Advanced USC Technology Development in Japan

Masafumi Fukuda

National Institute for Materials Science
High Temperature Materials Center
1-2-1 Sengen, Tsukuba, Ibaraki, 305-0047
Japan

Abstract

The 600 deg-C class Ultra Super-Critical (USC) steam condition technology was mainly developed through projects led by J-Power in the '80s and '90s. In 2001, the project was successfully finished with newly developed 9-12% chromium steels. These materials were selected for the major parts of the USC power plants in Japan and almost half of the coal power plants have the USC steam condition today.

On the other hand, aged plants, which were built in the '70s and early '80s, will need to be replaced or retrofitted in the near future. The steam temperatures of the aged plants are 538 deg-C or 566 deg-C. We did a case study of retrofitting these plants with the USC and an advanced USC (A-USC) technology that takes 700 deg-C class steam temperature to increase thermal efficiency and to reduce CO_2 emissions. The study showed that the A-USC is suitable for the retrofitting of aged plants and can reduce CO_2 emissions about 15%. The A-USC that aims 46% (net, HHV) thermal efficiency of coal power generation is included in the technologies.

We started a large-scale development of the A-USC technology in 2008 August. The target of the project is developing the 700 deg-C class material and component technology to achieve 46% (net, HHV) thermal efficiency of coal power generation. Boiler, turbine and valve technologies, which include high temperature material technology, will be developed. Some candidate materials for boilers are being tested. Turbine rotor and casing materials are being developed and tested, as well.

We are preparing for the component test in an actual boiler, and the turbine rotor test in 700 deg-C atmosphere, which will be conducted from 2014 to 2016. The boiler component test includes the testing of superheater panels, large diameter pipes, safety valves and a turbine bypass valve. Three candidate rotor materials will be tested at actual speed in a rotor test rig.

Keywords: power plant, steam condition, heat resistant alloy, creep failure, greenhouse gas

1. Introduction

Almost all primary energy resources used in Japan are imported from abroad. The 'Oil shock' in the '70s awakened us to the harsh facts before us. Since then, coal fired power plants have been steadily replacing oil fired power plants. Today, one-quarter of the electricity in Japan is produced by coal. Because of the relatively high cost of imported coal and the dense population in Japan, highly efficient and clean technology has been preferred historically to reduce fuel consumption and environmental stress. The improvement in the efficiency of the coal fired power plants has been mainly achieved by raising steam conditions as shown in Figure 1. The steam temperature was raised from 538deg-C to 566deg-C at the end of the 50's, and remained at this temperature until 1993. Steam power plants that have been built recently usually have a steam temperature of around 600deg-C and a steam pressure of 25MPa. We usually call such a steam condition USC (Ultra Super Critical steam condition).

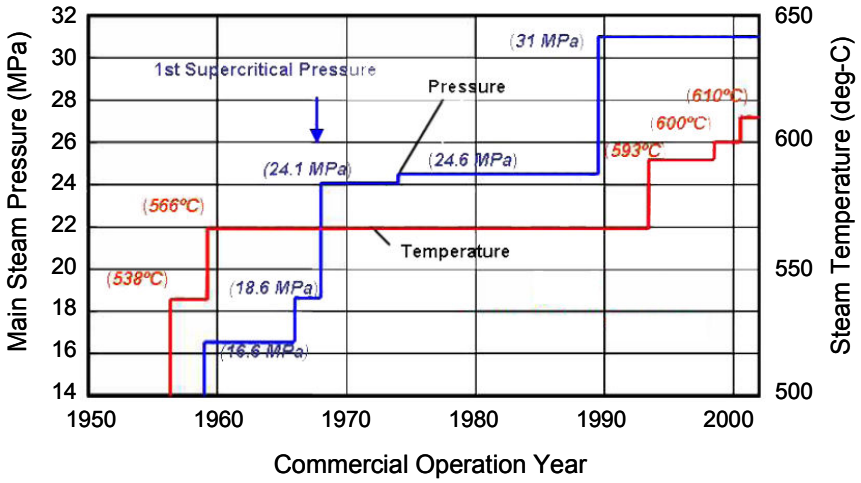

Figure 1 Trend of steam conditions in Japan

Figure 2 shows the history of the capacity of coal power plants. The capacity has risen to 35GW today and about half of the capacity is produced using USC technology. After the earth quake and tsunami in March 2011, the importance of coal power became higher.

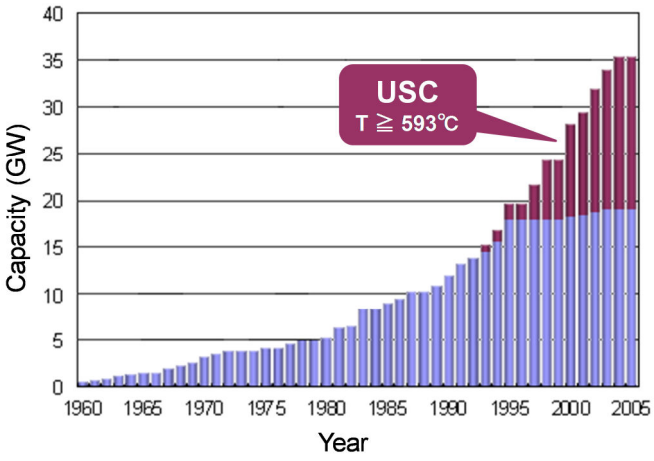

Figure 2 Capacity of coal power plant in Japan

Electric Power Development Company (J-Power) started a comprehensive development program of USC technology in 1981 to develop the USC technology, subsidized by the Japanese government. Materials to be used for 600 to 650deg-C systems were developed through the year 2000. The materials which contain 9 to 12 Cr steels and were developed at that time are being used for the USC plants in Japan today.

Figure 3 shows J-Power's Isogo power station which is located in the Tokyo metropolitan area [1]. Isogo #2, the newest power plant in Japan, was built in 2009. The temperatures of the main steam and reheat steam are 600 and 620deg-C.

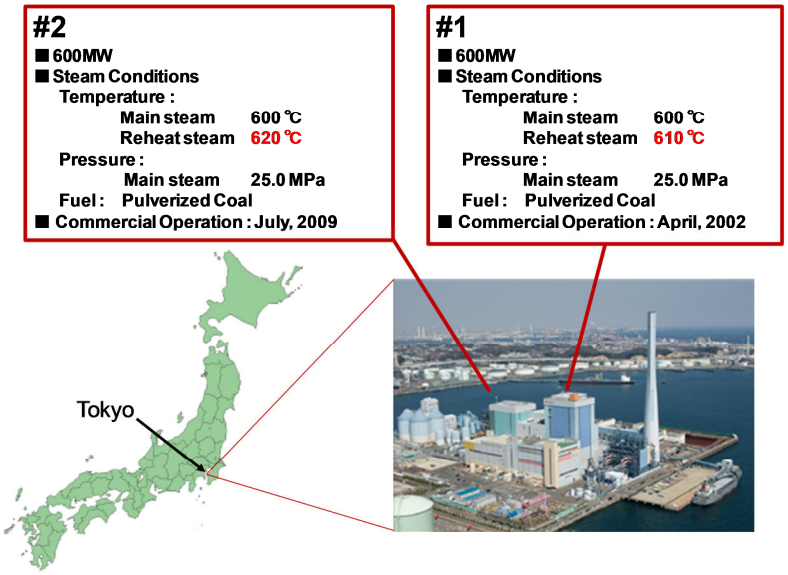

Figure 3 Isogo Power Station [2]

Following these programs, we studied the feasibility of a system which has a 700deg-C class steam temperature. Encouraged by the results of this study, we began the advanced USC technology (A-USC) development project in 2008, which features a 700deg-C steam temperature.

2. Concept of A-USC

The 700deg-C class A-USC technology will be developed based on today's latest 600deg-C class USC technology by raising the steam temperature 100deg-C (Figure 4). The target net thermal efficiency for the higher heating value base is 46 to 48%. This is more than 10% higher than that of the 600deg-C class USC. That means more than a 10% drop in CO_2 emissions.

In addition to the efficiency improvement, biomass co-firing and CCS (Carbon Capture and Storage) can be coupled to reduce CO_2 emissions further. If a CCS system is added on to a coal power plant, a considerable amount of energy is consumed and there is a large reduction

in the efficiency of the plant. It is necessary to use a high efficiency system such as A-USC for power generation to make CCS feasible.

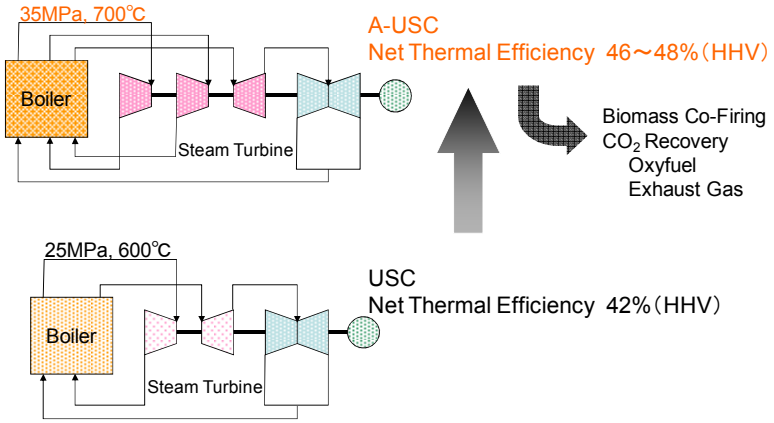

Figure 4 700deg-C class advanced USC (A-USC)

A-USC was selected as one of technologies which are expected to contribute to substantial reductions in CO_2 emissions through efficiency improvement by the Japanese government's 'Cool Earth-Innovative Energy Technology Program' in March 2008 [2]. The net thermal efficiencies which are targeted by the Cool Earth Program are shown in Figure 5[3]. In the near future, A-USC and IGCC both aim at 46 to 48% efficiency.

We think that the A-USC technology is more suitable for the retrofitting of old coal power plants because the basic system configuration of A-USC is similar to that of the old plants. It will be possible to reuse many parts of the old plants such as their environmental equipment and water system.

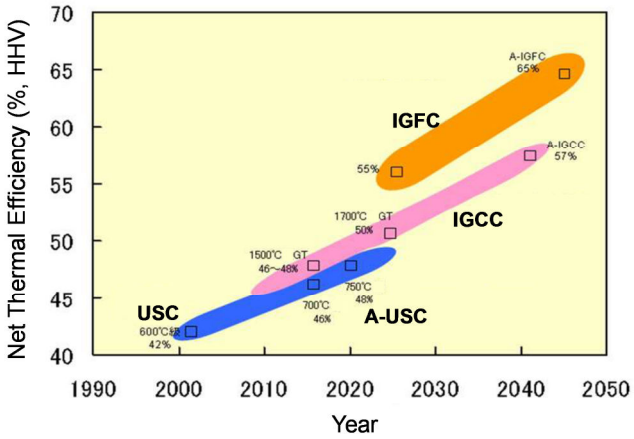

Figure 5 Net thermal efficiencies of coal power plants (HHV) [3]

A typical example of material selection for A-USC is shown in Figure 6. The blue color represents conventional materials; green means gas turbine materials, pink means materials under development. And solid dark pink means Ni-based alloys under development. Ni-based alloys, which have not been used for USC, were chosen for a part of the superheaters and

reheaters, the large steam pipes and the valves going from the boiler to the turbines, and a part of the turbine rotors and casings. The turbine rotors consist of Ni-based alloy and 12Cr steel, which are welded together. The turbine nozzles and blades for the high temperature stages use Ni-based materials that are being used for gas turbines.

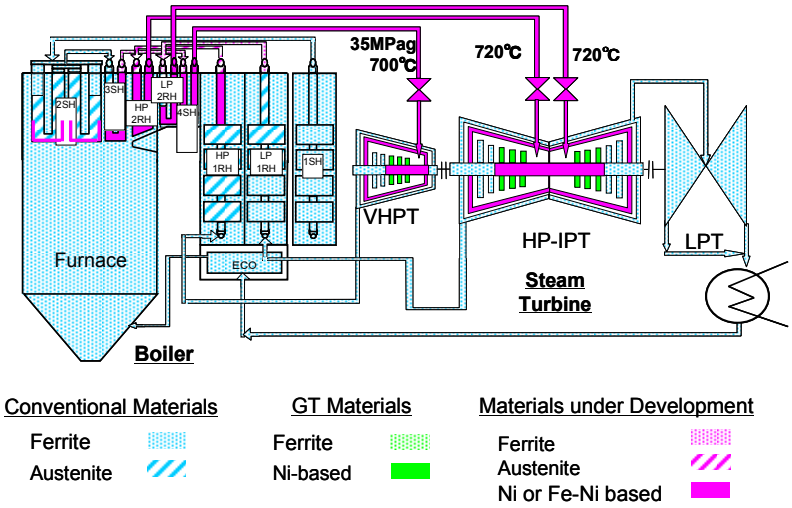

Figure 6 Selected materials for double reheat system

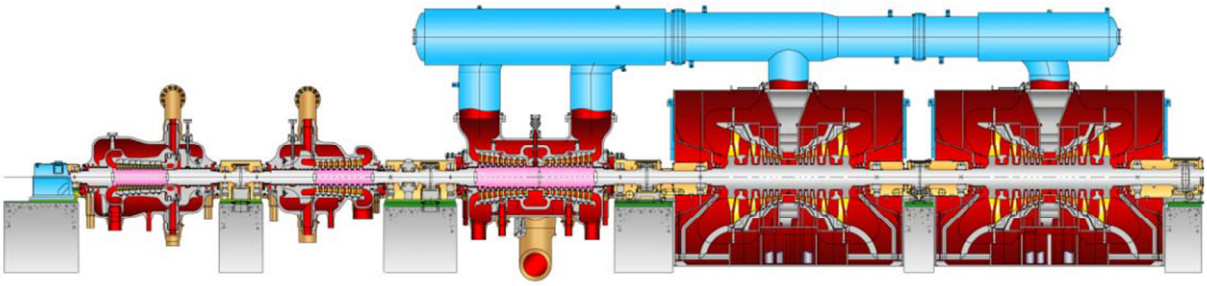

Figure 7 Concept of 1000MW class double reheat steam turbine (Courtesy of Toshiba)

The concept of 1000MW class steam turbine is shown in Figure 7. Five turbine casings and rotors are aligned in tandem. From the left, there is a very high pressure turbine (VHPT), a high pressure turbine (HPT), an intermediate pressure turbine (IPT) and two low pressure turbines (LPT). Part of the rotors of VHPT, HPT and IPT consist of a newly developed Ni based material.

3. A-USC technology development project

A long term A-USC technology development project began in 2008. In the first half of the project, boiler, turbine and valve materials are being developed and verified. In the second half, boiler components and small turbine tests will be done to verify the reliability of each component (Figure 8). Throughout the project, long term creep rupture tests will be done on each candidate material and welded joint.

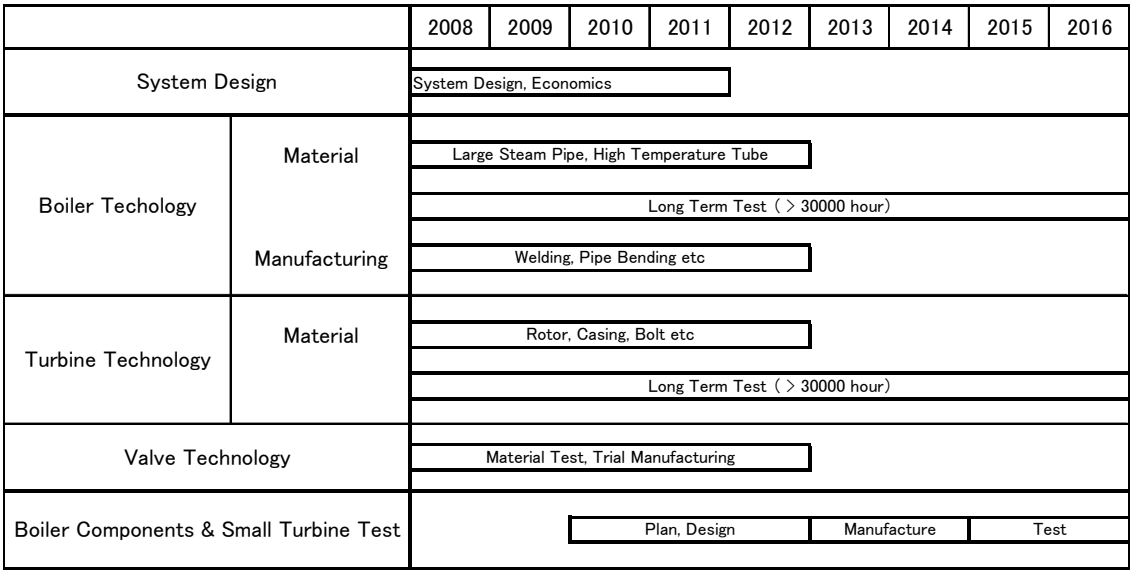

Figure 8 Master Schedule

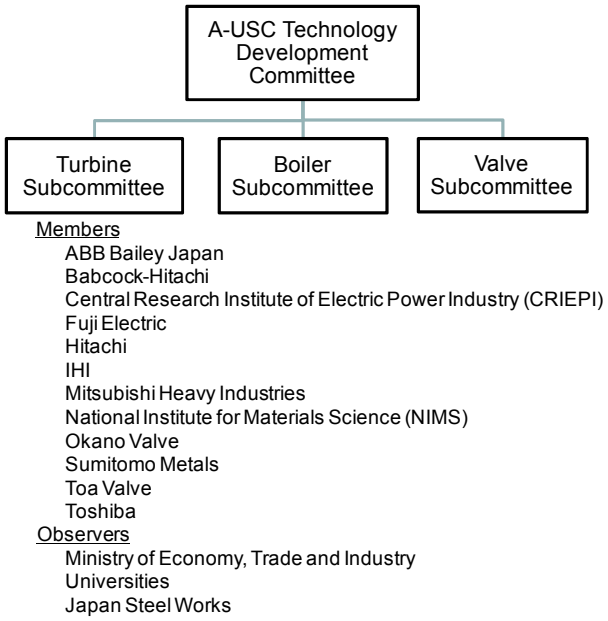

Figure 9 Project Structure

Twelve companies and institutes, ABB Bailey Japan, Babcock-Hitachi, Central Research Institute of Electric Power Industry (CRIEPI), Fuji, Hitachi, IHI, MHI, NIMS, Okano Valve, Sumitomo, Toa Valve, and Toshiba are participating in this project (Figure9). ABB Bailey Japan, CRIEPI, IHI, MHI, NIMS, and Sumitomo are working together on the boiler technology development. ABB Bailey Japan is developing the valve technology for turbine bypass valves. The boiler materials for testing are provided mainly by Sumitomo. Fuji is in charge of the valve technology for steam turbines. Hitachi, MHI and Toshiba are supporting Fuji's research. The steam turbine technology is being developed by Hitachi, MHI and

Toshiba. Okano Valve and Toa Valve are developing the technology for general-purpose valves and safety valves.

Once we decide to develop and use a new material, we need to thoroughly develop related technologies such as maintenance, fabrication, component, and system design technology (Figure 10). Long term reliability, high temperature corrosion resistance, steam oxidation resistance, and fatigue resistance are crucial characteristics for the material. Life assessment and welding technology for aged materials are necessary to repair used components. Welding, bending, and NDT technologies must be developed to fabricate components. Valves, desuperheaters, and headers are essential to build a boiler system. In addition to the hardware technologies, system design technologies, such as piping design, structural design, and thermal analysis are the key to the successful construction and operation of the boiler system. The companies participating in the project are working together to develop each technology.

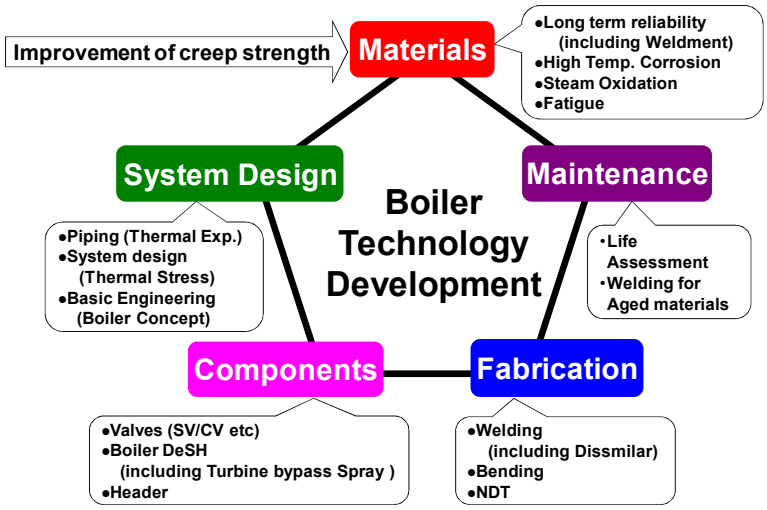

Figure 10 Boiler development tasks

Figure 11 shows the candidate materials for boilers which were prepared by Sumitomo. *HR6W* is a Ni-Fe based alloy and *HR35*, Alloy 617, Alloy263, Alloy740, and Alloy141 are Ni based alloys for use at temperatures higher than 650deg-C. High boron 9Cr steel, low carbon 9Cr steel and *SAVE 12AD* are ferritic steels for use at temperatures lower than 650deg-C. These materials are being tested to verify the characteristics regarding creep rupture, fatigue, oxidation and corrosion. Welding and bending tests have been conducted to check the manufacturability of the materials.

A 100,000hr creep rupture strength higher than 90MPa at 750deg-C is the target for super heater tube materials. *HR35*, Alloy617, Alloy263, Alloy740, Alloy141 are the candidates for these. A 100,000hr creep rupture strength higher than 90MPa at 700deg-C is the target for large steam pipe materials. *HR6W*, *HR35*, Alloy617 are the candidates because they have favorable characteristics for making large pipes. The advanced 9Cr steels, B-9Cr, LC-9Cr, and *SAVE12AD* are targeting 80MPa at 650deg-C. If these targets are successfully achieved,

we will have a material list to build the system shown on Figure 8. In addition, as Figure 12 shows, we can select other system configurations to satisfy various customer needs.

Figure 11 Boiler Candidate Materials (Courtesy of Sumitomo Metal Industries)

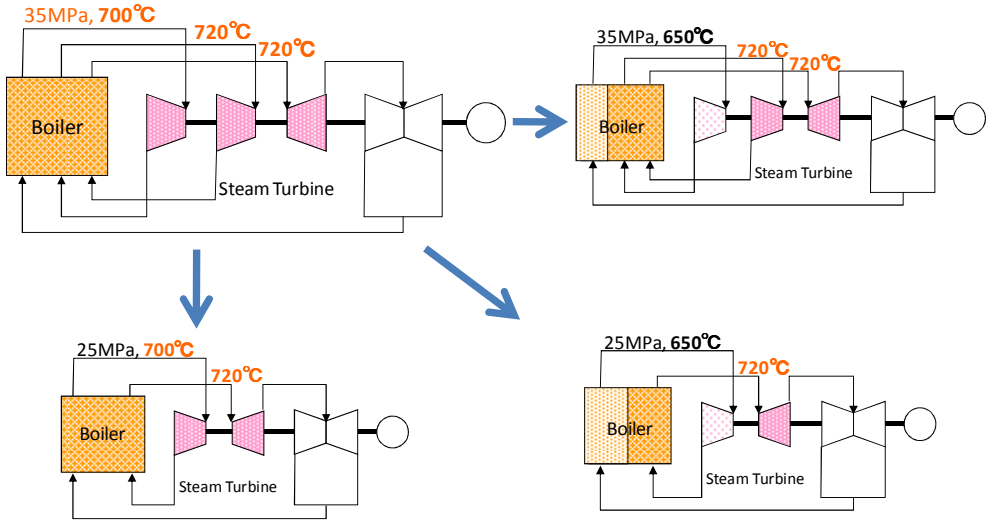

Figure 12 Variety of system configurations

Figure 13 shows an example of creep rupture strength which was derived from *HR6W* creep rupture tests. *HR6W* is being developed by Sumitomo Metals for pipes and tubes in the A-USC system, and designed to have good corrosion resistance to combustion gas in the boiler and good creep strength for pressurized pipes and tubes at 700deg-C. 100,000hr creep rupture stress at 700deg-C is expected to be about 90MPa which is the target for large steam pipe materials

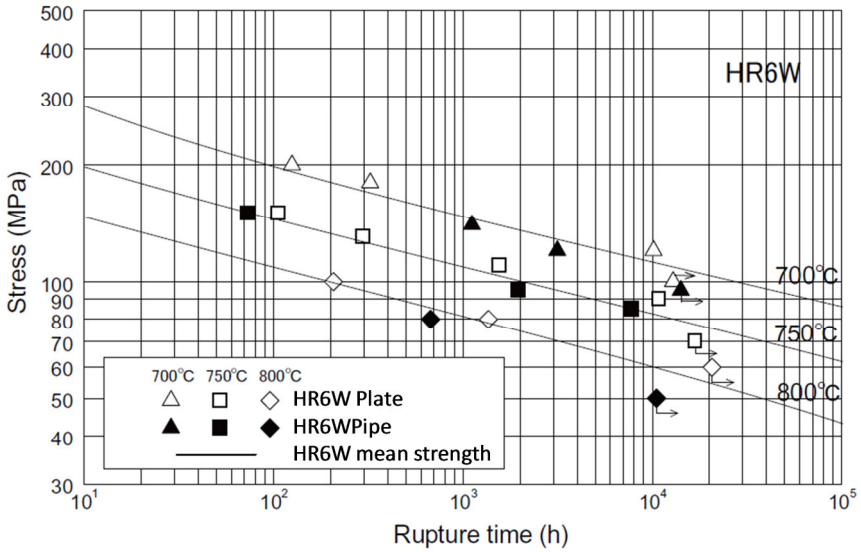

Figure 13 HR6W creep rupture strength (Courtesy of Sumitomo Metal Industries)

The creep rupture strength of *HR6W* weld joint is shown in Figure 14. Creep tensile specimens which contain welded portions were cut out from welded *HR6W* plates. Weld material was Alloy617. When tested, all specimens broke at base material. We can see that the strength of the welded material is equivalent to or higher than that of *HR6W* without a weld joint.

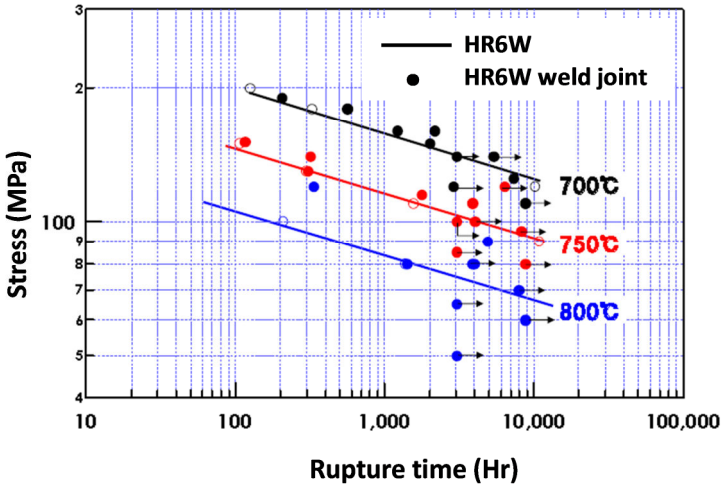

Figure 14 Creep rupture strength of HR6W weld
(Courtesy of Babcock-Hitachi, IHI, Mitsubishi Heavy Industries)

We have made pipes of *HR6W*, *HR35* and Alloy617 using the Ehrhardt push bench method (Figure 15). These pipes were prepared in order to conduct material tests, such as welding, bending and the long term creep test.

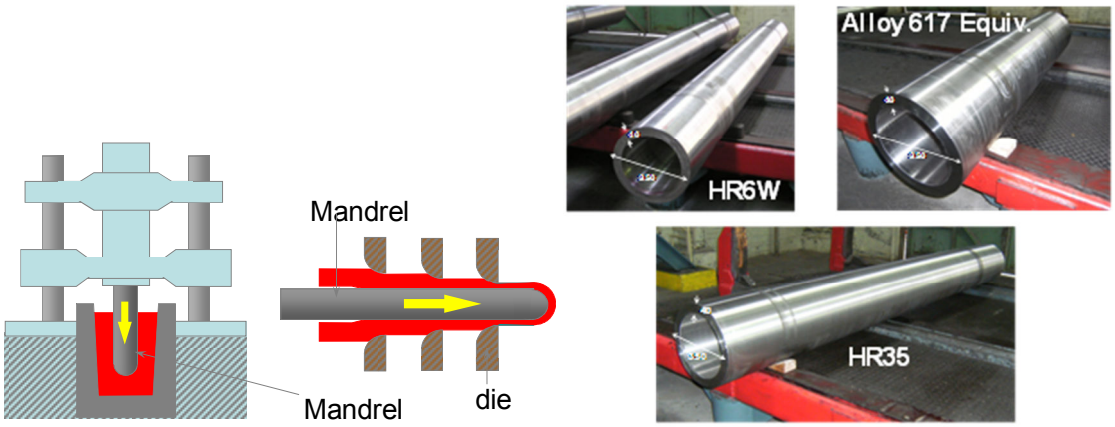

Figure 15 Pipes prepared for material test (Courtesy of Sumitomo Metal Industries)

Figure 16 shows bended pipes which are made of Alloy617 and *HR6W*. These pipes were cut into pieces to check the shape of the cross section and to make test specimens. Pipe welding tests are being carried out now. A sample of welded pipes is shown on Figure 17.

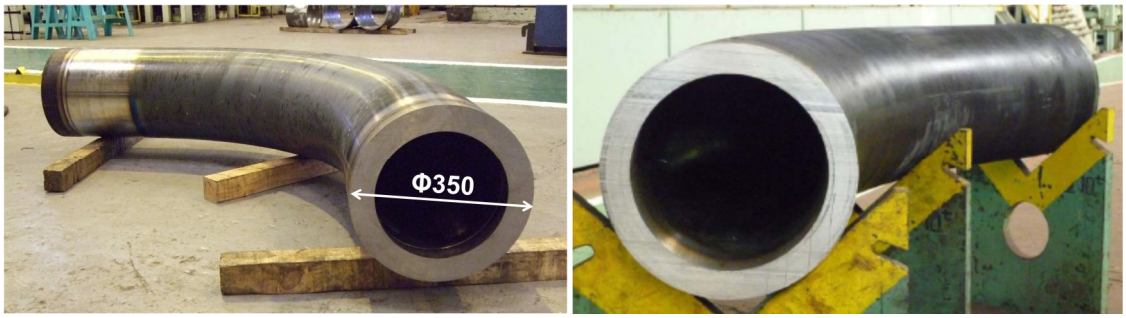

Figure 16 Pipe trial bending (Courtesy of Babcock-Hitachi and Mitsubishi Heavy Industries)

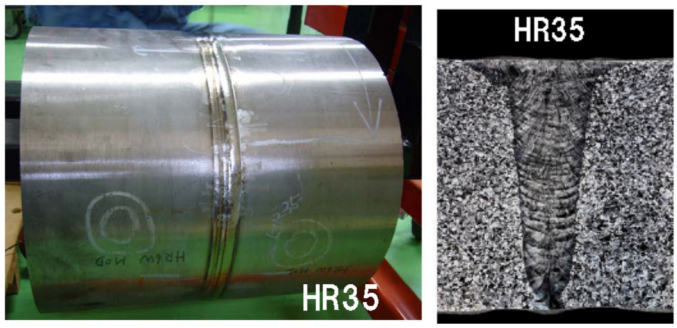

Figure 17 Pipe welding test (Courtesy of IHI)

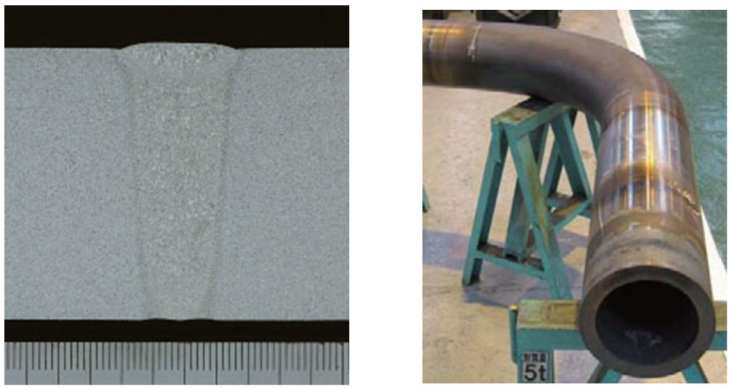

Figure 18 SAVE12AD pipe welding and trial bending (Courtesy of Babcock-Hitachi)

Some advanced 9Cr steels are also tested. Figure 18 shows the cross section of welded *SAVE12AD* pipe and a bended pipe. In the HAZ section of welds, we didn't find any small grain structure.

There are three candidate materials for steam turbine rotors (Figure 19). Ni based alloys, *FENIX-700*, *LTES* and *TOS1X*, are being developed and tested for use at temperatures higher than 700deg-C. The aim of the development of *FENIX-700* is to build a rotor heavier than 10 tons without segregation in the material. The purpose of *LTES* and *TOS1X* is to target a weight of around 10 tons which will be welded to steel parts to make a 30 to 40-ton rotor.

Materials	Temper-ature Level	Weight	Development Target
FENIX-700	700℃	>10ton	Ni-base material heavier than 10 tons without segregation
LTES700R	>700℃	30～40ton ↑ Ni:10ton + Steel:20~30ton Welding	10 ton Ni-base material with good weldability to steel
TOS1X	>720℃		10 ton Ni-base material with good weldability to steel

Figure 19 Steam turbine rotor materials

FENIX-700 which has superior long-term stability at 700deg-C was developed from Alloy706 by reducing Nb content and increasing Ti and Al content [4]. The 100,000 hour creep rupture strength at 700deg-C is expected to be higher than 100MPa.

LTES700R is a Ni-based alloy that has been developed by MHI. This alloy was developed to have a thermal expansion coefficient similar to 12Cr steel, so it conforms well to conventional steels (Figure 20). In addition, the creep rupture strength of *LTES700R* is higher than the target for 700 deg-C class rotor material (Fig21). Originally, *LTES700* was developed for

small parts, such as casing bolts. *LTES700R* was developed from *LTES700* for large steam turbine rotors. Fig. 22 shows a large *LTES700* material which will be forged soon. Welding technology is crucial for this material. Welding tests including the welding of dissimilar materials are being carried out. Figure 23 shows a similar and a dissimilar welding of *LTES700R*.

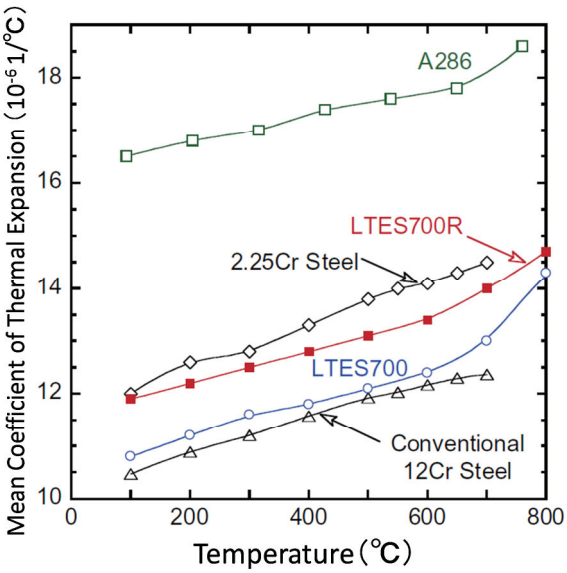

Figure 20 Coefficient of thermal expansion of LTES700R
(Courtesy of Mitsubishi Heavy Industries)

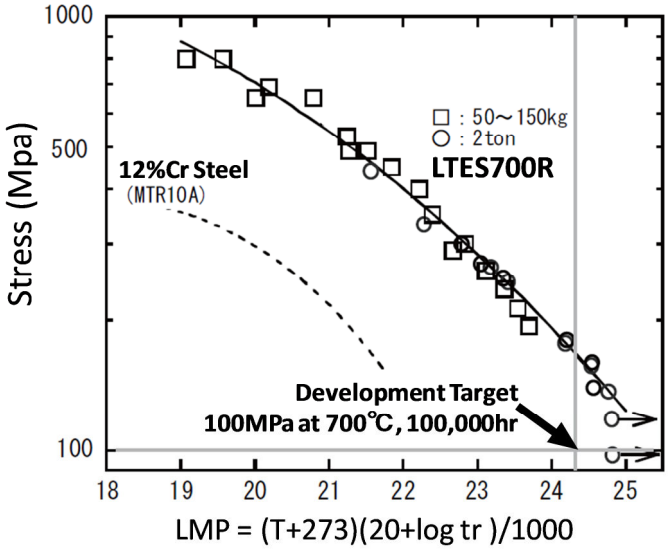

Figure 21 Creep rupture strength of LTES700R
(Courtesy of Mitsubishi Heavy Industries)

Figure 22 Large LTES700R material before forging
(Courtesy of Mitsubishi Heavy Industries)

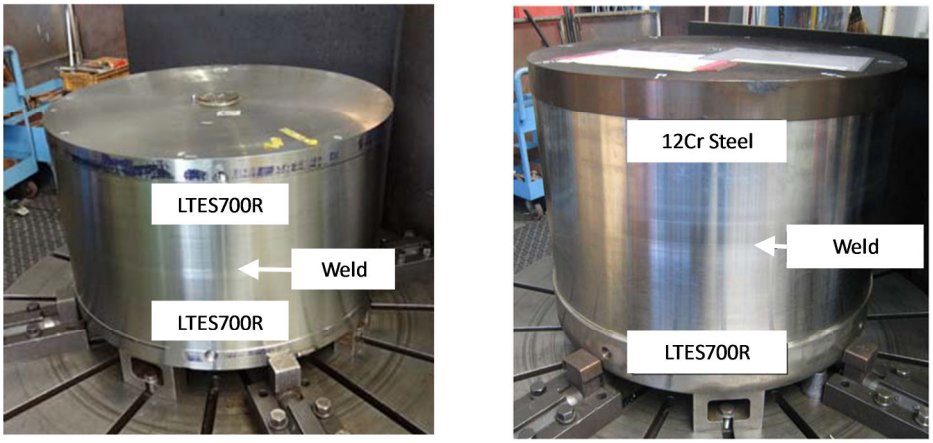

Figure 23 Welding test of LTES700R
(Courtesy of Mitsubishi Heavy Industries)

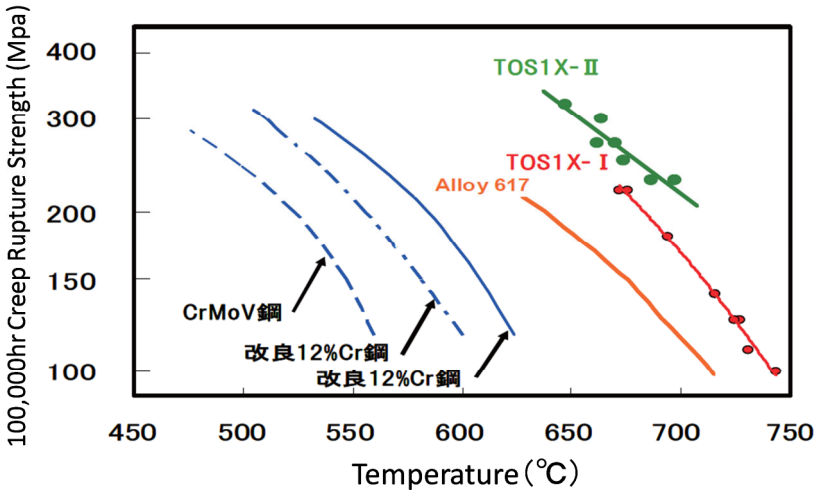

Figure 24 TOS1X creep rupture strength (Courtesy of Toshiba)

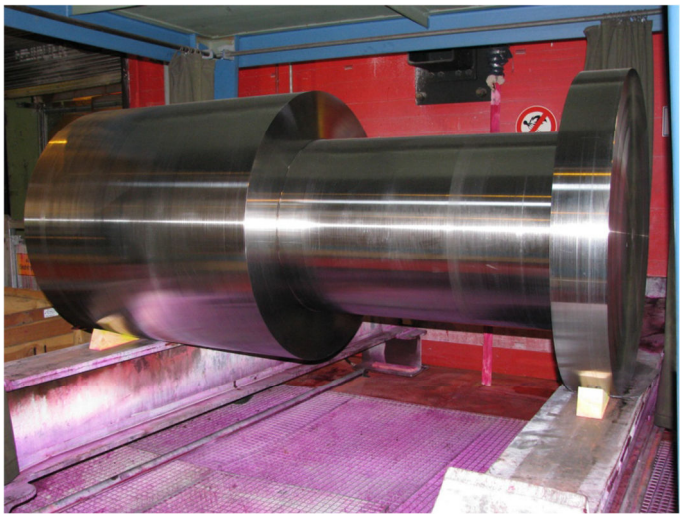

Figure 25 TOS1X rotor material (Courtesy of Toshiba)

TOS1X was developed from Alloy617. The earlier version of *TOS1X*, which is now called *TOS1X-I*, is expected to have around 150MPa of 100,000 hour creep rupture strength at 700deg-C (Figure 24). A piece of forged material, 1000 mm in diameter and weighing 7tons, has been made successfully using *TOS1X-I*. *TOS1X-II* was developed from *TOS1X-I* by increasing the Al and Ti content. *TOS1X-II* is expected to have around 200MPa of 100,000 hour creep rupture strength at 700deg-C. A 14 tons forged material of *TOS1X-II* has been made successfully (Figure 25).

Figure 26 shows materials casted for testing. Three alloys, which are Alloy740, Alloy 625, and Alloy 617, were casted. The thickness of the casting varies like steps. The maximum thickness resembles the thickness of the flanges of steam turbine casings. We cut them into pieces to make specimens for material tests, such as the tensile test, creep test, macro and micro observation and so on. We will choose one of these materials to cast an actual sized casing of a steam turbine valve.

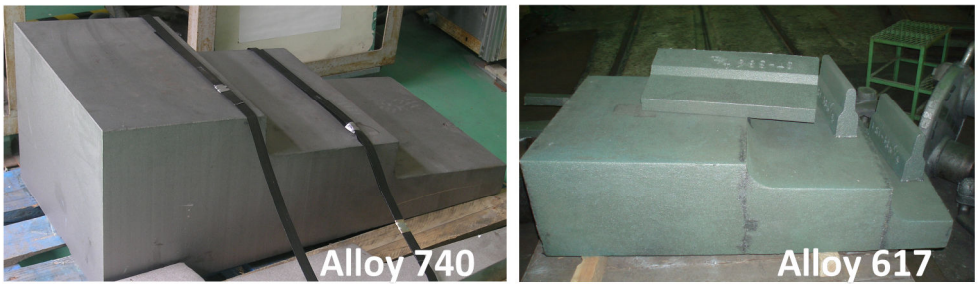

Figure 26 Casted materials (Courtesy of Toshiba and Mitsubishi Heavy Industries)

Today, we are preparing for the boiler component test and the turbine rotor test as shown on Fig. 27. In 2015 and 2016 boiler components such as super heaters, pipes, and valves will be

tested in an actual boiler. Three rotors made of the three candidate rotor materials will be tested in 700 deg-C atmosphere and at actual speed from 2014 to 2016.

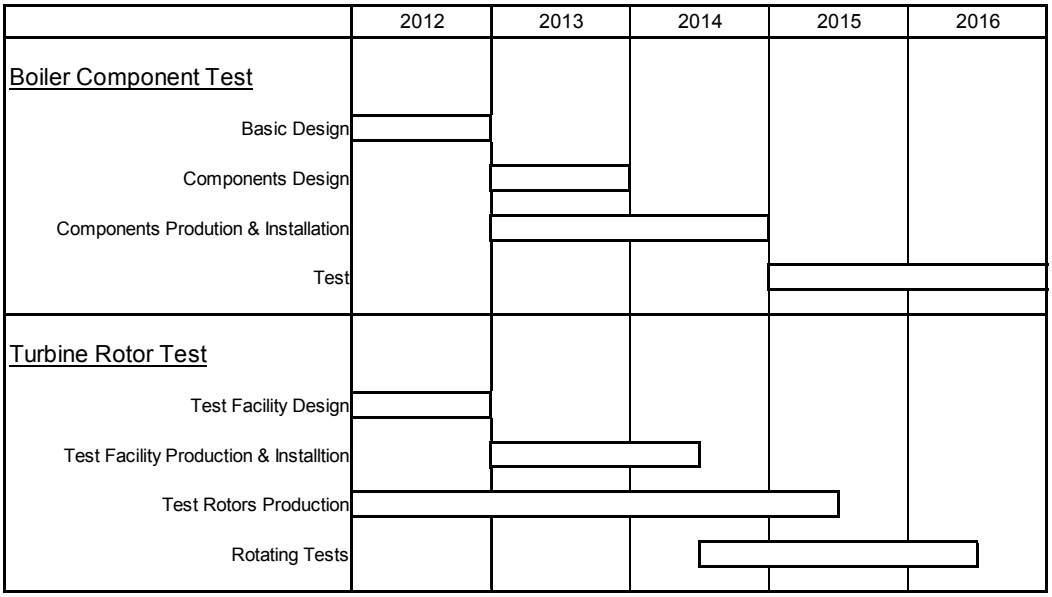

Fig. 27 Schedule for boiler component test and turbine rotor test

4. Conclusion

The development of the USC technology began in Japan in the '80's, aiming at a cleaner and more economical use of coal. Today, almost half of the coal power plants have a 600deg-C class USC steam condition.
A-USC is one of the remarkable technologies being developed to reduce CO_2 emissions from fossil fuel power plants and one which was chosen by Japan's 'Cool Earth-Innovative Energy Technology Program' which was launched in 2008 to contribute to substantial CO_2 emissions reductions.
A large scale 9-year project began in 2008 to develop A-USC technology thoroughly. Major Japanese manufacturers of boilers and steam turbines and some institutes are cooperating in the project to develop the technology efficiently and quickly.
Almost four years from the beginning of the project, we have made some boiler materials and begun some fundamental tests, such as tensile, creep, welding, bending etc. Turbine rotor and casing materials have been forged and casted and are being tested as well.
Today, we are preparing for the boiler component test and turbine rotor test. In 2015 and 2016 boiler components such as superheaters, pipes, and valves will be tested in an actual boiler. Three rotors made of the three candidate rotor materials will be tested in 700 deg-C atmosphere and at actual speed from 2014 to 2016.

References

[1] J-Power, Commencement of Commercial Operation of New No. 2 Unit at Isogo Thermal Power Station, available at http://www.jpower.co.jp/news_release/news090716.html.
[2] Ministry of Economy, Trade and Industry, "Cool Earth-Innovative Energy Technology Program", available at
http://www.meti.go.jp/english/newtopics/data/pdf/CoolEarth_E_revised.pdf.
[3] Ministry of Economy, Trade and Industry, available at
http://www.meti.go.jp/report/downloadfiles/g90630a01j.pdf, pp. 43.
[4] Shinya Imano, Jun Sato, Koji Kajikawa and Tatsuya Takahashi,
'Mechanical Properties and Manufacturability of Ni-Fe base Superalloy
(FENIX-700) for A-USC Steam Turbine Rotor Large Forgings'
5th international conference on advances in materials technology for fossil
power plants, EPRI, 2007

Product names mentioned herein may be trademarks of their respective companies.