Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-45549

Development and Strategy for A-USC Steam Turbine Cycle

Nobuo Okita
New Energy and ECO Business Promotion Dept.
Power Systems Company
TOSHIBA CORPORATION
Tokyo 105-8001, Japan

Takashi Sasaki
Thermal Power Plant Project Eng. Dept.
Power Systems Co.
TOSHIBA CORP.
Tokyo 105-8001,Japan

Takeo Suga
New Energy and ECO Business Promotion Dept.
Power Systems Co.
TOSHIBA CORP.
Tokyo 105-8001, Japan

Shogo Iwai
Turbine Design and Assembly Dept.
Power Systems Co.
TOSHIBA CORP.
Yokohama 230-0045

ABSTRACT

Efficiency improvement of thermal power plants is one of the key technologies to protect the global environment because of lower emission gas. There are many approaches in this regard, which are investigated and developed around the world. Thermal efficiency of fossil power plants has been improved by raising steam temperature as high as 620 C in a realization of Ultra Super Critical (USC) steam turbine system. In order to enhance the thermal efficiency further, we are developing the Advanced Ultra Super Critical (A-USC) steam turbine system using high pressure and high temperature steam of 700 C or over 700 C.

The main focus of the Research & Development of A-USC steam turbine is the verification of the alloys for the large rotor, casing and valve components, and the main issue for application to the power plant is an economical aspect and field of technology for the realization of such steam conditions with cost-effectiveness, for instance, optimization of cycle heat balance, turbine design, welding technology and so on.

This paper describes briefly about R&D results of A-USC steam turbine and suggests an economical strategy in order to make it possible to be realized sooner.

INTRODUCTION

Demand of electric power has increased all over the world, and carbon dioxide emissions and global warming have become critical problem in proportion to increase of power plants. In view of environmental protection and energy saving, the efficiency enhancement is one of the most effective and indispensable countermeasures. As the reserve capacity of natural gas and oil has been increasing in recent years due to the new development of gas fields and oil shale fields around the world, construction of combined cycle is expected to increase hereafter. On the other hand, coal fired power plant system is still much utilized and will be attractive due to their rich reserve capacity of wide area and cost competitiveness. However, the critical issue for coal fired power plant system is the large amount of carbon dioxide emission, therefore raising efficiency is one of the most fundamental ways of decreasing carbon dioxide emission.

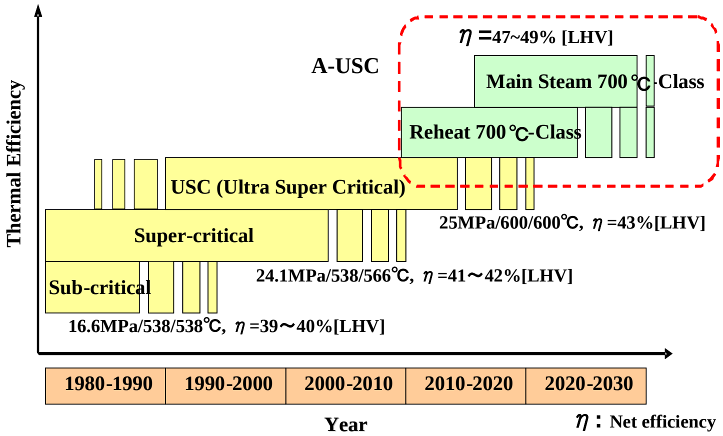
Integrated Gasification Combined Cycle (IGCC) and Advanced Ultra Super Critical plants (A-USC) are promising next generation power plant systems using coal. In IGCC, coal is converted to gas and sent to a Combined Cycle system. Coal of lower melting point is suited to IGCC. On the other hand, that of higher melting point is suited to A-USC because slugging and fouling should be avoided in A-USC boilers. In this context, both IGCC and A-USC are valuable to be allowed flexible and wide usage of coal.

Thermal efficiencies of both systems are almost equal level, but A-USC has advantages in following points. Firstly, A-USC is an extension of existing technology without changing the system itself. Therefore, there will be no big difference between present technology of operation and maintenance and that of future A-USC. Secondary, innovative area of technology to achieve A-USC can be clearly defined and focused on. Namely, if proper material is developed the most critical issue for A-USC can be solved. Thirdly, this technology can be partially applied to existing units in the case of retrofitting, which promises wider application to old existing coal fired units.

TREND OF RAISING STEAM CONDITIONS

Figure 1 shows the transition of steam conditions in Japan. The standard steam conditions for large fossil-fired steam plant were 24Mpa, 538/566 C until early 1990s. The improvement of main steam temperature and reheat steam temperature has come into reality by turns. During this trend of raising steam conditions, we have some epoch making machines. Kawagoe 700MW, whose main steam pressure is 31Mpa, and double reheat temperatures are 566/566/566 C [1],[2]. Nanao 700MW has temperatures of 593/593 C both for main steam and reheat steam. Hekinan No.4 and No.5 are 566/593 degree C, and their capacity is 1000MW, which is still the largest one in the world as a 60Hz tandem-compound turbine.

Fig. 1 Transition of Steam Conditions in Japan



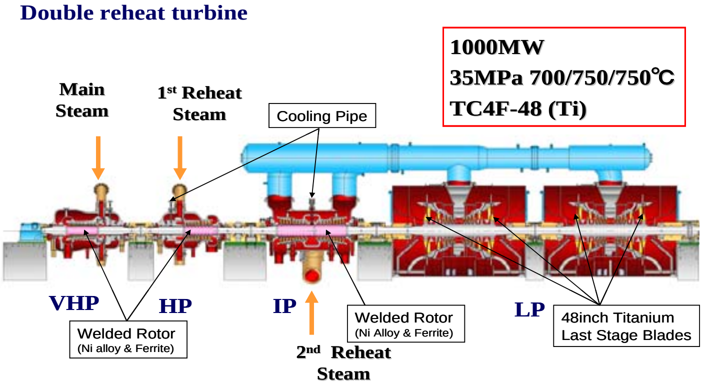
Being supported by material development, design tools, and operational experience, steam temperature in Japanese steam plant reached 610 C at the beginning of this century. This trend has spread worldwide. For instance, we exported two sets of steam turbines to China recently, whose main steam and reheat steam temperatures are 600 C. Also Ultra Super Critical steam condition has become very common in most parts of the world from the beginning of 2000s. The highest temperature in Japan is 620 C at reheat temperature, namely, 600/620 C of 600MW plant. An important aspect of this improvement is that raising reheat steam temperature always realized prior to that of main steam. This is because enhancement of reheat steam temperature is easier than that of main steam temperature and because the cost impact on initial investment of power plant is lighter.

Next approach will be reheat temperature of 700 C or more than 700 C, and then main steam of 700 C will be realized based on material development within next decade in order to raise plant efficiency up to 49% level.

Figure 2 is A-USC steam turbine by our design of 1000MW (60Hz). Inlet steam conditions are 35MPa, 700/750/750 C of double reheat turbine. It consists of a single flow VHP cylinder, a single flow HP cylinder, a double flow IP cylinder and two double flow LP cylinders with 48in length titanium last stage blades. Its plant efficiency is 48 to 49% (LHV base) and its cycle optimization is being carried out to increase economical benefit in consideration of material properties, welded rotor and cooling method etc.

Fig. 2 A-USC Steam Turbine of Toshiba Design

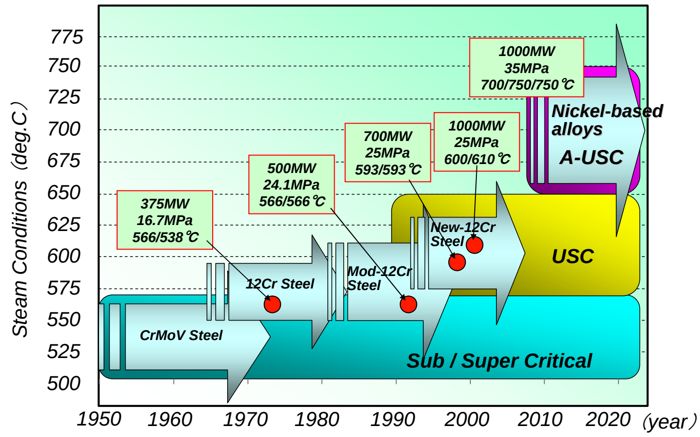
Double reheat turbine



MATERIAL DEVELOPMENT

The main focus of the R&D for realizing such high temperature is, of course, developing high heat-resistant material as described in Figure 3. We have developed and improved high Cr content ferritic steel with resistance to higher temperature from 538 C to more than 600 C since 1960s. Next step in this decade is developing Nickel-based alloys keeping enough creep rupture strength up to 750 C which can be applied to 1000MW double reheat steam turbine mentioned above. We are now focusing on large component verification with an actual size rotor and casing.

Fig. 3 Transition of Steam Turbine Materials



As far as material selection for A-USC turbine is concerned, there are many features to be considered. They are creep rupture strength, welding applicability, forging applicability and so on. Table 1 compares these features among the Ni-base alloys applied to gas turbine high temperature parts. As steam turbine parts are considerably larger than gas turbine parts, its required features are deferent and peculiar, for example, forging applicability for its large rotor. Therefore, special consideration and modification is necessary in order to apply these Ni-base alloys to steam turbine. Based on this comparison and survey, we selected "IN617" for a rotor base material because of its high welding and forging applicability. Welding applicability is also important because Ni-base rotors should be welded with cheaper conventional material rotors which can be applied to lower temperature part in order to cost optimization and/or to keep strength constrained by weight or size of forging (i.e. forging applicability) .

Table. 1 Comparison of Ni-base alloy Forging Materials

Material	Creep Rupture Strength(700 C 10^5h)	Welding Applicability	Forging Applicability
"IN706"	–	○	◎
"Waspaloy"	175	△	△
"IN718"	164	○	△
"IN617"	120	◎	○

High Welding Applicability
High Forging Applicability Improve Creep Rupture Strength

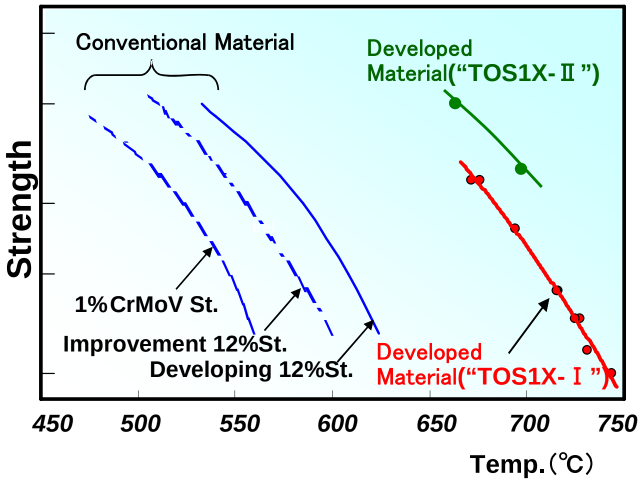
"IN617" → **"TOS1X—I"** → **"TOS1X—II"**

Product names mentioned herein may be trademarks of their respective companies

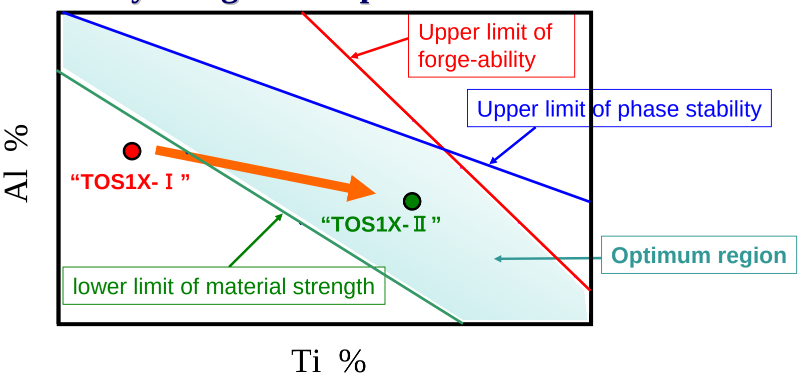
Based on "IN617", we modified it to improve creep rupture strength within the limits of forge-ability and phase stability by optimal chemical composition, and then "TOS1X-I" and "TOS1X-II" (higher strength) have been developed. Actual size verification is now carried out and creep rupture strength is being verified as well as mechanical properties. Enough creep rupture strength at 700 to 750 C is forecasted in case of "TOS1X-II" as shown in Figure 4.

Fig. 4 Development of Heat-resistant Alloy for Large Size Parts

10^5 Hour Strength



Alloy Design Concept of "TOS1X-Ⅱ"

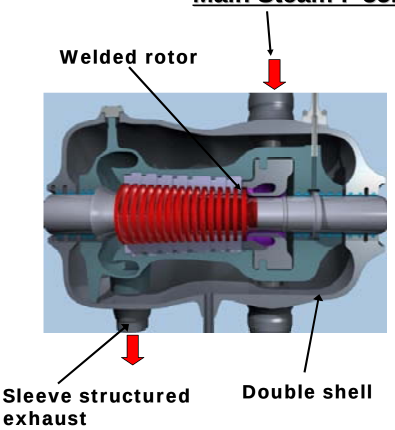


Chemical composition is optimized considering alloy characteristics

As results from the material development so far, a basic design of double reheat steam turbine shown in Figure 2 has been completed. Figure 5 shows material application and design consideration for VHP turbine, which inlet steam conditions are 35MPa and 700 C. Ni-base alloys are applied to limited parts which suffer directly high temperature steam, namely, inner casing, rotor of higher temperature part, nozzle box (first stage nozzle), and higher temperature parts of nozzles and blades. The other parts are of conventional ferritic material because of lower temperature by double shell construction and welded rotor.

Fig. 5 Very High Pressure section of A-USC

Main Steam : 35MPa, 700C.



Part	Material
Outer casing	Ferritic steel
Inner casing	Ni base super-alloys
Rotor (welded structure)	"TOS1X" & ferritic steel
Nozzle box	Ni base super-alloys
Nozzle and Blade	Ni base super-alloys & ferritic steel

STRATEGY FOR EARLIER APPLICATION

Main issues for realization of A-USC are not only for reliability of new material and construction, but also for economical benefit for users. Figure 6 shows relative improvement of thermal efficiency and cost performance comparison (image) of several steam conditions. Toshiba is carrying out a feasibility study for 35MPa, 700/750/750 C double reheat system, however, capital cost increase is fairly large, and therefore, cost performance of capital cost increase v.s efficiency improvement may be worth than the phase I condition, namely, 25MPa,600/700 C. We consider Phase I is earlier applicable than phase II because of more economical and reliable. As for phase II condition, it could be an option for the plant of very low CO2 emission in future, which will be discussed later. Improvement in economics is necessary, anyhow.

Fig. 6 Earlier Application of Reheat 700 C

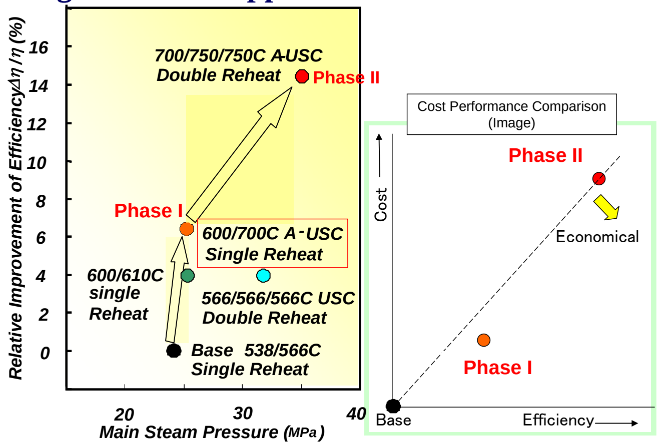


Figure 7 shows our concept for phase I of reheat 700 C system. As shown in the figures, phase I applies fewer Ni-base new material and its design is simpler including boiler portion in comparison with phase II of double reheat. That is why we consider phase I is practical and economical, then therefore, it can be realized earlier than phase II.

Fig. 7 A-USC Phase Ⅰ Reheat 700 C System

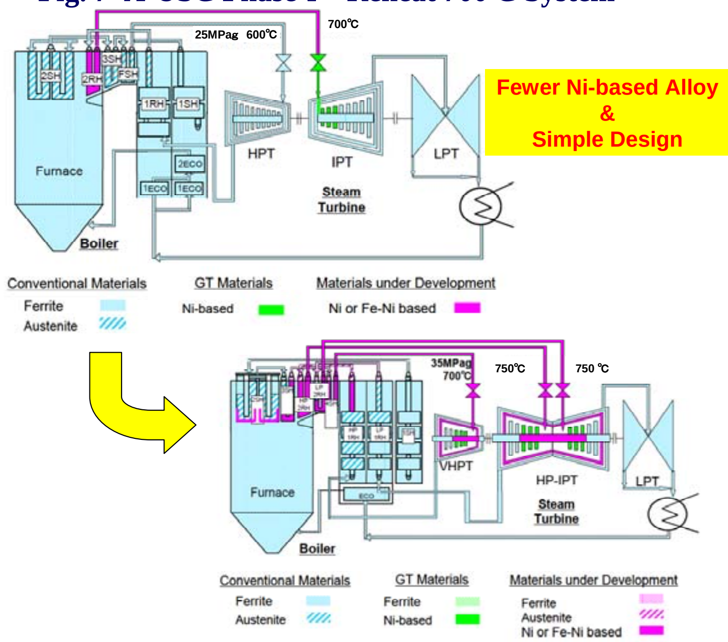
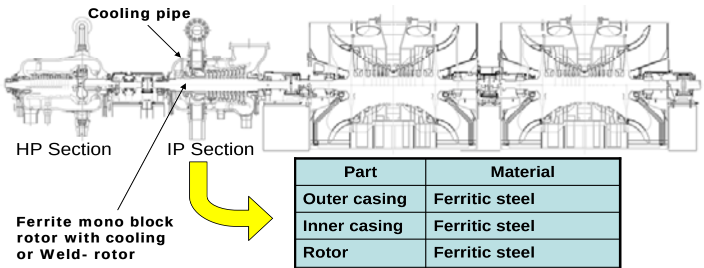


Figure 8 shows our design concepts of phase I turbine. As shown clearly, Ni-base material is applied only for IP nozzle box and higher temperature portion of nozzles and blades of IP turbine, which application is fewer than phase II (Figure 5). It has double shell structure and cooling will be applied to rotor, casing and so on. Reheat steam of 700 C flows into the turbine from inlet pipes located on upper half and lower half. In order to avoid direct contact of inlet steam from outer casing, inlet pipe is double structured with cooling. The most important part is, of course, rotor material. Cooling and protection of bucket fixation are promising candidate measure to solve this task. External cooling of reheat section has been used in steam turbine design, and in fact, extraction of cooling steam is possible from high pressure section. This external cooling makes it possible to apply ferritic steel to both rotor and inner casing. Otherwise, Ni-base material ("TOS1X") of IP rotor can be used in limited area by weld-rotor in case of no external cooling for higher efficiency.

Fig. 8 TOSHIBA Design Concepts (Phase I)

Single reheat turbine (Reheat 700C)



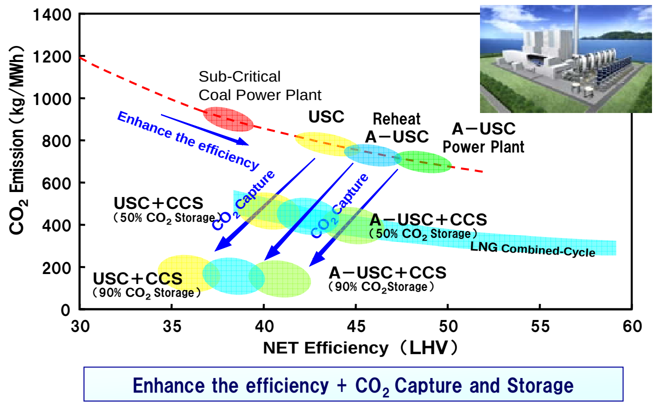
Part	Material
Outer casing	Ferritic steel
Inner casing	Ferritic steel
Rotor	Ferritic steel
Nozzle box	Ni base super-alloys
Nozzle and Blade	Ni base super-alloys & ferritic steel
Cooling pipe	Ferritic steel

STRATEGY FOR FUTURE APPLICATION

In general, CO2 emission will be restricted more severely in future because of protection of global environment. However, coal-fired power plant will be still utilized because of rich reservation of coal mine and increase of demand for electric power. Under this situation, efficiency improvement and CO2 capture are very important in the future.

Figure 9 shows our concept and approach to near-zero emission for coal-fired power plant for the future. CCS (Carbon Capture and Storage) requires energy for carbon capture, which comes from thermal power of the plant. Therefore, the thermal efficiency of a power plant with CCS is lower than the plant without CCS, although CO2 emission reduction is very large. It is fundamental issue for the future, and one of countermeasures may be A-USC with CCS integration. As shown in Figure 9, the net thermal efficiency of existing plants of sub-critical and USC are less and more than 40% (LHV base). In case of A-USC (Phase II) with CCS (90% CO2 capture), its efficiency will be around 40%, which is almost same as existing level. In other words, thermal efficiency can be kept as it is and CO2 emission can be greatly reduced by A-USC with CCS integration. In case of 50% CO2 capture, thermal efficiency and CO2 emission are both as same as LNG combined cycle with 1100 C class gas turbine. Please note that USC+CCS with 90% CO2 capture will result in lower efficiency than existing plants, which can not be accepted in general. Therefore, A-USC+CCS is important in the future.

Fig. 9 Approach to Near-Zero Emission coal Power Plant



As far as carbon capture technologies are concerned, there are three methods as shown in Figure 10, namely, post combustion capture, oxy-fuel combustion and pre combustion capture (IGCC). Each technology has advantages and challenges (issues). Toshiba has selected and is developing a post combustion capture, because it can be applied widely to thermal power plant even for retrofit and industrial plant with proven technologies. Issues are energy loss mentioned above and capital cost increase, which will be discussed later. Anyhow, some incentives are necessary in order to introduce CCS technology to power plants because of increase of capital cost and less efficiency.

Fig. 10 Carbon Capture Technologies

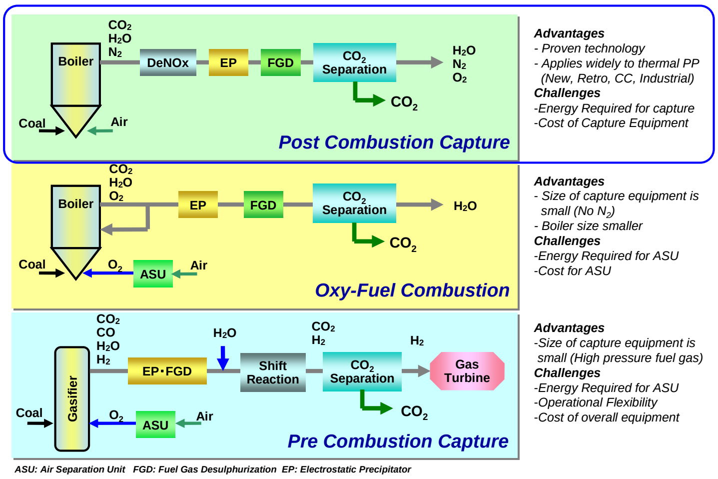
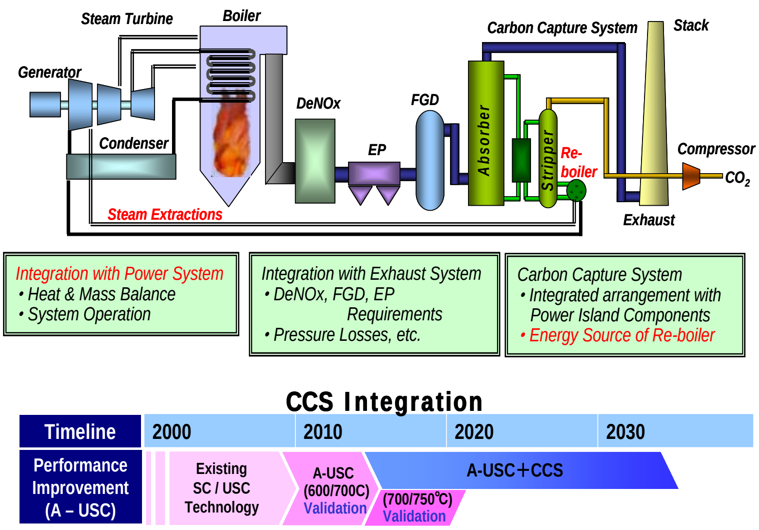


Figure 11 describes integration of thermal power plant with CCS. It is important to make the energy loss for capture minimal by integration between CCS and power system. Main loss for capture energy comes from re-boiler energy into stripper when stripping CO2 from amine solution. There may be some options for selection of energy source for the re-boiler.

Lower half of Figure 11 describes a road map for A-USC validation and A-USC+CCS integration. Phase I and Phase II of A-USC will be realized continuously in the next decade followed by CCS integration.

Fig. 11 Thermal Power Plant Integration



SUGGESTION AND RECOMMENDATION

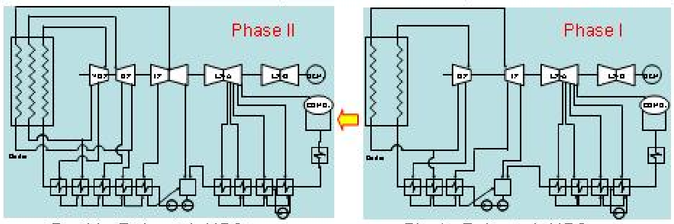
We have a strategy to introduce A-USC phase I and phase II by step as described before. Phase I is very recent when the existent law is applied and there is no incentives for CO2 capture in the field of power plants. Target cost and efficiency must be reached without any incentives or credits. In this situation, phase I is rather appropriate and easier to be economical than phase II as described in Figure 6. For future incentives, some credit for CO2 reduction may be regulated, and then the target cost performance of phase II with CCS will be decided.

It is suggested that under recent situation and common regulations, phase I is recommended from economical and realistic aspects without CCS. Then for the future case of CCS regulation and incentives with CO2 credit, phase II is recommended after validation which will take several years from now on. Turbine and boiler manufactures should prepare for the future market.

Figure 12 is an example of the Phase II system aimed to more than 48% (LHV) of plant efficiency being studied based on the Phase I system.

Fig. 12 Design comparison of A-USC System

	Double reheat (Phase II)	Single reheat (Phase I)
Output(MW)	1000	500 to 600
Main steam Press.(MPa)	35	25
Main steam Temp.(C)	700	600
First reheat Temp. (C)	750	700
Second reheat Temp.(C)	750	–



Turbine manufacturer and Boiler manufacturer should cooperate in feasibility studies on the selection of parameters between each portion in order to realize economical and reliable A-USC plant for the future in consideration of CCS option.

CONCLUSION

We have developed heat-resistant alloys such as "TOS-1X" rotor which can be applied to 750 C. The reheat 700 C turbine cycle (phase I) can be realized sooner than double reheat 750 C turbine cycle (phase II). A-USC with CCS is one of the near-zero emission cycles, which can be optimized integrally by our experiences. We are carrying out feasibility studies and we can contribute to realize reliable, economical and environmentally friend coal-fired power plants.

ACKNOWLEDGMENT

"TOS1X" rotor forging was manufactured as a part of Strategic Development Energy Conservation Technology Project sponsored by NEDO (New. Energy and Industry Technology Development Organization,. Japan)

REFERENCES

1. Suzuki, A., Nomoto, H., and Kakishima, M., Development of a 700MW Double Reheat Turbine with Advanced Supercritical Conditions, IMechE, C386/002, 1990.
2. Mimuro, H., and Nomoto, H., The Development and the Operational Experience of the Steam Turbine with Advanced Steam Conditions, American Power Conference, April 1990.
3. Hideo Nomoto**,** Yoshikazu Kuroki, Masafumi Fukuda, Shinya Fujitsuka, Recent Development of Steam Turbines with High Steam Temperature, Proceedings of the International Conference on Power Engineering-05 (ICOPE-05) April 5-7, 2005, Chicago, USA
4. Kazutaka Ikeda, Hideo Nomoto, Koichi Kitaguchi, Shinya Fujitsuka, and Takashi Sasaki, Development of Advanced-Ultra Super Critical Steam Turbine System, Proceedings of the International Conference on Power Engineering-09 (ICOPE-09) November 16-20, 2009, Kobe, Japan