Advanced steam turbine technology for improved operating efficiency

Steam turbine efficiency has risen steadily in recent years, largely due to progress in the materials area, improvements to the development software and blade geometries, and modern production methods. As a result, steam power plants from ABB achieve efficiencies in excess of 45 percent. ABB designs steam turbines today for power ratings of up to 1,000 MW with live-steam conditions of 250–300 bar and 580˚C, and a reheat temperature of 600˚C. Proven design features have been retained, guaranteeing high reliability and availability as well as easy adaptation to different operator requirements.

The efficiency of steam power plants can be improved by increasing the live-steam and reheat-steam parameters and by introducing high-efficiency, low-loss turbine blade geometries.

The first goal, to increase the steam parameters, is primarily achieved by choosing appropriate materials for the components operating under live-steam and reheat-steam conditions while retaining the proven designs. Collaborative European programmes have led to the development and qualification of steels with much improved creep properties at temperatures of up to 600˚C, appropriate for the manufacture of key components.

At the same time, optimization of the blade profiles and geometries has allowed a further major improvement in operating efficiency. The chosen approach combined theoretical optimization, involving numerical analysis of the fluid dynamics solutions, and experimental confirmation by means of model and full-scale testing.

Turbine design features

Advanced design concepts and special features of the power plant render ABB steam turbines particularly appropriate for operation under advanced steam conditions.

The *steam admission* is designed as a scroll for all turbine sections, resulting in a low-loss steam flow in the inlet zone and an optimum flow to the first row of radial-axial blading. This first row of blading allows the inlet zone to be kept short, which has a positive effect on the overall length of the turboset. In addition, the thermal stresses acting on the shaft in the admission region are reduced.

Due to the adoption of a *double-casing design* it is possible to distribute the pressure and temperature gradients over two casings, ensuring optimum wall thickness and an optimum flange configuration on the outer casing. Both casings have a simple cylindrical basic shape.

The horizontally split inner casing of the HP turbine is held together by shrink rings. This shrink ring connection ensures a rotationally symmetrical inner casing, fixed axially on the steam inlet plane at the height of the outer casing joint.

The *turbine rotors* are supported by a single bearing between the turbine sections and between the last LP turbine and the generator. The small number of bearings results in a shorter unit with clearly defined critical speeds and bearing loads.

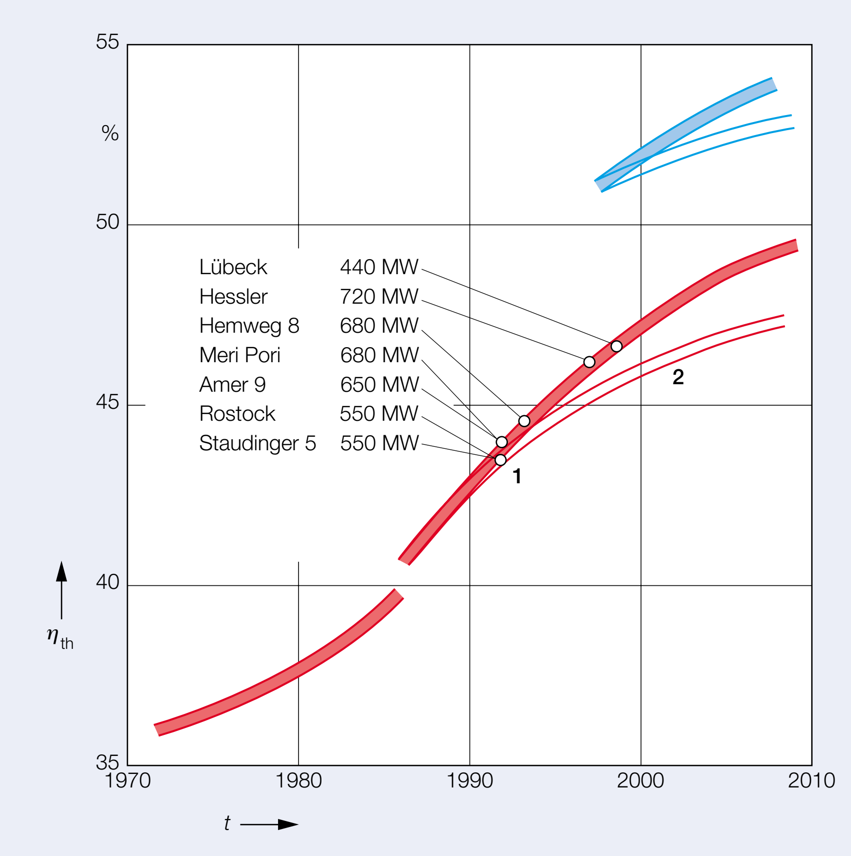
The turbine rotors are made of forgings welded together, as has been the practice for more than 60 years. Today, more than 4,000 shafts manufactured in this way are in operation. The advantages of this design are that it uses small forgings which are easy to manufacture and inspect, the thermal stress level is low and the stresses are evenly distributed, ensuring good thermal flexibility for start-up and shutdown as well as for load changes.

Each *moving blade* and HP and IP *stationary blade* is manufactured from one piece, ie, the blade root and shroud are milled from the same piece of solid bar material. This improves the sturdiness of the design and ensures suitability for two-shift operation, plus excellent reliability (the blade has no component parts) and simple assembly and disassembly. Blades are pretwisted during assembly, thereby minimizing blade vibration during operation.

Efficiency improvement

The achievable improvement in efficiency is about 0.5 % per 10˚C live steam (LS) and reheat (RH) temperature increase, and 0.2 % per 10 bar pressure increase.

Dr. Brendon Scarlin
ABB Power Generation



Improvement in efficiency of coal-fired power plants with high-temperature steam process, referred to the lower heat value **1**

η_{th} *Thermal efficiency, including desulfurization and denox plant*

Red *High-temperature steam process*
Blue *Combined cycle facility with natural gas fired topping GT and high-temperature steam process*

1 *New-generation plants recently commissioned with live-steam data of 250 bar/540˚C and 560˚C reheat*
2 *High-temperature steam process; materials used: forged steel St 10TS, cast steel 10T; live-steam data of 270 bar/580˚C and 600˚C reheat*

Additional measures, such as the introduction of high-performance blading (HPB), allow a further increase in efficiency.

1 shows the recent improvement in plant efficiency of some modern European coal-fired power stations. It is seen that a significant increase of approximately 0.5 % per year has been achieved [1, 2].

2 shows the heat balance of a coal-fired power plant with high-temperature steam turbine exhibiting a net plant efficiency of 46 %.

The final feedwater temperature of approximately 300˚C with a 9-stage feedheating system utilizes the potential of the supercritical steam process to the maximum. It is achieved by means of an extraction point in the blading section of the HP turbine – a concept that has already been used successfully in many plants with 8 feedheaters.

The high steam parameters are mainly facilitated by the choice of newly developed materials for the components operating under live-steam and reheat-steam conditions. The proven turbine and boiler designs remain unchanged.

Material development for turbine components

The step towards more efficient steam power plants called for forged and cast ferritic steels with improved creep strength for the main components. Among the key components exposed to the more demanding steam conditions are the:

- Forged HP and IP rotors
- Cast valve bodies and turbine casings
- Main steam lines

The new ferritic steels should exhibit improved mechanical properties (such as the same creep strength at 600˚C as currently at 565˚C) under similar or simpler processing conditions (eg, casting, forging, bending, welding).

Although the microstructural relationships in creep-resistant steels are well understood, the material characteristics can only be determined by means of long-term tests. The challenge for the materials specialists was therefore to develop new ferritic steels with improved creep strength for the critical components to ensure safe operation with steam at higher temperatures and pressures. The work was undertaken as part of a collaborative development programme by a group of steam turbine manufacturers, forgemasters, casting foundries, utilities and research institutes [3–5].

Potential alloys were identified after a critical review of existing grades of 9–12 % Cr steel, steelmaking developments in Europe and other development activities elsewhere in the world. Trial melts of the candidate steels were produced and subjected to various heat treatments in order to optimize their properties.

The most promising alloys were selected, and used to gain experience in the manufacture of full-size components. To date, three rotor forgings and a valve chest casting have been produced within the programme. They have been subjected to detailed destructive examination to determine their susceptibility to segregation, the variation in microstructure and properties throughout the components, and their longterm performance. Very long-term creep tests (up to 100,000 hours) are most important if the uncertainties inherent in the extrapolation of short-term test results, especially for such very complex alloyed steels, are to be avoided.

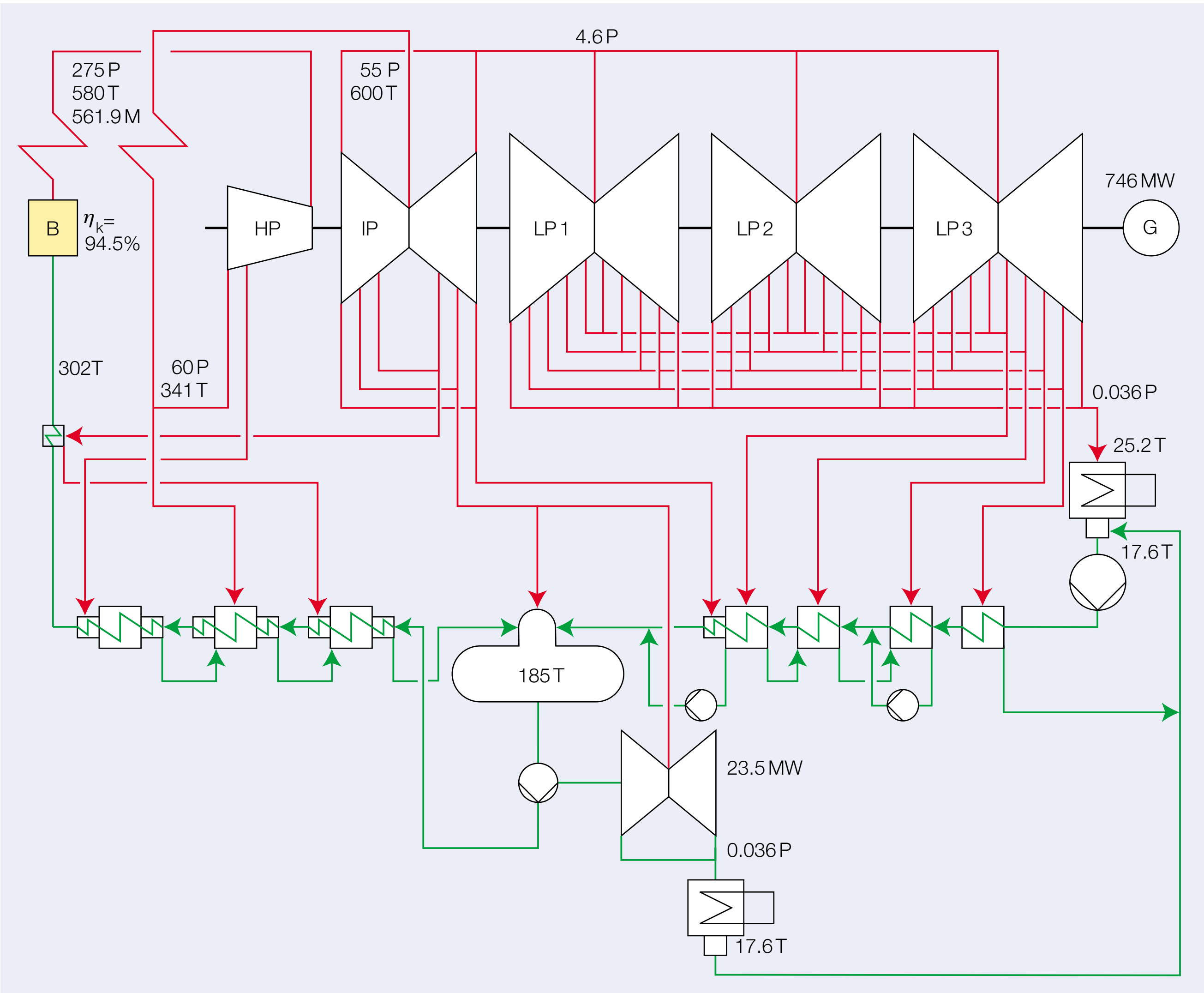
The aim of the research programme has been to develop steels for both cast and forged components with the following properties:

- A creep strength at 100,000 hours and 600°C of about 100 MPa
- Through-hardening to a diameter of at least 1.2 m for forgings and to a wall thickness of up to 500 mm for cast components
- Good casting and welding properties

3 shows the creep strength of the improved 10 % Cr rotor steels in a comparison with the mean value for the conventional 12 % Cr steel according to the German standard SEW 555 data sheet. The currently available results of creep tests at 550 to 650°C, with durations of up to about 60,000 hours, indicate a considerable improvement in the creep strength for 600°C and 100,000 hours.

Heat diagram and heat balance of a coal-fired power plant with high-temperature steam turbine **2**

Fuel	*Hard coal with LHV of 29,300 kJ/kg*	B	*Boiler*	P	*Pressure in bar*
Total output, net	*712 MW*	HP	*High-pressure turbine*	T	*Temperature in °C*
Thermal efficiency η_{th}, net	*46.0 percent*	IP	*Intermediate-pressure turbine*	M	*Mass flow in kg/s*
		LP	*Low-pressure turbine*	η_k	*Boiler efficiency*
		G	*Generator*		



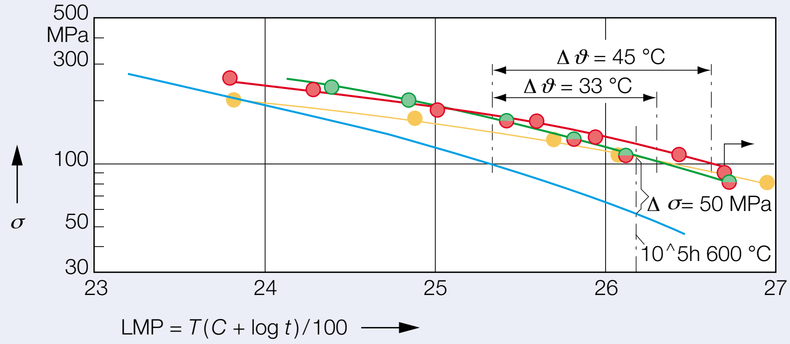
This steel (alloyed with tungsten and molybdenum) is specified by ABB for use in supercritical steam turbines.

Two compositional variants were investigated during the first phase of the steel casting development programme, each containing 1% Mo and one an additional 1% W. The highest creep strength was exhibited by the 1% W variant. Currently, the longest testing time is about 50,000 hours. Based on the available results, a creep strength of about 100 MPa may be expected at 600˚C and 100,000 hours.

ABB has standardized this steel internally and has specified it for use in supercritical steam turbines. Current orders for high-temperature steam turbines include valve bodies and HP as well as IP inner casings which are made of this steel.

The new tube and pipe steel T91/P91

St	C	Cr	Mo	W	V	Nb	N	B	Rp. 0.2 RT
X 21 Cr Mo V 121	0.23	12	1.0	—	0.30	—	—	—	min. 600 MPa
X 12 Cr Mo V Nb N 101	0.12	10	1.5	—	0.20	0.06	0.05	—	~ 600 MPa
X 12 Cr Mo W V Nb N1011	0.12	10	1.0	1.0	0.20	0.06	0.05	—	~ 700 MPa
X 18 Cr Mo V Nb B 91	0.18	9.3	1.5	—	0.27	0.06	—	0.01	~ 650 MPa

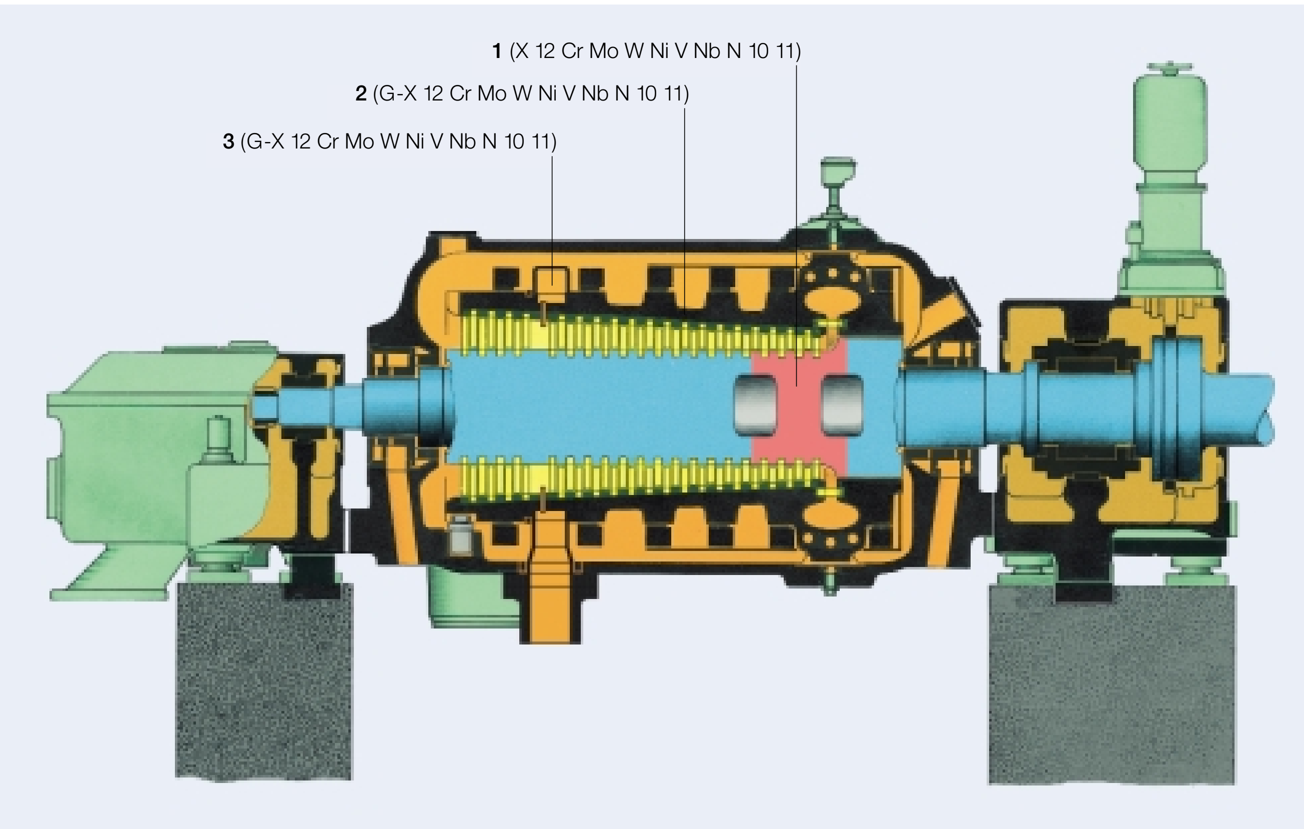


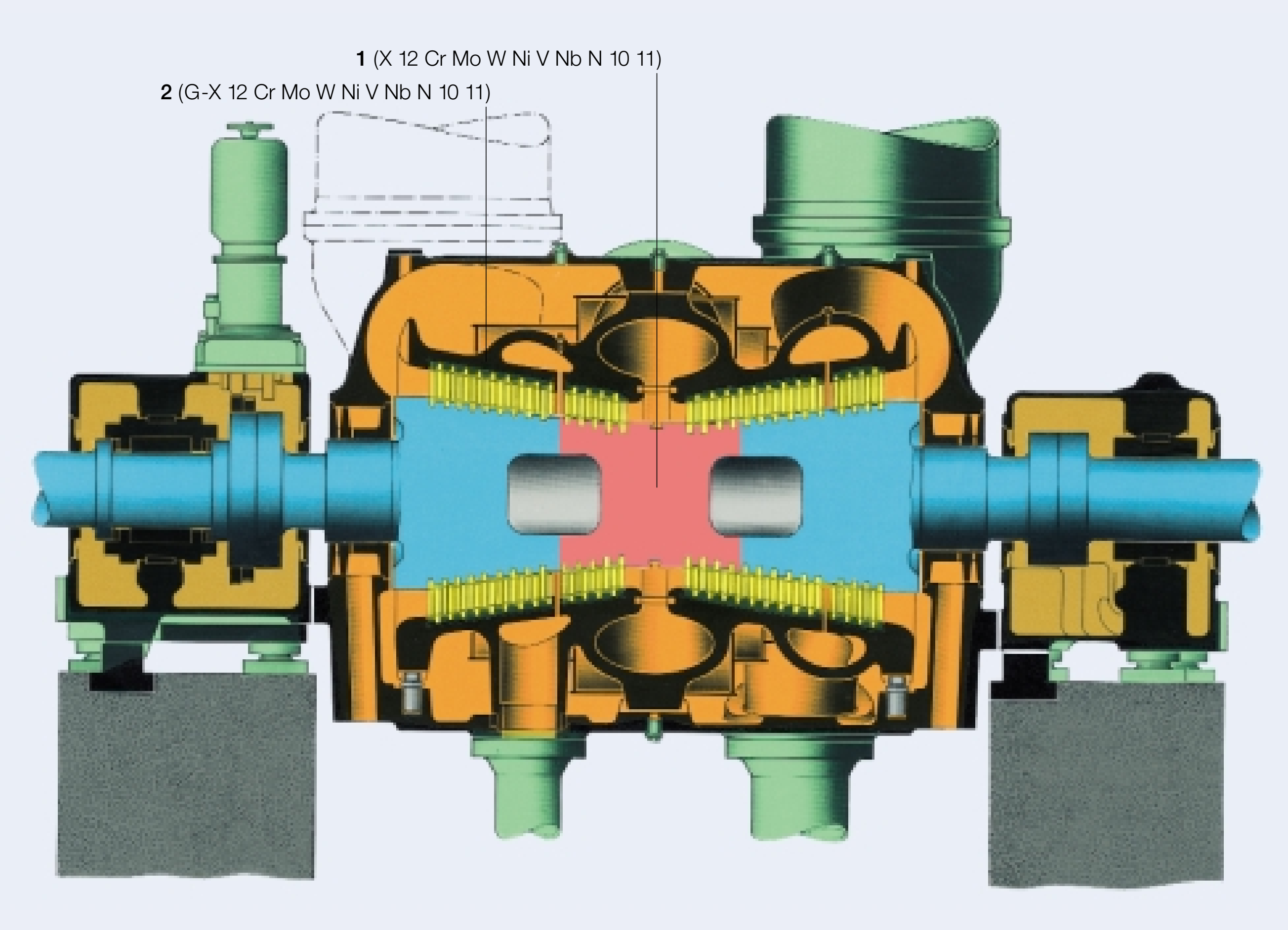
Creep strength of improved 10% Cr forged steels compared with conventional 12% CrMoV forged steel **3**

St	*Steel*	*T*	*Temperature in ˚C*
Rp 0.2 RT	*0.2% yield strength at room temperature*	*C*	*Constant*
σ	*Creep rupture strength*	*t*	*Time in h*
LMP	*Larson-Miller parameter*	$\Delta\vartheta$	*Temperature difference*

Longitudinal section through a high-pressure turbine section, showing the materials used. The shaft ends exhibit no overlay welding; no cooling steam is used. **4**

1 *HP rotor inlet* 2 *HP inner casing* 3 *HP extraction*





Longitudinal section through an intermediate-pressure turbine, showing the materials used. The turbine operates without cooling steam. **5**

1 *IP rotor inlet* 2 *IP inner casing*

(X10 CrMoVNb 91) was developed by Oak Ridge National Laboratory and is standardized in the USA (ASME Code). To determine long-term values for design purposes, long-term creep tests were performed. Meanwhile, running times of over 70,000 h have been recorded in European testing programmes. On the basis of these results, values for the 100,000 h creep strength were obtained which are higher than those of the X20 CrMoV 12 1. A temperature improvement vis-à-vis X20 CrMoV 12 1 of almost 30˚C is possible. Extensive tests have demonstrated the simplicity of cold and hot bending as well as welding of T91/P91 tubes.

Proven design principles

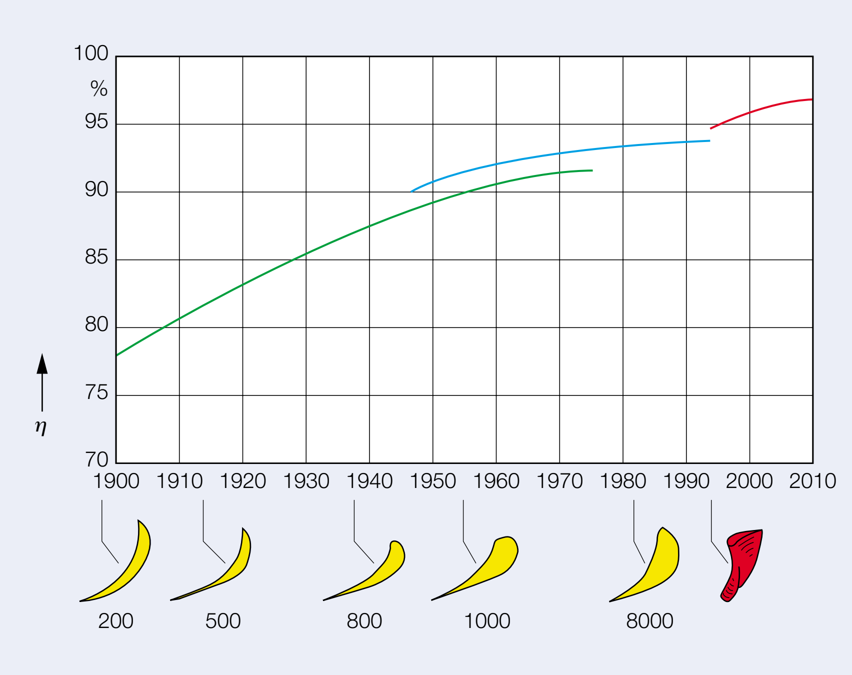
The main design features of the *HP turbine section* for the high temperature process are shown in **4**. The proven design principles of this turbine series can be applied without any modification. Only the inner casing, valve bodies and middle rotor section are manufactured from the new 10 % chromium steels.

Since the steam expands and cools in the direction of the rotor ends, a low-alloyed 1 % CrMoV steel is used in these regions. Because of the good running properties of this steel, there is no need for overlay welding of the rotor journals, which are stressed by bending and torsion. The weld between the high-alloyed and low-alloyed steel is made using conventional methods and filler metal. Operating temperatures and loads do not exceed the usual present-day values.

Additional advantages of the welded rotor are:

- Simplicity and accuracy of non-destructive testing
- Wide selection of forging suppliers
- Uniformity of mechanical properties and high toughness value

An advantage for medium-load operation results from the rotationally symmetrical inner casing constructed with a shrink-ring connection. By avoiding non-uniform wall thickness, no inadmissible high

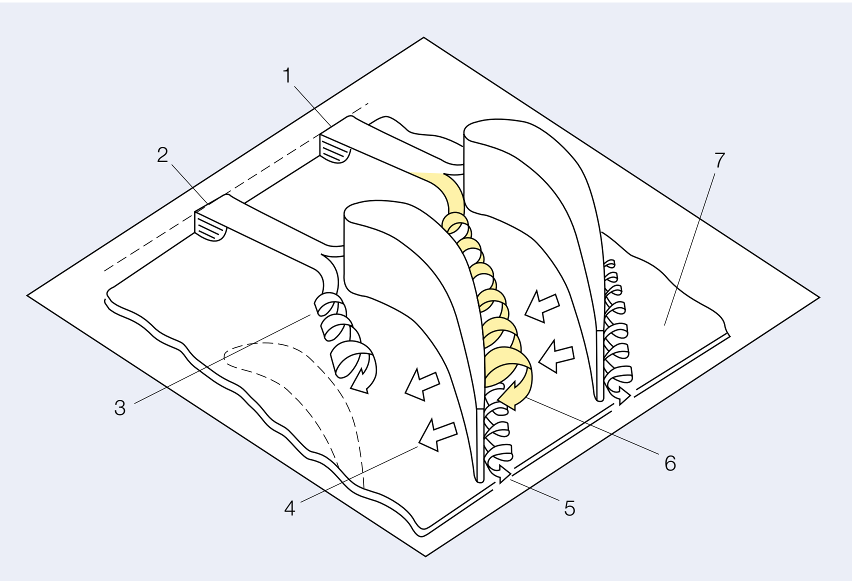


Development of the blade efficiency η **6**

Green *Without shroud*
Blue *With shroud*
Red *High-performance blading*

Schematic model of the secondary flow near the end-wall of a turbine blade row **7**

1 *Stream surface*
2 *Inlet boundary layer*
3 *Pressure side horseshoe vortex (becomes passage vortex)*
4 *End-wall crossflow*
5 *Suction-side horseshoe vortex*
6 *Passage vortex*
7 *End-wall*



thermal stresses and hence plastic deformations occur. Situated in the HP exhaust, the shrink rings are always cooler than the inner casing and the necessary shrinkage force is maintained under all operating conditions. Thus, the load change and start-up gradients of this design do not differ from those for turbines operating with lower live-steam temperatures.

The *diffusers* which pass the steam from the inlet valves to the HP turbine are of the free-expanding type and equipped with piston ring sealing elements in the inner casing. They are also cooled by HP exhaust steam. The advantage is that no part of the outer casing is exposed to the live-steam temperature. This means that the HP extraction required for the process can be achieved with very little effort. Such an extraction concept has already been employed in many steam power plants.

The *IP turbine section* operates with an inlet temperature of 600˚C. Despite the high reheat temperature, the entire design concept can be adopted without change.

5 shows the material changes in the IP turbine section. Only the inner casing, the valve bodies and the middle rotor section are made of the new 10 % chromium steels. The halves of the IP casing are held together by bolts which are cooled by exhaust steam from the IP turbine. They can be manufactured from the usual steels as their temperature does not exceed approx. 500˚C.

The *LP turbines* operate under conventional steam conditions.

High-performance blading – aims and general concept

Development of the stationary and rotating blades is ongoing and has advanced the efficiency of the turbines considerably over the years. Important boundary conditions here include keeping the root and shroud geometries the same as for the current series 8000 blades and maintaining the axial spacing between the blade rows to facilitate retrofitting of existing ABB machines with high-performance blading (HPB).

An increase in efficiency can be achieved by introducing blades with optimized airfoils. These improve the heat rate by minimizing the flow losses. New processing and manufacturing techniques help to prevent cost increases, while milling the blade with integral root and shroud from solid bar ensures highest quality. The development concept is based on fluid dynamics computations, systematic heat rate testing in a test turbine, and full-scale power plant verification.

The current blade form (8000 series) was arrived at as a result of many years of development work 6, different profiles having been developed and introduced periodically since the beginning of the century [6]. When it was introduced in 1980, the 8000 series profile offered a number of new features, all of which contributed to a simpler design, more economical production, mechanical rigidity and a high level of stage efficiency. These features are:

- Insensitivity to inlet angle variations
- An optimized controlled diffusion zone
- A thin trailing edge

3D airfoil development

The development of a generalized airfoil concept was prompted by two major factors:

- The emergence of powerful computing tools for the numerical analysis of 3D viscous and compressible flow in turbomachinery.
- The parallel development of advanced computer integrated manufacturing technologies.

The use of advanced computing tools has improved the understanding of the physical phenomena and permitted an acceleration of the traditional experimental development process. Considerable effort was invested in fluid dynamics computations [7, 8] aimed at determining steam core flow patterns through the blade rows and in the vicinity of the end-wall. The classical model of secondary flows [9] is shown in 7. Vortex interaction is very effective in dissipating kinetic energy, and hence particularly harmful.

An approximate breakdown of the efficiency losses arising from end-wall secondary flow, profile shape and clearance flow exists. Whereas the profile losses are the same in the HP, IP and LP turbines, the end-wall losses and clearance/leakage losses are highest for the shortest HP turbine blades. While previous blade types have been cylindrical in shape (parallel sided), the fluid dynamics calculations showed that improvements could be obtained by introducing further degrees of freedom in blade shape (ie, variable profile shape, twist and lean 8) to take account of the non-uniform flow and pressure distribution over the blade height. 9 shows a typical example. The following strategy was adopted:

Stator blades

- Variable airfoil sections
- Twisted and bowed airfoil

Rotor blades

- Variable airfoil sections
- Reverse twist, no bow

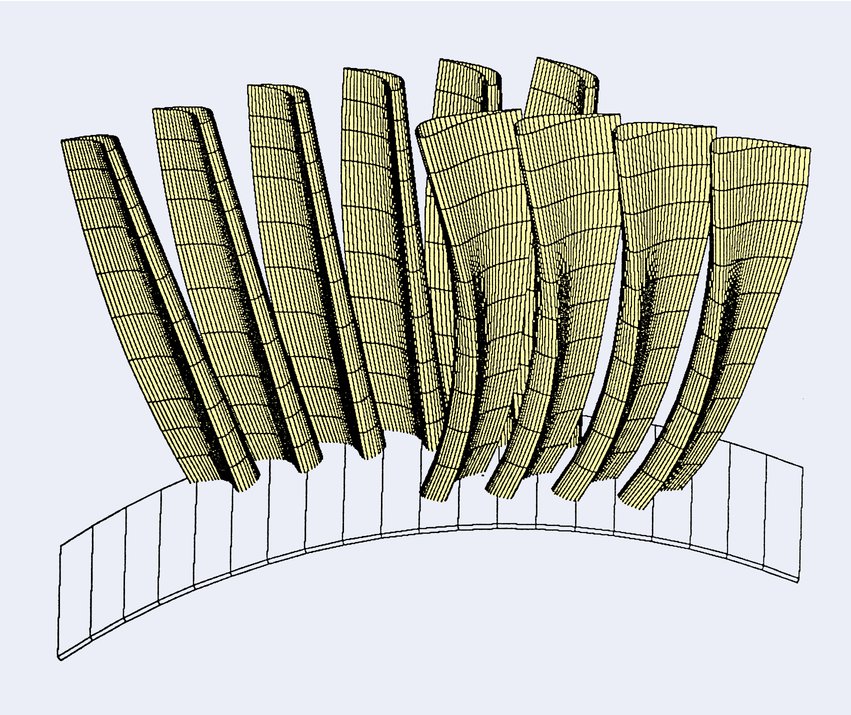
High-performance blade with profile twist and lean to take account of non-uniform flow and pressure distribution over the blade height 8

Clearance losses

In the reaction blading, the degree of reaction (the relative pressure drop in the rotating row) is on average 50 percent. However, it varies from about 40 percent at the hub section to 60 percent at the tip. This distribution implies that 60 percent of the stage pressure drop occurs at the shroud seals of the prismatic (cylindrical) stator and rotor blades, resulting in high leakage losses. A more favourable reversal of the distribution of the degree of reaction (ie, 60 percent at the hub and 40 percent at the blade tip) can be achieved by increasing or reducing the twist of the stator and rotor blade airfoils by an appropriate amount, thereby reducing the leakage losses.

End-wall losses

Frictional losses which occur in the side-wall zones of the turbine flow channel are amplified by the secondary flows [10]. As a result, the flow losses concentrate in the end-wall area. The interaction of the re-entering leakage flows is also an important factor in the generation of the losses. The secondary flow is an unavoidable consequence of the deflected flow in the blade channel. However, the effect on the side-wall



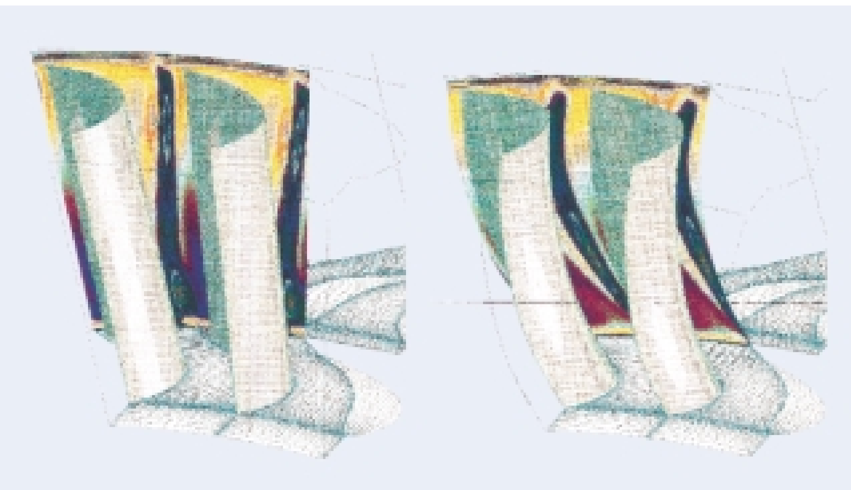
Computer representation of a high-performance blading stage **9**

losses can be attenuated by choosing an appropriate local profile section and blade shape. One known possibility is to lean the blade in the circumferential direction [11]. Applied to the hub and tip, such a modification leads to a bowed blade form. To ensure adequate mechanical strength, this stacking strategy is only applied to the stator blades. Since blade twist also affects blade lean, the complex optimization of a 3D airfoil in the end-wall region involves matching of lean, twist and profile shape.

Early successful development work on single-stage turbine blading with 'vortex control' [12] was based on the concept of reducing the load on the blade ends by reducing the specific stage work through a combination of reduced blade camber and associated lean. However, the conditions in multistage turbines inevitably produce a radially uniform stage work distribution which is independent of vortex control.

As illustrated in **10**, the passage vortex associated with the secondary flow appears radially stretched downstream of the blade row. This reduces the dissipation of energy and the familiar over/underturning of flow caused by the passage vortex.

Effect of vortex control on passage vortex (theoretical calculation) **10**

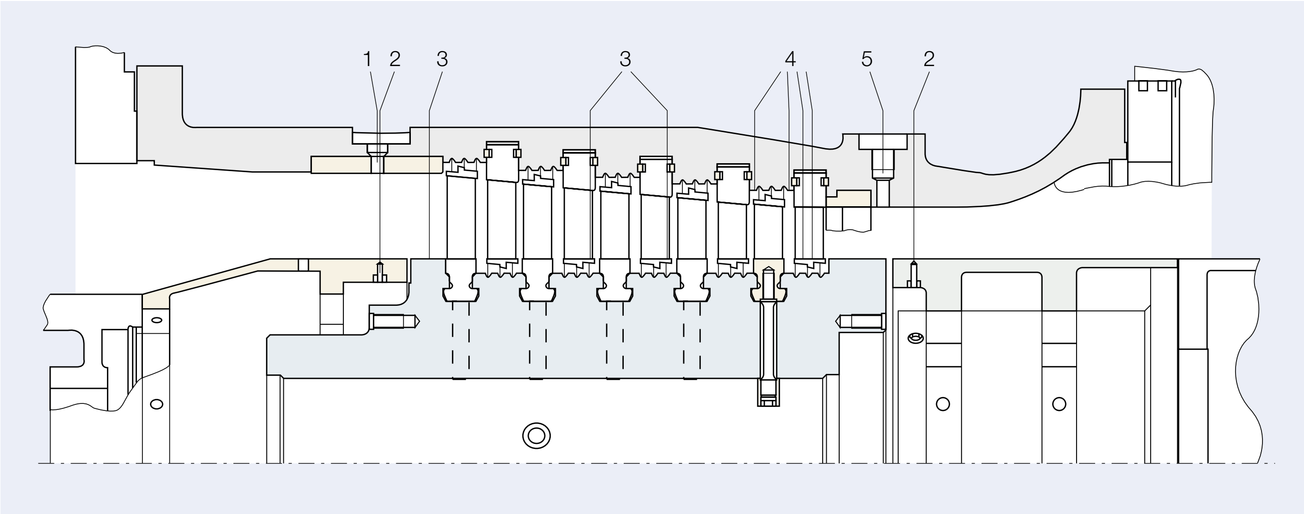


Model test turbine supports development work

The model test turbine is a crucial element in the development process in that it serves to validate the computing tools as well as quantify the performance of the blading. The test rig has to facilitate stage performance measurement under the proper boundary conditions, ie, the natural flow environment encountered in a multistage turbine. Such conditions are best achieved in a multistage test configuration composed of similar (repeating) stages **11**. The results obtained with this air-driven rig are then scaled for application to power plants, where field measurements supplement the database.

In addition, the validation of computing tools calls for detailed measurement of the flow field. This is accomplished by means of aerodynamic probes traversing at various locations and by numerous static pressure taps located at the internal flow boundaries.

The establishment of representative flow conditions near the end-walls is important for the numerical optimization as well as for the experimental evaluation of the airfoil design. The numerical modelling is based on 3D Navier Stokes codes and must account for the inter-



Section through the model turbine test rig **11**

1 *Fixed probes*
2 *Static pressure*
3 *Probe*
4 *Stage pressure, all rows*
5 *Intrascope*

ference of clearance flow and the cumulative effects of repeating stages.

Advanced manufacturing process

An efficient production process is the key to successful exploitation of the performance improvement of 3D airfoils as it makes the necessary design flexibility affordable. ABB steam turbines are custom-designed with optimized flow-path geometry. This implies an infinite variety of stator and rotor blades within the given frame of application.

Computer-integrated manufacturing (CIM) requires a complete specification of the entire blade geometry as a continuous surface, including the local slope and curvature and the additional attributes of dimensional tolerance and surface finish. It is generated automatically from the engineering design parameters for the optimized blade row.

Manufacturing takes place in fully automated, high-precision production cells to ensure the high quality standard demanded by the market. All the manufacturing documents, such as production plans and numerical control programs, are generated automatically.

Higher overall efficiencies

12 shows the efficiency values that are achievable for coal-fired steam power plants. The efficiency of 46.0 % achieved with single reheat and 46.7 % with double reheat represent a major improvement. The improved figures are due to a number of factors:

- Improved boiler efficiency
- Introduction of high-performance blading
- Reduction of leakage losses
- Improved cycle efficiency through the use of a feedwater pump turbine
- Increased live-steam and reheat-steam pressure
- Cold-end optimization with improved condenser pressure
- Increased live-steam and reheat-steam temperature
- Increased final feedwater temperature
- Use of 9 feedheaters

Steam turbine technology for today's market

Major efficiency improvements have been achieved in recent years. From the results of the material development programmes it is seen that for piping, forgings and castings, steels are now commercially available with much better properties than the materials used previously. For such parts, the newly developed steels offer considerable advantages with regard to temperature. This benefit can be fully exploited whilst retaining the proven design features of ABB turbines.

The better thermal characteristics of the steels, combined with the improvements obtained by optimizing the blade profiles and geometries, allow ABB to offer power plants that meet the current market requirements in every way. Expressed in figures, these include:

- Outputs of 400–1,000 MW
- Live-steam data of 250–300 bar/580˚C
- Single reheat temperature of 600˚C

in each case with a relative heat rate improvement of at least 7–8 percent.

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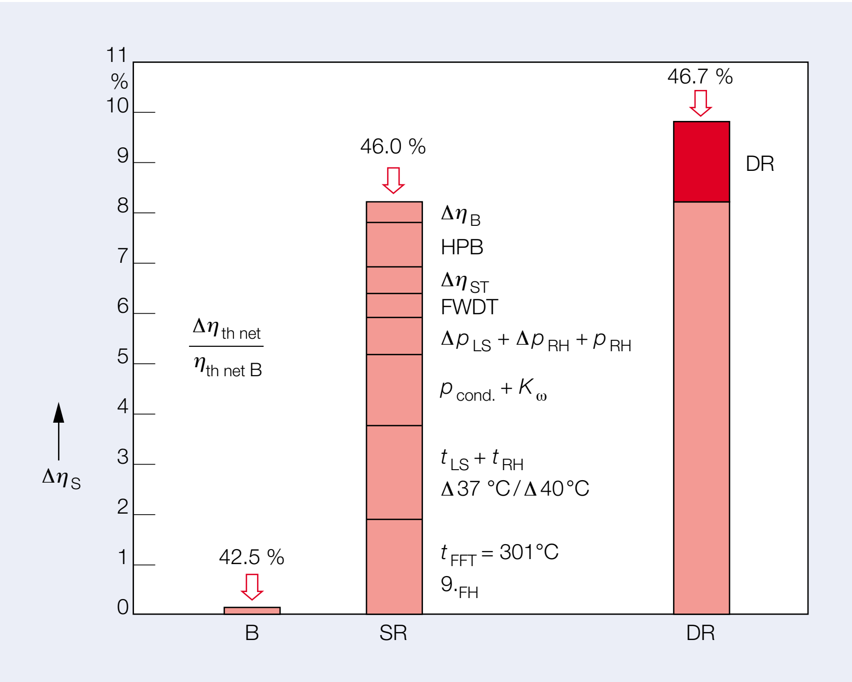
Possibilities for improving the efficiency of coal-fired steam power plants **12**

η_{th}	*Thermal efficiency*
$\Delta\eta_S$	*Improvement in efficiency*
B	*Basis*
SR	*Single reheat*
DR	*Double reheat*
$\Delta\eta_B$	*Improvement in boiler efficiency*
HPB	*High-performance blading*
$\Delta\eta_{ST}$	*Leakage losses reduced*
FWDT	*Feedwater drive turbine*
$\Delta p_{LS} + \Delta p_{RH} + p_{RH}$	*Higher pressure of live and reheat steam*
$p_{cond.} + K_\omega$	*Condenser optimized and condenser pressure improved*
$t_{LS} + t_{RH}$	*Live- and reheat-steam temperature increased*
t_{FFT}	*Final feedwater temperature raised to 301 °C*
$9._{FH}$	*Use of 9 feedheaters*



Author's address

Dr. Brendon Scarlin
ABB Power Generation Ltd
CH-5401 Baden
Switzerland
Telefax: +41 56 205 56 05