Low-pressure steam turbine retrofits

LP steam turbine retrofits are generally undertaken as a result of mechanical problems, for example due to stress corrosion cracking, torsional vibration or erosion. They present plant operators with an opportunity to introduce advanced aerodynamic technology, and at the same time improve efficiency and availability. Standard components, the majority proven in long-term service, can be used to obtain a permanent solution to the problems. In several European countries, retrofits have been carried out on intact LP steam turbines owned by utilities whose primary motivation is efficiency improvement.

Economic power generation calls for power plants that exhibit long lifetimes at high levels of availability. In recent years, the power industry has experienced frequent cases of deficient OEM design, often with the result that the required availability was no longer being achieved after a number of years. A case in point is the low-pressure steam turbine.

Numerous reports have appeared that deal with specific low-pressure (LP) turbine problems. While the problems have essentially concerned the strength of the rotors, disks and blades [1, 2], the dynamic design of the shaft line has also been a cause of failure [3]. In addition, steam expansion in zones where the moisture level is high can lead to water droplet impingement and loss of material from blades and blade carriers. Expensive repair work may have to be carried out as a result.

Many plant operators tackle such problems by installing an updated version of the original design. Often, this is available from the original equipment manufacturer (OEM) and forms part of his spare parts business. There are also operators, however, who prefer completely different technical solutions, developed and installed by other companies. In such cases, the operators benefit from the substantial progress that has been made in the area of aerodynamics in recent years. Besides solving the original mechanical problems, these solutions also improve the efficiency, allowing payback of the cost of modification in just a few years. A recent market trend which is especially evident in Europe is towards LP turbine retrofits which are driven entirely by the desire to improve the efficiency.

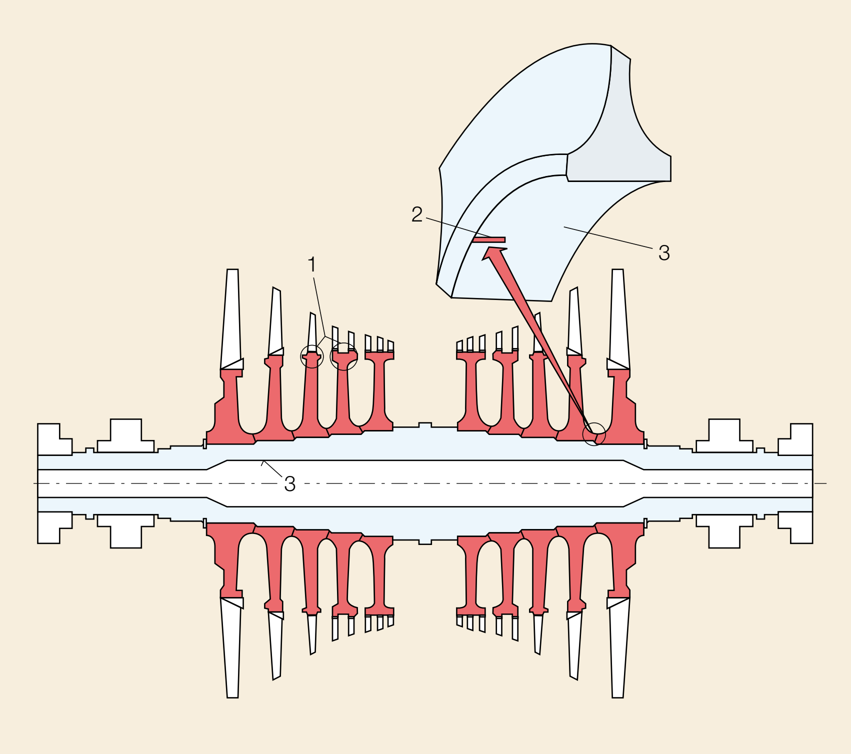
Examples are given in the following which highlight possible retrofit solutions to problems caused by stress corrosion cracking, torsional vibration and erosion. In all of the cases described, it will be seen that advantage can be taken of proven technologies and that predominantly long-term-tested standard components can be used. Thorough investigation of the original weaknesses in the OEM design of older LP turbines has made it possible to match the retrofit solution exactly to the conditions existing in the plant, and hence totally eliminate the problem area.

Edwin Krämer
Hans Huber
Dr. Brendon Scarlin
ABB Power Generation

Stress corrosion cracking

Stress corrosion cracking of steam turbine rotors in both nuclear and fossil-fired power plants has been receiving considerable attention for many years because of the large number of cracks which have been detected in the course of inspections and, more dramatically, because of occasional rotor bursts [1]. Early surveys showed that the problem existed worldwide and involved all manufacturers of LP rotors with shrunk-on disks. Specifically, an analysis of keyway inspections in one manufacturer's turbines showed that 96 percent of the boiling water reactors' and 36 percent of the pressurized water reactors' LP turbines showed signs of stress corrosion cracking. Moreover, the signs were not limited to the keyway and shrink-fit areas, being also found in the disk rim and blade attachment area **1**. A detailed analysis of the cracks observed showed that cracking rates were highest for materials with a high yield strength. Depending on the temperature at the crack location, the apparent propagation rate can as high as 25 mm (one inch) per year. It was estimated that safe operation would only be possible providing inspections are carried out at unrealistically short intervals. A plant operator's recent publication [4] states that the lifetime of such LP rotor disks can be as short as 10,000 hours, and that propagation rates even higher than those predicted by laboratory tests occur.

2 gives an overview of the observed crack depths known from the literature



Problem areas for LP steam turbine rotors with shrunk-on disks **1**

1 *Blade attachment*
2 *Keyhole*
3 *Shrink-fit area*

and other sources. When considering crack depths in actual turbines, it must be borne in mind that the time at which initiation takes place is not known. This means that the actual cracking rate is greater than that generally calculated on the basis of the full operating time. The following rules were adopted for the evaluation of the data in the literature:

- A maximum of two cracks from the same unit were considered. This was to avoid putting too strong an emphasis on a specific unit type.
- Cracks were detected in different zones of the LP disks (keyways, shrink areas, blade fixation, edges). The data were not classified according to location, since it has not been proved that there are significant differences in the crack depths detected at the dominant crack locations.

In three cases repeat measurements were performed on cracks that had been observed and measured during an inspection, after which the turbine was allowed to remain in service until a later inspection. This made it possible to determine the true propagation rate. The highest rate in the three cases lies at 7.0 × 10^{-10} m/s (ie, 21 mm per year).

It is also important to note that, in the light of more recent observations, empirical formulas based on the operating temperature and material yield strength, and dating from 10 years ago, no longer offer any safety margin at all when used to predict cracking rates for turbines in service. In other words, turbine rotors in which cracks of this kind have been observed can no longer be run with the required margin of safety.

Observed crack propagation rates for LP turbine rotors **2**

D *Maximum crack depth*
t *Operating time*

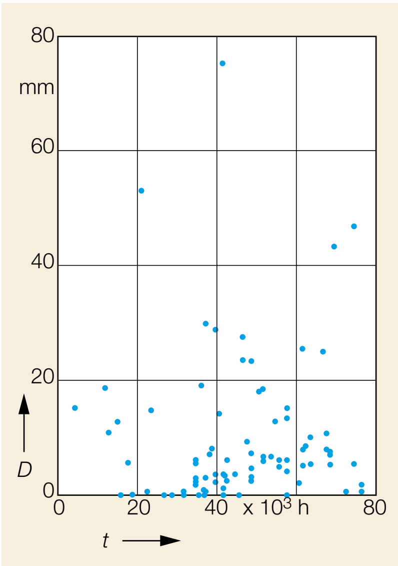
Stress corrosion cracking is avoidable

For stress corrosion cracking (SCC) to occur, three conditions must be satisfied: a sufficiently high *tensile stress* must be applied to a susceptible *material* in a corrosive *environment.*

Different LP rotor designs have different stress levels and feature different materials.

In the design area there are various ways in which the risk of SCC can be minimized:

- *Tensile stress:* Reduction is possible by lowering the service stresses, avoiding shrink-fit stresses and minimizing residual tensile stresses.
- *Environment:* Stagnant conditions should be avoided, for example in crevices and particularly in areas with higher stress levels.
- *Material:* The yield strength of the material should be minimized and a steel grade which is less susceptible to SCC should be chosen.



The ABB LP rotor design employs an entirely different approach which completely avoids the problem of stress corrosion cracking. The rotor consists of solid disks welded together at their periphery in the region of lowest stress. There are no crevices for corrosive contaminants to concentrate in, nor regions of higher stress, such as keyways or center bores. Welded turbine rotors of this kind have been used for over 60 years [5]. More than 4,000 such rotors have been delivered. Some of the nuclear LP turbine rotors have been in operation for over 200,000 hours, and more than 50 LP rotors have been running for more than 150,000 hours. An SCC failure has never occurred in such a rotor. **3** shows the basic differences in the design of the welded rotor and the rotor with shrunk-on disks.

LP rotor retrofits have been undertaken in many cases where SCC has occurred and the remaining lifetime was very short. The most successful approach has been to replace the cracked rotor by one of welded design. For example, in 1986 ABB replaced LP turbines installed by a US vendor in the Zion power plant. The rotors in this plant had cracked after only 6 years of operation. Inspection showed that the retrofitted welded LP rotors still showed no signs of SCC after 47,000 hours of operation. To date, ABB has delivered 70 such LP rotors for retrofit projects with a total installed rating of more than 20 GW. Orders for a further 24 LP rotors are currently being processed.

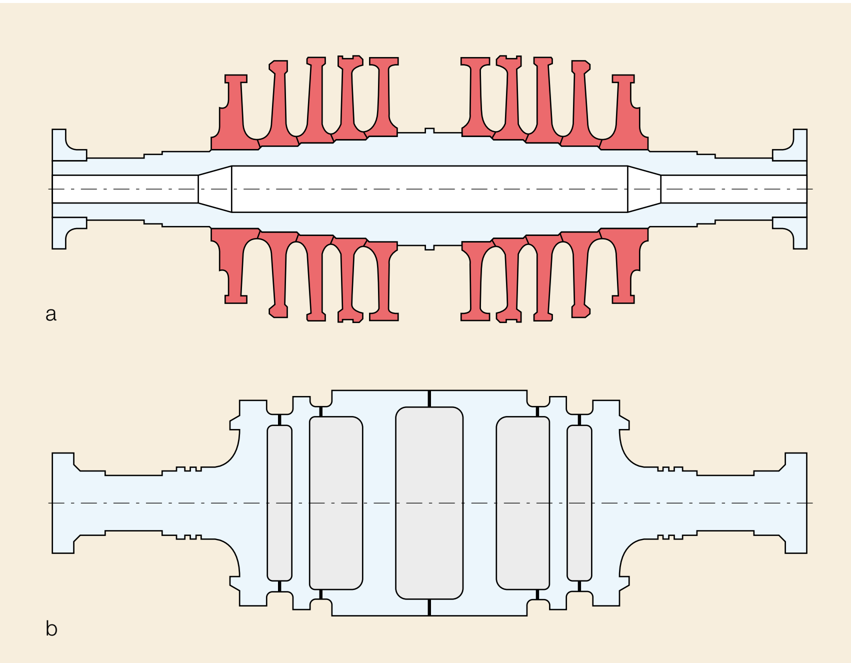
Torsional problems with turbine shafts

After severe damage to a turbine generator that included failure of several last-stage blades in Taiwan in 1985, the power industry became aware of a problem which it had thus far underestimated. Since the natural frequency of the last-stage blades is close to double the grid frequency, blade vibration, which occurred quite often on account of the limited capacity of the power network, caused resonances that produced excessively high dynamic stresses in the blade root fixations.

Initial repairs were carried out by the original supplier, who used a design similar to the original but which strictly limited the tolerable grid frequency bandwidth. During the search for a long-term solution, for which the customer required a turbine generator with no natural frequencies in the range of 120 ± 6 Hz, it was found that the LP rotor design was a strong influential factor [3]. The higher vibration mode of the turbine generator and the last-stage blades was only one of three which had been close to 120 Hz **4**. The LP rotors, generator rotors and the last-stage blades made a significant contribution to all three modes.

Rotor designs for LP steam turbines **3**

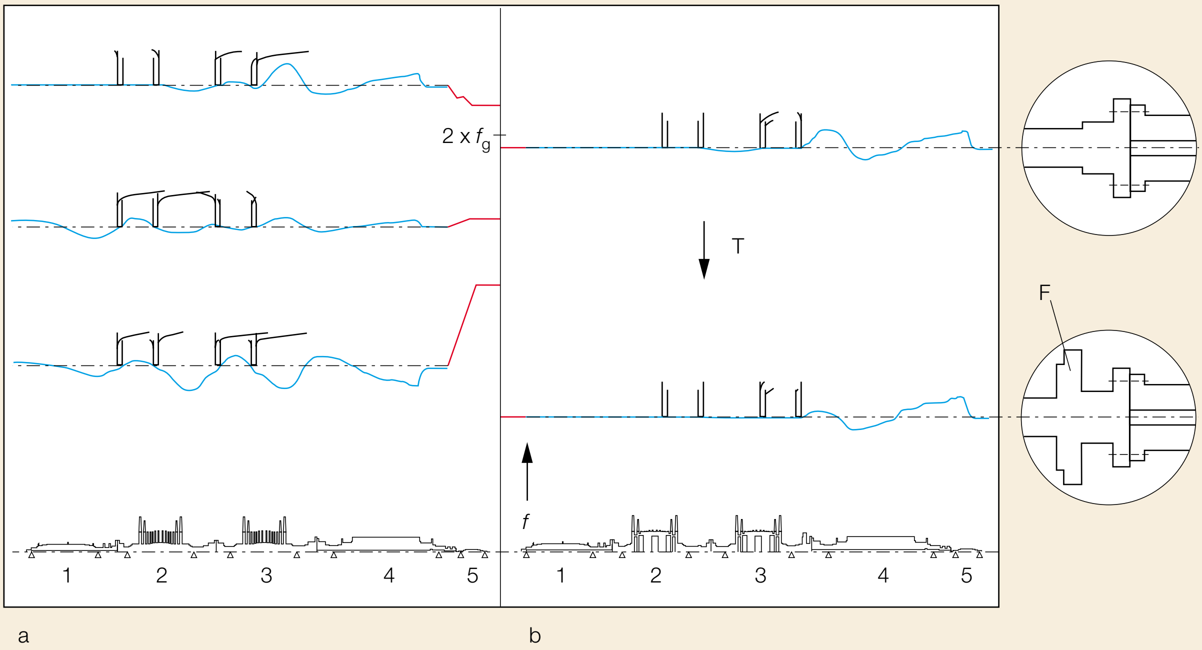
a *Shrunk-on disk rotor*
b *Welded drum-type rotor*



Solving the torsional problems

By replacing the original shrunk-on LP design by the stiffer welded drum-type rotor, the interactions between the blades and the rotor could be avoided. This eliminated the limitations imposed by the resonant frequencies of the blades **4**. However, the generator rotor's second mode remained close to double the grid frequency. This mode could be brought below the prohibited range only with the help of a large flywheel integrated in the LP turbine next to the generator.

To verify the calculated and guaranteed frequencies, torsional vibration measurements were carried out on site. A permanent short circuit on the high-voltage side of the step-up transformer, in combination with low power excitation of the alternator field, provided a 4th harmonic torsional excitation of the shaft. By slowly accelerating the machine up to 110 percent of rated speed, all natural frequencies of the shaft up to 132 Hz



Resonant frequencies for different LP rotor designs **4**

a *Disk-type rotors*
b *Welded drum-type rotors*

f *Frequency*
f_g *Grid frequency*
T *Tuning*
F *Flywheel*

1 *HP turbine*
2 *LP turbine A*
3 *LP turbine B*
4 *Generator*
5 *Exciter*

could be excited. Signals were taken off strain gauges on two last-stage blade rows and at two locations on the shaft. All the modes could be clearly identified (*Table 1*). The measured frequencies confirmed the predicted values, demonstrating that torsional problems are eliminated even under unfavourable conditions by a welded drum rotor exhibiting high torsional stiffness.

Erosion problems

A variety of erosion problems can arise in wet steam areas [6]:

- *Water droplet impact erosion*, primarily of rotating last-stage LP turbine blades.
- *Surface erosion/corrosion* in cross-over pipes, and particularly in LP casings and blade carriers.
- *Wire drawing* (crevice erosion) due to steam leakage in sealing areas.

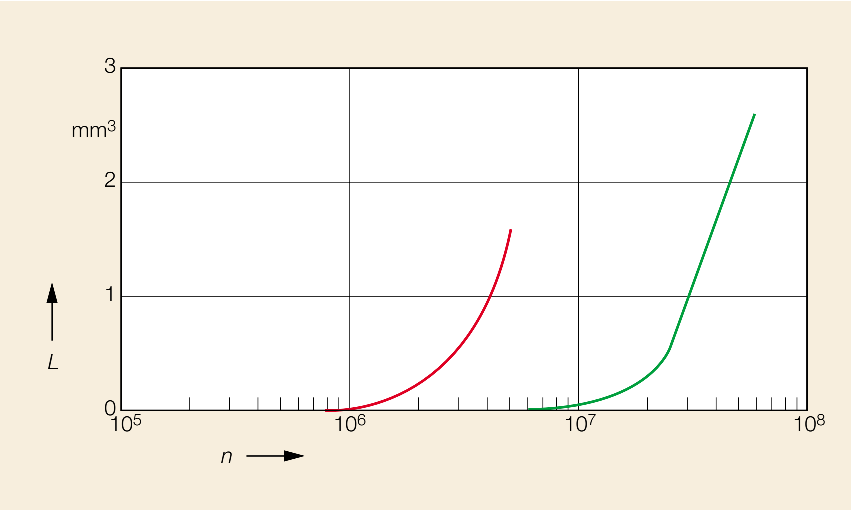
Water droplet erosion

This problem can be solved through the use of 12 % Cr steel blades with induction-hardened leading edges where the water droplets impact the rotating blade. **5** shows the results of laboratory tests in which water droplets of certain sizes impact the surfaces of selected specimens at high velocity. The weight loss of the specimens is measured as a function of the test duration. The superiority of the induction-hardened 12 % Cr steels over non-hardened material is apparent. Unlike the solutions with protective shields, this solution does not require milling work on the blade, which could impair its mechanical integrity. Problems such as erosion of the softer brazing material, loss of the shield or the use of

Table 1: Calculated/measured torsional frequencies

Mode	Torsional frequency Calculated Hz	Measured Hz
1	9.6	9.6
2	18.2	*)
3	19.2	19.2
4	22.7	22.4
5	68.6	68.6
6	69.4	70.0
7	72.5	71.6
8	110.4	111.7
9	129.0	129.7

*) Not measured (exciter mode)



Effect of induction hardening on the erosion/corrosion resistance of blading steel **5**

n *Number of water droplet impingements*
L *Volume loss*

Red *Untreated*
Green *Induction hardened*

Water droplet size 0.2 mm
Impingement velocity 300 m/s

shields containing cobalt in BWR power plants are eliminated from the outset when the leading edges of the blades are induction-hardened.

Surface erosion/corrosion

These phenomena can lead to a major loss of material on certain components, especially at high moisture levels in the medium temperature range (eg, in LP turbines without a reheat stage). Generally, higher alloyed materials and, where possible, steam with a higher oxygen content and pH value, have a positive effect since, under such conditions, an erosion/corrosion-resistant magnetite film forms on the surfaces. At the same time, the turbine should be designed to ensure a homogeneous, low-velocity, streamlined flow, without any local excesses in the steam flow rates. Because of this, the risk of erosion varies for the different components:

A moderate risk of corrosion/erosion exists on the crossover pipes, inside the extraction components and on the back of the blade carriers. This does not generally endanger the machine parts themselves. The chief negative effect is that the iron content in the steam cycle increases (particularly in BWR plants). Use of low-alloy steels or spray coatings will avoid or even eliminate the removal of material through corrosion/erosion.

A strong risk of corrosion/erosion exists in certain areas on the inside of the blade carrier in cases where high steam flow rates and moisture exist in a certain, sensitive temperature range. Local damage can be minimized with the help of erosion-resistant spray coatings or rings made of 12 % Cr steel. The best results are achieved when components such as the blade carrier are manufactured from 12 % Cr cast steel.

Wire drawing

Wire drawing occurs at connecting points, but only in cases of leakage in the sealing gaps in the wet steam area and with high pressure gradients. Risk is greatest at the horizontal connecting flange and the blade carrier suspension points. This type of erosion is more aggressive than any other and can cause massive local cavitation in a very short time. Besides having a negative effect on the turbine efficiency, it also impairs the strength and operational reliability of the component.

The standard ABB design has proved to be an outstanding success for LP turbine retrofits for reasons that include the following:

- It is free of distortion, does not hinder expansion and ensures a tight seal, thereby allowing low-alloy steels to be used.
- Elastically supported sealing rings made of erosion-resistant material are used at locations where relative displacement occurs.
- Protection rings made of erosion-resistant material are used at fixed blade carrier suspension points and other similarly endangered sites.

Higher efficiencies improve cost-effectiveness

Many power supply utilities are committed to maintaining a high technical standard for their plants. One approach is to improve the operating efficiency of older turbogenerators. In connection with this, it should be noted that the plants often exhibit good availability and, unlike the examples discussed previously, have no mechanical deficiencies that represent a potential risk.

A German utility had its entire fleet of 300-MW and 600-MW turbines investigated in order to determine their potential for improvement. The turbines were about 20 years old and had run up more than 130,000 hours of operation. The results of the study indicated that, quite apart from alterations to the power plant process (heat extraction, gas turbine topping cycles), redesign of the LP turbines would represent a profitable investment 6. The higher efficiency arises on the one hand from the optimized flow path and modern blade profiles, and on the other from the reduction in exhaust losses. The latter is the result of using longer last-stage blades, thereby increasing the exhaust area by about 25 percent. Good experience with the new components allowed the customer to increase the interval between major inspections in which the turbine has to be opened to 10 to 12 years. The financial benefit of this is considerable.

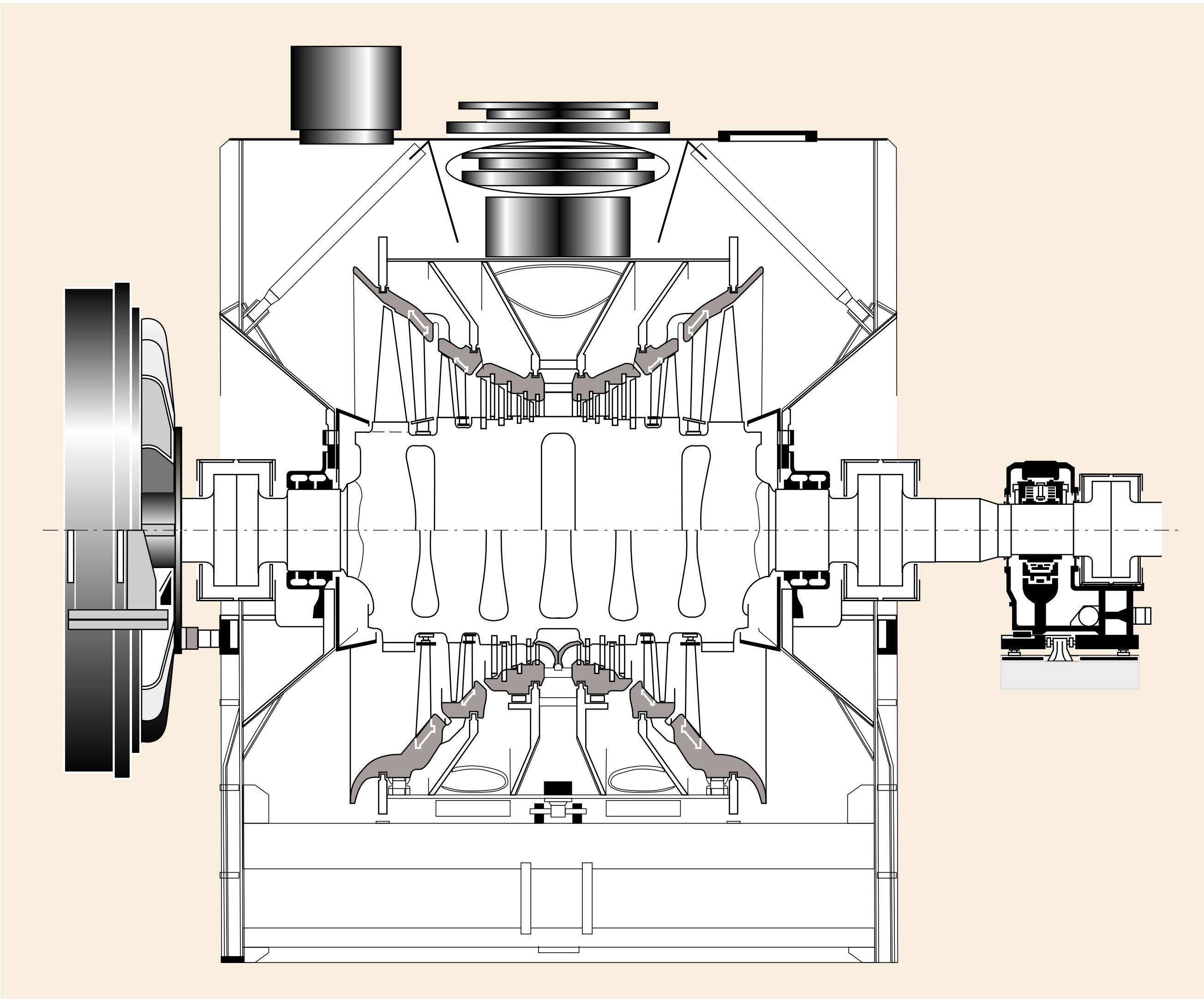
Potential for increasing efficiency of LP turbines

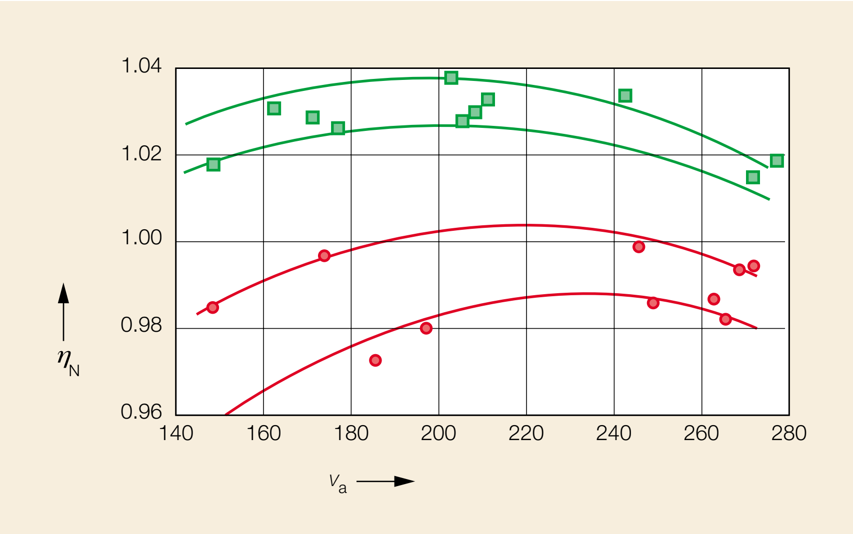
In order to maximize the power and reliability gain vis-à-vis the utility's investment, only damaged parts, potential generic weak points or sections with a large potential for efficiency improvement are replaced or modified. A cost/benefit analysis shows that for LP turbine upgrades, it makes sense to retain the outer casing and to modify the inner casing and diffuser as well as replace the blade carriers, rotor and stationary and rotating blades.

If the outer casing of the LP turbine remains unchanged, limits are placed on the extension of the axial length of the flow path, the increase in the exhaust area and changes to the hub diameter of the new last-stage blades. In addition, the pressure at the extraction points may not differ much from the original values.

Most of the existing LP turbine applications with potential for retrofit commissions were designed in the 1960s and 1970s. In those days, steam turbine development was based on 1D and quasi 2D flow codes. With these codes, only the flow situation at the midspan of

LP turbine retrofit for efficiency improvement (original design below, improved version above). The ratio of the area at the steam exit of the retrofit version to that of the original design area is 1.25 : 1. 6





Efficiency improvement with new LP turbines **7**

η_N *Normalized efficiency*
v_a *Axial velocity at rotating blade row exit*

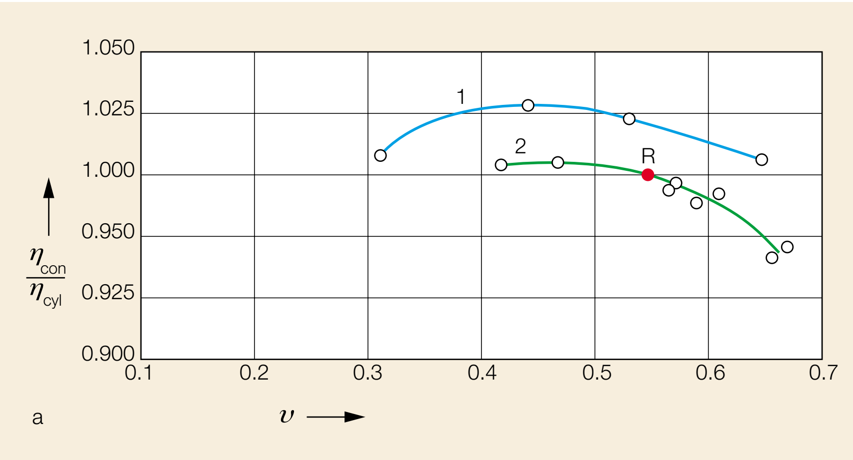
Green *New LP turbine design*
Red *Old LP turbine design*

the blades could be predicted with any accuracy.

In recent years, computational fluid dynamics (CFD) has become an essential tool for turbomachinery design [7]. With CFD, three-dimensional and quasi three-dimensional programs calculate the flow situation with a very high resolution and are able to resolve flow phenomena such as:

- Secondary flow at the end walls
- Blade seal leakage flow at the end walls
- Blade surface boundary layer development
- Local flow separations
- Precise shock positions and their strength

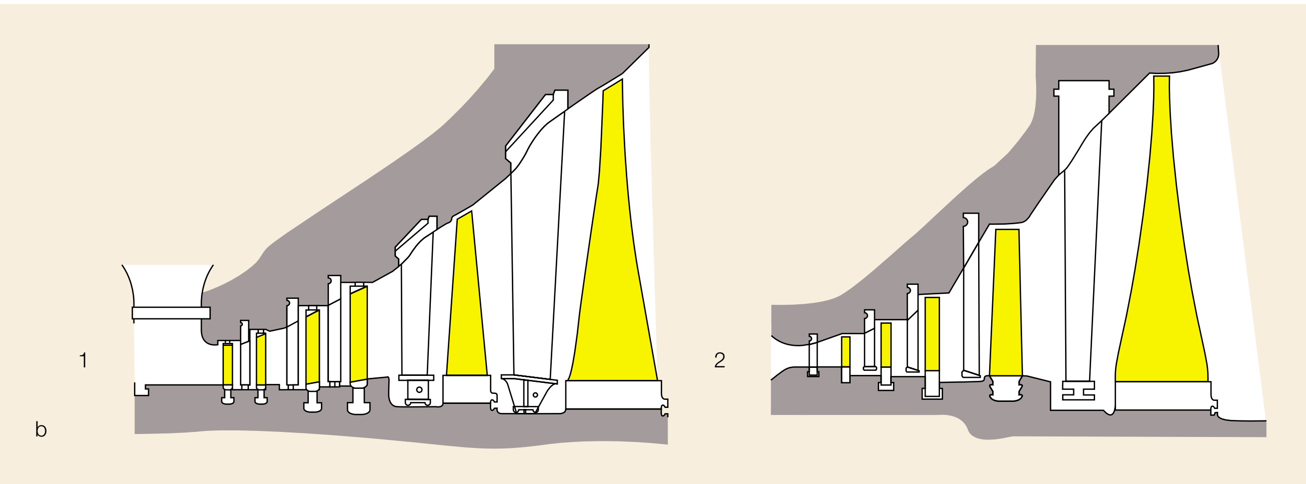
By combining this data with the results from test turbines, significant efficiency



Measured gain in performance (a) due to the introduction of a conical flow path (b) **8**

η *Efficiency*
υ *Flow coefficient*
R *Reference point*

1 *Conical*
2 *Cylindrical*



improvements can be obtained over earlier designs **7** [8].

Blading

Almost half of the power output of an LP turbine is generated by the last two stages. Due to the pronounced three-dimensionality of the flow in this domain, the design of the steam path and the profiling of the blades are of utmost importance when optimizing performance. By using improved tools for calculation and applying current LP turbine design rules, a substantial improvement in efficiency over older designs can be achieved:

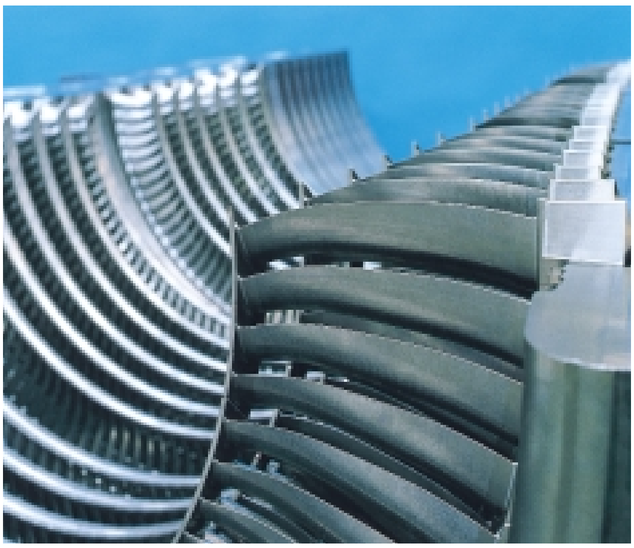
- An increase in the hub reaction (expansion) of the last-stage blades over previous designs eliminates the risk of separated flow in the hub region, especially with smaller volume flows.
- The loss-intensive channel shock at the hub section of the last-stage blades that was typical in the past is avoided in modern designs.
- Optimization of the radial exit angles of the last-stage blades not only helps to minimize the exit losses but also ensures a uniform radial mass flow distribution, which improves the performance of the diffuser.
- The improved resolution of the actual flow situation at the end walls avoids incidences in these regions, resulting in reduced secondary flow [9].
- A conical flow path shape results in a performance gain over the traditional stair shape **8**.
- Use of an integral shrouded L-1 rotor blade substantially reduces losses, compared with a conventional tip seal configuration **9**.

The application of Q3D/3D Navier-Stokes flow programs at an early design phase enables the designer to detect and improve shock-induced separations.

Recent development work has led to an additional efficiency gain through the introduction of 3D-shaped airfoils **10**. This new improved reaction blading, which is already in use in several turbines, has the same roots and is fully compatible with existing blading, making it highly suitable for retrofits.

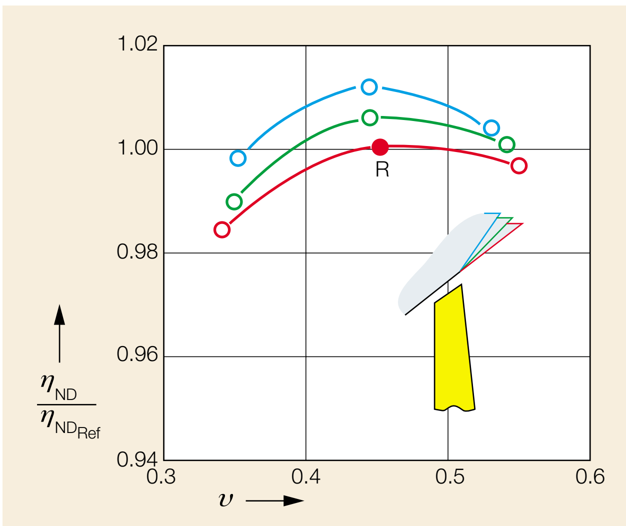
Geometry of the new shrouded L-1 rotor blade **9**

Modern high-performance reaction blading of an LP steam turbine **10**



Influence of the diffuser hood angle on the overall LP turbine efficiency, measured on a test unit **11**

η *Efficiency* υ *Flow coefficient* R *Reference point*

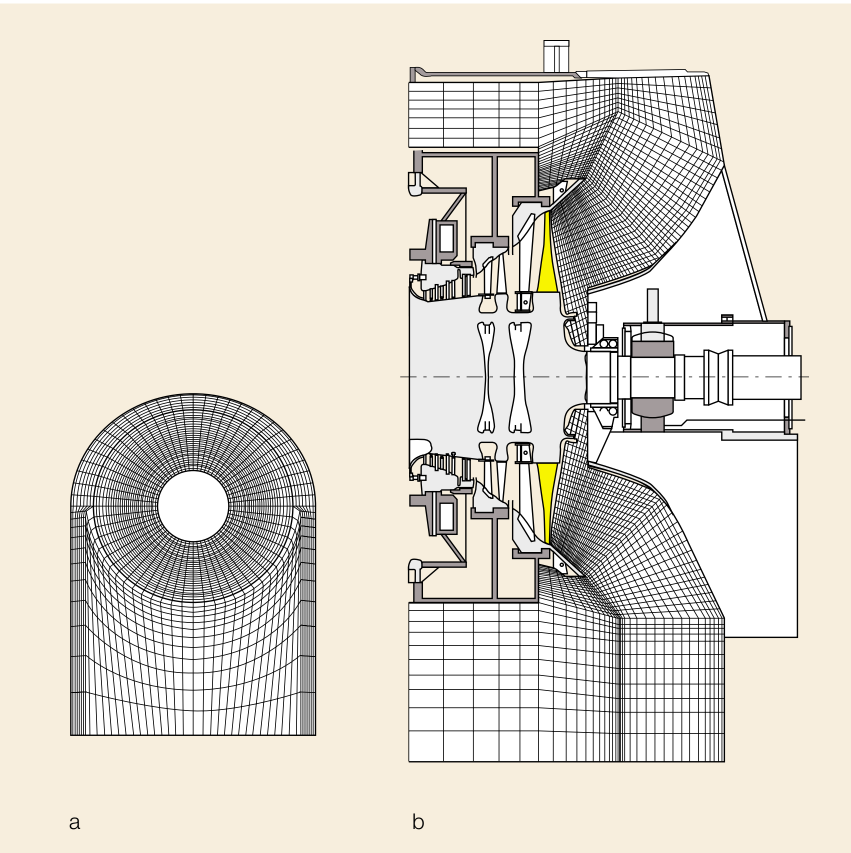


Diffuser and steam exit

Further potential for improvement lies in the design and optimization of the diffuser and steam exit. In most large utility steam turbines, the steam leaves the last-stage blading and passes into the diffuser axially, so that it has to turn almost 90° before entering the steam exit. In this last flow section, the steam is distributed in the outer casing and then guided down through the condenser flange. The steam flow velocities leaving the last-stage blading are quite high and vary between 0.4 and 0.6 Mach, depending on the backpressure conditions. The task for a well-designed diffuser is to accommodate this high velocity flow, retard its speed and recover as much of the kinetic energy as possible. Subsequently, the steam flow should exit with the minimum pressure loss. A wrongly designed diffuser and steam exit could cause major losses, resulting in a reduction of several megawatts in power output [10]. Measurements in a representative LP test turbine have verified the predicted overall efficiency improvements that are possible with an optimized diffuser design **11**.

Today, the very complex flow in the diffuser and the steam exit can be resolved in detail with the help of modern three-dimensional CFD tools **12**. This enables the designer to predict and optimize the diffuser and steam exit performance for a given application range.

Calculation grid for a diffuser (a) and steam exit (b) **12**



Retrofitted LP turbines in Leibstadt nuclear power station, Switzerland

Leibstadt is a steam power plant with boiling water reactor and was commissioned in 1984 with an electrical output of 1,054 MW. Although the plant had been running trouble-free, it was decided after 74,000 hours of service (1994) to retrofit its LP turbines **13**.

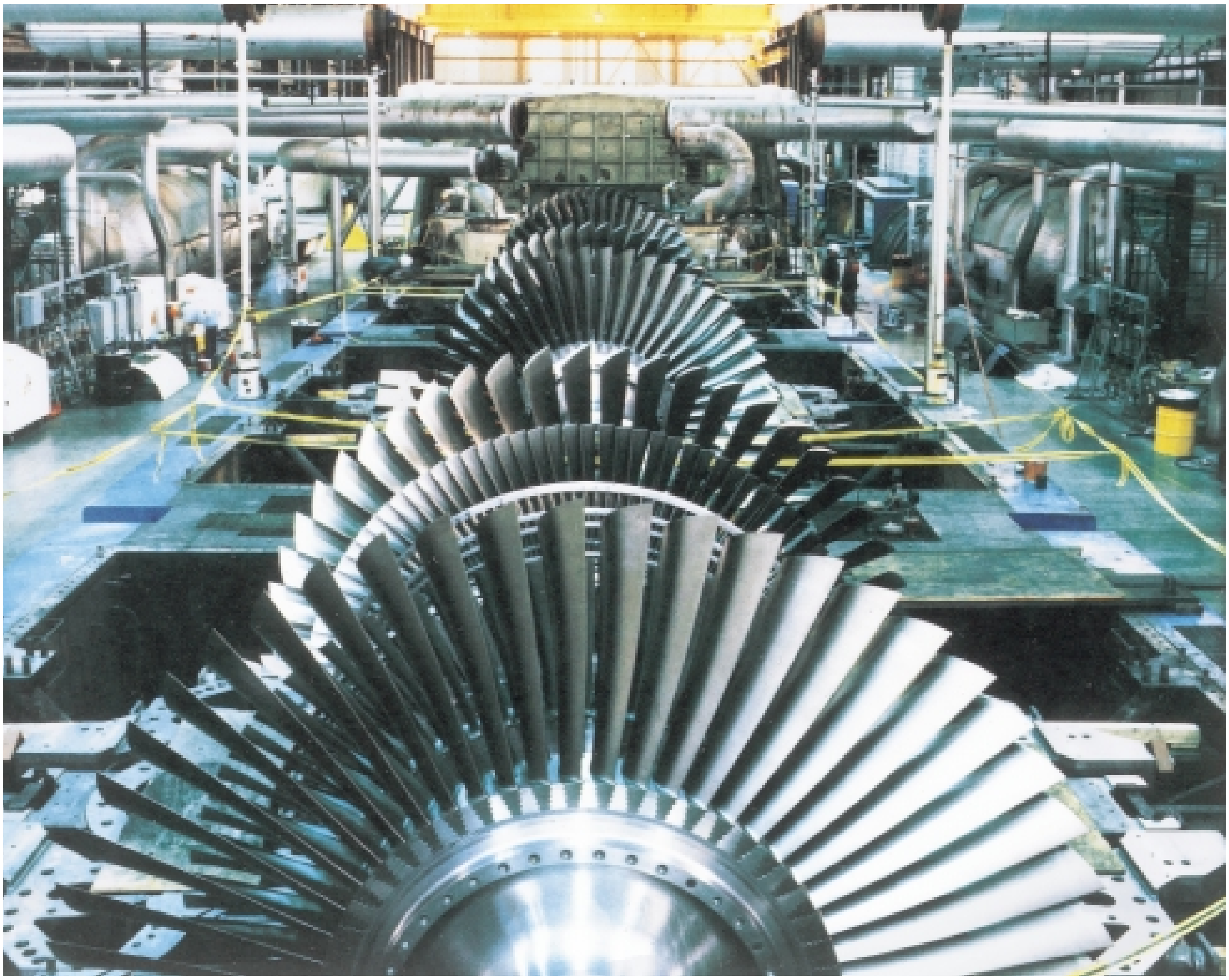
In order to fit blading that represented the state of the art in aerodynamics know-how, it was necessary to also replace the rotors and blade carriers. Measurements before and after the retrofit recorded an increase in output of 46 MW. Future major inspections are planned at ten-year intervals.

Adding value with ABB LP turbine retrofits

A variety of reasons exist for electric utilities and industrial operators retrofitting their turbines or turbine parts. The usual reason for undertaking an LP turbine retrofit in the past has been poor availability due to stress corrosion cracking of the rotor. In some cases, retrofits have been initiated by rotor-dynamic considerations and erosion problems. For all of these cases, technology can be offered which is proven in numerous nuclear as well as conventional steam power plants. LP turbine retrofits are also an interesting proposition in many European countries for purely economic reasons, even when no availability problems exist, since advanced aerodynamic technology allows a significant increase in operating efficiency.

References

[1] M. O. Speidel, J. E. Bertilsson: Stress corrosion cracking of steam turbine rotors. Corrosion in Power Generating Equipment. Plenum Press, 1984, p. 331.



New LP turbine rotors installed in the Leibstadt nuclear power plant, Switzerland **13**

[2] A. Atrens, H. Meyer, G. Faber, K. Schneider: Steam turbine blades. Ibid, 1984, p. 299.

[3] K. Steigleder, E. Krämer: Coupled vibrations of steam turbine blades due to torsional excitation by negative sequence currents. American Power Conference, Chicago, 1989.

[4] J. Y. Lin et al: Life prediction for nuclear LP rotor SCC cracks. 5th International Symposium on Environmental Degradation of Material in Nuclear Power Systems' Water Reactors, 1991.

[5] J. E. Bertilsson, G. Faber, G. Kuhnen: Fifty years of welded turbine rotors. ABB Publ. No. CH-T 060 303E.

[6] R. Svoboda, G. Faber: Erosion-corrosion of steam turbine components. Corrosion in Power Generating Equipment. Plenum Press, 1984, p. 269.

[7] O. Novak, O. Schäfer, B. Schönung: Use of advanced CFD codes in turbomachinery design process. ASME 92-GT-324.

[8] H. P. Meer, P. Meylan, F. Rölli, U. Wieland: Modern large steam turbines for reheat power stations. JPGC, 1987.

[9] J. Perdichizzi, C. Dossena: Incidence angle and pitchchord effects on secondary flows downstream of a turbine cascade. ASME 92-GT-184.

[10] J. K. Owcarek, A. S. Warnock et al: Improvement of the exhaust flow of a low pressure turbine. EPRI Report GS-7993, November 1990.

Authors' address

Edwin Krämer
Hans Huber
Dr. Brendon Scarlin
ABB Power Generation
CH-5401 Baden
Switzerland
Telefax: +41 56 205 5605