MATERIALS ISSUES FOR TURBINES FOR OPERATION IN ULTRA-SUPERCRITICAL STEAM

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ABSTRACT

Coal-fired supercritical-steam power plants are currently operating with steam temperatures at the inlet to the high-pressure turbine close to or slightly above 600°C. The use of recently-developed martensitic-ferritic steels is expected to allow this temperature to be raised to 620°C, which probably represents the inherent limit of capability of these advanced steels. Further increases in temperature capability will require the use of Ni-base alloys, and efforts in this direction have been pioneered in Europe where there are plans to build a plant operating on steam at 700°C. In the U.S., there is a significant effort aimed at qualifying alloys that could be used for tubing and piping to deliver steam at 720/760°C. In this paper, the technical and business considerations involved in determining and prioritizing the materials needs for turbines operating under these ultra-supercritical steam conditions are discussed.

BACKGROUND

It is widely recognized that, because of the very large role that coal plays in power generation, efforts to reduce overall CO_2 emissions will, of necessity, involve efforts to find cleaner ways in which to use coal. Removing carbon from coal before or after combustion introduces costs that seriously detract from the competitiveness of that power generation process. If the efficiency of the overall cycle were to be improved, however, less CO_2 would be produced for each unit of electricity generated.

In typical U.S. supercritical steam practice, steam is delivered to the turbine at temperatures up to 566°C and at a typical pressure of 238 bar. There is experience in the U.S. of operation at higher steam conditions: Philo Unit 6 of American Electric Power (started up in 1957) operated with steam at 621°C/310 bar, with two reheats to 566°C[1]. In addition, Eddystone Unit 1 of the Philadelphia Electric Company (started up in 1961) operated with steam conditions of 649°C/340 bar, with double reheats to 566°C[2]. Both were relatively small units by modern standards, 125 and 325 MW, respectively; the size was essentially determined by the size of the austenitic steel high-pressure rotor that could be made at the time[3]. The steam turbines were manufactured by General Electric (GE) and Westinghouse, respectively. Problems were experienced with these early, pioneering units, some of which were materials related, and these contributed to a decision to derate to less ambitious steam conditions to improve reliability. Subsequent supercritical plants in the U.S. employed steam conditions which are typically 541-566°C/238 bar. As of 1986, some fifteen percent of the U.S. fleet of operating steam power plants used a supercritical steam cycle, and these are mostly 1960s-1970s-vintage units[4]. The turbines installed in the U.S. supercritical fleet were manufactured principally by GE and Westinghouse, with some from the Brown Boveri Company.

Elsewhere, there has been a gradual push for the use of steam conditions in advance of those generally used in the U.S. As an example, the Avedøre Unit 2 Power Station of the SK Power Company in Denmark, which started commercial operation at the beginning of 2001, operates with a main steam

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temperature of 582°C, at 300 bar, with a single heat reheat to 600°C[5]. The turbine used in this case was supplied by Ansaldo Energia. The materials development to support these advances has come from major programs in Europe[5] and Japan,[6] with support from EPRI[7]. The overall strategy employed was to use ferritic-martensitic steels to their maximum temperature capability, and then to switch to Ni-based alloys for the final sections of the steam generator, so avoiding the need to use austenitic stainless steels and the associated problems of dissimilar metal joints and susceptibility to thermal fatigue that arise from the coefficient of expansion mismatch and low thermal conductivity of these alloys. While significant improvements in the temperature capability of ferritic-martensitic steels have been achieved, it appears that the limit for the strengthening mechanisms currently employed will be of the order of 620°C[8]. This is based on a criterion of a stress rupture strength of 100 MPa for 10^5 hrs to allow the use of sufficiently thin section thicknesses to minimize thermal fatigue concerns. As a result, the high cost of the higher-strength Ni-based alloys will likely lead to the development of cheaper variants.

THE CASE FOR ULTRA-SUPERCRITICAL STEAM

The efficiency of the Carnot cycle is defined as $(T_{max}-T_{min})/T_{max}$, (where T_{max} is the maximum temperature in the thermodynamic cycle, and T_{min} is the minimum temperature, both as absolute temperatures). Therefore, the most practical route to increase the efficiency of a coal-fired power plant is to increase the maximum steam temperature; decreasing T_{min} is possible only in a few locations, such as Scandinavia, where unusually cold cooling water is available from the Baltic Sea. Figure 1 is an illustration of the extent of improvement possible, as well as the relative effects of increasing steam temperature and pressure[9,10]. It is claimed that a change from the steam conditions most often used in the U.S. (541°C/238 bar) to those that form the goal of the U.S. Ultra-Supercritical (USC) Steam Tubing Consortium (740/760°C/340 bar), results in an increase in overall cycle efficiency of more than five percentage points.

U.S. Domestic Perspective

As mentioned earlier, some fifteen percent of the U.S. 1960s-1970s-vintage fleet of operating steam power plants uses a supercritical steam cycle[4]. The stigma of lower reliability compared to subcritical steam units that resulted from early difficulties with supercritical technology is long past, and these units match or exceed the reliability of subcritical units of the same vintage[11]. However, until recently, the low cost of coal in the U.S. has been a major disincentive to investment in the increased efficiency of new supercritical steam power plants. The current listing of orders placed for coal-fired steam generators in the U.S.[12] contains only three supercritical units, which represent 2 GW of the 51 GW on order. This is surprising, since the major customers for new steam plant are utilities, compared to the predominance of independent power producers in the 1990's, so that the longer-term advantages of the supercritical cycle would be expected to be an obvious attraction. The supercritical plants on order are the 790 MW Council Bluffs Unit No. 4 of MidAmerica Energy, Iowa, and two 600 MW units at the Oak Creek station of Wisconsin Energy and Madison Gas. For these, supercritical conditions were mandated by concerns for the need to decrease emissions of CO_2. In fact, the steam conditions of these plants represent only a small advance on the 'standard' U.S. conditions, despite that fact that the Council Bluffs plant is being built by Hitachi, which has experience with supercritical conditions up to 600°C/310 bar.

Since 1978, EPRI has championed the case for advanced steam conditions[7,13], and promoted a staged approach in which Phase 0 was considered to be state-of-the-art in 1978:

- Phase 0: 566/566/566°C/310 bar;
- Phase 1: 593/593/°C/310 bar;
- Phase 1b: 620/620/620°C/310 bar; and
- Phase 2: 649/649/649°C/345 bar.

The conditions of Phase 2 were considered to be beyond reach, so that the intermediate Phase 1 goals were then included. This major program addressed the development of 12Cr alloys for high-pressure (HP) rotors (General Electric); 3.5 Ni-1.5Cr-MoV alloys for low-pressure (LP) rotors (Toshiba)[14,15]; castings in 9Cr and 12Cr steels for casings and Nimonic 80A (see Table 1) for bolting (Alstom/MAN)[16]; and cast 9Cr or forged 9Cr and 12Cr MoVNbN alloys for valve bodies (Alstom)[17]. A major issue that was confronted was the limited availability of facilities able to melt, cast, and forge the large ingots required, particularly for the intermediate pressure (IP) rotor. Such facilities were developed (in Europe and Japan), and led to the wide adoption of improved rotor steels.

The Clean Coal Technologies Integrated Roadmap[18] of the Coal Utilization Council (CURC), EPRI, and the U.S. Department of Energy (DOE) has the vision of providing the ability to generate steam from pulverized coal with increasingly stringent control of emissions. The baseline for comparison is the state of the art steam temperature of 600°C, and Roadmap Destinations of particular interest are plants generating steam at 677°C by 2010, and 760°C by 2020. Since there is little experience of steam conditions above 566°C/240 bar in the U.S., and since a relatively recent EPRI report[13] concluded that available alloys only *showed promise* for use to 650°C, the 2010 Destination is surprising. If ferritic alloys indeed reach a barrier at 620°C, presumably the 677°C goal was intended to make use of the Ni-base alloys under development in the Thermie/AD700[19] and U.S. USC Steam[20] programs, while developing some of the other combustion and pollution control aspects of the Roadmap.

European and Japanese Perspectives

Japan conducted a major program in the 1980s and 1990s intended to greatly increase the coal-fired power generation capacity of that country[21,22]. All of the new power plants used supercritical steam conditions in order to attain low heat rates (high efficiencies). The first of these new plants was introduced in 1989, with steam conditions of 566°C/310 bar[23]. It was planned that the steam conditions would be increased in three stages from the 'standard' conditions of 538°C/240 bar:

- Phase 1a: 593/593/593°C/314 bar using ferritic steels;
- Phase 1b: 649/649/649°C/343 bar using austenitic steels
- Phase 2: 630/630°C/300 bar using ferritic steels

Programs to develop new rotor steels were conducted, in collaboration with the EPRI-led efforts[24], by the major steam turbine manufacturers and research institutes. Companion programs led to the development and qualification of new ferritic-martensitic steels for use in furnace walls and superheaters, as well as new austenitic steels where increased resistance to fireside corrosion was a major goal. While there is some continuing effort in Japan to increase the temperature capability of ferritic-martensitic steels, Japanese industry appears to have settled on a maximum steam temperature of about 610°C, and a maximum pressure of 250 bar. As of 2001, there were six units operating in Japan with steam conditions of 593/593°C/241-250 bar; three with 600/600°C/241-250 bar; and three with 600/610°C/241-250 bar[23].

In Europe, USC steam cycles are viewed as a necessary part of an integrated power generation portfolio intended to realize the reduction in emissions needed to minimize global warming. The focus of the various advanced steam cycle programs is the demonstration of a USC steam cycle at 700°C/340 bar as part of the Thermie/AD700 project[19]. Significant effort in support of materials development has been provided through the European Union's COST 501 and 522 projects[25,26] and by associated national programs, and these results are being applied in a series of new power plants in which the steam conditions are being incrementally increased. The final push to the AD700 goal of a full demonstration plant has recently been decelerated due to a sharp reduction in funding for fossil-fired power generation in the new European five-year program (Framework V), in which emphasis has been switched to renewable fuel issues[27]. Nevertheless, significant advances have been made in producing and testing trial components using the alloys intended for service in 700°C steam, and a component test facility for boiler parts is being established. The core group that manages the AD700 program is actively revising the next steps in the process in light of their reduced funding, but the intention still remains to demonstrate the capabilities of these alloys under conditions where information needed by the power plant industry can be generated.

MATERIALS NEEDS

The range of alloys used in steam turbines is relatively small, partly because of the need to ensure a good match of thermal properties, such as expansion and conductivity, and partly because of the need for high-temperature strength at acceptable cost. The commercial alloys used depend on the maximum temperatures and pressures to which specific components will be exposed, and these are heavily dependent upon the detailed design of the turbine, which can vary significantly among the various manufacturers. Since this is the case, the starting point for any overall discussion of materials issues is to list the main components of interest, and to identify the conditions under which they will be required to operate. The main components considered here are: the turbine casing/shell (including the steam chest), cylinders and valve bodies; bolting; turbine rotors or discs; and vanes and blades. The materials issues associated with the piping required to transport the steam to and from the turbine have been discussed elsewhere at this conference[20,28]. The simplified schematic diagrams shown in Fig. 2 are attempts to illustrate the general location of these components in the HP and IP sections of a generic steam turbine.

It is instructive to examine the approaches used for materials selection for the earlier, pioneering ultra-supercritical steam turbines. The materials used for Eddystone 1 (649/566/566°C/340 bar) represented the latest high-temperature alloys of the time[29,30]: cast type 316 stainless steel was used for the nozzle blocks, inner cylinder, diaphragm, and vanes (the main steam piping was 316H); the rotor was forged from Discalloy (Fe-25Ni-13.5Cr-Mo,Ti); and the blades were K42B (Ni-22Co-18Cr-TiAl). The bolting material was W-545 (a proprietary Fe-Ni-Cr alloy similar to A286), and the outer casing was 2.25Cr-1Mo steel (operated at 538°C/170 bar). The later design of a steam turbine for use in demonstrating a coal-fired topping system (cyclic operation) with steam at 704°C/323 bar, drew upon gas turbine experience with superalloys[31]. The design embodied the smallest efficient diameter and the fewest stages (two 32 cm blade root diameter wheels), with full admission and maximum symmetry. The design rotational speed was 14,000 rpm; small diameter shafts were used to minimize leakage. The inlet duct and first stage nozzles were made from cast IN939, and the rotor disc, vanes and blades from forged IN718. The steam valve was forged from Hastelloy X.

In the following, 620°C is used as the practical upper limit for ferritic steels; while there are continuing efforts to examine alternative strengthening strategies that could push beyond this perceived temperature barrier[32-34], translation into commercial production (for successful developments) is still some way off. On this basis, it appeared pertinent to examine the changes in materials usage necessitated by the raising steam conditions from 566/238 bar to 620°C/340 bar, as well as materials requirements for 700 and 760°C/340 bar steam. Table 2 summarizes the typical materials selection as a function of component for the temperatures considered.

Casings/Shells

The casings of steam turbines typically are large structures with complex shapes that must provide the pressure containment for the steam turbine. Depending on the design of the turbine, an inner casing or cylinder may be employed to enclose the hot gas path, so that the main steam from the steam generator first flows into the steam chest, through the inner cylinder, over the vanes and blades, and then returns through the annulus between the inner cylinder and the outer casing before being sent to the reheater (Fig. 2). In this arrangement, the duty of the outer casing is to contain steam at the temperature and pressure corresponding to the exit of the hot gas path, while the inner cylinder must handle steam at the maximum temperature and pressure, with the proviso that the pressure difference across the inner cylinder wall is controlled by the pressure of the return steam. The inner cylinder and steam chest should be fabricated from the same material as the rotor, to avoid thermal mismatch.

Because of the size of these components, their cost has a strong impact on the overall cost of the turbine. The materials used currently for inner and outer casings are the 1-2CrMo steels, usually as castings[35,36]. The temperature limit of these alloys in this application is approximately 566°C, and is set by their resistance to oxidation in steam. For higher temperatures, cast 9CrMoVNb alloys are considered to be adequate in terms of strength capabilities to 593°C[36], while the 12Cr steels in either cast or forged form currently appear to be limited to 620°C, assuming that their steam oxidation resistance is acceptable[37-39]. Recent developments in new, cast, austenitic stainless steels, such as CF8C-Plus[40] (a proprietary version of CF8C) have resulted in an increase in strength at temperatures to greater than 650°C but, by analogy with current 300-series stainless steels, their oxidation rate in steam may limit their useful service temperature to somewhat less than 700°C. Appropriate testing of these and other advanced austenitic alloys currently in development is expected to confirm improved capabilities, and preclude the need for initiating such alloy development. The use of Cr-rich coatings, claddings, or other surface modification approaches should be considered to ensure resistance to steam oxidation of the 9-12Cr ferritic steels and 16-18Cr stainless steels in the 600-700°C temperature range[20, 41].

For higher temperatures, Ni-based alloys will be required, and the question will be whether adequate strengthening can be developed in cast alloys, or whether wrought alloys will be needed. The candidate alloys chosen for evaluation in the AD700 program goals included both Fe-based superalloys and Ni-base alloys: 155, 230, 263, 617, 625, 706, 718, 901, and Waspaloy[39]. For castings, uncertainties in extrapolating properties measured for small laboratory heats to those of large components mandate that either full-scale or prototypical components are used for testing. With present foundry practice in the U.S., the preference would be to make these components by forging castings from Europe and Japan to ensure reliability, whereas using cast shapes would be a considerably less expensive route. Therefore, there are strong incentives to minimize the temperature requirement for the outer shell components by design, and to improve the quality of large 12-Cr and austenitic castings. There is considerable experience in producing castings of Inconel 625 and, in the European programs, data were generated from trial castings of Inconel alloys 617 and 625. A step-block casting geometry was used for the prototypical component, and a full-scale valve chest was cast in alloy 617. Experience also exists for large forgings of alloys such as IN 706 and 718[39], and long-term creep data are available for the wrought forms of alloys such as 617, 625 and Haynes 230[5]. Of these, only a modified version of 617 (CCA617), and a new alloy, Inconel 740, appear to meet the strength and creep-rupture criteria for the 760°C goal of the U.S. USC steam program. An extensive data generation effort for wrought versions of these alloys is in progress[20,28] in the U.S.

The major materials needs are for Ni-based alloys for operation at 760°C with (i) adequate creep rupture strength; (ii) abilities to cast them into the required size and shape, and to inspect for defects[42]; and (iii) ability to perform initial fabrication welding (on cast or wrought forms, including dissimilar metal welds), and to make repair welds on aged material. The effort required is considerable, and involves the development of rupture, creep, and rupture ductility relationships for these materials. Substantial progress has been made in Europe for both processing methods and procurement of design data. The data requirements include long-term creep behavior of castings, weld metal, similar and dissimilar metal weldments, as well as the effects of aging (and steam oxidation) on the microstructure, hence strength/toughness of these materials. Comparison of observed changes in precipitated phases and distribution with time at temperature with theory will be important.

Bolting

The major requirements for bolting materials are high resistance to stress relaxation (ageing characteristics) at temperatures that can range up to the maximum steam temperature experienced by the casing for the hot gas path; thermal expansion characteristics compatible with those of the structure to be bolted; and low notch sensitivity. There is a wide range of alloys available for this application, and the specific alloy selection depends for the most part on the criteria used by each manufacturer[36]. In current usage, ferritic steels (variants of type 422 steel) are used up to approximately 566°C, and the Ni-base Nimonic alloys are typically used for higher temperatures. Based on world-wide experience, Nimonic 80A and a few proprietary alloys (such as Refractaloy 26) appear to be good candidates for temperatures up to 593°C[43]. For the bolting needs to 720°C in the European program, and to 760°C in the U.S. USC Steam Program, Ni-based alloys will be required and, as shown in Table 2, there is a range of candidates, with Waspaloy apparently being preferred up to 700/720°C.

The major property data needed for these materials are: creep-relaxation behavior; effect of component size on microstructure; and compatibility with steam at the higher temperatures of interest. Long-term creep data are available for a number of these alloys, including U-700, U-710, U720 variants, Nimonic alloys 105 and 115. The required stress relaxation properties can be calculated from the measured creep properties using creep law equations, and/or extrapolated to long times using parametric methods. Both approaches have merit. It is considered important to determine the effect of bolt diameter on microstructural characteristics such as grain size, gamma prime content, and chemical segregation. Modeling can be used to estimate the effect of observed microstructural variations (including heat-to-heat variability) on ageing response and mechanical properties, but ageing and stress relaxation data also are needed to confirm such estimations.

Overall, for bolting, the choice of materials appears to be relatively straightforward. There do not appear to be significant manufacturing issues, since these alloys are available as bar stock suitable for rolling or grinding to shape. Similar requirements exist for gas turbines, although there may be some scale-up issues to be addressed.

Rotors/discs

The HP rotor/discs will have to handle the highest steam conditions, so that a Ni-based alloy will be required for temperatures greater than 620°C; a mitigating factor is that this component may be relatively small (depending on the overall steam turbine design). The IP rotor handles steam at the maximum system temperature, but at reduced pressure; while the strength requirement may be relaxed compared to the HP rotor, the issue of oxidation in steam remains. Materials selection for this component may be a critical issue because of its size. For maximum overall efficiency, it would be desirable also to increase the temperature of the steam entering the low-pressure (LP) rotor[3]. This component will require a NiCrMoV steel of the type in current use for HP/IP rotors, but which is likely to be susceptible to temper embrittlement in this application (>316°C). Resort may be made to cooling of this rotor, or to alloy modification. Alternatively, metallurgical processing changes may be introduced to reduce the susceptibility to temperature embrittlement (by reducing the levels of P, Sn, Mn, Si).

The alloys most commonly used for steam turbine rotors and/or discs are the CrMoVWNbN steels, which can vary in chromium content from 1-13% depending on the preference of individual manufacturers. These alloys are widely used up to a temperature limit of about 566°C, and the higher-W, lower-Nb and -C versions are capable of 593°C. The issues for alloys for higher-temperature use are similar to those for materials for steam piping. Versions of these ferritic steels, based on the advanced 9-12% Cr compositions, are already in service at steam temperatures of 600°C, and it is expected that they will be usable to approximately 620°C (and possibly 650°C)[44-46]. Ni-based alloys will be required for the higher temperatures, and candidates include Inconel alloys 617, 625, and the new 740, and Haynes 230. Except for 740, these alloys are approved by the ASME Boiler and Pressure Vessel Code (not required for rotors), so that a significant design database exists for them, although this does not include fatigue data.

The main issues for rotors/discs concern manufacturing, especially the capability to produce large castings and forgings. With modern secondary steel making practices, such as ladle furnaces, electroslag remelting to control freezing segregation, and control of the sulfur and phosphorus levels in the alloy, very large rotors now can be produced, but experience is related mostly to Cr-Mo-V alloys (used in current 541-566°C plants), and for 12 Cr alloys (needed for advanced steam cycles to 620°C). A further major issue, depending on the design approach used, is the need for developing the techniques required for making dissimilar metal welds when Ni-based alloys are used for the HP turbine, and the lower alloy/ferritic steels used for the IP turbine.

Blading

The current supercritical steam plants in the U.S. typically use vanes and blades made from 12 Cr ferritic steels such as type 422, or proprietary alloys of similar composition. For higher temperatures there is available a wide choice of wrought Ni-based alloys, for which a substantial design database exists from their application in gas turbines. For operation with steam at 760°C, it is considered likely that materials new to steam use will be necessary for at least four stages in the HP turbine, and probably also in the IP turbine[47]. The choice of blading material will depend on (i) the temperature of the rotor, hence on the thermal expansion characteristics of the material from which it is made, and (ii) the size and shape of the blade, which will be designed using computational fluid dynamics modeling. There will be a requirement for the generation of data on the interaction of these materials with steam; results from recent research suggest that it will be important to have higher-Cr levels in these alloys to avoid preferential internal attack in steam[48]. While it is not known if solid particle erosion from entrained particles of oxide scale that may exfoliated from the superheater and reheater tubing will be a greater problem than encountered in current steam turbines, it will be prudent to ensure the availability of erosion-mitigating coatings that are compatible with the high-temperature blading materials.

Overall, there do not appear to be significant manufacturing issues for blading alloys, given the gas turbine experience and the fact that these components are largely made in the U.S. However, effort will be necessary to ensure that current manufacturing procedures have the capability, and that processing data are available for producing the large blades that may be needed in some steam turbine designs.

Testing and Life Prediction

An extensive account of the current status of these topics is beyond the scope of this review, but it is important to recognize that the efforts to obtain databases for design at high temperatures will be costly and time-consuming. Accordingly, it will be necessary to use accelerated methods (such as those proposed by Woodford[49]) where possible. Also modeling methods to predict materials performance, for example, in creep and fatigue, will enable testing to be targeted on the most critical conditions, thereby reducing the overall size of mechanical test programs. An import initial step will be to validate the various models to ensure the level of reliability of the predicted properties. Similarly, life prediction techniques will be important in enabling the life of critical components to be estimated, thereby limiting the need for large-scale testing.

SUMMARY AND CONTINUING NEEDS

The materials issues resulting from the need for turbines to operate under ultra-supercritical steam conditions are summarized in Table 3, which attempts to provide a simple ranking of the level of effort needed to provide materials choices for three target steam temperatures, 620, 700, and 760°C. In the Table, the level of effort required is given a numerical rating, from 1-5, where '5' suggests that considerable research and development will be needed, while a ranking of '1' indicates that most of the capability required is already available.

Overall, materials are available now to build steam turbines capable of 593°C and 310 bar. Further, there do not appear to be irresolvable materials difficulties for a plant designed for 620°C/340 bar steam conditions. The shortcomings in currently-qualified materials have been carefully examined in several international programs, and solutions in the form of advanced ferritic-martensitic steels, have been formulated and appear to be perfectly feasible. For steam temperatures above 620°C, Ni-base alloys will be necessary, and a modified version of Inconel 617 as well as new alloys such as Inconel 740 are available that can meet the property requirements for 700°C/340 bar, and possibly 760°C/340 bar steam.

Pressing issues involve selection of materials and manufacturing routes that would satisfy both reliability and first-cost criteria for the large components such as casings or shells, for which the preferred manufacturing route currently is casting. It may be necessary to consider forging these components where Ni-base alloys are needed, but this is a more expensive option. For rotors and discs, modern secondary steel making practices enable large rotors to be produced from the Cr-Mo-V and 12 Cr alloys used up to 620°C, and the European programs have explored the capabilities for Ni-based alloys. However, since there is a limited range of alloys from which to choose for HP rotors for operation at 700 and 760°C, investment in resources needed to process these alloys may be a major factor. The IP rotor is a critical item because of the size, but it is expected that the turbine can be designed so that this component can use ferritic steels. For the airfoils, while there is a range of wrought (and cast) Ni-base alloys suitable for use in the higher-temperature HP turbine, there appears to be a need to generate the property data necessary for processing these components, which may be large, and involve complex shapes to maximize efficiency. For higher-temperature bolting materials, the issue also is one of selecting from a range of materials; this will be driven by the need to match the thermal expansion of the alloys used for the major components, and the generation of creep/relaxation data at the higher temperatures. Finally, there exists a major need to demonstrate that available materials can be made into actual components that work as intended, and to obtain property data for design purposes and service life prediction. While demonstration of the workability of a USC steam cycle is an expensive undertaking, even at component demonstration level, it represents a necessary milestone that must be reached in order for the utility industry to accept this technology, and so is a common culmination point for all materials and components development programs.

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Table 1. Chemical Compositions of Alloys Mentioned in the Text (in weight percent)

Alloy	Fe	Ni	C	Co	Cr	Nb	Mo	W	Ti	Al
T92	Bal	0.4	0.1	—	9	0.1	0.5	1.8	—	—
Type 422	Bal	0.7	0.22	—	12	—	1	1	—	—
T122	Bal	0.3	0.1	—	12	0.05	0.4	2	—	—
Nimonic 901	Bal	42.5	0.04	1	12.5	—	6	—	3	0.3
A286	Bal	26	0.05	—	15	—	1	—	—	2
Type 316	Bal	11-14	<0.08	—	16-18	—	2-3	—	—	—
Refractaloy 26	Bal	36	0.03	19	18	—	3	—	2.6	—
CF8C	Bal	10	0.08	—	19.5	0.85	—	—	—	—
N155	Bal	20	0.15	20	21	—	3	2.5	—	—
Haynes 230	3	Bal	0.1	5	22	—	2	14	—	0.3
Hastelloy X	18.5	Bal	0.1	1.5	22	—	9	0.6	—	—
CCA617	0.7	Bal	0.06	12	22	—	9	—	0.4	1.2
Inconel 625	3	Bal	0.05	22	—	9	—	0.2	0.2	3
Inconel 740	2	Bal	0.07	20	24	2	0.5	—	2	1
IN706	40	Bal	0.03	0.5	16	—	0.5	—	2	0.2
IN718	—	Bal	0.04	—	19	5	3	—	1	0.5
IN939	—	Bal	0.15	19	22	1	—	2	3.7	1.9
Nimonic 80A	5	Bal	0.1	2	20	—	—	—	3	2
Nimonic 105	1	Bal	0.2	20	15	—	5	—	2	4
Nimonic 115	—	Bal	0.2	15	15	—	4	—	4	5
Nimonic 263	1	Bal	0.06	20	20	—	6	—	2	0.5
U700	1	Bal	0.15	18.5	15	—	5.2	—	3.5	4.25
U710	—	Bal	0.07	15	18	—	3	1.5	5	2.5
U720	—	Bal	0.01	14.7	16	—	3	1.25	5	2.5
Waspaloy	2	Bal	0.07	14	20	—	4	—	3	1

Table 2. Materials Selection for the High-Pressure Steam Turbine

Component	566°C	620°C	700°C	760°C
Casings/Shells (valves; steam chests; nozzle box; cylinders)	CrMoV (cast) 10CrMoVNb	9-10%Cr(W) 12CrW(Co) CrMoWVNbN	CF8C+ CCA617 Inconel 625 IN 718 Nimonic 263	CCA617 Inconel 740
Bolting	422 9-12%CrMoV Nimonic 80A IN718	9-12%CrMoV A286 IN718	Nimonic 105 Nimonic 115 Waspaloy IN718	U700 U710 U720 Nimonic 105 Nimonic 115
Rotors/Discs	1CrMoV 12CrMoVNbN 26NiCrMoV11 5	9-12%CrWCo 12CrMoWVNbN	CCA617 Inconel 625 Haynes 230 Inconel 740	CCA617 Inconel 740
Vanes/Blades	422 10CrMoVNbN	9-12%CrWCo	Wrought Ni-base	Wrought Ni-base
Piping	P22	P92	CCA617	Inconel 740

Table 3. Ranking of Overall Materials Needs

Component		Steam Temperature, °C			Major Issues
		620	700	760	
Casing	Materials	3	4	5	Design data; improved alloys
	Manufacturing	3	5	5	Cast vs wrought; process control
Bolting	Materials	1	3	3	Design data; design procedures
	Manufacturing	1	1	1	
Rotors/Discs	Materials	3	3	5	Design data; weldability
	Manufacturing	4	4	4	Melting and fabrication
Vanes/Blades	Materials	3	4	4	Improved austenitics; Ni-base alloys
	Manufacturing	3	4	4	Forging process (modeling)

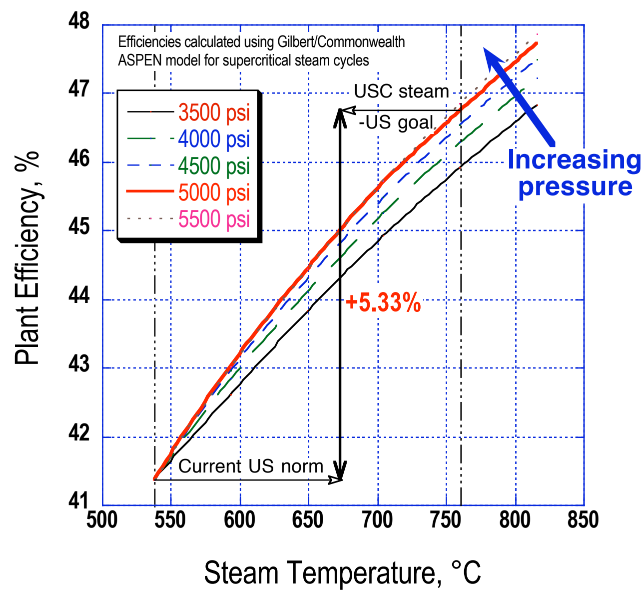

Figure 1. Effect of increasing steam temperature and pressure on cycle efficiency (after White, 1995; and Birks, 1995)

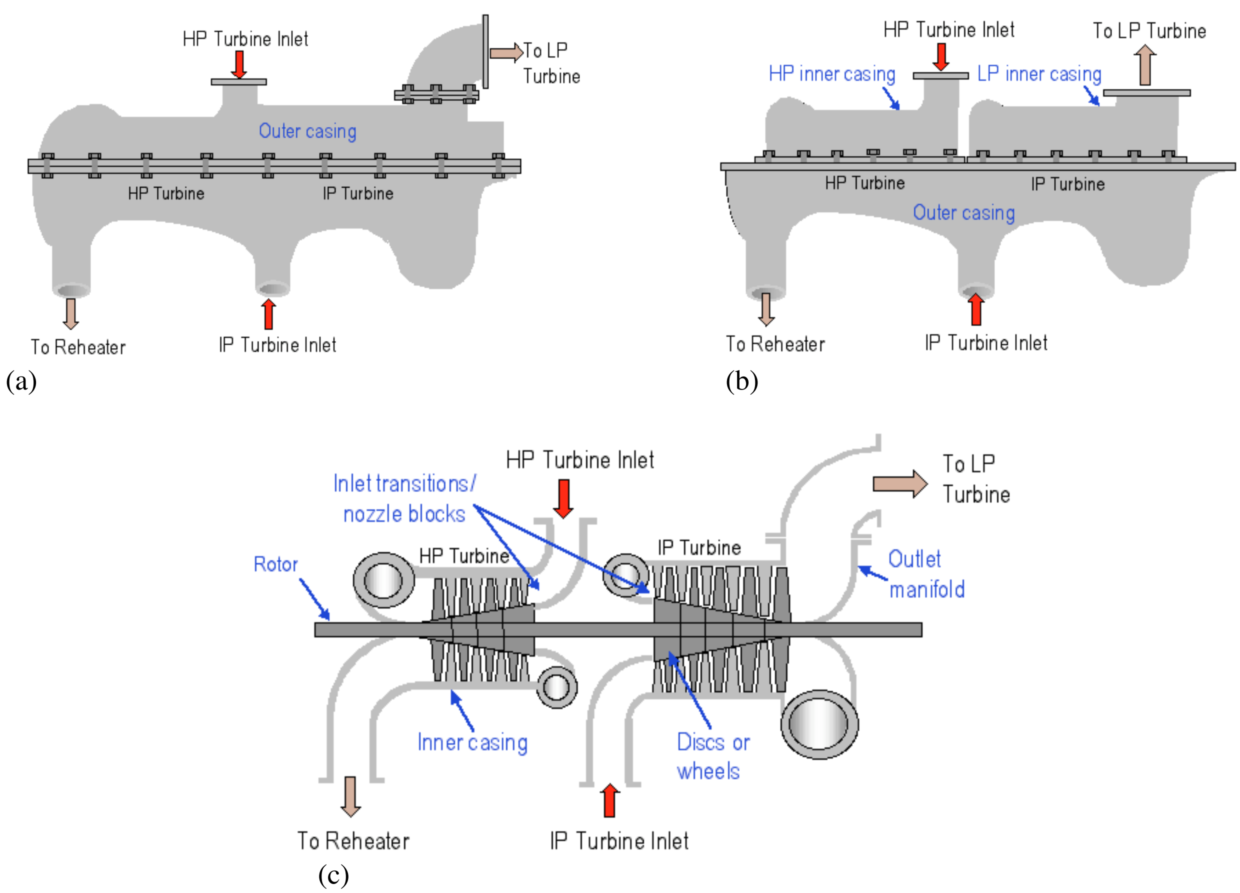

Figure 2. Simplified schematic external view of a steam turbine (a) overall external view; (b) with outer casings removed; and (c) with outer and inner casings removed