 kt press in the USA. A mock-up header using Inconel 740 and hot-wire narrow-groove GTAW has been manufactured. A 9700 kg ingot of Inconel 740 with an outer diameter of 750 mm has been produced (Shingledecker, 2012). Fabrication studies have been successfully completed for all alloys; which

Figure 17 Mock-up header manufactured by Alstom USA (Viswanathan, 2008b)

Figure 18 Inconel 740H pipe after extrusion (Shingledecker, 2012)

includes the production of large boiler components (Shingledecker, 2012).

4.1.8 Task 8: Material standards

Inconel 740/740H was found to have sufficient high creep rupture strength of over 100 MPa for 100,000 hours, fireside corrosion resistance of 2 mm per 200,000 hours and weldability for operation at 760°C. Based on the consortium's data, Inconel 740/740H and related header to superheater welds were approved by ASME in September 2011 (Code Case 2702 for UNS N07740) (Shingledecker, 2012).

4.2 Steam turbine

The steam turbine part of the programme is split into phases. Phase 1 screens alloys for further investigation in phase 2. Phase 2 is split into the following six tasks (Romanosky, 2012):
- rotor/disc testing (large-scale forgings);
- blade/air foil alloy testing;
- valve internals alloy testing;
- rotor alloy welding and characterisation;
- cast casing alloy testing;
- casing welding and repair.

Phase 1 found the following materials for steam turbine application, Haynes 282, Alloy 617, Alloy 263, Sanicro 25, Inconel 740 and Alloy 625. Haynes 282 appears the most attractive for the steam turbine rotors (Shingledecker, 2012). Phase 2 is under way.

Alstom have used their conventional and proven steam turbine design for AUSC steam parameters, with the application of nickel alloys and austenitic steels in the highest temperature regions. Nickel alloy and ferritic steel are used to forge rotors and casings. There is no change in standard procedures and design rules for the safe introduction of a higher temperature steam turbine. However, new fabrication techniques are required for new materials. One challenge is the DMW when welding ferritic steel to nickel alloy for the HP and IP steam turbines. To simulate the rotor DMW, Alstom have welded a full-scale test block of Alloy 617 to ferritic steel and Alloy 625 to ferritic steel. However, the stability in operation of the DMW remains unproven. Operational flexibility is ensured by using a shrink-ring inner casing design that has minimal thermal stresses during cyclic operation. This ensures capability for rapid start-up and shut-down load changes (Shingledecker, 2012).

Research on castings identified key materials for large turbine and valve components, including Haynes 282. The first ingot of triple melted Haynes 282 was produced in 2012 and is now being subjected to microstructural analysis. This work is being undertaken by the Foundry Research Institute in Poland (Sobczak and others, 2012). However, work continues on the scaling-up of castings and forgings for steam turbine components. Development of steam turbine materials is ongoing – the steam turbine materials technology is predicted to be ready by 2017 (Shingledecker, 2012).

4.3 Candidate materials

Table 4 summarises material selection for the critical components a 1000 MW two-pass boiler and steam turbine by Alstom.

Table 4 Candidate materials for the US programme – Alstom 1000 MW two pass boiler (Marion, 2012)

Component	Candidate material
Economiser	Carbon steel
Membrane walls	T23, T92
Super heater panels	S304H, Inconel 617, Inconel 740
Super heater platens	347 HFG, Inconel 617, Inconel 740
Super heater finish third	Inconel 740
Super heater finish in	Inconel 740
Super heater finish out	Inconel 740
Reheat low temp 1	T23, P91
Reheat low temp 2	S304H
Reheat pendants	S304H
Reheat platens	S304H, HR120, Inconel 617, 230
Valves	Haynes 282
Blades	Haynes 282, Alloys 617, Alloy 263, Sanicro 25, Inconel 740 and Alloy 625, austenitic steel, martensitic steel
Casing	Haynes 282, Alloys 617, Alloy 263, Sanicro 25, Inconel 740, Alloy 625, ferritic steel
Rotor	Alloy 617, Alloy 625, ferritic steel

4.4 CTF and FSDP

The US programme is aiming for an operational component test facility (CTF) at the start of 2014. Once adequate component testing has been completed, the next stage would be to design, build and operate a full-scale demonstration plant (FSDP) in order to guarantee operational characteristics and economics. A supply chain for advanced material components will also need to be secure.

The US FSDP will consist of a single unit in the range of 350–1000 MW (possibly 600 MW) and it is planned to be operational in 2021. The superheater steam temperature is likely to be 700°C. However this temperature will increase providing the materials are capable and those temperatures offer an economic advantage (Shingledecker, 2012; Romanosky, 2012; Phillips, 2011).

4.5 Topping cycle

Aspects of the AUSC technology could be used in existing subcritical PCC plant with the addition of a

Topping Cycle. Steam at 680°C would pass from the superheaters to the Topping turbine-generator before passing through the existing three stage steam turbine; which can raise the efficiency by 3–3½ percentage points (Phillips, 2012).

4.6 Summary

The US research programme started in 2001. There are ten participants, consisting of the major US boiler and steam turbine manufacturers and national laboratories. The American programme is aiming for higher steam temperatures than other programmes, with up to 730°C superheat and 760°C reheat steam temperatures under air-fired and oxyfuel conditions. Significant progress has been made on the boiler side. Tests in the laboratory and in larger -scale boiler test loops have been completed. Welding processes and fabrication techniques have been established for some materials. A design for a boiler with a list of candidate materials for critical components has been completed. This progress has led to the code approval of Inconel 740/740H for use in boilers by the American Society of Mechanical Engineers. Research on the steam turbine is progressing, Alstom plan to use their proven steam turbine design with nickel alloys and use welded rotors to reduce costs.

A large-scale component test facility (CTF) is planned to be operational from 2014 to 2017. There are plans in the USA to build a FSDP (350–1000 MW at 700/730/35) in 2017–21 with operation and feedback in 2021-26. An interesting research spin-off is where an AUSC steam turbine is added to a USC pulverised coal combustion (PCC) plant.

5 Japan

Japan imports fossil fuels due to scarce indigenous reserves – this makes energy in Japan expensive. Japan has a high population density, creating relatively high amounts of pollutant emissions per unit area, adversely affecting the environment and public health. To counter these two factors, Japan uses fossil fuels efficiently and has substantial pollutant mitigation technologies in place. It is no surprise, therefore, that Japan operates one of the most efficient and cleanest fleet of PCC plant in the world.

Research and development on super alloys for use in AUSC technology started in Japan in 2000. The work was headed by the Electrical Power Development Centre (EPDC) and strongly supported through the Ministry of Trade and Industry (Sven, 2001). Prior to 2008, the National Institute for Materials Science (NIMS) completed a feasibility study of AUSC technology with superheat steam temperature of 700°C. The study showed that efficiencies can reach 46–48% (net, bituminous coal, HHV) which is economically and environmentally favourable, and that technical viability looks promising. The study also found that it is technically feasible to retrofit AUSC technology to older PCC plant in Japan.

In March 2008 AUSC technology was selected by the Japanese government's 'Cool Earth-Innovative Technology Programme' as one of the technologies to reduce carbon dioxide emissions (Fukuda, 2012a). The Japanese programme has four committees; the lead AUSC technology development committee, and three sub-committees, for the boiler, valves and steam turbine. The twelve companies and institutions participating in the programme and organised into their working topics are (Fukuda, 2012a):

- **boiler**: ABB Bailey Japan, Central Research Institute of Electric Power Industry, Ishikawajima-Harima Heavy Industries, Mitsubishi Heavy Industries, NIMS, and Sumitomo;
- **valves**: Fuji Electric (lead), Hitachi, Mitsubishi Heavy Industries, Toshiba, ABB Bailey Japan (bypass valves), Okano Valve and Toa Valve (safety and control valves);
- **steam turbine**: Babcock-Hitachi, Mitsubishi Heavy Industries and Toshiba.

Observers include numerous Japanese universities, the Japan Steel Works and the Ministry of Economy, Trade and Industry. Figure 19 shows a Gantt chart of the Japanese AUSC research programme, which started in August 2008 It has detailed plans for nine years until 2017 and rough plans until 2026. The programme aims to have an operational demonstration plant by 2021 (Saito, 2012; Fukuda, 2012a,b; Imano, 2012).

5.1 Chemical and mechanical tests

The first part of the Japanese research programme will identify new materials through mechanical and chemical tests. Mechanical tests include fatigue, tensile, long-term creep rupture, bending, welding and non-destructive testing. Chemical tests include steamside oxidation and fireside corrosion, which are explained below.

5.1.1 Fireside corrosion

A material corrosion database is being compiled from materials testing in laboratories, steam loops and the investigation of operating power plants. The amount of corrosion can be extrapolated given data about the corrosion rate of the material, flue gas composition, metal and gas temperatures and ash deposition via computational fluid dynamic (CFD) analysis. Material protection methods such as weld-overlays and chromising will be tested. Laboratory testing has shown that nickel alloys and nickel and iron based alloys have similar fireside corrosion resistance to conventional austenitic steels.

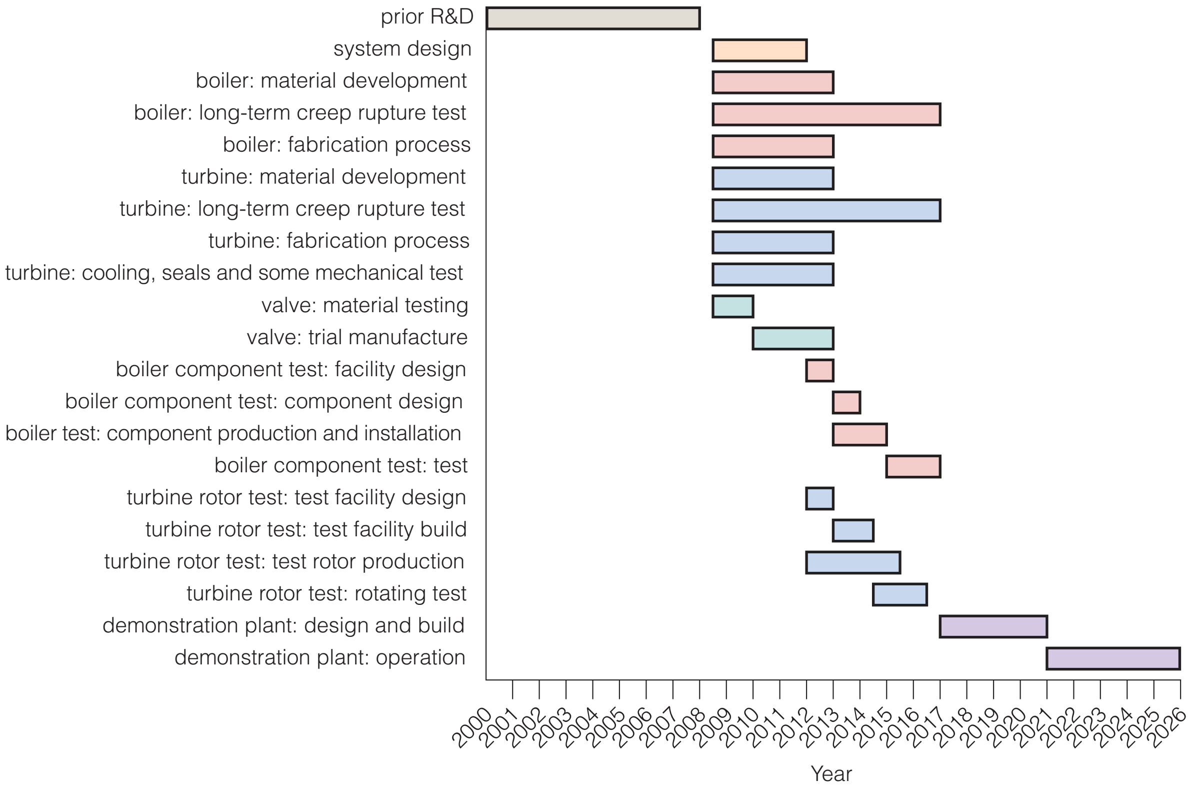

Figure 19 Gantt chart of the Japanese research programme (Saito, 2012; Fukuda, 2012a,b; Imano, 2012; Sven, 2001)

The testing of fireside corrosion on new materials and protection methods under biomass cofiring will be undertaken (Fukuda, 2012b).

5.1.2 Steamside oxidation

A materials oxidation database is being compiled from materials testing in laboratories and from the investigation of operating plants. The amount of oxidation can then be extrapolated from the oxidation rate of the material and temperatures of the steam and metal. Materials protection methods will be investigated such as shot blasting for austenitic steels and the varying of silicon content for new 9–12% chromium martensitic steels. Nickel alloys show slight internal oxidation, but this has not been shown to affect creep resistance. Shot blasting has been shown to be effective for increasing the oxidation resistance of austenitic steels. Longer-term testing is needed to prove the scale stability of new materials and protective coatings (Fukuda, 2012b).

5.2 New materials

By 2012 the Japanese programme had already developed the following new materials specifically for AUSC technology – FENIX700, USC141 and USC800MOD.

5.2.1 FENIX700

FENIX700 is a low cost nickel/iron alloy developed for steam turbine rotors. FENIX700 has a high creep rupture strength of over 100 MPa at 700°C for 100,000 hours and it is typically a third cheaper than nickel alloys. A 12.5 tonne rotor has been forged (Saito, 2012).

5.2.2 USC141

USC141 is a high strength nickel alloy developed for tubes, steam turbine blades, nozzles and bolts. USC141 has a low thermal expansion and a high creep rupture strength (>180 MPa at 700°C for 100,000 hours). A solution treated version of USC141 is in qualification for use in boiler tubes (Saito, 2012).

5.2.3 USC800MOD

With some funding from the New Energy and Industrial Technology Development Organisation, Hitachi have developed USC800MOD, an nickel alloy capable of operating with steam temperatures up to 800°C. Imano (2013) has investigated properties and manufacturability of USC800MOD. Results estimate that the creep rupture strength is over 100 MPa at 800°C for 100,000 hours. Trial fabrication of a three tonne forging and extrusion of tubes have been successful (Imano, 2013).

5.3 Steels for 650ºC USC technology

EPDC lead a programme called STX-21. This programme contains a sub-project called ‘advanced ferritic heat resistant steels for 650ºC USC steam boilers’ that focuses on the continued development of 9–12% chromium martensitic steels for 650°C steam parameters (the same principal aim of COST 536). This project is scheduled to last for 15 years. The first five-year phase involved a total of 35 researchers at the NIMS in Tsukuba. The project has made significant progress with modifying martensitic steels via boron additions (Osgerby, 2007; Mayer, 2001; Gibbons, 2013).

5.4 CTF and FSDP

Towards the end of 2012, component test facilities (CTF) and full-scale components are being prepared. Component testing will start from mid-2014 and finish by 2017. The superheater panels, large diameter pipes, safety valves and a turbine bypass valve will be tested in steam loops installed in a commercial boiler. Three rotors made of candidate materials will be tested at actual speed in a rotor test rig at a temperature of 700°C. The results should verify the predicted material life assessment and effectiveness of maintenance procedures, such as repair welding.

In 2012, four years into the programme, candidate materials were selected for components through preliminary testing (*see* Table 5) (Fukuda, 2012a,b; Saito, 2012). Common issues with all nickel alloys are that they are expensive, segregate easily during manufacture, have a low tensile strength and high linear coefficient of expansion. Figure 20 shows a flow diagram of an AUSC PCC plant with double reheat with selected materials (Fukuda, 2012a). There are plans in Japan to design, construct and build a 600 MW full-scale demonstration plant (FSDP) in 2017-21, with operation and feedback in 2021-26.

5.5 Summary

The Japanese programme officially started in August 2008 and has twelve participants. However, research in this area started in 2000. In 2012, studies concluded that supercritical or USC PCC plant could be upgraded to AUSC steam parameters. Laboratory tests have mostly been completed – long-term creep tests for boiler continue to run until 2017 and from 2012 the programme was preparing for large-scale component testing to start from mid-2014 and finish in 2017. The superheater panels, large diameter pipes, safety valves and a turbine bypass valve will be tested in steam loops installed in a commercial boiler. Three rotors made of candidate materials will be tested at actual speed in a rotor test rig at a temperature of 700°C.

Table 5 Candidate materials for the Japanese FSDP (Fukuda M, 2013; Fukuda Y, 2012; Saito, 2012)

Component	Steam temperature	Alloys	Creep strength requirement	Welding procedure	Material issues
Membrane walls	<650°C	Conventional ferritic steels	–	–	Corrosion fatigue, sulphidation, circumferential cracking
Tube (superheaters and reheaters)	>700°C	Nickel based: HR35, Alloy617, Alloy263, Alloy740, Alloy141, USC141, USC800 Nickel/Iron based: HR6W	>90 MPa (750°C, 10^5 hours)	–	Creep, fireside corrosion, steam oxidation
Nickel/Iron based: HR6W	>90 MPa, 750°C, 10^5 hours	–	Creep, fireside corrosion (exfoliation), steam oxidation (scale, exfoliation)	–	–
Eco and PrySH	–	–	–	–	Pitting, erosion, thermal fatigue
Pipe	<650°C	Ferritic steels: B9Cr (high Boron), LC9Cr (low Carbon) and SAVE12AD	>80MPa, 650°C, 10^5 hours	Narrow gap hot wire switching TIG, high-speed TIG, hot-wire laser TIG, welding	Creep, steamside oxidation, thermal fatigue, type IV cracking
	>650°C	Austenitic steels: 18-8 series and 25 Cr20Ni	–		Creep, steam oxidation, thermal fatigue, poor large ingot manufacturability
	750°C	Nickel based: HR35 and Alloy 617 (B) Nickel/Iron based: HR6W	>90MPa, 700°C, 10^5 hours		
Headers	Same as pipe	–		Stub welding	
Valve bodies	>700°C	Alloy 625	–	–	Poor hot workability
Casing inner	>700°C	Alloy 625, Inconel 740, Alloy 617	–	–	Poor hot workability
Casing outer	<650°C	12% chromium steels	–	–	–
Blades (nozzle)	750°C	Nickel based: USC141 (Nickel alloys directly from gas turbines could be used)	–	–	–
Rotor	>750°C	Nickel based: FENIX-700, LTES and TOS1X	~>100 MPa, 700°C, 10^5 hours	–	Poor hot workability, poor large ingot manufacturability
Bolts	>700°C	Nickel based: USC800, USC141	–	–	Poor hot workability
All above	–	–	–	–	Nickel alloys are expensive, segregate easily during manufacture, and have low tensile strength, high linear coefficient of expansion

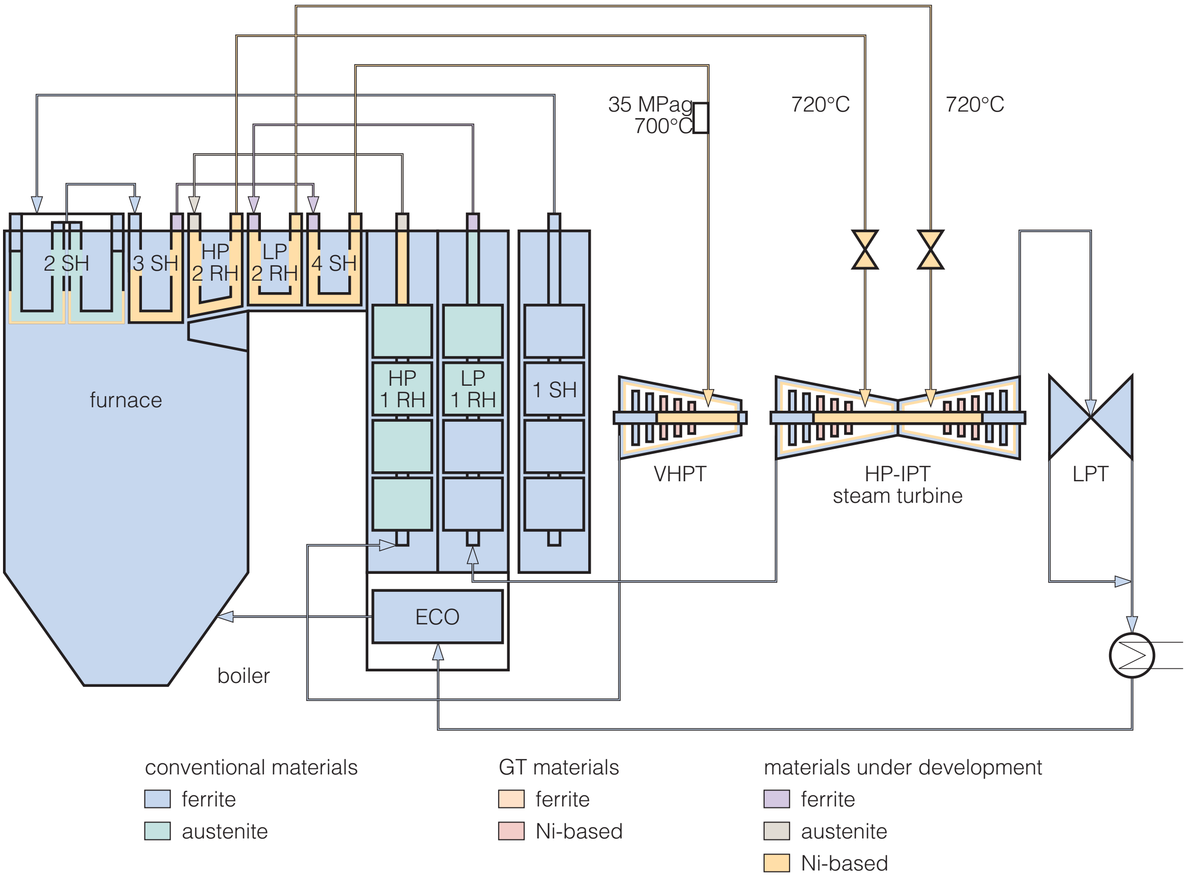

Figure 20 Flow diagram of a Japanese double reheat AUSC PCC plant (Fukuda, 2012a)

The programme has gained sufficient information to create a P&ID for a double reheat AUSC PCC plant with a detailed list of candidate materials for critical components. The programme has developed three new materials specifically for AUSC technology including FENIX700, USC141 and USC800MOD.

There are plans in Japan to build a FSDP (600 MW at 700/720/720/35) from 2017 to 2021, with operation and feedback from 2021 to 2026. The Japanese are assessing advanced ferritic heat resistant steels in a separate project, which has pioneered work on boron-modified martensitic steels.

6 China

In 2011, China had a total generating capacity of 1056 GW of which 765 GW was thermal power. the total generating capacity is forecast to reach 2380 GW in 2030, of which 1270 GW would be thermal power. Through legislation and financial incentives, China is upgrading its entire fleet of coal-fired power plant, replacing the old, small, inefficient and dirty units with new, large, efficient and clean units in order to sustain resources, minimise pollution and produce lower cost, reliable power. It is no surprise therefore that China operates some of the cleanest and most efficient PCC plant. Waigaoqiaw PCC plant has achieved a peak efficiency of 46.5% (net, LHV). Guodian Taizhou PCC plant is a new build with two 1000 MW double reheat USC units (600//610/610/31) aiming for an electrical efficiency of 47.6% (LHV, net) (Sun and others, 2012).

In July 2010, the National Energy Administration (NEA) launched the 'National 700°C USC Coal-Fired Power Generation Technology Innovation Consortium' whose principal aim is to develop and commercialise AUSC technology. The NEA and the following 18 members are involved in the programme: Thermal Power Research Institute, Shanghai Power Equipment Research Institute, Institute of Metal Research of Chinese Academy of Science, China Iron and Steel Research Institute Group (CISRI), Electric Power Planning & Engineering Institute, China Power Engineering Consulting Group Cooperation, Shanghai Electric, Dongfang Electric Corporation (DEC), Harbin Electric Corporation, China First Heavy Industries, China National Erzhong Group, Baoshan Iron & Steel, Dongbei Special Steel Group, Huaneng Group, China Datang Corporation, China Huadian Corporation, China Guodian Corporation and the China Power Investment Corporation (Sun and others, 2012).

Figure 21 shows a Gantt chart of the Chinese research programme. The research programme has five main areas of study: identifying the critical high temperature components, material research, developing manufacturing capability for new alloys, operating a component testing facility followed by a FSDP (Sun and others, 2012).

The programme has a council that meets once a year to make the significant decisions. A committee made up of experts arranges a workshop every six months to organise, guide and inspect the research projects, review achievements, propose new research and thus develop the technical roadmap. The technical committee is sub-divided into four special working groups, which are the system and engineering solutions, boiler, turbine and material group (Sun and others, 2012; Liu, 2012).

Once a new project is proposed, members capable of completing the work apply for funding from the government (NEA or the Ministry of Science and Technology). There is a secretariat which is responsible for dealing with daily operations and arranging a meeting every three months. Figure 22 shows the financing structure (Sun and others, 2012).

6.1 Ministry of Science and Technology

The Ministry of Science and Technology has set up a project called 'Research on advanced boilers key pipes of USC thermal power units'. The project is co-ordinated by CISRI along with nine partners and has received RMB29.5 million in funding to date. This project consists of three sub-projects (Sun and others, 2012).

- **Manufacturing the boilers key pipes of 600–700°C USC unit**: This sub-topic focuses on selecting materials for the temperature range of 600–700°C in the demonstration plant; P92, P122, G115/G112, CCA617, Inconel740H are currently being assessed;
- **Research on alloy GH2984 and its technology process used in 700°C USC thermal power**

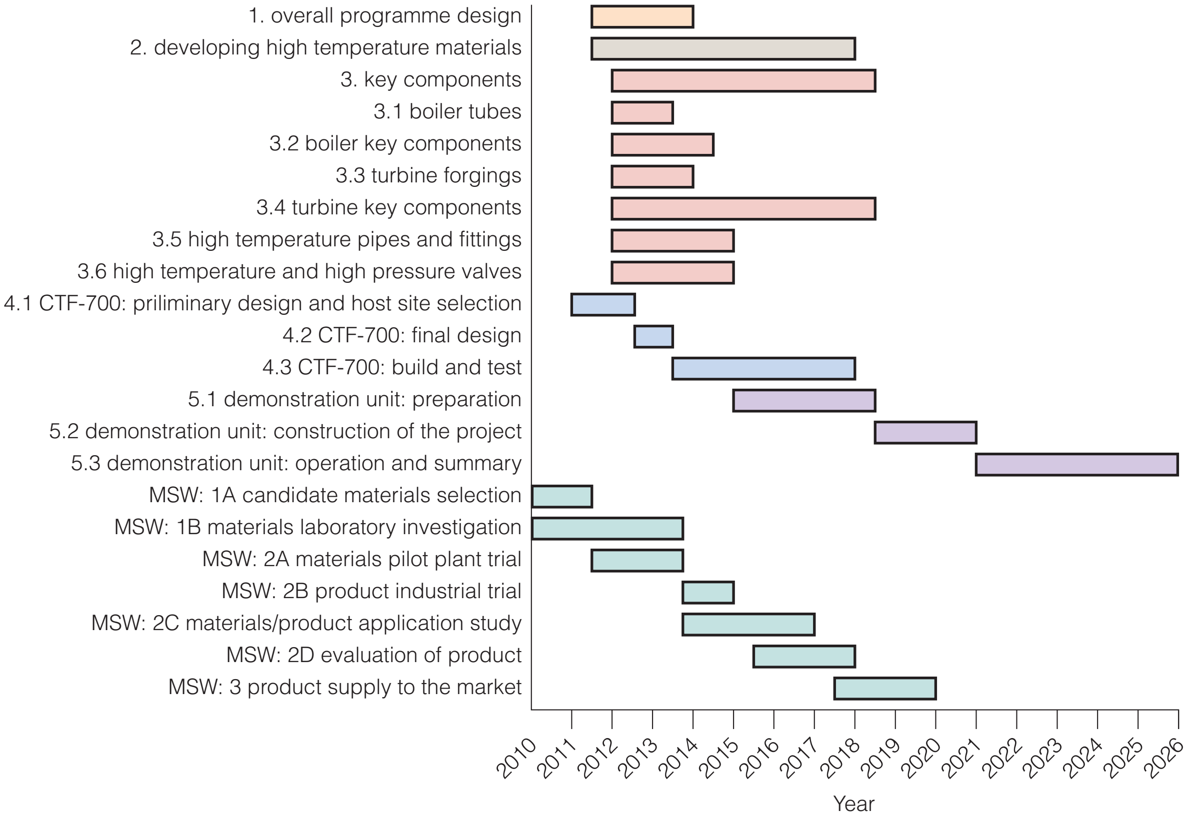

Figure 21 Gantt chart of the Chinese research programme (Sun and others, 2012; Liu, 2012: Jiang, 2012)

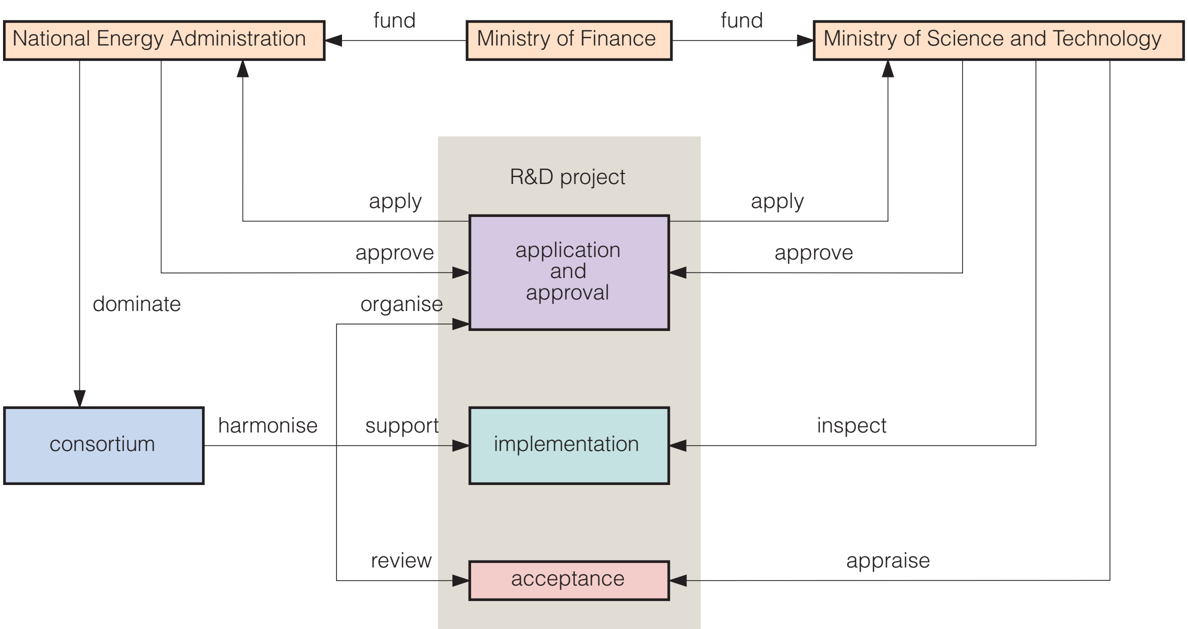

Figure 22 Financing structure of the Chinese programme (Sun and others, 2012)

units: Developed in China, GH2984 is a low cost nickel and iron based alloy that has been used in superheater and reheater tubes in Chinese PCC plant since the early 1990s. This sub-topic aims to optimise its constituents for application in tubes, headers and rotors operating at 700°C (Wang and other, 2012; Gibbons, 2013);

- **Research on new-type austenitic high temperature steel used in 650°C USC thermal power units**: This project aims to develop several types of new austenitic materials for use with steam temperatures up to 650°C. In 2012, there were plans to extrude a full-scale sample pipe by the end of 2013.

6.2 Material special workgroup

The material special workgroup (MSW) has agreed on four criteria that make up their goal. The first criterion is establishing which materials and components should be developed in China. Secondly, those selected materials will be optimised. The third criterion is to assess materials worldwide for application in Chinese PCC plant. The fourth criterion is to ensure that these materials are economically competitive. The material special workgroup (MSW) is funded by the NEA and MST. Table 6 shows a list of the candidate alloys for a full-scale demonstration plant (FSDP) (Liu, 2012):

Table 6 Candidate materials for the Chinese FSDP (Lui, 2012)

Component	Candidate materials
Water cooling tubes	T91, HCM12
Pipe and header	P91, P92, G115/G112, GH2984G, CCA617CN
Tube and pipe	GH2984
Tube (superheater and reheater)	T91, T92, NF709R, Sanicro25, GH2984G, Inconel740HM

6.3 NEA

In 2012, projects funded by the NEA were segregated into six distinct sub-topics. These projects have so far been allocated RMB50 million (Sun and others, 2012):

1. **Research on overall design proposal:** This includes parameters, capacity, thermal system and layout scheme. In 2012, the chosen unit capacity was 600 MW, 700/720/35 steam parameters with efficiencies above 50%. Research is being carried out into the viability of a double reheat system.
2. **Research on key materials**: Material characteristic, non-destructive and weld testing. The programme is actively seeking international co-operation on key materials.
3. **Research proposal on key technology of boiler**: This topic will develop the details of the boiler such as performance, grid layout, frame design, process design of steam/water/flue gas/air, expansion system, piping thrust, heating surface arrangement of all levels, nitogen oxide removal system selection, pre-heater selection and flue gas/air duct design. A draft boiler design has been completed.
4. **Research on turbine key technology:** This project develops fabrication techniques and refines design of steam turbine components.
5. **Construction and operation of test platform for key components (CTF-700)**.
6. **Feasibility study on constructing a demonstration power plant**: This includes site selection, general layout, capacity, steam parameters, detailed design and economic evaluation of a full-scale demonstration unit. In 2012, the demonstration plant was said to consist of one 600–1000 MW unit with steam parameters of 700/720/35. In 2013, the NEA decided that the demonstration unit would be 600 MW with a superheater steam at 700°C (Gibbons, 2013).

6.3.1 CTF-700 and FSDP

The aims of a test platform are to test the performance and reliability of full-scale components over a long period of time in order to verify their use and therefore limit the risk involved in building a

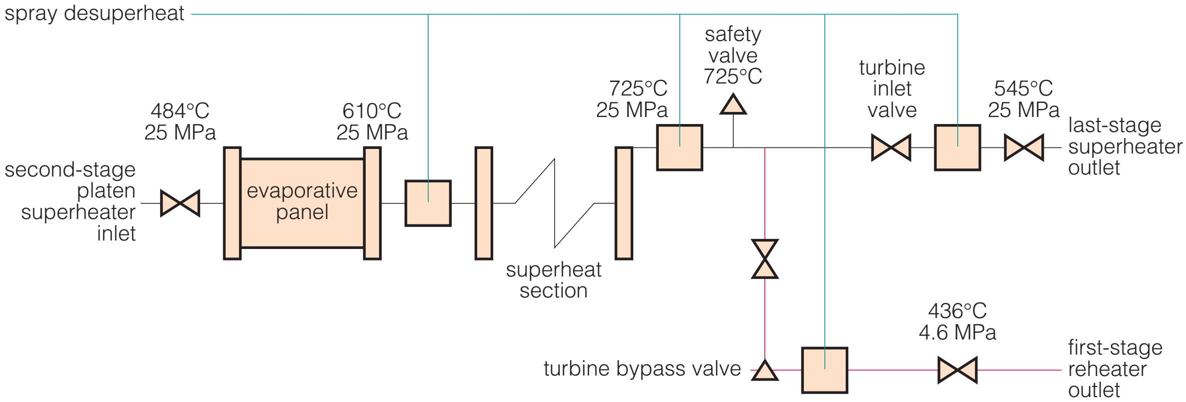

Figure 23 P&ID of the Chinese CTF-700 (Jiang, 2012)

demonstration plant. The Clean Energy Research Institute, which is part of the Huaneng Group, is undertaking this project and plans to build a component test facility to operate at 700°C (CTF-700). The CTF-700 will be capable of reaching 725°C and 35 MPa with 3 kg/s of steam flow. A P&ID of the CTF-700 is shown in Figure 23. The CTF-700 will test an evaporator panel, superheater, header, large diameter pipe and valves. It will be installed in unit 2 of Huaneng Nanjing PCC plant (two pass, 300 MW, 540°C and 25 MPa superheat steam). Materials tested will be those developed in China and possibly foreign materials from other programmes. Tests will run for >100,000 hours (approximately eleven years) in order to verify performance (Jiang, 2012). As shown in Figure 21, the Chinese research programme aims to have an operational 600–660 MW FSDP in 2021 – after only eleven years from the programme start date.

6.4 Future projects

In 2012 there were nine additional 700ºC material research topics preparing to apply for support from government national scientific research funds (Sun and others, 2012):

1 boiler membrane wall technique;
2 components of boiler superheater and reheater;
3 research on boilers header;
4 high temperature steam pipes and fittings;
5 manufacturing technology of turbines HP-IP rotor;
6 manufacturing technology of high temperature cylinder valve housing;
7 turbines high temperature blades and fasteners, valve cores wear resisting components;
8 high temperature turbine forgings;
9 high temperature turbines castings.

6.5 Plant configuration

The cross compound at high/low position arrangement (CCHLPA) of the steam turbine is where the HP and IP turbines are both mounted at the same level as the boiler steam headers and the LP turbine remains at ground level – this is shown in Figure 24. The CCHLPA reduces the pipework length, which reduces cost the pressure drop. A 1350 MWe unit with double reheat and CCHLPA operating at USC steam parameters (600/620/610/30) is estimated to reach 48.92% net efficiency (Mao, 2012).

6.6 Summary

Starting in 2010, the Chinese programme is supported by nineteen organisations. Despite the recent start of this research programme, substantial progress has been made. The majority of laboratory

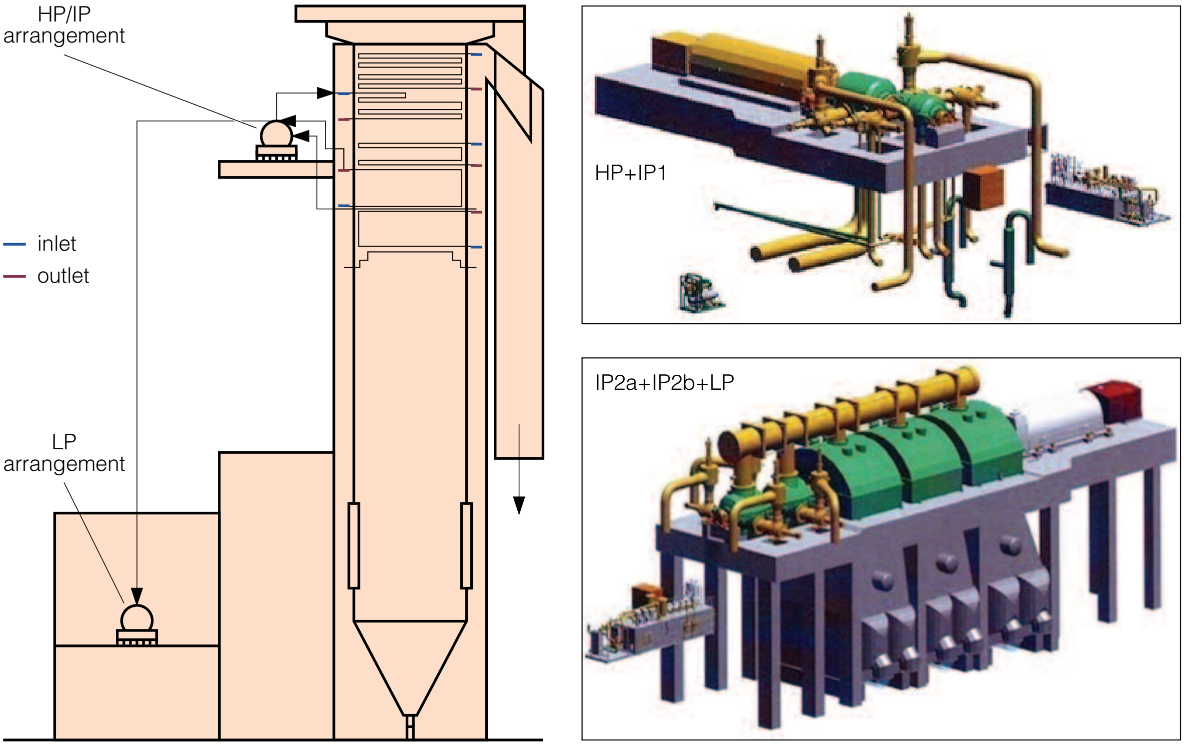

Figure 24 CCHPLA (Mao, 2012)

testing will finish in 2014-15. In 2012, a list of candidate materials for the critical components in the boiler was established with some materials developed in China, the steel G115/G112 developed by CISRI and nickel/iron alloy GH2984/GH2984G developed by the Institute of Metal Research of Chinese Academy of Science. Alternative plant configuration to minimise the length of the pipework has been found with the cross compound at high/low position arrangement (CCHLPA). Manufacturing of large-scale components and construction of a CTF started in mid-2013 and a FSDP is planned to be operational in 2021; this is only eleven years from the start of the programme. The FSDP will be 600 MW at 700/35 with a possibility of double reheat and CCHLPA.

7 Russia

Russia has one of the largest reserves of coal in the world; however the prominence of coal power in Russia has been declining since the 1990s. There is a partnership between the private and public sectors which has set up a research programme for cleaner and more efficient power from coal called 'Foundation: Energy without Borders'. The partners are the Ministry of Energy, the Institutes of Development (Vnesheconombank, Rosnano and Russian Venture Company), the Ministry of Education and Science and the Ministry of Industry and Trade. Within the Foundation: Energy without Borders programme (Portfolio 1, Action 1) AUSC is a key technology aiming at 51–53% net efficiency with steam parameters 700/720/35. Research in Russia has previously tested steels for use up to 650°C. Inter RAO are researching steels for use in AUSC technology. Austenitic steels 12Cr18H12T and 10Cr16H16B2MBR are being developed for heating surfaces and martensitic steels 10X9MFB, 10Cr9B2MFBR, 10Cr9K3B2MFBR AND 12Cr10M1V1FBR are currently on development for the pipes and rotors. Figure 25 shows a diagram of a possible CTF by the All-Russian Thermal Engineering Institute. The programme is open for collaboration both on a bilateral and multilateral basis (Rogalev, 2012).

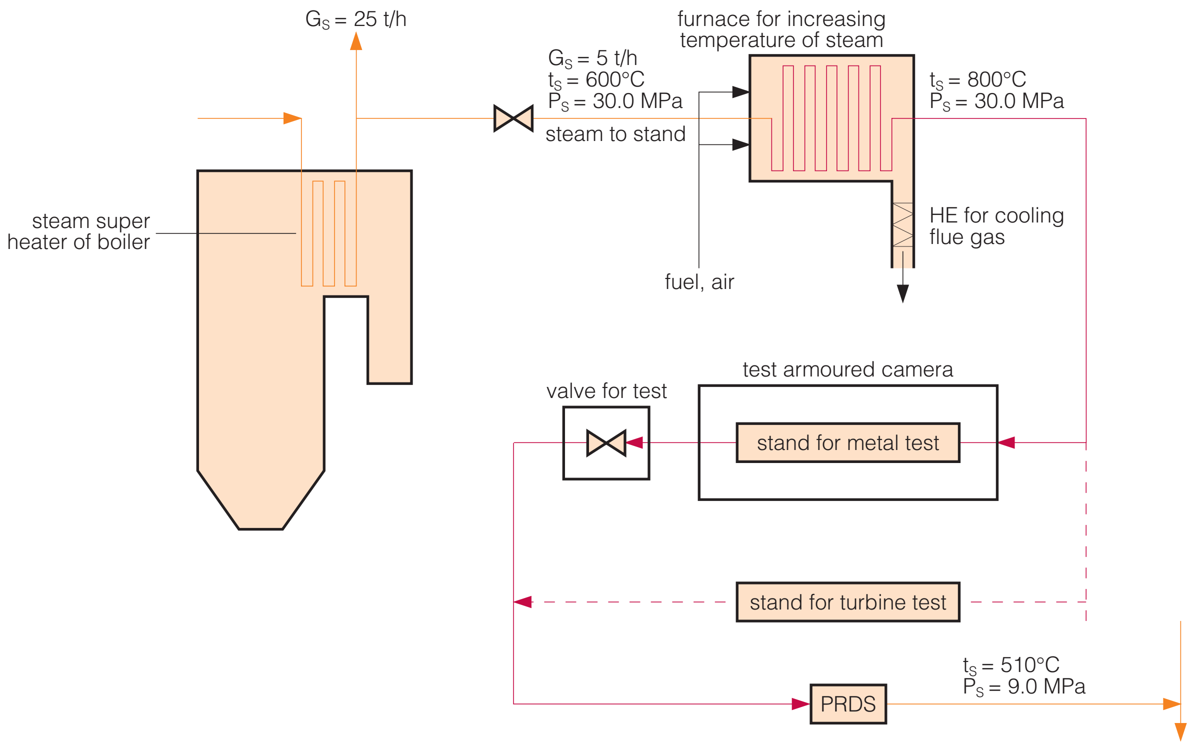

Figure 25 P&ID of the Russian CTF (Rogalev, 2012)

8 India

Coal is India's largest fossil energy reserve, at 293 Gt and an annual consumption in 2012 of 0.5%Gt – power from coal is expected to rise to 320 GW in 2031. The Indian government have a programme called the 'the AUSC project' under the ninth National Mission on Clean Coal Technologies in keeping with the National Action Plan for Climate Change.

The Indian Material Research Programme was initiated in 2008 and was estimated to cost at least RS6,000–10,000 CRORE. The programme is being funded and undertaken by a joint venture between the research institute Indira Gandhi Centre for Atomic Research (IGCAR), the equipment manufacturer Bharat Heavy Electrical (BHEL) and the power generating company National Thermal Power Corporation (NTPC). IGCAR will develop the materials, Misra Dhatu Nigam and BHEL will design, manufacture, and commission the equipment and NTPC will construct the test loop and demonstration unit.

IGCAR will design and develop new '70% nickel alloys' capable of 710°C and 35 MPa superheater steam parameters, raising net efficiency from 38–40% to 46% (LHV) and reducing carbon dioxide emissions by 15–20%. IGCAR have experience with new nickel alloys through its prototype 'fast breeder' nuclear reactor project. Materials include Super 304H, Inconel 617, Haynes 230, T92 and T91.

BHEL will manufacture and commission the demonstration unit and NTPC will operate it. Components for USC plant in India are often purchased from other countries – indigenous commercialisation of AUSC technology has a large potential market. In 2013, BHEL submitted the project design memorandum for an 800 MW AUSC boiler, including technical and economic details, to the office of the Principal Scientific Adviser of the Government of India. The Welding Research Institute (WRI) at BHEL are studying new welding techniques such as GTAW. The Hyderabad-based public sector Misra Dhatu Nigam will help fabricate the new nickel alloys.

New high temperature components will be tested in a component test facility (CTF) at the NTPC 210 MW unit in Dadri PCC plant in Uttar Pradesh. Providing successful completion of a CTF, operation of a demonstration unit is planned to start in 2018 and is likely to be based at the NTPC Dadri complex (The Hindu, 2013a,b; The Hindu Business Line 2013; The Economic Times, 2010).

9 Conclusions

The AUSC material research consists of three main stages, which can overlap each other by a few years depending on technical readiness and funding availability:

- **Stage 1**: Small-scale laboratory tests (8–13 years);
- **Stage 2**: Large-scale components test facility. Part A: Design and build (4–5 years). Part B: Operate and evaluate (3–5 years);
- **Stage 3**: Full-scale demonstration plant. Part A: Design and build (4–6 years). Part B: Operate and evaluate (6 years).

The process starts with small-scale laboratory tests to characterise and screen materials. This includes mechanical tests, such as tensile, hardness, toughness, creep and fatigue. Long-term creep tests take 100,000 hours or 11½ years. Chemical tests include resistance to steamside oxidation (found in most components in the steam cycle) and fireside corrosion (to which most boiler materials are exposed). Once sufficient information has been gained from laboratory tests, candidate materials are manufactured into large-scale components, demonstrating fabrication and welding techniques. Large-scale components are then tested in a components test facility, using a slipstream from an operational power plant. After three to four years of operation, the facility is dismantled and the components are thoroughly investigated. Provided the large-scale components operate successfully and without signs of failure, these materials, component design and manufacturing methods can be used to build a full-scale demonstration plant (FSDP). This demonstration plant will be operated for roughly five years to verify performance. After which the high temperature components will be removed and evaluated to qualify the materials. Provided all goes well, AUSC technology will have proved technically viable. This process of gradually scaling-up materials is designed to minimise technical, and therefore financial, risk.

Figure 26 compares the progress of each material research programme. The timeline shows that programmes in the USA, China, Japan and India have largely completed stage 1 (except for long-term

Figure 26 Comparison of research programme timelines

Table 7 Comparison of full-scale demonstration plant details

	EU	USA	Japan	China
Steam loops	Yes	Yes	Yes	Yes
Component test facility				
Full-scale demonstration plant capacity, MWe	500	350–-1000	600	600–660
Full-scale demonstration plant steam parameters, °C/°C/MPa	705/720/35	700/730/35	700	700/720/35
Estimated full-scale capacity, MWe	500–1000	550-1100	600	600
Estimated full-scale steam parameters, °C/°C/MPa	705/720/35	700–730/ 730–760/35	700/720/720/ 35	700/720/35
Estimated full-scale efficiency, %, net, hard coal	>50 (LHV)	45–47 (HHV)	46–50 (LHV)	>50 (LHV)

creep tests) and are progressing towards stage 2. The European programme is still at stage 2 after encountering technical difficulties. By 2018, results from stages 1 and 2 will provide enough technical data to decide further progression of the technology to stage 3. FSDP are planned to begin operation in 2021, operation will last for five years in order to qualify the materials and verify the technology performance. Table 7 compares the steam parameters and capacity the FDSP and possible commercial plant for each programme. Providing the FSDP operates successfully, the commercial plant will be of similar size, as scaling the technology up is risky. The electrical efficiency of a commercial unit will depend largely on its location and whether it has single or double number of – it could reach 52%.

Each major research programme is assessing a slightly different set of candidate materials. This is largely due to different requirements for the boiler materials as the fireside corrosion mechanisms vary according to the type of coal fired and whether biomass and waste are cofired. The candidate materials for all programmes are similar. Low cost and proven ferritic steels (such as grade 23) are employed in components exposed to steam temperatures below 550°C (such as the membrane walls and part of the steam turbine rotors and casing). Proven state-of-the-art 9–12% chromium martensitic steels (such as grade 92) are used in components exposed to steam temperatures of 550–625°C (such as superheaters, reheater and headers, valve, casing and pipes). Austenitic steels (such as HR3C and Sanicro 25) can be used for superheater and reheater applications only with steam up to 625°C; and may be suitable for up to 700°C. The new generation of mostly unqualified nickel alloys (such as nickel alloy 617, 625 and 740) is expected to be applied in thin and thick-section components at temperatures above 630°C. To maintain economic favourability, most research programmes are improving steels to fill in the temperature gap between 625°C and 650°C. New nickel and nickel/iron alloys have been developed in Asia specifically for AUSC technology. Coatings are being assessed in most programmes but with no tangible benefits to date. Japan is proposing to retrofit AUSC technology to older plant. The cyclic capability of AUSC technology is being assessed as it is important in the USA and EU. Table 8 summarises the research topics in each programme.

High temperature material research programmes have produced valuable research spin-off technologies for existing PCC plant. For example, alternative plant configurations for coal-fired power plant to reduce capital expenditure and improve steam cycles which can be retrofitted and raise electrical efficiency. Improved steels will be used in more flexible and slightly higher temperature ultra-supercritical technology.

Collaboration between the material research programmes could hasten research progress through knowledge sharing and increased finances. For example, a common material database containing information on mechanical tests, such as long-term creep tests, and resistance against chemical attack will facilitate all research programmes. In 2012, the National Energy Administration (NEA) in China

Table 8 Comparison of research topics

Research topic	EU	USA	Japan	China
Retrofit to older units	No	No	Yes	No
Cyclic operation	Yes	Yes	No	No
Oxyfuel	Yes	No	No	No
High sulphur coal firing on fireside corrosion	No	Yes	No	No
Biomass cofiring on fireside corrosion	Yes	No	Yes	No
Waste cofiring on fireside corrosion	Yes	No	No	No
Coatings	Yes	Yes	Yes	No
New 650°C steels	Yes, MARBN	Yes	Yes, MARBN	Yes, G115/G112
New nickel/iron alloys	No	No	Yes, FENIX700	Yes, GH2984
New nickel alloys	No	No	Yes, USC141 and USC800MOD	No
Welded rotors	Yes	Yes	Yes	Yes
Alternative plant configuration	Yes, Compact Design, Inline Arrangement	No	No	Yes, CCHLPA
Improved steam cycle	Master Cycle	Topping Cycle	No	No

was actively seeking international collaboration on key materials and programme the in Russia is open for collaboration. One of the purposes of this report is help initiate collaboration.

Global research is proving that nickel alloys can operate at advanced ultra-supercritical (AUSC) parameters in pulverised coal combustion (PCC) plant. PPC plant operating at AUSC steam parameters are estimated to reach electrical efficiencies of 50% (net, LHV, hard coal). A higher efficiency not only reduces coal consumption and emissions for a given amount of coal but also lowers the cost of potential CCS (carbon capture and storage) technology.

Increasing the superheater steam temperature will continue to provide gains in electrical efficiency. However this trend will diminish at 900°C (as this is where the Carnotisation gap almost closes) reaching electrical efficiencies of over 60%. Therefore, AUSC technology would be the first of many generations of higher steam parameters that utilise super alloys.

A commercial unit could be brought online in 2031, providing the material research programmes proceeds as planned, and the time frame for a new build PCC plant is four years. However, the commercialisation of AUSC technology will then rest entirely on the economics, which depend on variable factors, such as the future value of coal, cost of nickel alloys and the carbon tax.

10 References

Allen D, Du H, Vanstone R, Moody P, Barnard P, Roberts S, Maclachlan R and Thomson R (2013) The 'IMPACT' project – development of 'MARBN' steel for next generation steam plant. Paper presented at: *Second workshop on upgrading and efficiency improvements in coal-fired power plant*, Nottingham, UK, 19-20 Mar 2013; 25 pp (2013)
Breeze P (2012) Pushing the steam cycle boundaries. *Power Engineering International*; 20 (4); 17-20 (Apr 2012)
Cieszynski K, Kaczorowski M (2012) Boiler design at ultra supercritical steam parameters (653ºC/672ºC – 303/60 bar). Paper presented at: Advanced ultrasupercritical coal-fired power plants, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 12 pp (2012
COMTES700 (2013) *COMTES700 website* www.comtes700.org/index.xhtml; (accessed Apr 2013)
COORETEC (2013) *COORETEC website* www.cooretec.de; (accessed Apr 2013)
CRESTA (2013) *New creep resistant stable steel for USC power plant website.* Available at www.cresta.cc; (accessed Aug 2013)
Feng W, Yu X (2012) Challenging the efficiency limitation of the existing coal-fired power technology. Paper presented at: *Upgrading and efficiency improvements in coal-fired power plants*, Melbourne, Vic, Australia, 19-20 Apr, 2012. Available from: http://upgrading.coalconferences.org/ibis/Upgrading-workshop/my-event; 14 pp (2012)
Fukuda M (2012a) Advanced USC technology development in Japan. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 15 pp (2012)
Fukuda Y (2012b) High temperature corrosion and steam oxidation of candidate materials for 700C class A-USC. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 15 pp (2012)
Gazzino M (2012) ENCIO project: overview, status up-date and planned fireside corrosion tests. Paper presented at: Advanced ultrasupercritical coal-fired power plants, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 16 pp (2012)
Gibbons TB (2013) Recent advances in steels for coal fired power plant: a review. *Transactions of the Indian Institute of Metals*; in press 1-10 (2013)
Gierschner G, Ullrich C, Tschaffon H (2012) Latest developments for the flexible high efficient power plant of the future. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 21 pp (2012)
Grab T, Stahl F (2012) Welding of heavy wall pipes made from high temperature alloys, special requirements and welding procedures**.** Paper presented at: *1st International VDI conference on alloys in power plant technology*, Berlin, Germany, 15-16 Jun 2012; 12 pp (2012)
Hagen I, Bendick W (2013) Creep resistant ferritic steel for power plants from Mannesmann Forschungsinstitut GmbH. Available at: www.cbmm.com.br/portug/sources/techlib/science_techno/table_content/sub_4/images/ pdfs/040.pdf; 24 pp, (accessed Aug 2013)
Henderson C (2013) IEA Clean Coal Centre, London, UK, *private communication* (Sep 2013)
Henderson C (2004) *Understanding coal-fired power plant cycles*. CCC/91, London, UK, IEA Clean Coal Centre, 47 pp (Oct 2004)
Hernblom J (2012) Properties of advanced high strength austenitic alloy Sanicro 25 developed for A-USC plants. Presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 20 pp (2012)
Holcomb G R (2013) Ultra-supercritical steam corrosion. Available at: www.netl.doe.gov/publications/proceedings/03/materials/manuscripts/Holcomb_m2.pdf; 6 pp, (accessed Aug 2013)

Holmström S, Auerkari P (2012) Material and component requirements in existing and new plants. Paper presented at: *1st International VDI conference on alloys in power plant technology*, Berlin, Germany, 15-16 Jun 2012; 15 pp (2012)
IEA (2012) *IEA high efficiency, low emissions (HELE) coal roadmap.* IEA, Paris, France; 42 pp (2012)
IEA Clean Coal Centre (2012) *Coal power database*. London, UK, IEA Clean Coal Centre (2012)
Imano S (2012) Development of Ni-base super alloys for A-USC power plant with temperature capability 800ºC. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 18 pp (2012)
Jedamzik M D (2012) 700C steam generator technology – HPE activities and scope of work in R&D projects. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 32 pp (2012)
Jiang J (2012) Component test facility project in China. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 21 pp (2012)
KMM-VIN (2013) *Newsletters*. Available at www.kmm-vin.eu/node/83 (accessed Aug 2013)
Kranzmann A, Olbricht J, Skrotzki B (2012) Concepts for complementary materials testing simulating the service conditions of high efficiency power plants. Paper presented at*: Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 18 pp (2012)
Kuhn B, Talik M, Li C, Zurek J, Quadakkers W J, Beck T, Singheiser L (2012) Development of creep- and corrosion-resistant steels for future steam power plants. Paper presented at: *1st International VDI conference on alloys in power plant technology*, Berlin, Germany, 15-16 Jun 2012; 10 pp (2012)
Liu Z (2012) The research and development of heat resistant steels and alloys used for 700C A-USC-PP in China. Paper presented at: Advanced ultrasupercritical coal-fired power plants, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 7 pp (2012)
MACPLUS (2013) MACPLUS project website www.macplusproject.eu/home (accessed Aug 2013)
Maile K (2012) High temperature materials for advanced fossil fired plants**.** Paper presented at: *1st International VDI conference on alloys in power plant technology*, Berlin, Germany, 15-16 Jun 2012; 12 pp (2012)
Maile K, Metzger K (2012) GKM test rig – HWT I, HWT II**:** Qualification of materials for 700°C power plant**.** Paper presented at: *1st International VDI conference on alloys in power plant technology*, Berlin, Germany, 15-16 Jun 2012; 12 pp (2012)
Mao J, Feng W (2012) Ways to further improve efficiency for ultra-supercritical coal-fired power plants in China. Paper presented at: *Advanced ultrasupercritical coal-fired power plants,* Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 9 pp (2012)
Marion J L (2012) Advance ultrasupercritical steam power plant. Paper presented at: *Advanced ultrasupercritical coal-fired power plants,* Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 28 pp (2012)
Mayer K H (2001) New ferritic steels for advanced power stations. In: *BALTICA V, 5th international conference on condition and life management for power plants*, Porvoo, Finland, 6-8 Jun 2001. VTT symposium 211, Espoo, Finland, VTT Information Service, vol 1, pp 11-33 (2001)
McCauley K (2012) Technical readiness for A-USC plant deployment – a B&W perspective. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 14 pp (2012)
McCoy S A, Holmes T, Baker B A, Gollihue R D, deBarbadillo J J, Maitra D B (2013) Characterisation of age-hardenable superalloy INCONEL alloy 740H for advanced ultra supercritical service Paper presented at: *Sixth international conference on clean coal technologies*, Thessaloniki, Greece, 12-16 May 2013; 30 pp (2013)

Modern Power Systems (2008) AD700 innovations pave the way for 53 per cent efficiency. *Modern Power Systems*; 28 (11); 15-20 (Nov 2008)
Mohrmann R, Stolzenberger C G (2012) Demands on materials and components for existing and new conventional power plants. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 17 pp (2012)
Moreea-Taha R (2002) *Materials development for coal, biomass and waste fuel plants*. CCC/61, London, UK, IEA Clean Coal Centre, 58 pp (Aug 2002)
Morrison G (2011) The energy balance as the 21st century unfolds and the role of coal. Presentation at: European power generation strategy summit, Prague, Czech Republic, 29 Nov 2011; 50 pp (2011)
Nalbandian H (2008) *Performance and risks of advanced pulverised coal plant*. CCC/135, London, UK, IEA Clean Coal Centre, 70 pp (May 2008)
National Coal Council (2007) Technologies to reduce or capture and store carbon dioxide emissions. Washington, DC, USA, The National Coal Council, 178 pp (Jun 2007)
NDT Resource Center (2013) www.ndt-ed.org/index_flash.htm (accessed Aug 2013)
Nippon Steel and Sumitomo Metal (2013) *Fossil fuel power material database*. Available at: www.tubular.nssmc.com/product-services/specialty-tube/tube-application/fossil-fuel-power (accessed Aug 2013)
Osgerby S (2007) *Mat UK energy materials review: R&D priorities for steam turbine based power generation, Version 1.2*. London, UK, Alstom Power, 11 pp (3 Aug 2007)
Phillips J (2011) US program for advanced ultrasupercritical (A-USC) coal fired power plants. Webinar from the McIlvaine Company. Available at: www.mcilvainecompany.com/Decision_Tree/subscriber/Tree/DescriptionTextLinks/Jeffrey%20Phillips%20-%20EPRI%20-%203-24-11.pdf (Mar 2013)
Phillips J (2012) The US Department of Energy project on advanced materials for boilers and steam turbines. Paper presented at: *Upgrading and efficiency improvements in coal-fired power plants*, Melbourne, Vic, Australia, 19-20 Apr, 2012. Available from: http://upgrading.coalconferences.org/ibis/Upgrading-workshop/my-event; 17 pp (2012)
Rogalev N D (2012) Foundation: energy without orders and its R&D program. Presentation at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 11 pp (2012)
Romanosky R (2012) A comprehensive overview of the United States advanced ultrasupercritical (USC) materials research program. Presentation at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, 19-20 Sep 2012. Available from: www.ausc.coalconferences.org/ibis/ausc.coalconferences/home; 18 pp (2012)
Saito E (2012) One of the concrete action plans which supply 700C class A-USC technology to a coal fired power market. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 21pp (2012)
Shingledecker J (2012) U.S. program on advanced ultrasupercritical power plant materials – the economy of using advanced alloys. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 18 pp (2012)
Sobczak N, Pirowski Z, Purgert R M, Uhl W, Jaskowiec K, Sobczak J (2012) Castability of HAYNES 282 alloy. Presentation at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 24 pp (2012)
Scott D H (2001) *Improving the competitiveness of next generation coal-fired plants*. CCC/52, London, UK, IEA Coal Research, 48 pp (Sep 2001)
Stam A (2012) NextGenPower. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: www.ausc.coalconferences.org/ibis/ausc.coalconferences/home; 29 pp (2012)
Starkey M (2013) Bromsgrove, UK, Metstar Consulting, *private communication* (Aug 2013)

Stein-Brzozowska G (2012) Fireside corrosion of dedicated austenitic steels in ultra-supercritical coal-fired power plant. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 25 pp (2012)
Stultz S C, Kitto J B (eds) (2005) Metallurgy, materials and mechanical properties. In: *Steam: its generation and use*. 41th edition. Barberton, CO, USA, Babcock and Wilcox Co, pp 7/1-7/25 (2005)
Subanovic M, Schneider A (2012) Creep-resistant steels for high temperature applications in conventional power plants. Paper presented at: *1st International VDI conference on alloys in power plant technology*, Berlin, Germany, 15-16 Jun 2012; 14 pp (2012)
Sun R, Cui Z, Tao Y (2012) Development of 700C USC coal-fired power generation technology in China. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 10 pp (2012)
Sven K (2001) The advanced super critical 700°C pulverized coal-fired power plant. Paper presented at: *VGB congress power plants 2001*, Brussels, Belgium, 10-12 Oct 2001; 9 pp (2001)
The Economic Times (2010) *IGCAR to develop advanced boiler for coal-fired power plants*. Available at: www.articles.economictimes.indiatimes.com/keyword/kalpakkam/recent/2; (7 Sep 2010)
The Hindu (2013b) *BHEL readies design for 800 MW plant with ultra supercritical parameters*. Available at: www.thehindu.com/todays-paper/tp-national/tp-tamilnadu/bhel-readies-design-for-800-mw-plant-with-ultra-supercritical-parameters/article4636067.ece; (20 Apr 2013)
The Hindu (2013a) *WRI carries out study for fabrication of ultra super critical boilers*. Available at: www.thehindu.com/news/cities/Tiruchirapalli/article3857944.ece; (4 Sep 2013)
The Hindu Business line (2013) *BHEL-NTPC-IGCAR effort to boost efficiency of power plants*. Available at: www.thehindubusinessline.com/companies/bhelntpcigcar-effort-to-boost-efficiency-of-power-plants/article4603180.ece; (10 Apr 2013)
VGB (2012a) *Electricity generation – facts and figures.* Available from www.vgb.org/en/data_powergeneration; 28 pp (Dec, 2012)
VGB (2012b) Pre-engineering study 'NRW Power Plant 700°C' NRWPP700. Berlin, Germany, VGB PowerTech e.V.; 112 pp (Jan 2012)
VGB (2013a) *KOMET 650*. Available from; www.vgb.org/en/komet650_download; 36 pp (Mar 2013)
VGB (2013b) Power plant technologies. Available from: www.vgb.org/en/research_fossil; Apr, 2013
Viswanathan V, Purgert R, Rawls P (2008b) Coal-fired power materials part II. *Advanced Materials & Processes*; 166 (9); 47-49 (Sep 2008)
Viswanathan V, Purgert R, Rawls P (2008a) Coal-fired power materials. *Advanced Materials & Processes*; 166 (8); 47-49 (Aug 2008)
Viswanathan R, Armor A F, Booras G (2004) A critical look at supercritical power plants. *Power*, New York; 148 (3); 42-49 (Apr 2004)
Wang C S, Wang T T, Zhao H Q, Guo J T, Zhou L Z (2012) Optimization of microstructure and mechanical properties of Ni-Fe-based super alloy GH984. Paper presented at: *Advanced ultrasupercritical coal-fired power plants*, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 19 pp (2012)
Wilde M (2012) European Union research activities and new approach on international cooperation. Paper presented at: Advanced ultrasupercritical coal-fired power plants, Vienna, Austria, 19-20 Sep 2012. Available from: http://ausc.coalconferences.org/ibis/ausc.coalconferences/home; 11pp (2012)
Zanin E (2013) Material-component performance-driven solutions for long-term efficiency increase in ultra supercritical power plants. Paper presented at: *Second workshop on upgrading and efficiency improvements in coal-fired power plant*, Nottingham, UK, 19-20 Mar 2013; 29 pp (2013)