Todays Technology "Upgrades" for Previous Generation Turbines

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IP7_006306

Todays Technology "Upgrades" for Previous Generation Turbines

Trevor Clarke : Nuclear Electric
Alan Hesketh : ALSTOM Energy
Arun Puri : Tennessee Valley Authority

Synopsis

Research and Development in the 1990's, dedicated to improvement of the performance of low aspect-ratio blading of HP steam turbines, has led to remarkable improvements in efficiency. The profile, secondary and leakage losses in the typical stage have responded in a straight-forward way to practical development, guided with CFD techniques, and coupled with turbine rig-test aerodynamic evolution to give very good efficiencies. Similar progress has been made on IP and LP modules.

These advances have resulted from a major development effort to attain the best possible levels of turbine efficiency for application in the highly competitive market for new plant. Replacing older generation plant with this same modern technology, therefore, has the potential for realising those substantial advances made over the last 10 to 20 years. The performance gain, taken together with improved reliability and reduced maintenance, is proving to be cost effective in an increasing number of potential retrofit cases.

Retrofitting is complimentary with R&D: on the one hand developments give the modern technology required for potential advantage in installation; and retrofitting gives the early opportunity for application and proving in the field.

Successful retrofit application cases are described which include two 660MW HP cylinders, one OEM machine in Europe and one non-OEM type in USA, which illustrate the practical considerations, hardware interfaces and BOP/cycle implications of plant modernisation. The utility viewpoint in each case illustrates the considerations behind the plant upgrades and reviews the co-operation and co-ordination required throughout.

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Introduction - Why Retrofit?

The trend towards privatisation of utilities coupled with deregulation of electricity supply markets has been a prime mover in the drive to increase profits from electricity generation. The fundamental reason why many utilities have chosen to retrofit existing steam turbine plant, rather than replace it with "new" or build additional generating capacity on new "greenfield" sites, is that it is often more cost effective.

With the exception of large nuclear LP plant, steam turbine retrofits can often be justified on the grounds of performance improvement alone. The case for retrofitting on the grounds of performance uplift is stronger if efficiency improvements can be combined with an increase in steam passing capability (or, for nuclear plant, rematching the turbine capacity to suit actual steam generator outlet conditions).

For large nuclear LP turbines, the motivation for retrofitting is always long term reliability. However, the case for retrofitting (rather than major spares or repair programmes) is strengthened if improved performance offsets the capital investment. Conversely, the case for retrofitting fossil HP and IP turbines is stronger if there are benefits from improved reliability. Turbine retrofits are always more economically attractive on plant operating at high load factors.

The replacement of LP rotors for typical 500MW units, shown in Fig. 1 and which gave 4% improvement in heat rate, illustrate the alternative benefits available:-

either • a reduction of 4% in fuel costs and emissions for remaining life of the plant

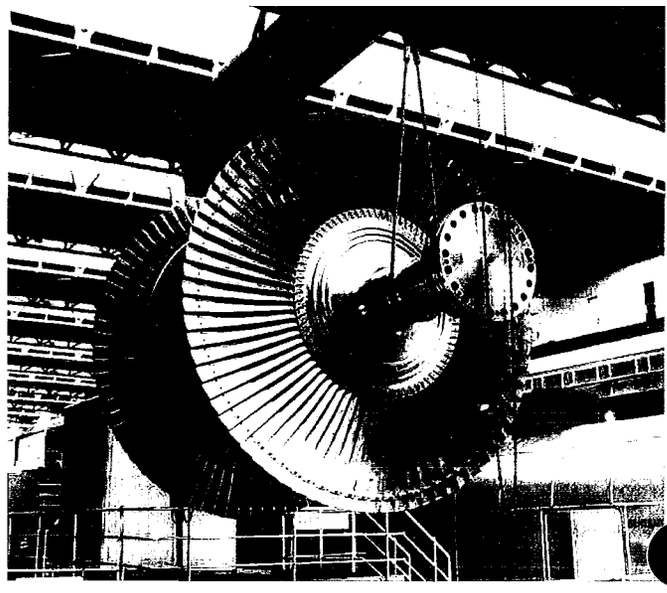

Figure 1

or • an increase in rating of 20MW to generate future revenue in the years to come

plus • improved reliability and reduced maintenance

Increasing pressures to reduce CO_2 levels together with other noxious emissions are being imposed by national governments seeking to satisfy agreed targets. Improved plant efficiency reduces the environmental impact of fossil plant, allowing less fuel to be used for the same electrical output with less gaseous emissions and less wasteful heat rejection to the environment.

Increasing the output from existing power plants reduces the need for new plant (eliminating planning permit problems), avoids building on greenfield sites and allows the most inefficient plants to be retired. Additional output is often achieved at lower capital cost/kW than, say, new combined cycle plant and at no extra operating cost. The opportunity can even be taken to use the extra generated power to sustain a flue-gas clean-up installation without loss to the net electrical plant output.

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HP and IP Blading

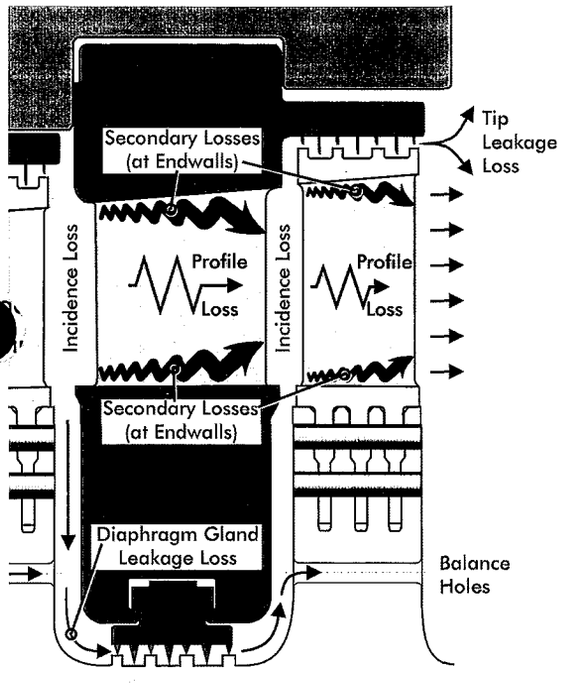

Figure 2

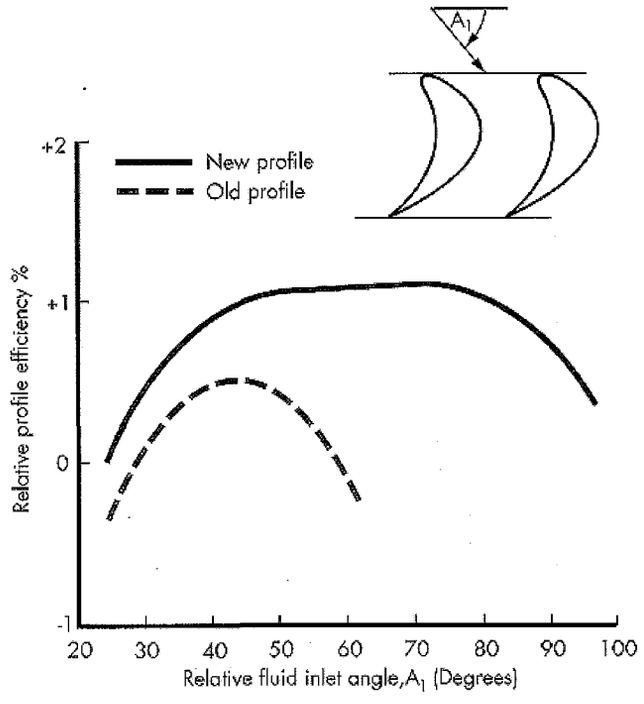

Figure 3

Fig. 2 shows the configuration of a typical low root-reaction steam turbine stage and the corresponding performance loss mechanisms. The greatest efficiency gains on short height stages have been obtained by reducing blading profile and secondary losses. ALSTOM has an ongoing research and development programme focused on minimising these important losses. A new and highly efficient range of blading has been developed using advanced Computation Fluid Dynamics (CFD) analysis, supported by model turbine tests and proven by in-service measurements. [Ref. 1]

Profile Losses

Analysis of the velocity distribution over profile surfaces has allowed profile performance to be improved significantly. Fig. 3 shows the improvement in efficiency obtained at the root section of a new standard blade over a wide range of steam inlet angles. The inlet edge is designed to tolerate potential mismatches between profile and steam inlet angles in the "off-design" areas of nozzle wakes or at end-wall regions. Blade sections are carefully designed to optimise both efficiency and mechanical strength.

Secondary losses

Complex vortices and loss-producing secondary flows occur at the end-wall regions of blade passages. The influence of these on stage efficiency can be reduced fundamentally by using longer aerofoils and narrower blade-chords (ie better aspect ratio). However, secondary flow losses are also influenced by the cross-channel pressure gradient arising from the main flow curvature in the passage. Advanced CFD analysis allows this pressure field to be predicted and the benefits of refined passage geometry determined. Using this analysis, supported by model turbine tests, ALSTOM has established a number of blade geometries which are effective in controlling secondary flows. Fig. 4 (and 'A' in Fig. 6) shows the efficiency gains in fixed blade passages from reduced end-wall losses at hub and tip regions, emphasising the importance of the aerodynamic quality of the 2-D profile.

Benefits additional to this have been obtained from advanced technology 3-D blades (Fig. 5) which reduce the effect of secondary losses still further. In the 'controlled-flow' case this is achieved by increasing passage throat areas towards the mid-height region to reduce the flow in the high-loss end-wall regions. Another leap in efficiency level has been fully confirmed by testing ('B' in Fig. 6) the application of the latest ALSTOM series of rotating blades together with the 'controlled-flow' nozzles.

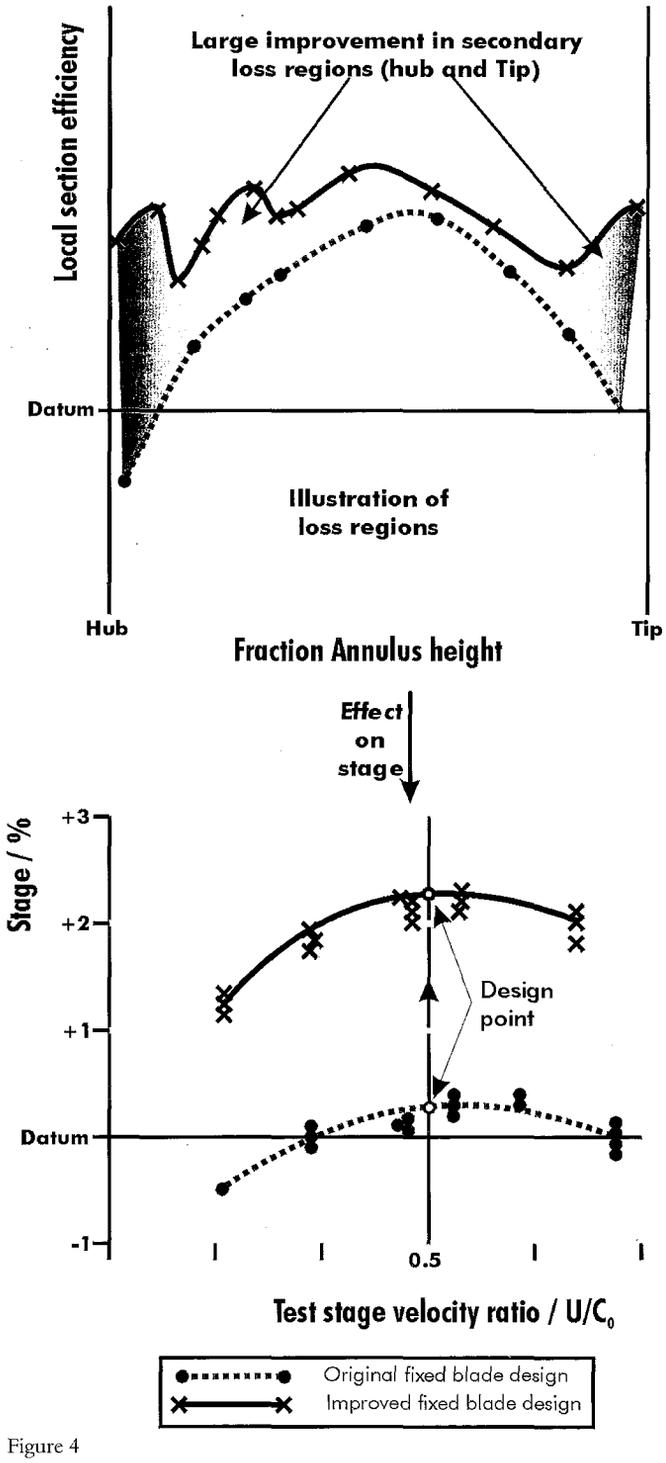

Figure 4

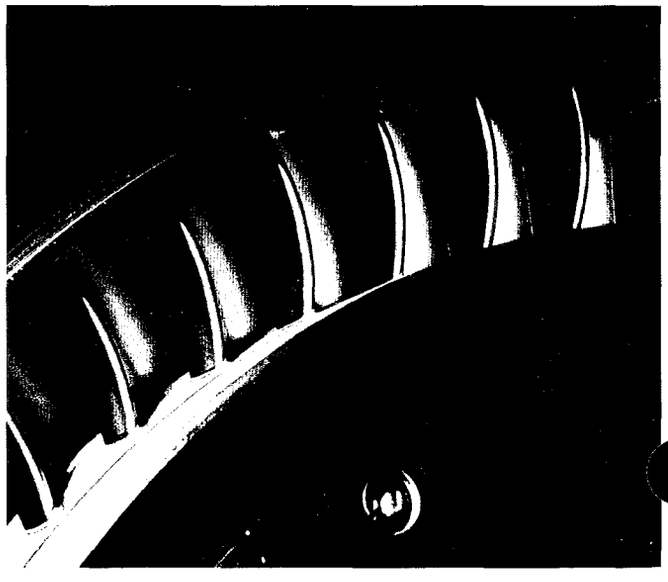

Figure 5

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Leakage and Other Losses

The steam leakage flows at the rotating blade tips and diaphragm hubs of low reaction turbines can be minimised by careful design.

Diaphragm gland leakage is controlled by spring-backed labyrinth seals which provide protection against damage in the event of rotor rubs.

Diaphragms are kinematically supported to allow free radial expansion so that gland clearances can be reduced to a practicable minimum irrespective of casing distortion. Inefficiencies caused by re-injection of gland leakage flow into the main steam flow are avoided by using disc panel leakage ports. These leakage ports provide an efficiency gain on short height stages (Fig. 7) and also reduce rotor axial thrust. Blade tip leakage is controlled by sealing fins mounted on extensions of the diaphragm rims which co-operate with the integral blade tip shroud ribs to form a labyrinth seal.

Many other detailed improvements are additive and even small gains accumulate to become worthwhile in total. For example, provision of the optimum fillet radius between blade-form and end-wall precludes the formation of corner vortices and gives maximum efficiency for the correct design (Fig. 8).

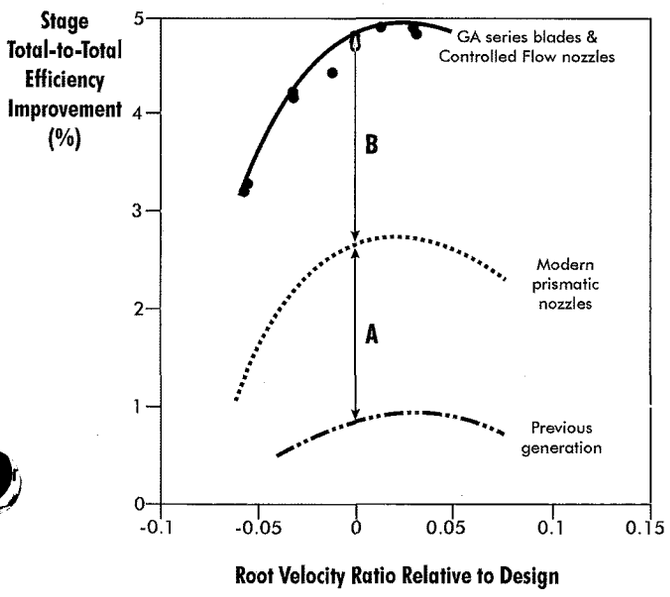
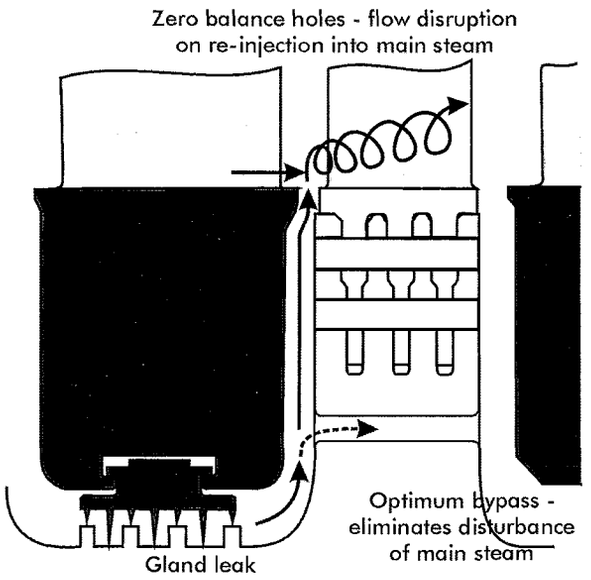


Figure 6



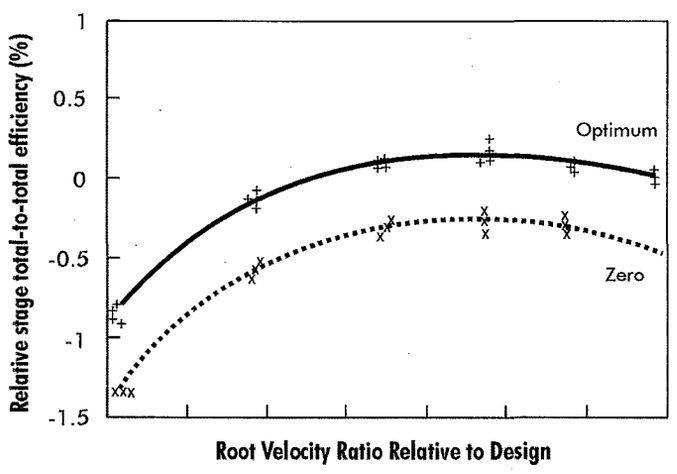
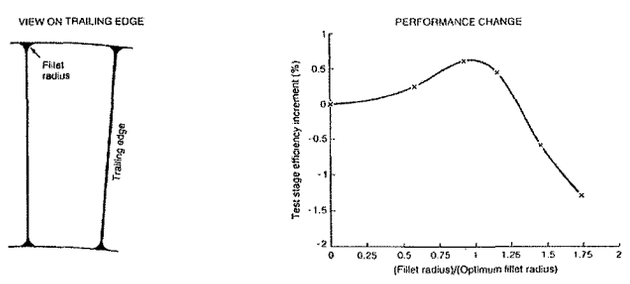


Figure 7



Effect of fillets on performance

Figure 8

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LP Blading

The efficiency of the LP cylinder is particularly important because it produces the largest proportion of the turbine power. Expansion to low condenser pressures results in a huge increase in volumetric flow rate through the LP cylinder where the design is dictated by rapid increases in blade heights and steeply flared outer boundary on the latter stages.

The last stage (L-0) is the most difficult to design aerodynamically. It has the highest volumetric flow rate with a large radius ratio (typically $R_{tip}/R_{root} = 2.5$), a high pressure ratio (up to 6:1) and the blading operates under conditions of extreme aerodynamic loading with supersonic outlet Mach numbers. The rapid increase in blade height from the L-1 stage gives a significant radial velocity component near the tip of the L-0 fixed-blade. A large radial variation in static pressure is generated in the fixed/moving blade interspace by the centrifugal field of the highly whirling flow (Fig. 9) which tends to give negative reaction at the root and increased reaction at the tip. Consequently, the inlet Mach numbers at the root and tip of the moving blade are high and serious breakdown in the flow structure can arise if these effects are not recognised and controlled.

Older turbines often had irregular outer boundaries and were normally designed on a two-dimensional basis using simple radial equilibrium to account for centrifugal effects. This is unsatisfactory since the pronounced flare along the irregular outer annulus wall gives rise to significant radial and curved velocity components causing breakdown of the flow structure. Axisymmetric streamline curvature techniques for throughflow calculations provided the capability to analyse flow structure in groups of stages and, in particular, to recognise the problems associated with radial flows and curved boundaries. Further refinements have since been achieved using three-dimensional time-marching methods. The intensity of the interspace pressure field can be controlled and reduced by two major design options:

- The fixed blade can be leaned circumferentially inwards so that the pressure surfaces make an acute angle at the hub casing (Fig. 9) to produce a steam force component acting radially inwards

- The fixed blades can be twisted with throat openings increased at the hub and reduced at the tip, to cause more flow to pass through the hub region giving local downward curvature of the streamlines

The effects of lean and twist are complementary and can be applied together along with smoother boundaries to control the flow structure.

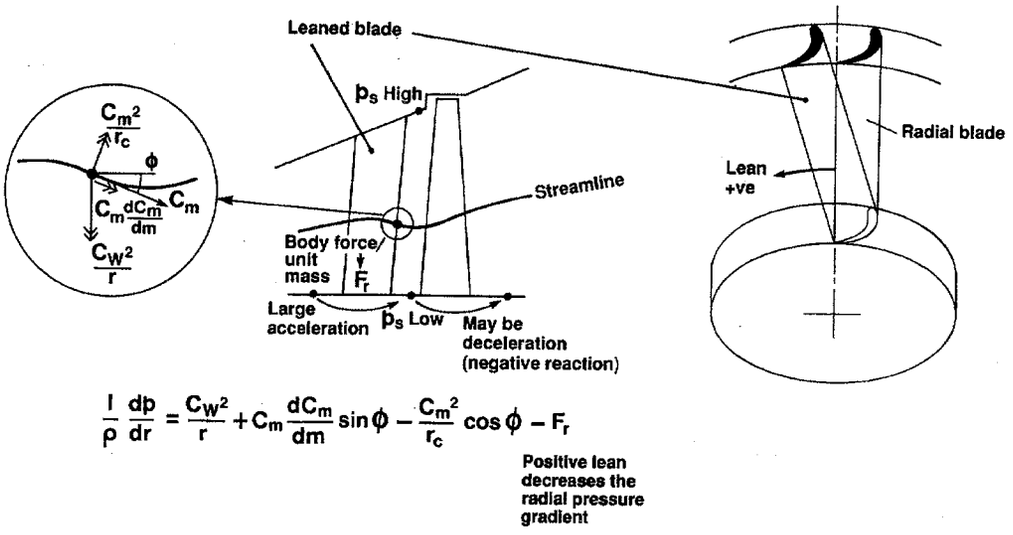

Figure 9

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Other Performance Factors

On plant where the boiler operation demands the use of reheater sprays to prevent excessive reheat temperatures, improvements in HP turbine efficiency (which reduce cold reheat steam temperatures) permit reheat sprays to be turned down, leading to additional cycle benefits.

On nuclear plant, steam generator degradation often leads to reduced steam pressure and hence increased volumetric flow at inlet to the steam turbine. In order to continue using the full main steam flow at best efficiency it is necessary to increase the steam passing capability of the HP turbine. This rematching of the HP turbine to the steam generator outlet conditions can be combined with an HP turbine retrofit for internal efficiency improvement. [Ref. 2]

HP turbine retrofits can also take advantage of increased steam flow capacity from over-designed fossil-fired boilers or nuclear reactor upgrades.

Overall Improvement

The advances described above have resulted from the ALSTOM major development effort to attain the highest possible levels of turbine efficiency for application in the highly competitive market of new plant. Retrofitting older generation plant with the same modern technology, therefore, has the potential for realising those substantial advances made over the last 10 to 20 years. This performance gain, taken together with improved reliability and reduced maintenance, is proving to be cost effective in an increasing number of potential retrofit cases.

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Reliability Issues

On large nuclear plant, the most common mechanical reliability problem is stress corrosion cracking (SCC). LP turbine rotors in nuclear applications which use "shrunk-on" disc construction or certain types of blade root attachments can be particularly prone to SCC but the problem is also not entirely unknown in nuclear HP turbines. Certain constructions necessitate regular inspection and, once SCC is discovered, require ongoing repair or replacement programmes. The threat of SCC and associated cost penalties can be eliminated by appropriate turbine retrofit technology which also provides a performance improvement to offset the capital cost.

Clearly, the case for nuclear turbine retrofits becomes more pressing if the unit concerned has other mechanical reliability problems (e.g. recurring blade failures or moisture erosion damage) which could be solved by retrofitting.

On steam turbines in fossil applications there is a variety of reliability issues which can influence the decision to retrofit. In the USA, perhaps the most common problem is solid particle erosion (SPE). In this case, exfoliated particles (principally magnetite) from boiler tubes are carried over into the turbine to cause erosion damage of either HP turbine nozzles or first stage IP blading (or both). In severe cases, SPE can seriously compromise the mechanical integrity of the nozzles or, in the case of rotating blades with separate shrouding, damage the shroud rivets. HP and IP section efficiencies can fall off by up to 5% over 3-4 years of operation. The costs associated with regular inspection, repair or replacement of SPE damaged components can be very high and turbine retrofit solutions based on blade path geometry are now available to remedy the worst excesses of this problem.

Other persistent reliability problems which further the case for retrofitting fossil-based steam turbines include thermal fatigue cracking of rotors or casings, life limitation due to steady state creep damage, rotor instability problems or recurrent blading failures.

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HP and IP Turbine Retrofits on UK 660 MW Units

The Advanced Gas-cooled Reactor units in the UK operate with similar steam conditions to modern conventional fossil units (159 bar, 538 °C, 538 °C). The original HP turbine, supplied as OEM, had inner casings which were contained within an intermediate barrel casing requiring end-assembly. Although these operated satisfactorily, the increased risk of losing generation due to extended dismantling and inspection outages became unacceptable to the Nuclear Electric utility. HP turbine inner cylinder retrofits were ordered for 5 units to improve performance and remove the assembly difficulty (Fig. 10). IP turbine retrofits (rotors and diaphragms) were also ordered for 4 of these units as the value of the extra MWs justified the capital cost.

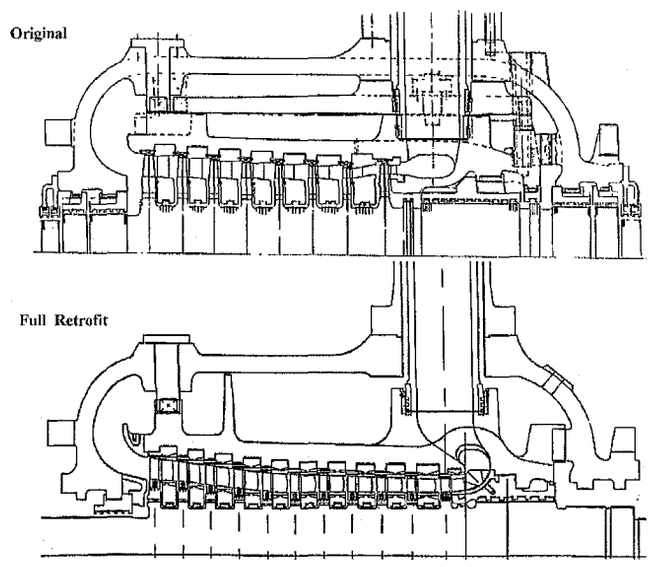

Figure 10

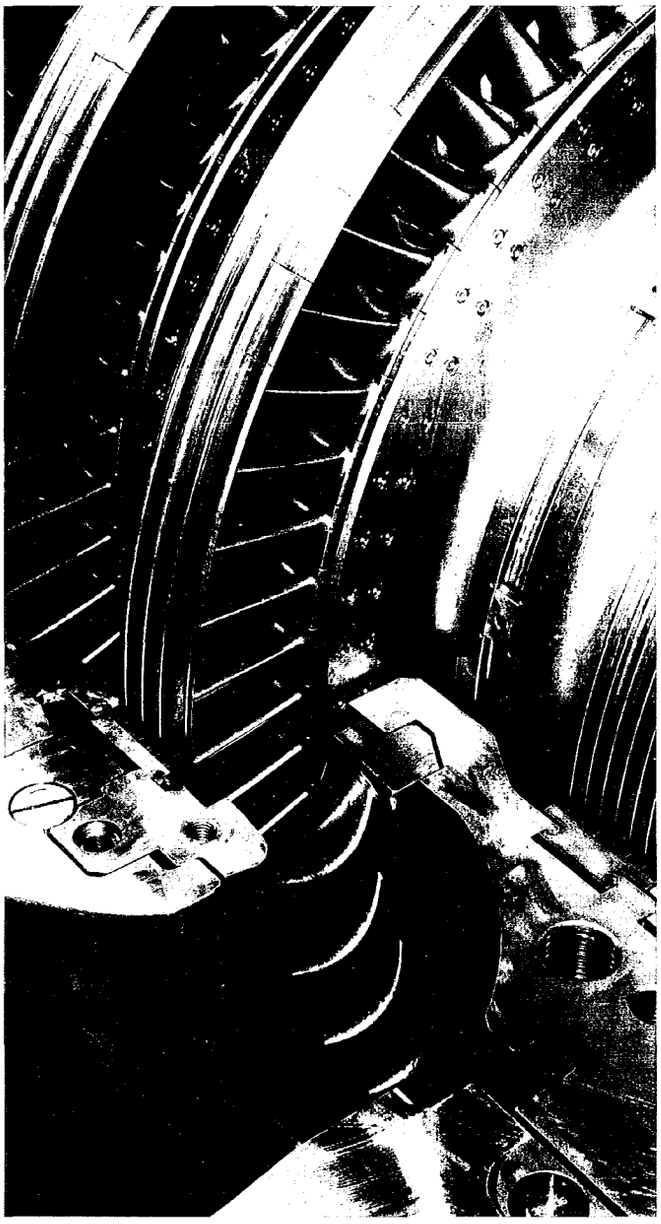

Figure 11

The expected improvement in heat rate on the replanted HP and IP cylinders was predicted to be more than 2%. This gain was realised on the first three units which have already been replanted and tested. With performance enhancements arising from a design with 11 compact stages replacing 8 original and incorporating some of the advanced technology presented earlier (Fig. 11), the efficiency of the HP cylinder was tested and

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monitored for prolonged operation after installation, demonstrating that the high level of efficiency is being sustained (Fig.12).

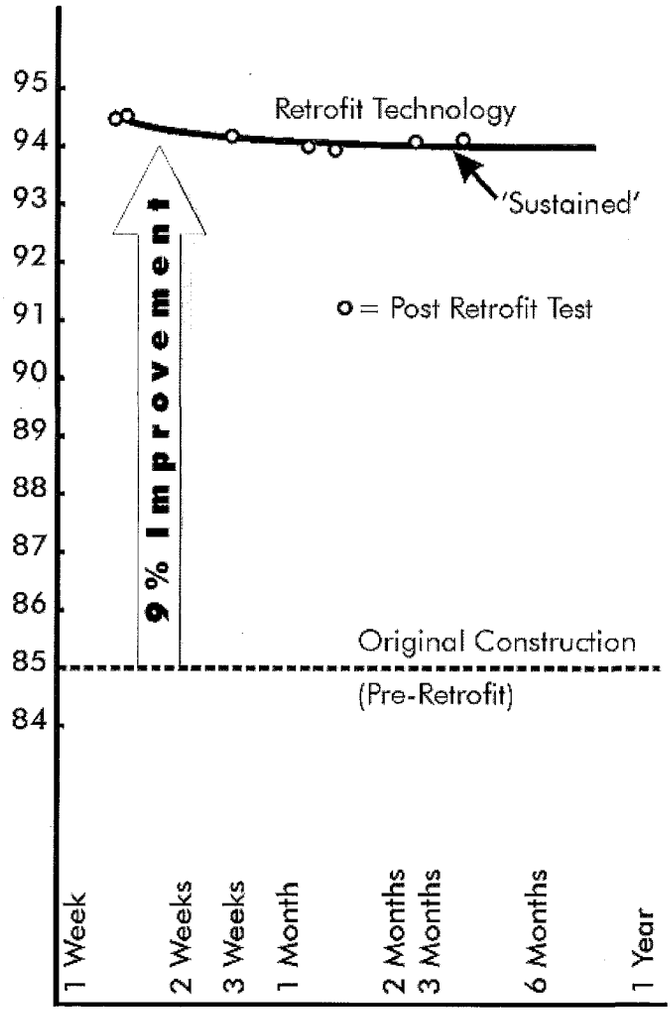

Figure 12

This case is a clear example of how plant modernisation is complementary with R&D: on the one hand developments give the modern technology required for potential advantage from installation; and retrofitting gives the early opportunity for application and feedback from field experience.

HP Turbine Retrofits on USA 660 MW Units

New inner modules, comprising casing, rotors and diaphragms, are being supplied on several non-OEM 600-700MW coal-fired power plants in the USA. In past operations, the HP turbines had suffered particularly from Solid Particle Erosion (SPE). Improvements have been to introduce full-arc admission with its lower steam velocities, and apply wider blades. These replace the partial-arc configuration, so avoiding the high velocities, and change the narrow original blades which had turned the flow too sharply to give guidance to the particles and so allowed damaging impacts on the thin trailing edges.

To give improved performance, modern blade profiles are used throughout and substantially more stages, 11 rather than 7, are packed into the module in the well established ALSTOM "compact-design" practice (Fig. 13). With unchanged cylinder enthalpy drop/ volumetric flow and optimum blade/steam speed ratio, this permits the steam-path base-diameter to be reduced to give the double benefit of correspondingly increased blade height (better aspect ratio) and reduced steam velocities (loss α Vel^2).

Care has to be taken with balance of plant equipment when replacing HP cylinders, especially if increased flow capacity is involved. Whole-cycle studies are required to ensure that the feedtrain components (eg feed-pumps) have sufficient capacity. The improved HP efficiency, which reduces cold-reheat temperature, can have a significant effect on the reheater duty and the boiler operation, therefore, needs to be reviewed.

Of course, special attention has to be paid to dimensional accuracy by thorough site internal inspection when replacing a cylinder inner module of one type of design with one of different origin.

These practical considerations are vital for success and hardware interfaces, control aspects and BOP/cycle implications must be reviewed. The utility viewpoint is essential in each case and the co-operation and co-ordination between the parties is indispensable.

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LP Turbine Retrofits on 500/660 MW Units in Europe

ALSTOM antecedent companies supplied a total of thirty 500 MW and 660 MW units in the UK between 1961 and 1974. All these units utilised three double-flow LP cylinders with the same length of last stage blade. The 500 MW units had shrunk-on-disc type LP rotors. Several approaches have been taken in replanting these cylinders for improved performance.

Partial Retrofit - Aerodynamic probe measurements on a 660 MW LP cylinder [Ref. 3] revealed the poor flow structure at outlet from the last and penultimate stages referred to earlier (Fig. 14).

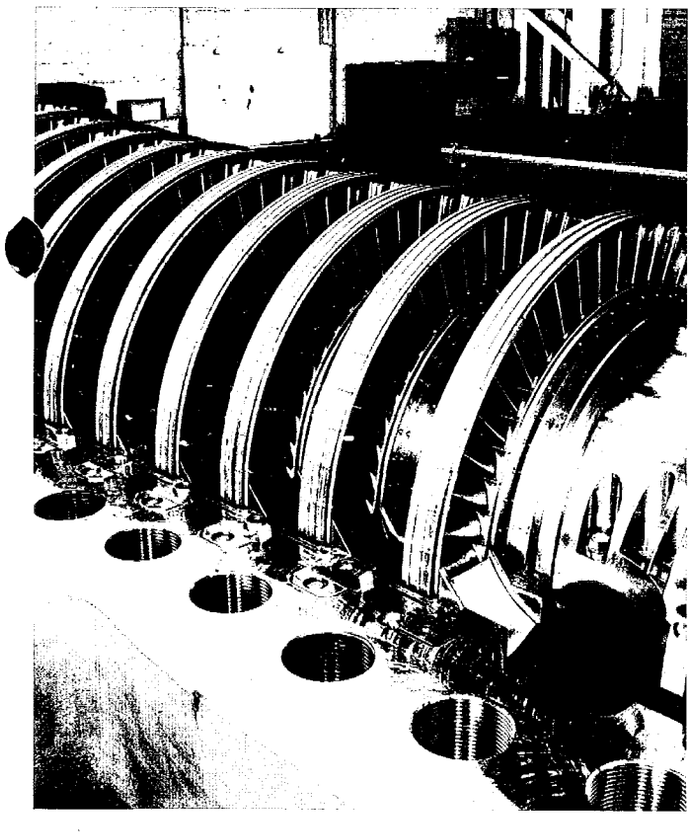

Figure 13

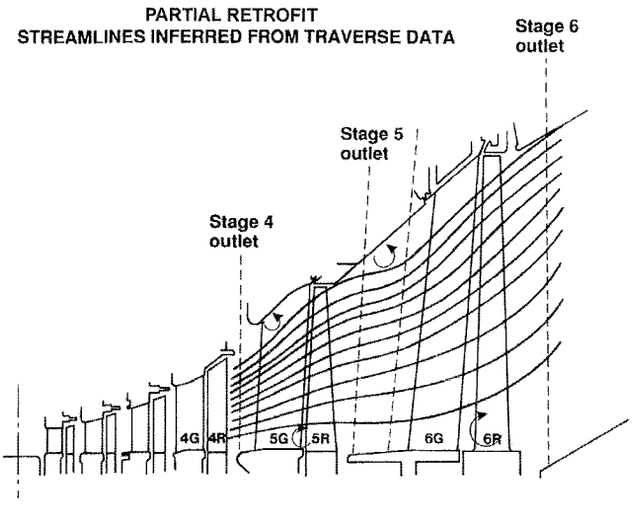

Figure 14 Test Streamlines - Old Design

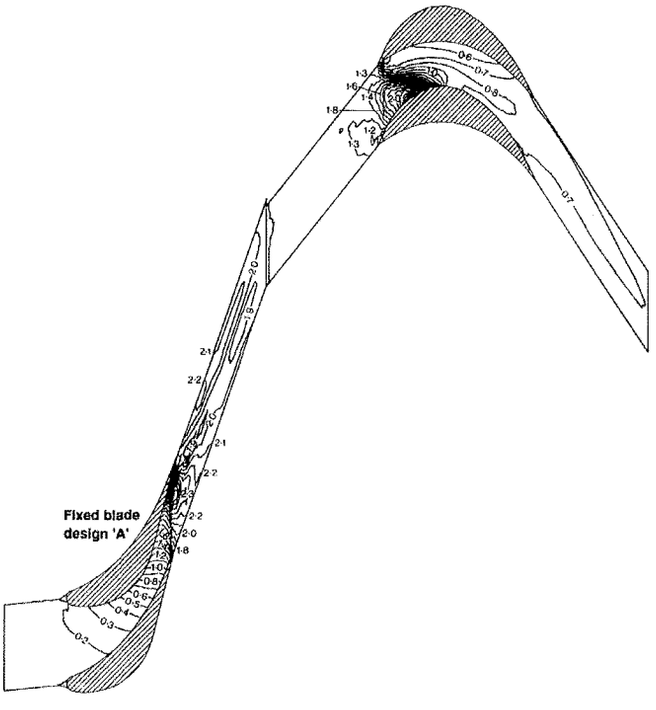

Figure 15 Original Design

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Subsequent computational analysis and model testing confirmed that flow was choked at root inlet (Fig. 15) and separation was occurring in the moving blade root passages on these stages. To alleviate this effect, new diaphragms were designed with leaned and twisted profiles. L-0 and L-1 diaphragms have now been replaced in two 500 MW units and six 660 MW units. Site traverses (Fig. 16) have shown the improved flow structure and performance tests have confirmed that the expected heat rate improvement of 1% has been achieved (at a very cost effective price).

Full Retrofit (UK 500MW) - More recent 660 MW machines incorporated a second generation LP cylinder design with monobloc rotors and a slightly longer last stage blade. This later LP has a considerable record of efficient and reliable operation and was an obvious replacement choice when LP turbine upgrades were considered for the earlier units. The full replacement involves replacement of the bladed rotor, diaphragms and inner casing.

To date, LP turbine upgrades have been installed on nine 500 MW units at four UK stations. Improvements in heat rate of up to 4.2% have been observed.

Full Retrofit (E. German 500MW) - A similar modernisation project was applied to the LP cylinders on the six 500MW units at Janschwalde Power Station. The LP cylinder construction "before" and "after" retrofitting is shown in Fig. 17. These six turbines were of Russian manufacture and were installed at Janschwalde Power Station in the former GDR during the years 1981 to 1988. The station comprises three power blocks, each with four lignite-fired boilers servicing two turbine-generators. These in turn share three cooling-towers per power block for heat rejection purposes.

Although only approaching mid-life operation (30,000 to 80,000 hours service) several problems had persisted, the most important being unseating of the shrunk-on LP discs and poor operating performance. The latter item was thoroughly examined with a view to improving the environmental operation as well as increasing the efficiency of the units. Further improvements in the station were achieved by modernising the boilers and providing equipment for de-sulphurisation and removal of nitrogen products.

In this case, the retrofit was for replacement LP rotors including new blading, new diaphragms and new inner cylinders.

Basic improvement in the cylinder efficiency results from the application of the Company's modern proven blading. Twisted-profile moving blades are combined with integral shrouds of modern practice to give the smoother conical flow-path of present day designs. The overall LP flow structure, including optimisation of fixed blade settings, has been refined using a streamline curvature computer program. This has enabled the proven last two stages to be adapted from the established 600MW application with minimum change. The rotor system now operates well in service.

An improvement in heat rate performance of 4% has been achieved as a result of the update on the LP turbine.

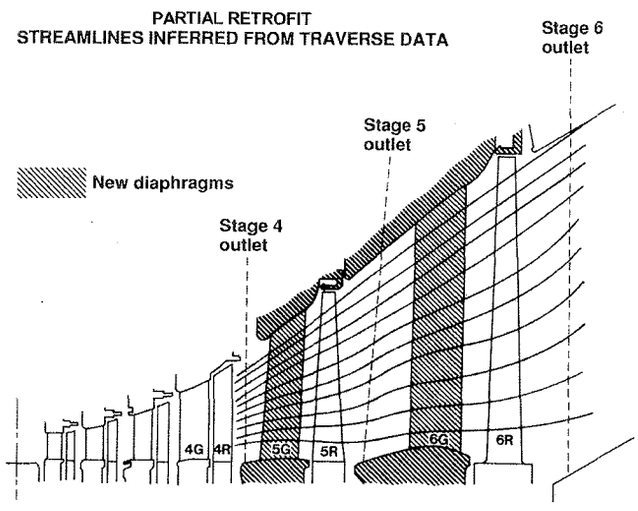

Figure 16a Test Streamlines - New Design

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LP Turbine Retrofits on Nuclear Plant

Much of the large nuclear plant in the world has turbine-generators which operate in saturated-steam thermodynamic cycles and are of half-speed (ie 1500 or 1800 rpm) construction. The original rotors on many of these were of the shrunk-on-disc type and these, in common manufacturer throughout the world, have suffered from stress corrosion cracking. This has affected disc bore, root fastenings and other details.

Two solutions have been implemented by ALSTOM:-

(i) Removal of discs, renovation and refitting.

(ii) Replacement by welded rotors.

The replacement by welded rotors is the complete solution and eliminates the need for continual monitoring and maintenance of the discs. Also a modern blade path of improved efficiency can readily be introduced leading to increased output which offsets the cost of the new rotors.

Two such 500MW, 1500 rpm units were first installed in a Belgian PWR Station in the 1970's and LP rotor SCC problems subsequently emerged. A detailed economic assessment of the available options was carried out [Ref. 4], including rotor refurbishment and the use of surface treatments to reduce the risk of disc cracking. Following this, the customer decided to replace the rotors, moving blades and diaphragms with their modern equivalents to improve performance.

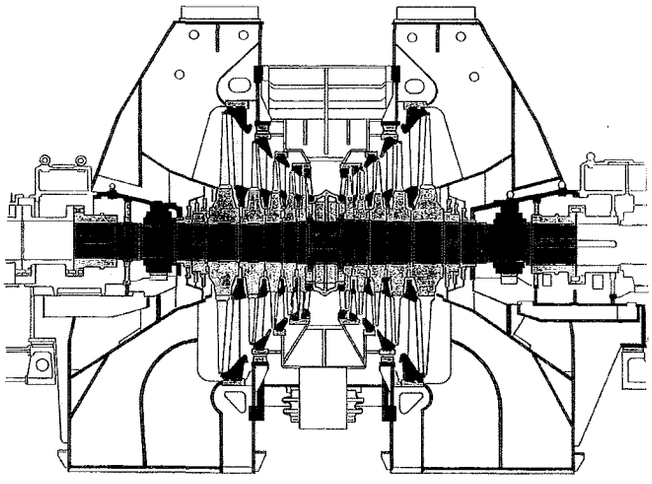

Figure 17a - Original

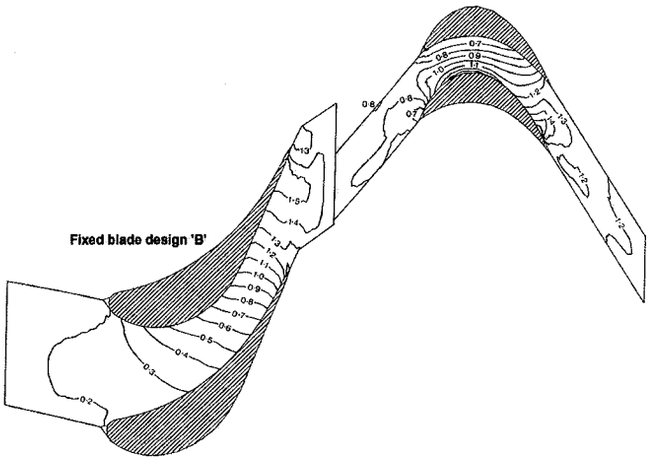

Figure 16b Retrofit Design

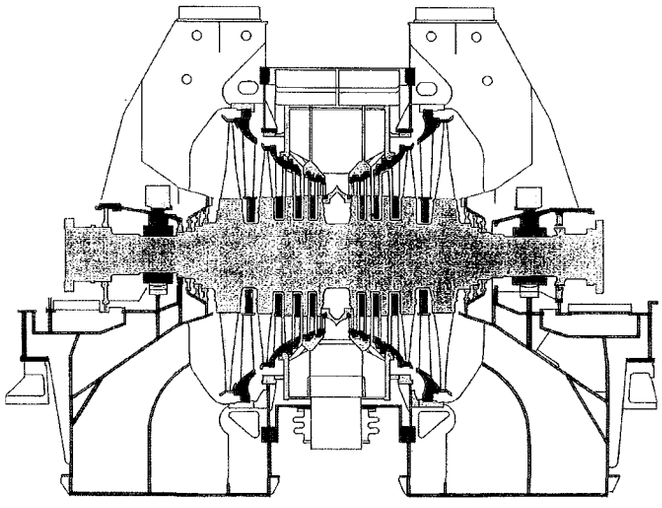

Figure 17b - Full Retrofit

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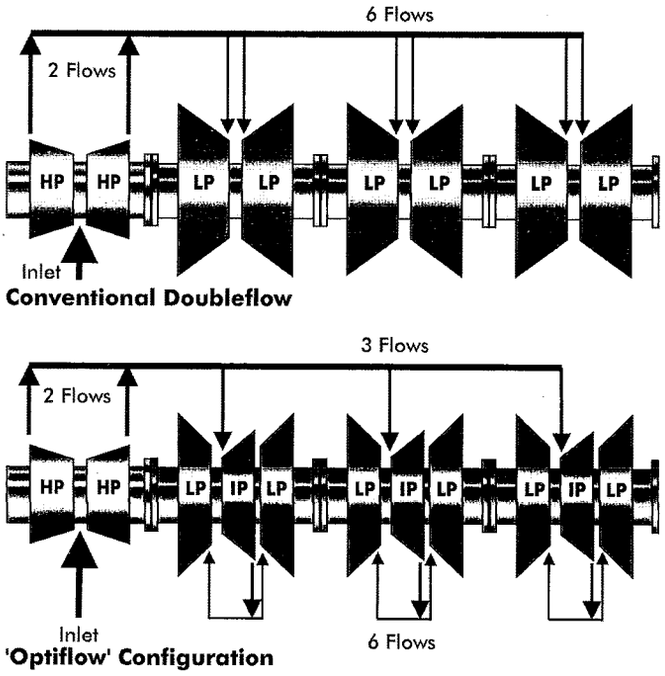

Figure 18

The new rotors are of welded construction, each composed of six elements. The technique is long-established in ALSTOM and allows the use of smaller forgings than the monobloc alternative, with much reduced cost and delivery time for very large rotors. It gives a highly satisfactory engineering solution with stresses reduced to levels below those which may cause stress corrosion cracking. The new construction incorporates the ALSTOM optiflow principle (Fig. 18) which has been used for several years. The main distinguishing feature is that it reduces the number of parallel flows in the steam expansion by including a single flow section before the double flow section in each LP. The inclusion of a single flow section means that leakage flows are reduced and blade aspect ratios are improved up to the point where volumetric flow becomes too great to be accommodated within a single flow. At this point, the flow in each cylinder splits into two and continues expanding in the double flow part of the turbine.

The new rotors (Fig. 19) have displayed excellent dynamic characteristics and substantial improvement in output due to the new blading and increased attention to steam sealing arrangements. The output increase of 36MW for the station has exceeded expectations.

Similar application of optiflow LP modules is currently under way on two 1150MW units in the USA. In this case, application of improved exhaust hoods also helps to boost the performance uplift.

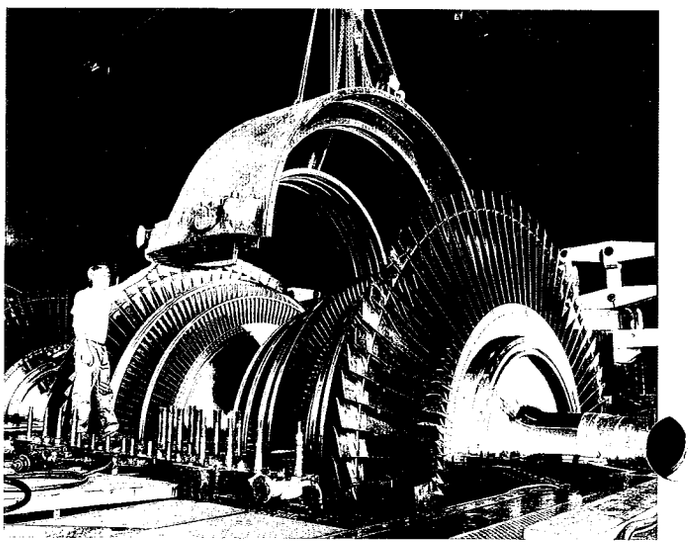

Figure 19

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Plant Efficiency Upgrades - A Utility View

Tennessee Valley Authority (TVA) has embarked on a program to optimize the plant cycle efficiency of its large unit fleet (500 MW to 1300 MW) and thereby reduce the plant heat rates. The governing principle of this program is to keep the boiler MCR levels unchanged, thus increasing the unit capacity, without increasing the unit emissions over the broad range of unit operations.

TVA's large unit fleet has an average life of over 30 years and the turbine steam path components have a significantly lower efficiency compared to modern turbines offered by the World Class turbine generator suppliers. Review of these modern steam turbines indicated that there was an opportunity to enhance the efficiency of the high pressure (HP) and low pressure (LP) sections of the turbine sections by replacing the worn out steam path components with modern, significantly higher efficiency components and without violating the governing principles of the program.

An additional advantage of modern turbine steam path sections is their ability to sustain their efficiency over a longer period of time. This critical aspect of the design is a crucial element of the program, in that it provides an ability to maintain the plant heat rate over a longer period time and save fuel far into the future.
These modern HP turbines are less prone to solid particle erosion (SPE) damage than their earlier counterparts, which, for plant supplied in USA during the 1960's, lost efficiency with depressing speed, significantly impacting on plant heat rate and requiring overhauls every 5 to 6 years. Modern HP turbines are, by design, less susceptible to SPE and the overhaul period is no longer dictated by this damage, so that the endurance to planned outages is doubled.

In support of this efficiency upgrade program TVA developed specifications for enhancing the HP and LP sections with modern steam path designs. Whilst the focus of this paper is the efficiency upgrade of the HP sections, some aspects of LP improvement are also mentioned. The LP efficiency enhancement program utilizes the LP steam path flow (pressure, velocity and quality) measurement technologies in conjunction with the computational flow dynamics modelling tools to design higher efficiency L-1 and L-0 stage sections. The LP program will be the subject of a subsequent paper.

In order to facilitate the selection of the most advanced HP turbine section steam path TVA developed a comprehensive specification and selection process. The key elements of the specification and selection criteria were:

- Maximum HP sectional efficiency at 100% and 90% MCR levels
- Lowest degradation rate (maximum sustainable efficiency) over a 10~12 year period.
- Net present value of the project taken over a twenty-year period.
- Initial project outlay, including any costs associated with reverse engineering necessary to support a non original equipment supplier (OEM) supplier.
- Value of increased initial and sustained output over the life of the project.
- Unit overhaul costs (labour and parts) and lost generation over 28 day outage duration.

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- Impact on plant auxiliary equipment as a result of the project, determined by the plant cycle optimization process.

- Net increase in unit output at the unit design MCR level and no increase in plant heat input.

- Plant optimization process.

In support of the HP section efficiency upgrade program TVA solicited bids from the World Class steam turbine suppliers for its large turbine fleet. Based on the above competitive bid evaluation process TVA selected ALSTOM designs of the type described in this paper for its Paradise Units 1&2 (2 x 650 MW) with an option to supply HP sections for Paradise Unit 3 (1100 MW), Bull Run (900 MW), and Widows Creek Unit 7 (500 MW).

The selected HP designs have cylinder percentage efficiencies (bowl to exhaust) approaching the mid-90's, with degradation rates less than half the earlier North American experience. ALSTOM achieves this performance through their advances in steam path technology using controlled flow design along with steam passage shapes which avoid SPE damage in order to provide sustained HP efficiency.

TVA conducted an extensive world-wide survey to verify the technology, including records of turbine generators on plants with various North American design boilers similar to those operating at the TVA units under consideration; with or without bypass systems and with typical superheater tubing materials (T-11 and T-22). The survey indicated that the ALSTOM HP modules did not degrade in the manner typical of existing units. The difference is clearly in the steam path design philosophy and not whether the boiler or plant cycle has influence on SPE but rather that the experience of European turbine manufacturers can show how to avoid the problem.

Having selected the HP module and its associated heat balance diagram a turbine cycle optimization study is carried out. The turbine cycle is modelled using the SYNTHA program. Changes to the turbine cycle are incorporated. Paradise Units 1~3 utilize boiler feed pump turbines (BFPT), whose performance must verified for the revised HP extraction conditions. Actual turbine cycle pre-upgrade tests are conducted to verify the system flow conditions. The boiler circulation model is used in conjunction with the turbine cycle SYNTHA model to optimize the plant cycle. This is an iterative process that can take several attempts to optimize the plant cycle. This process will identify component limitations (heaters at end of their capacity or a mismatch in the steam conditions for the BFPT). The impact of these deficiencies is evaluated and an economic decision is made to justify replacement or modification.

The cycle optimization process helped Paradise Plant to identify turbine cycle isolation problems associated with the start-up system. This system is being evaluated to ensure isolation. The start-up system bypass valves will be upgraded to ensure isolation over a four-year period. An electrical systems study has been conducted to identify any limitations associated with the increased station output. No significant deficiencies have been identified for Paradise units 1 & 2.

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Conclusion

The advances made in understanding turbine steam flows and reducing losses have led to the development of design methods and highly efficient blading which can be readily applied to improve the performance of steam turbines currently in operation. Retrofitting, as illustrated by the examples given, provides a cost-effective solution to problems of turbine operation or performance, while reducing inspection requirements and improving reliability. Increased turbine efficiencies are reflected in lower operating costs and higher revenues for power generated.

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ALSTOM

ENERGY Steam Turbines - Newbold Road, Rugby, Warwickshire. CV21 2NH Tel: +44(0) 1788 577111 Fax: +44(0) 1788 531700

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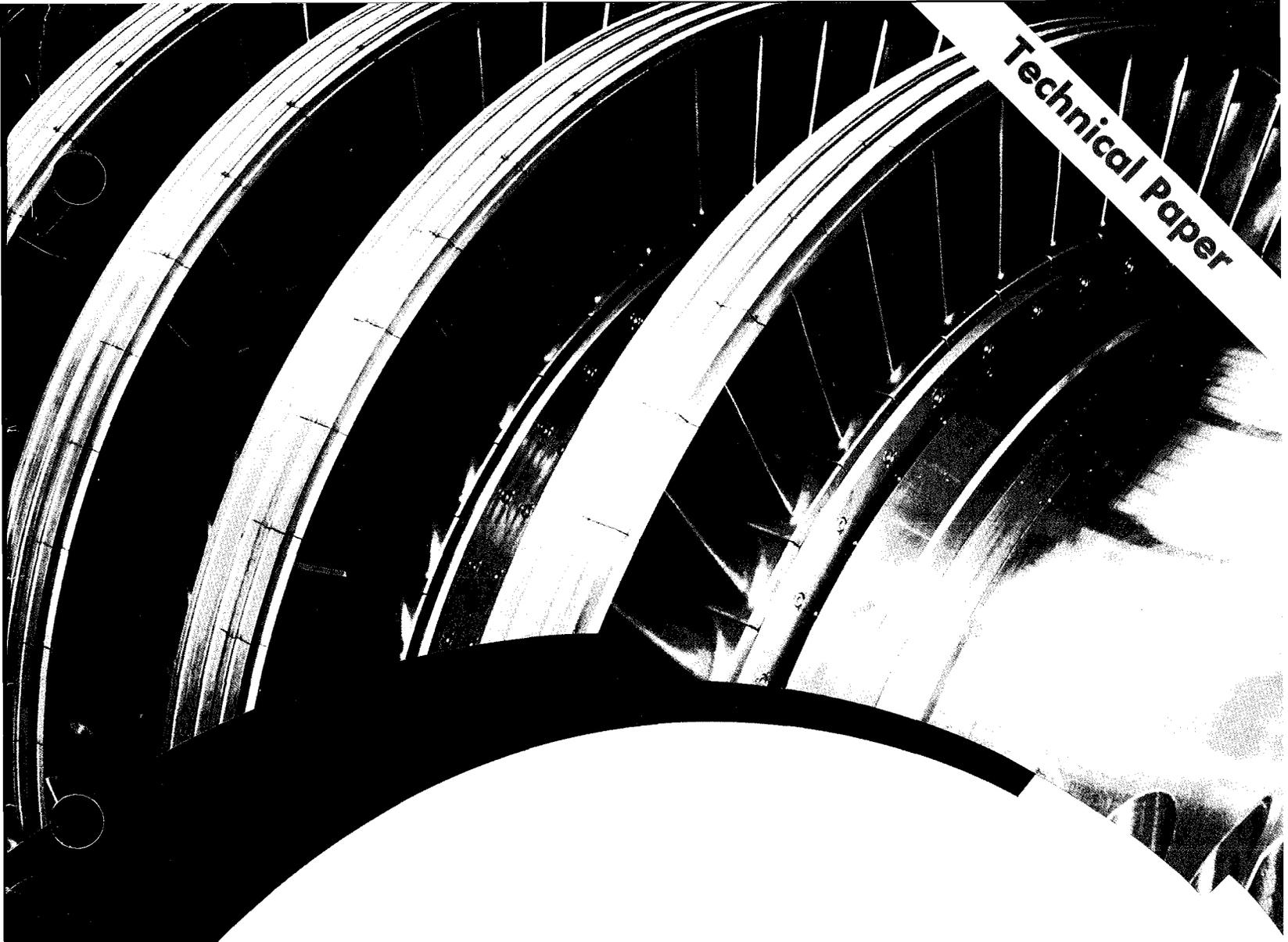
ALSTOM

ENERGY Steam Turbines - Newbold Road, Rugby, Warwickshire. CV21 2NH
Tel: +44(0) 1788 577111 Fax: +44(0) 1788 531700



Technical Paper

Steam Turbine Retrofits on Non-OEM Plant

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Steam Turbine Retrofits on Non-OEM Plant

John McCoach
ALSTOM Power, Steam Turbine Retrofit Engineering, Rugby, UK. john.mccoach@power.alstom.com

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Abstract

The intensified competition created by deregulation of traditional electricity generation markets has created the incentive for utilities to seek steam turbine efficiency upgrades using the best technology equipment available rather than depending solely on the support of the original equipment supplier. In recent years, ALSTOM Power has developed advanced technology 3-D blading capable of achieving the highest levels of steam turbine efficiency. Steam turbines over 25 years old upgraded by retrospective application of this technology have achieved performance levels equivalent to new plant. Conversely, the substantial efficiency improvements obtainable have made it economically worthwhile to upgrade plant less than 10 years old. In addition to providing performance improvement, reliability concerns associated with cracking/distortion of rotors and casings, rotor instability problems, component creep life limitations, solid particle erosion of blading or recurrent blading failures can be eliminated by retrofitting.

ALSTOM Power has access to advanced design solutions using both reaction and impulse type blading technology. In recent years these technologies have provided steam turbine retrofits giving improved efficiency and reliability on a wide range of non-OEM equipment. The efficiency improvements achieved can be used to provide additional marginal capacity often at lower capital cost/kW than new gas-fired combined cycle plant (offering significantly increased revenues during periods of peak demand) or to reduce fuel consumption and emissions for the same power output.

Incentives for Retrofitting

Utilities in countries such as the USA have already begun to reshape and reposition themselves to face the challenges which await them in deregulated markets. Part of this preparation process has involved evaluation of the economic benefits of upgrading existing generating plant for improved performance. This process has lead to a huge increase in demand for high technology efficiency upgrades on steam turbine plant which can provide rapid return on investment. Steam turbine manufacturers which have continued to invest in research and development have been in the best position to respond to this demand with proven advanced technology solutions.

The fundamental reason why many utilities have chosen to retrofit existing steam turbine plant rather than replace or supplement it with new equipment is that it is usually more cost effective.

With the exception of large nuclear LP turbines, steam turbine retrofits can often be justified on the grounds of efficiency improvement alone. However, the case for retrofitting on the grounds of increased efficiency is made even stronger if the retrofit acts to eliminate major reliability concerns. Where appropriate, steam turbine retrofits can also incorporate an increase in steam passing capability or, for nuclear plant, rematching of turbine capacity to suit actual steam generator outlet conditions.

For large nuclear LP turbines, the motivation for retrofitting is always long term reliability but a major secondary consideration is the level of performance

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benefit offered because this offsets financially the essential capital investment. Turbine retrofits are always more economically attractive on plant operating at high load factors.

Increasing pressures to reduce CO2 levels together with other noxious emissions are being imposed by national governments seeking to satisfy internationally agreed targets. Improved plant efficiency reduces the environmental impact of fossil plant, allowing less fuel to be used for the same electrical output with less gaseous emissions and less wasteful heat rejection to the environment.

Increasing the output from existing power plants reduces the need for new plant (eliminating planning permit problems and destruction of greenfield sites) and allows the most inefficient, environmentally damaging plants to be retired.

Efficiency Improvements

ALSTOM Power has developed advanced fixed and rotating blade designs using both reaction and impulse type technologies. The technology offered is selected according to its cost-effectiveness in each application. The following information on blading technology improvements relates primarily to impulse type blading but ALSTOM Power also commits significant effort in the continuing development of reaction type blading (Ref. 1).

HP and IP Blading

Fig. 1 shows the configuration of a typical low root reaction steam turbine stage and the corresponding performance loss mechanisms. The greatest efficiency gains on short height stages have been obtained by reducing blading profile and end wall losses.

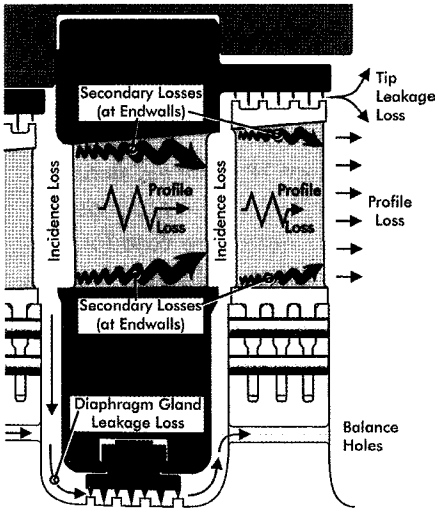

Fig. 1 Sources of efficiency loss in a typical low reaction turbine

An ongoing research and development programme is focused on minimizing these critical losses. A new and highly efficient range of blading has been developed using advanced computational fluid dynamics analysis (CFD), supported by model turbine tests (Ref. 2) and proven by in-service measurements.

Profile Losses

Analysis of the velocity distribution over profile surfaces has allowed profile performance to be improved significantly. Fig. 2 shows the improvement in efficiency obtained at the root section of a new standard blade over a wide range of steam inlet angles. The inlet profiles are designed to tolerate potential mismatches between profile and steam inlet angles in nozzle wakes or at endwall regions.

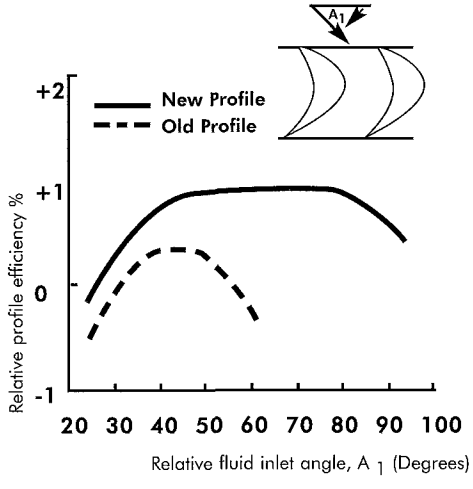

Fig. 2 Effect of improved rotating blade profile

End Wall Losses

Complex vortices and loss-producing secondary flows occur at the end wall regions of blade passages. The influence of these on stage efficiency can be reduced fundamentally by using narrower blade chords and longer aerofoils. However, secondary flow losses are also influenced by the cross-channel pressure gradient arising from the main flow curvature in the passage. Advanced CFD analysis allows this pressure field to be predicted and the benefits of refined passage geometry determined. Using this analysis supported by model turbine tests, ALSTOM Power has established blade geometries which give effective control of secondary flows. Fig. 3 shows the efficiency gains in fixed blade passages from reduced endwall losses.

Additional benefits have been obtained from advanced technology "controlled flow" 3-D fixed blades (Fig. 4) which reduce further the effect of secondary losses.

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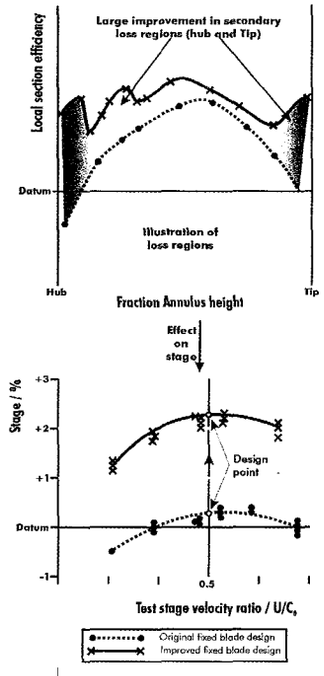

Fig. 3 Reduced secondary losses from improved fixed blade profile

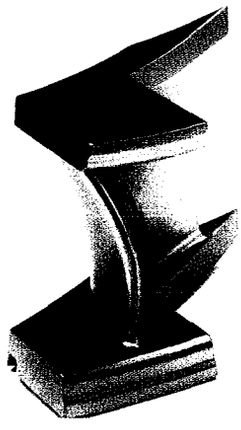

Fig. 4 Advanced 3-D fixed blade

The 'controlled-flow' blades have increased throat areas in the efficient mid-height region and reducing throat areas towards the endwall regions. The effectiveness of these 3-D fixed blades in conjunction with the latest ALSTOM series of rotating blades has been confirmed by testing (Fig. 5) and in retrofit applications.

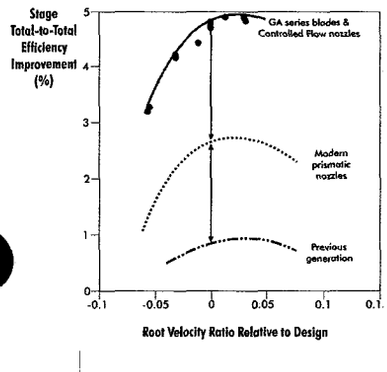

Fig. 5 Progressive improvement in HP and IP stage efficiency

Leakage and Other Losses

Steam leakage flows at the rotating blade tips and diaphragm hubs of low reaction turbines are minimised by careful design. Diaphragm hub leakage is controlled by spring-backed labyrinth seals which provide protection against damage in the event of rotor rubs. Diaphragms are kinematically constrained to allow free radial expansion so that gland clearances can be reduced to a practicable minimum. Blade tip leakage is controlled by sealing fins mounted on extensions of the diaphragm rims which co-operate with the integral blade tip shroud ribs to form a labyrinth seal. Blade tip leakage can be reduced even further by the application of brush type seals.

LP Blading

LP turbine efficiency is particularly important because it has a large influence on turbine power. Expansion to low condenser pressures results in huge increases in volumetric flow through the LP cylinder and a particularly rapid increase in blade height from the L-1 stage leading to a steeply flared outer boundary. The large radial velocity component near the tip of the L-0 fixed-blade gives rise to highly whirling flow and a significant radial variation in static pressure in the fixed/moving blade interspace, tending to give negative reaction at the root and increased reaction at the tip.

Older turbines often had irregular outer boundaries and the L-0 and L-1 stages were normally designed on a two-dimensional basis using simple radial equilibrium to account for centrifugal effects. Such designs exhibit significant breakdown of the flow structure. The intensity of the interspace pressure field can be controlled and reduced by two major design options:-

- By leaning the fixed blade circumferentially inwards so that the pressure surfaces make an acute angle at the hub (Fig. 6) to produce a steam force component acting radially inwards

- By twisting the fixed blades to increase throat openings at the hub and reduce them at the tip, to cause more flow to pass through the hub region.The effects of lean and twist are complementary and can be applied together along with smoother boundaries to control the flow structure

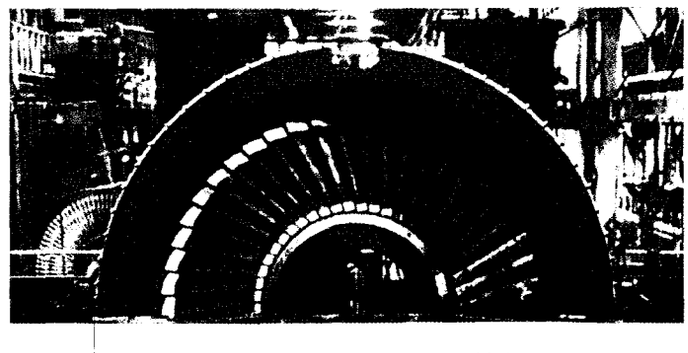

Fig. 6 Practical application of leaned fixed blades

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Other Performance Factors

On plant where the boiler design demands the use of reheater desuperheating sprays to prevent excessive reheat temperatures, improvements in HP turbine efficiency (which reduce cold reheat steam temperatures) permit reheat sprays to be turned down, leading to additional cycle benefits.

The essential rematching of HP turbines in nuclear plants to suit the increased volumetric flow from a degraded steam generator can be combined with an HP turbine retrofit for efficiency improvement. HP turbine retrofits can also take advantage of increased steam flow capacity from over-specified fossil-fired boilers or nuclear reactor upgrades.

Reliability Issues

On large nuclear plant, the most common mechanical reliability problem is stress corrosion cracking (SCC). LP turbine rotors in nuclear applications which use "shrunk-on" disc construction or certain types of blade root attachments are particularly susceptible. SCC can also occur in nuclear HP turbines. Certain constructions necessitate regular inspection and, once SCC is discovered, require ongoing repair or replacement programmes. The threat of SCC and associated cost penalties can be eliminated by appropriate turbine retrofit technology which provides a performance improvement to offset the capital cost.

On fossil plant, there is a variety of reliability issues which can influence the decision to retrofit. In the USA, perhaps the most common problem is solid particle erosion (SPE). In this case, exfoliated particles of magnetite from boiler tubes can cause erosion damage of HP and IP blading. In severe cases, SPE can seriously compromise the mechanical integrity of nozzles or of rivetted tip shrouding attachments after only 3-4 years' operation. HP and IP section efficiencies can fall off by up to 3-4% over this period. There are heavy costs associated with regular inspection, repair or replacement of SPE damaged components. Other persistent reliability problems which strengthen the case for retrofitting fossil-based steam turbines include thermal fatigue cracking of rotors and casings, life limitation due to steady state creep damage, rotor instability problems or recurrent blading failures.

Improved Design Features

Older types of rotating blades (Fig. 7) have many poor design features compared to modern blading. Various root fastening types were used - circumferential fir tree, axial entry fir-tree, T-root and pinned. Some of these had special closing blades with higher attachment stresses and uncertain vibration characteristics.

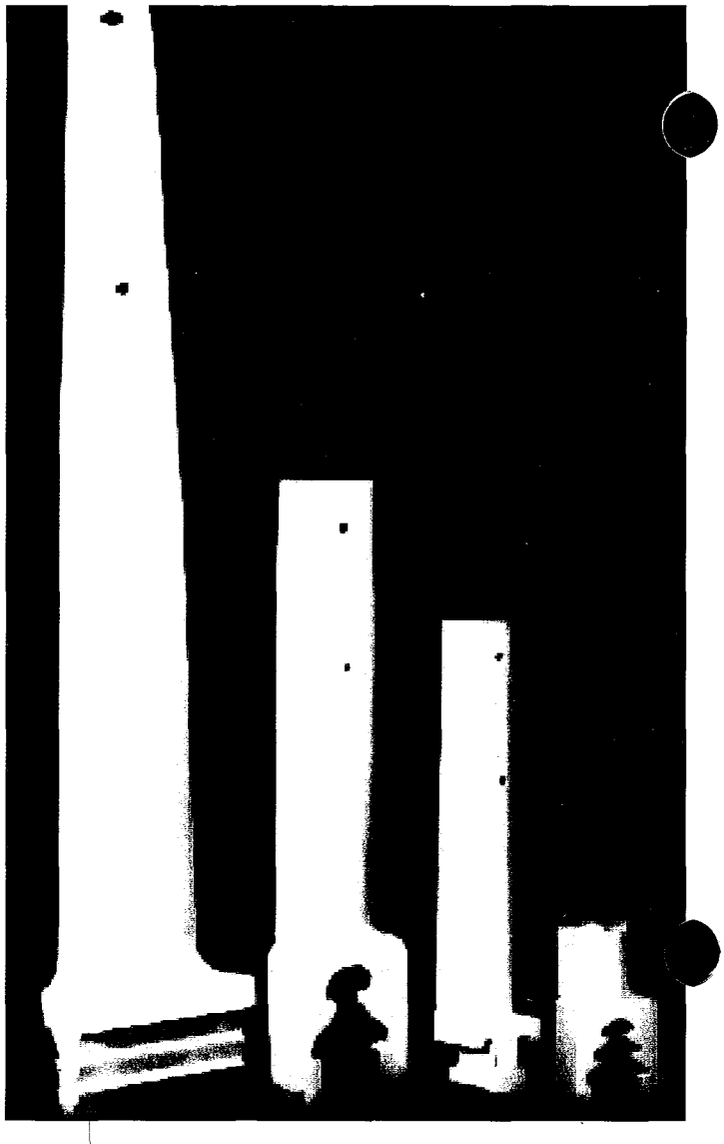

Fig. 7 Older types of rotating blades

Blade profiles in the HP and early IP stages were typically of constant section (without radial twist) with simple profile definitions. Consequently, steam inlet angles were ideally matched to blade inlet angles at one height only. Manufacturing constraints dictated that twisted sections were only used on longer IP and LP stages where the variation in steam flow angles with height was too excessive to permit using constant sections. Blade tip shrouding, generally comprising separate covers rivetted to groups of blades, limited the effectiveness of the tip seals and lead to uncertainty in predicting the complex vibration responses and increased risk of fatigue failures. Lacing wires used for vibration control on long IP and LP blades introduced flow disturbances and were also prone to failure. Manufacturing constraints often prevented using smooth boundaries at the floor and ceiling of the steam path.

Today, ALSTOM Power low reaction blading for HP, IP and early LP stages uses twisted profiles selected from standard ranges categorised by outlet angle.

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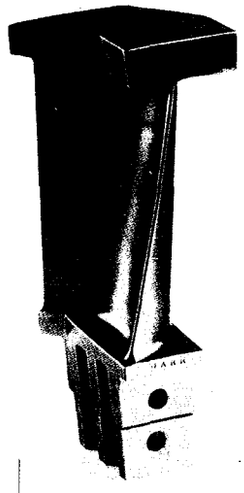

Fig. 8 Modern rotating blade with pinned root and integral shroud

Blades within each range are related by geometric similarity. These blades use forked pinned root fastenings and integral tip shrouding assembled with a controlled pretwisting force to provide a uniformly rigid circumferential structure with simplified vibration characteristics (Fig. 8). The integral shrouding permits a labyrinth type tip seal and can be machined conically on the underside to provide a smooth outer boundary. A typical design of LP last stage blade is shown in Fig. 9. These have curved side entry fir-tree fastenings and aerodynamically shaped shrubber interconnections integral with the blade profile.

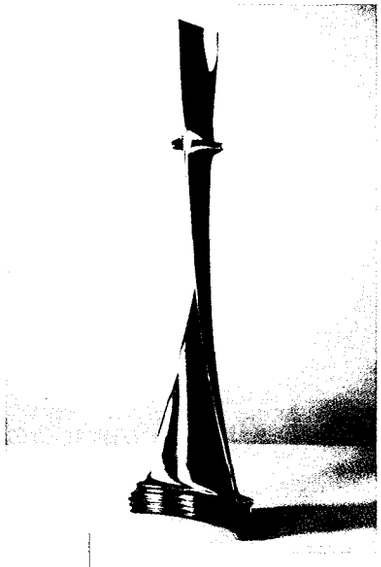

Fig. 9 Typical last stage blade

Retrofit Case Studies

General Considerations

In order to have any chance of success in the steam turbine retrofit market, manufacturers must be able to offer highly efficient blading together with the capability to apply it innovatively in practical schemes within the design constraints dictated by existing plant. ALSTOM Power has retrofitted many steam turbines from its own fleet since the 1980s up to the present day. This work has included many notable achievements (Ref. 3) and provides a sound foundation for its extensive involvement in the non-OEM steam turbine retrofit market today.

Interface Measurements

In order to retrofit non-OEM plant it is necessary to measure all the interface points with the existing equipment relative to a known datum. On multi-unit stations where the machines are nominally identical, measurements are taken from one unit and fitting allowances are introduced to ensure that the same retrofit design can be applied to all the units. Considerable expertise has now been established by ALSTOM Power in designing each equipment interface to ensure proper fit with minimum installation effort.

Retrofit Design Principles

ALSTOM Power applies some basic design principles to all retrofits. Major changes in design philosophy are avoided with the intention of making the retrofit invisible to the plant operator. Where feasible axial clearances are maintained at the original values to avoid changes to differential expansion alarm and trip settings. This approach is especially important on multi-unit stations where different limits between units could cause confusion. Care is also taken not to mix technologies. For example, the interspace between inner and outer casings on ALSTOM HP turbines is normally conditioned by cooling steam but this practice would result in unacceptable thermal stresses on similar non-OEM units which are designed to operate without cooling steam. If rotor stability is known to be marginal on existing units, care is taken not to increase rotor flexibility (e.g. by reducing the hub diameter to accommodate extra stages). Careful assessment of journal bearing stiffness is also made, and, in certain cases, bearings are modified to ensure satisfactory stability.

3-D solid modelling techniques are applied extensively to ensure proper fit and adequate clearances between retrofit components and existing plant.

Case Studies

HP Turbine Retrofits on Impulse Units

In the past four years ALSTOM Power has obtained orders from seven major utilities in the USA for HP turbine inner cylinder retrofits on 18 non-OEM impulse type steam turbines with outputs in the range 500-1000 MW. These include 10 units operating at sub-critical steam conditions and 8 units at supercritical conditions; some units

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arranged in tandem compound configuration, others in cross-compound; some with extraction steam for a heater above the reheat point, some without an extraction. At the time of writing, six of these retrofits have already been installed successfully. These retrofits have involved replacement of rotors and inner casings, permitting additional stages of blading with optimised base diameters. Partial retrofits which re-use existing rotors and casings offer less performance improvement and do not provide any grounds for extending the life of the unit.

Case 1: 4x670 MW Units in Alabama, USA

An order was placed in 1996 by a station in Alabama, USA for HP turbine retrofits on four coal-fired units operating at 2400 psig, 1000°F, 1000°F, originally supplied by a US manufacturer and installed in the period 1978-90. The units operate base load but the original HP turbines were arranged with nozzle control capability down to half arc admission with a double flow nozzle box configuration.

The early stages of the HP cylinder suffered severe SPE damage requiring repair every 4 years. HP section efficiency would fall by 3-4% over this period. The utility objective was to raise the baseline efficiency of the original 7-stage HP turbine above the "as new" level of 85%, prevent the efficiency deterioration and to eliminate the need for outages to repair SPE damage. The retrofit solution (Fig. 10) is arranged for full arc admission (improving performance at base load) with a forward flow first stage and integrally shrouded rotating blades.

The new first stage fixed blades are much wider than the existing nozzles, turning the steam more gradually. This feature minimizes the effect of particle impacts and vastly reduces solid particle erosion damage. The ALSTOM retrofit solution has an optimised 11-stage steam path with improved aspect ratio blading and advanced profiles. Three units have now been retrofitted successfully. The performance benefit obtained and the extension of outage intervals to 12 years has fully justified the capital cost of upgrading these turbines, one of which only entered service in 1990.

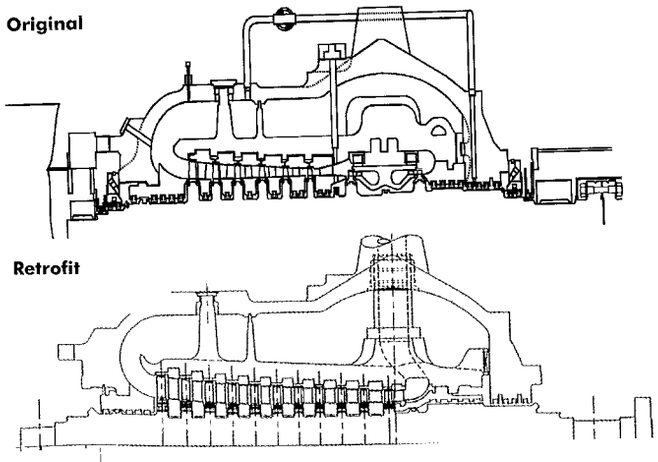

Fig. 10 HP turbine retrofit on USA 700 MW units

Case 2: 2x700 MW Units in Florida, USA

These two units are very similar in outline to those referred to in Case 1 above except that an extraction is taken from the blade path for a feedwater heater above the reheat point. However, these two units were required to maintain a load cycling capability such that the retrofit solution had to be arranged with nozzle boxes for partial arc admission (Fig. 11). Both of these units have now been retrofitted and contract requirements satisfied.

As there are more than 80 steam turbines in the USA using the types of HP turbine represented in Cases 1 and 2, ALSTOM Power developed a standard split-pattern inner casing which could accommodate four potential design variants for units with or without extractions and with or without nozzle boxes.

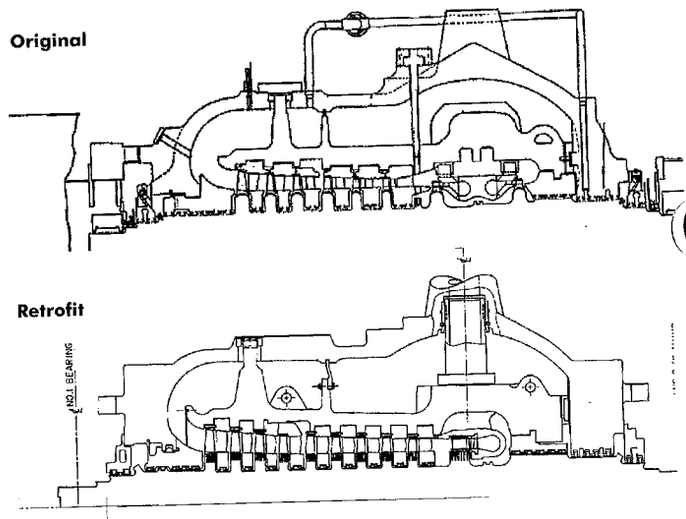

Fig. 11 HP turbine retrofit with nozzle control on 700 MW unit

HP-IP Turbine Retrofits on Impulse Units

There are approximately 120 impulse type reheat steam turbines in large output units (> 500 MW) in the USA using either sub-critical or supercritical steam conditions together with a few double reheat units which use combined HP-IP turbines for the main steam/first reheat steam expansion. Similar turbine types are used in other countries, notably Japan and Taiwan.

Case 3: 2x700 MW Units in N. Carolina, USA

Two double reheat machines operating with supercritical main steam conditions are being retrofitted by ALSTOM Power to provide efficiency improvements in the HP-IP1 turbine together with increased steam passing capability to take advantage of additional boiler capacity. These units were amongst the top ten efficient units in the USA before retrofitting.

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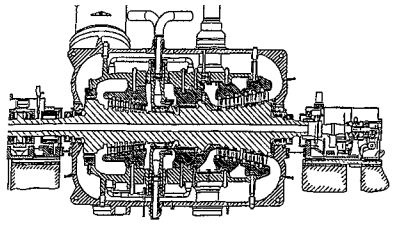
Original



Retrofit

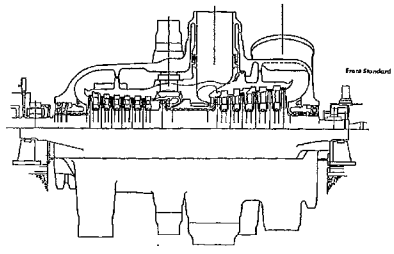


Fig. 14 Replacement HP-IP impulse turbine for USA 600 MW reaction unit

In this case, complete replacement HP-IP turbine modules (Fig. 14) using impulse type blading are being supplied in order to eliminate the existing reliability problems and to remove the need to stop the machines to measure internal interfaces. The new modules, based on a standard design already in service, have four HP and two IP inlets (compared to the existing with eight and four respectively) require some major pipework modifications during installation but the additional costs involved are fully justified by the performance benefit. The simplified turbine architecture eliminates the majority of the existing leakage paths inherent in the original reaction design and provides significant improvements in blade path efficiencies.

Performance Guarantee Issues

Many steam turbine retrofits on thermal power plants, including those referenced above, can be justified economically on the grounds of efficiency improvement alone. Since turbine efficiency is the main motivation for capital expenditure a great deal of attention is focused contractually on the issues surrounding retrofit performance guarantees and their verification. This subject has been dealt with comprehensively in IEC 60953 Part 3 (draft format soon to be finalised) and ALSTOM Power would normally follow these guidelines. Performance guarantees linked to retrofits of HP, IP or HP-IP turbine sections on fossil plants operating with superheated steam are normally based on the absolute level of section efficiency achieved after the retrofit installation. The expected effect of these efficiency improvements on unit heat rate and output are easily derived and are quoted for information. It is not normal practice to provide guarantees on absolute unit heat rate and output unless the entire turbine train is retrofitted. Performance tests on HP, IP and HP-IP turbine retrofits are based on simple enthalpy drop tests preferably using pressure and temperature measurements at cylinder inlet bowl and exhaust to eliminate any uncertainties associated with valve pressure drops.

The component efficiency of retrofitted LP turbines of fossil units operating partly in the wet region cannot be measured directly by enthalpy drop testing but must be derived from the overall plant performance. In this case, the guarantee would normally be given in terms of a unit heat rate/power improvement.

It is normal practice to test as soon as possible after the unit is restarted and to perform benchmark tests at frequent intervals beginning immediately after restarting. In this way, any unexpected change in efficiency can be monitored and the cause more easily identified. It is not unknown for a retrofitted turbine to perform according to expectations straight after restarting but then for sudden deterioration to occur due to factors outside the control of the turbine supplier (e.g. due to heavy copper deposition carried over from the HP feedwater heaters).

Efficiency deterioration is inevitably of interest when evaluating the long term economic benefits of retrofitting. It is not realistic to expect turbine suppliers to provide long term guarantees (as the extent of deterioration is heavily dependent on how the unit is operated) but suppliers should be able to provide verifiable evidence from past experience of trends in long term efficiency deterioration on similar equipment.

Closure

The practice of retrofitting non-OEM steam turbines is now firmly established in the power industry, driven by utilities seeking a competitive advantage from leading edge technology. In recent years, ALSTOM Power has provided steam turbine retrofits for a wide variety of non-OEM equipment, applying either advanced impulse or reaction type turbine technologies to give the most cost effective solution. Significant expertise has been developed in all aspects of the retrofit process permitting the development of standard proven solutions for a wide range of existing steam turbine designs.

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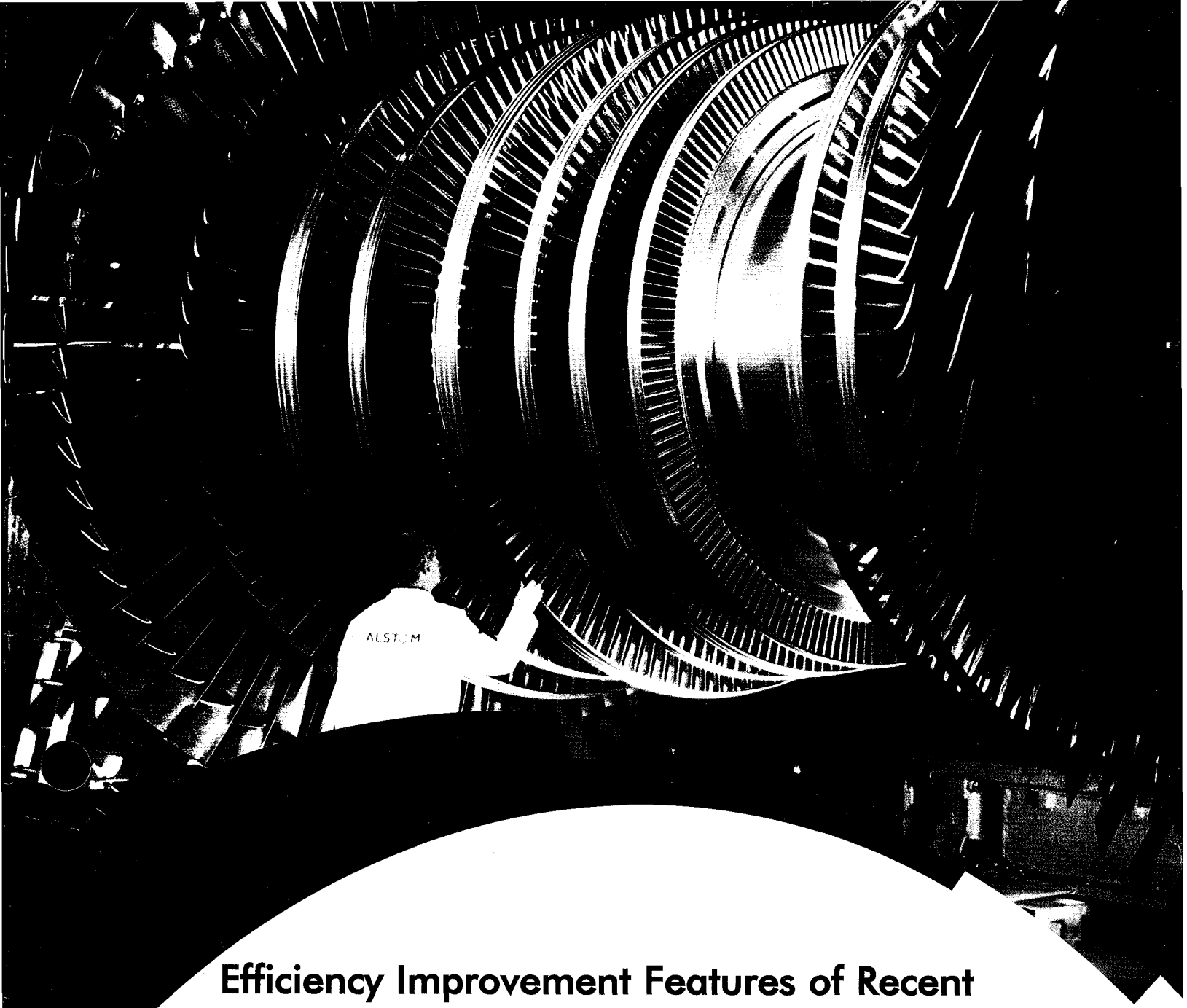
ALSTOM

ALSTOM (Switzerland) Ltd - Brown-Boveri-Strasse 10 - CH-5401 Baden/Switzerland
Tel. +41 56 205 8951 - Fax +41 56 205 3179 - www.power.alstom.com



Efficiency Improvement Features of Recent ALSTOM Power HP/LP Turbine Retrofit at Southern California Edison's San Onofre Nuclear Generating Station

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Efficiency Improvement Features of Recent ALSTOM Power HP/LP Turbine Retrofit at Southern California Edison's San Onofre Nuclear Generating Station

Robert D. Brown, ALSTOM Power, Rugby, England. Tel. +44 (0) 1788 531924
robert.brown@power.alstom.com
Fred Y. Simma, Southern California Edison, San Clemente, California, USA. Tel. 949 368 2306
simmaf@songs.sce.com
Russell J. Chetwynd, Southern California Edison, San Clemente, California, USA. Tel. 949 368 2306
chetwyndr@songs.sce.com

Abstract

A large US nuclear utility was faced with a necessity to perform numerous plant physical and operational modifications during the 1999 refuelling outages. In particular, it replaced low pressure (LP) turbines, high pressure (HP) turbine diaphragms, reduced steam generator operating temperature and pressure and made modifications to the main condenser. The significant performance improvements obtained from the LP turbine retrofit have offset the performance loss necessary to preserve steam generator life. The LP turbines have been retrofitted to address reliability problems associated with stress corrosion cracking (SCC). This opportunity was used to boost their performance with innovative ALSTOM Power design features. These included the unique "optiflow" steam flow arrangement six stages of integrally shrouded blades, a new 47" last stage blade, and generously sized aerodynamically efficient hoods with customized diffusers.

The HP turbines have been rematched, with only 3 stages of diaphragm replacement, to permit operation at full reactor thermal power with increased volumetric steam flow due to reduced steam generator temperature and pressure.

In order to quantify the LP turbine efficiency improvement, the performance impact of the multiple modifications was separated. Back-to-back performance tests were performed before and after each outage. The challenge was to obtain reliable results without incurring the considerable expense of performing a full performance test per ASME code PTC 6. An acceptably low uncertainty level was achieved using multiple station instrumentation and a few additional test quality instruments.

The utility and OEM approaches and finding that related to the overwhelming success of the project is discussed as well as a summary of the work performed. This paper will be of interest to utilities with a need to resolve turbine reliability issues, perform a power upgrade and also maximize & quantify performance improvement.

Nomenclature

SCC	Stress Corrosion Cracking
LP	Low Pressure Turbine
HP	High Pressure Turbine
SONGS	San Onofre Nuclear Generating Station
SCE	Southern California Edison
OEM	Original Equipment Manufacturer
PWR	Pressurized Water Reactor
MSR	Moisture Separator Reheater
SG	Steam Generator
NDE	Non Destructive Examination
RCS	Reactor Cooling System

Introduction

SONGS has two almost identical Nuclear Units. Each Unit consists of a 3410 MWth, pressurized water, Nuclear Steam Supply System. The steam generators were

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designed to deliver 855 psia saturated steam to the turbine inlet at 100% rated power.

The original 1800 rpm, 1127 MWe rated steam turbines entered service in 1983 and 1984 respectively. Both units had accumulated in excess of 100,000 operating hours before the installation of the turbine retrofits. Each unit has a 7-stage double flow HP turbine exhausting to a two-stage MSR, the reheat steam entering three 8-stage double flow LP turbines with 45" last stage (L-0) blades.

Reasons For HP Turbine Retrofit

Industry experience with the ABB-CE design steam generators together with SONGS NDE results indicated that intergranular stress corrosion cracking of SG tubing is the most significant life-limiting degradation mechanism. This phenomenon is known to be thermally activated and can be mitigated significantly by lowering the operating temperature.

The objective of reducing SG operating temperature was to extend service life of the SG without incurring the considerable expense of equipment replacement and to avoid lost plant output associated with high levels of SG tube plugging.

In order to determine the desired new operating temperatures a study was performed. The competing factors which dominated this study were the effects of decreasing steam pressure associated with reactor coolant system (RCS) temperature reduction and sharp decrease in plant output, since the amount of steam which the HP turbine can pass is directly proportional to the inlet steam pressure. A way needed to be found to direct the same amount of steam to the turbine with lower main steam pressures. The increase in flow area could be achieved by fitting new diaphragms in the first three HP stages with larger throat areas. In addition, the steam generators were chemically cleaned to remove heat transfer fouling deposits from the secondary side of the tubing. The result was a determination that RCS could be lowered by a total of 13°F and still pass the original full power steam flow to the turbines.

HP Turbine Modifications

The steam flow from the SG has two parallel paths: nominally 95% to the HP turbine, and the remaining 5% to the MSR (Fig. 1). It was therefore important to know both the absolute level of steam flow from the SG and the proportion of steam to each component, prior to making any changes to the HP turbine - too big an increase in capacity would lead to inefficient HP valve throttling in order to maintain steam generator outlet pressure, whilst too small an increase would not allow the full potential benefit of the reduction in RCS temperature.

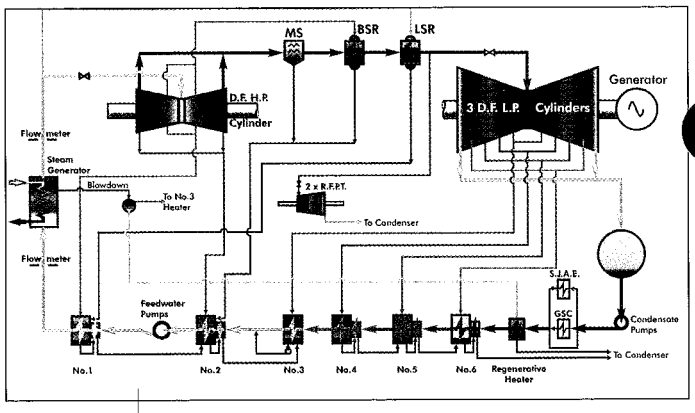

Fig.1 San Onofre Secondary Plant Cycle (Diagrammatic)

Many test measurements, mainly pressures and temperatures, were taken on Unit 3 secondary plant. Together with the use of chemical tracers to estimate some cycle flows, these measurements allowed the actual operating cycle to be modelled by ALSTOM Power, and hence the consequences of both cycle and component changes to be predicted with reasonable accuracy.

The increase in HP turbine capacity was achieved by firstly modifying the HP turbine throttle valves to reduce the full-flow pressure drop when wide open, and then increasing the HP turbine flow area by fitting new diaphragms, with fixed blades having larger throat areas, in the first three stages.

ALSTOM Power manufactured the replacement fixed blades using its latest approach in which the fixed blades have integral root and tip platforms (Fig. 2). The fixed blade platforms are then welded directly into the diaphragm rings.

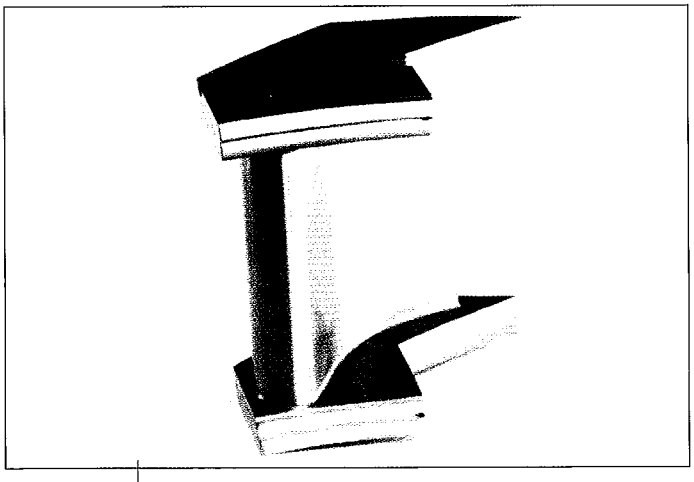

Fig.2 HP Turbine Fixed Blade

Reasons For LP Turbine Retrofit

The principal concern with the original LP turbines, in common with industry experience on units of similar construction, had been the discovery of SCC in the disc rim and balance hole regions of several rotor stages

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during the 1995 refuelling outages. These cracks were arrested by skimcutting, dressing out of larger defects, enlargement of steam balance holes and shot peening (Ref. 1). The discovery of SCC, together with the possibility of further SCC initiation at other vulnerable points on the rotors had lead to increased inspection requirements and the potential for extended or unplanned outages. A secondary reliability problem associated with the original turbine design included concerns over torsional resonance margins. (Ref. 2).

The temporary repairs performed during the C8 refuelling outages in 1995 were to permit operation of the turbines for one more cycle. Therefore, it became necessary to develop a strategy for managing the turbine cracking problem, to avoid costly and frequent inspections, and to ensure turbine integrity until the end of the licensed plant life. The purpose of this strategic plan was to provide the optimum approach for managing the LP turbine disc cracking. Based on the initial Unit 2 SCC findings, and subsequent Unit 3 findings, a multi-organizational team was formed to investigate various repair options that were capable of restoring the turbine rotors life in a timely and economical manner. The team make-up was chosen to address all aspects of a turbine refurbishment program.

Four options were considered (Options A, B, C, and D), ranging from the least cost to most cost respectively. The options included inspecting and repairing (A), refurbishing the rotors using two universal rotors as maintenance tools (B), purchasing three new rotors of an upgraded design (C), or purchasing 6 new rotors (D).

Of these options, Option D provided the least risk that cracking would not resume. Option C addressed the cracking problem, but did assume some risk since three of the rotors would be old, refurbished rotors. Option B was not realistic because it was maintenance intensive; and final rotors would not have been refurbished until the Cycle 12 outages. Finally Option A assumed a great deal of risk since none of the rotors would have been replaced, and all repair work planned had to occur during the outages. This option could not guarantee that cracking would not resume, and the risk was the economic impact the plant would have faced if cracking became worse than predicted.

The results of the present worth cost evaluation indicated that Option C, the purchase of three new rotors, was the strategic solution for addressing the LP Turbine cracking. However, factors such as the additional MWe gain and more competitive pricing, obtained during the bidding process, economically justified Option D, installation of 6 new and upgraded LP turbines.

LP Turbine Retrofit

In order to satisfy the twin objectives of eliminating the threat of SCC, and providing a substantial performance (MWe) improvement, the retrofit LP turbines had two important changes in turbine architecture compared with the original machine (Fig.3).

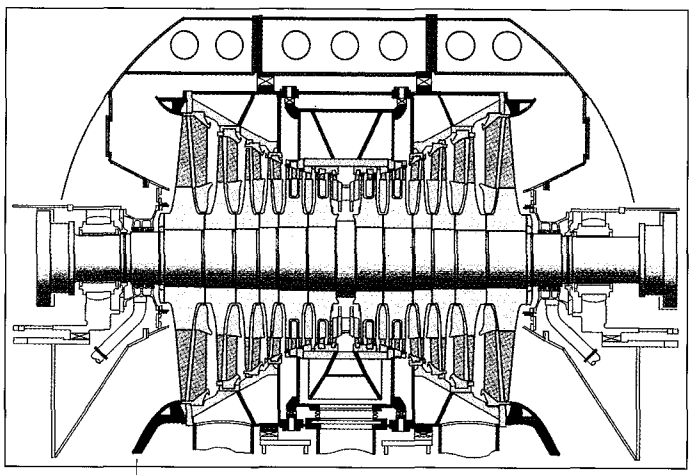

Fig.3 Original LP Turbine Design

SCC Avoidance

The San Onofre LP turbine retrofit (Fig 4) is based on the use of welded rotors constructed from two shaft ends and three intermediate "disks" assembled together by a highly automated welding process. Welded rotor technology has been applied by ALSTOM Power on large nuclear units since the 1970s.

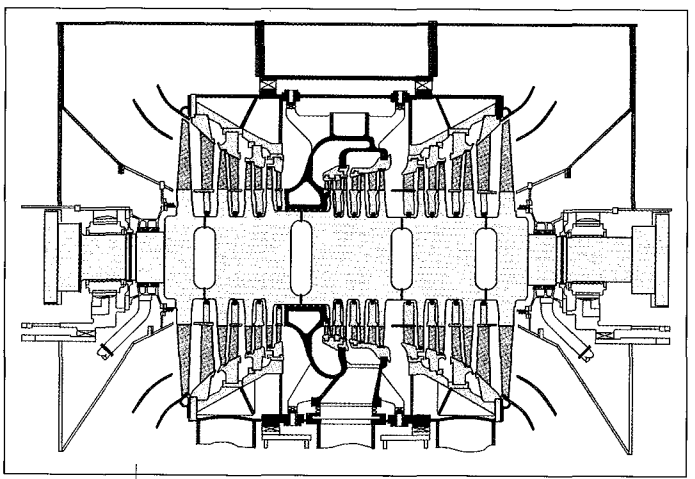

Fig.4 "Optiflow" LP Turbine Retrofit

The welded rotors do not have the high bore stresses and consequent high material strength associated with shrunk-on disc construction. The smaller forged pieces allow better control of material properties and are easier to inspect ultrasonically. The welded rotors never require a centreline bore for verification of bore properties.

The rotating blades on all stages except the L-0 and L-1 have forked-pinned root attachments in place of the older fir-tree (straddle) type. The pinned root fixing has much lower peak stresses for an equivalent blade load than the

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fir-tree type. The elimination of the shrink-fit stress and the reduction in disc rim peak stresses allows the rotor yield strength to be specified 15-20% lower than an equivalent shrunk-on disc rotor.
Discussion on the results of extensive ALSTOM Power research into the causes and the avoidance of SCC is given in Ref 3.

Performance Improvements

The second major design change over the original double flow LP turbine design is the adoption of the unique ALSTOM Power "Optiflow" LP turbine configuration, developed to maximize performance.

The new LP blade path comprises a single flow (Optiflow) section with four stages of blading, followed by a conventional double flow section also with four stages (Fig 4). Steam enters the LP turbine inlets and divides three ways (rather than the original six) as it expands through the Optiflow section (Fig 5). The flow then divides into the double flow section and expands down to condenser pressure via longer, 47" L-0 blades and larger LP exhaust hoods.

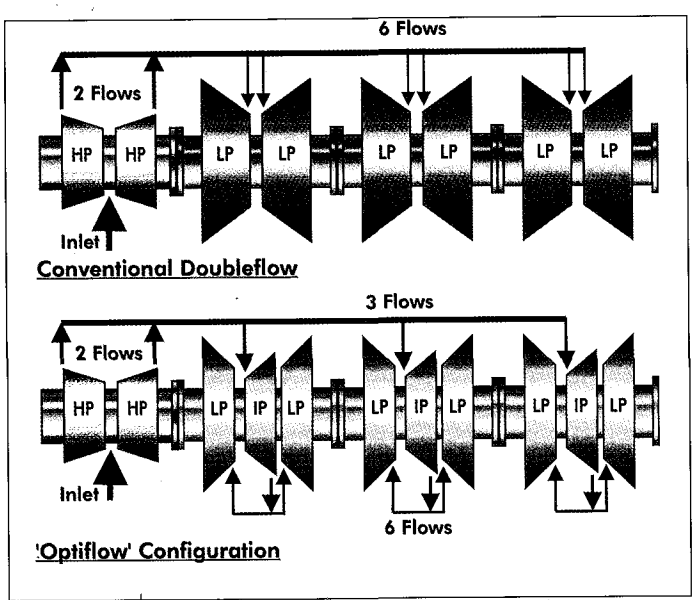

Fig.5 Comparison of Inlet Arrangement

The Optiflow principle is applied by ALSTOM Power to avoid the use of short and inefficient blades in the early stages of LP turbines. The increased blade aspect ratios (blade height/width ratio) - effectively doubled compared to conventional double flow arrangements - provide a distinct improvement in early LP stage efficiencies. This more than outweighs the sum total of flow reversal and leaving loss at the end of the single flow expansion and the leakage through the inlet gland seal.

All fixed and moving blades have modern high efficiency profiles and, with the exception of L-0 and L-1 stages, the moving blades have forked-pinned attachments and integral blade tip shrouding (Fig 6).

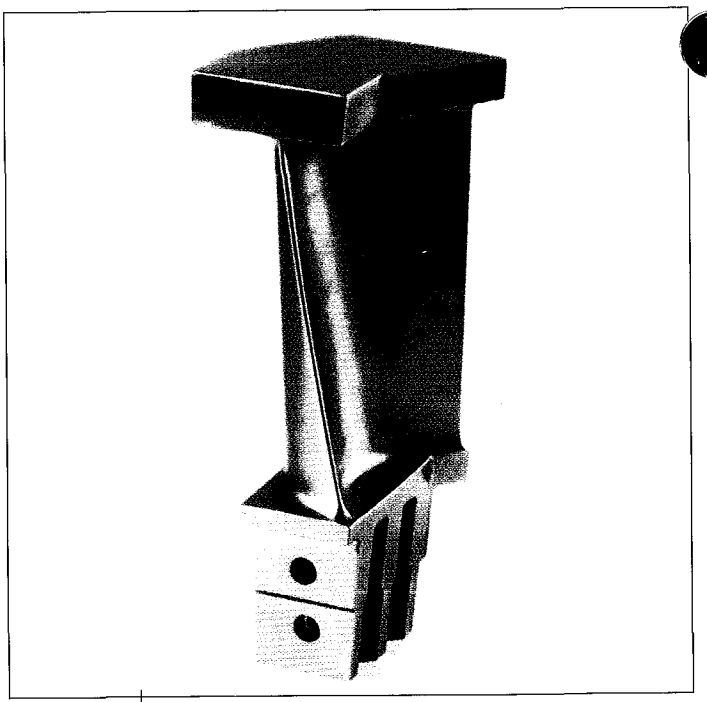

Fig.6 Typical Rotating Blade with Integral Shroud

Integral shrouding permits the application of both a smooth conical outer boundary to the steam path on the shroud underside and highly efficient labyrinth type seals on the shroud topside (Fig 7).

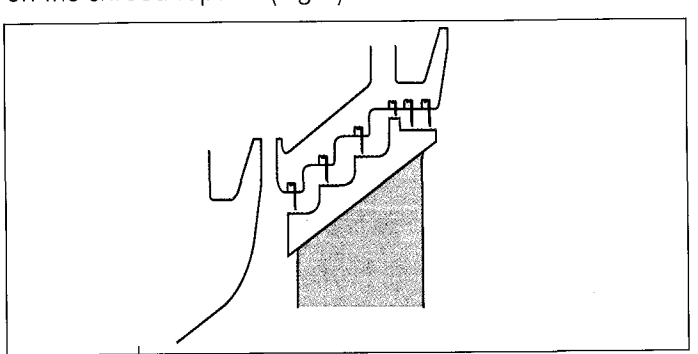

Fig.7 Typical Stepped Shroud for High Flare LP Blading

Spring-backed, slant-finned gland seals provide improved sealing at the diaphragm bores compared to the original design which had straight-finned, caulked-in seals.

The L-1 moving blade is a freestanding design with an axial entry root fastening.

The longer 47" L-0 blade improves performance by reducing the loss associated with residual kinetic energy in the exhaust steam at the design condenser pressure. A proven design, the L-0 blade has a highly cambered section, curved axial entry root fastening and integral snubbers (Fig 8).

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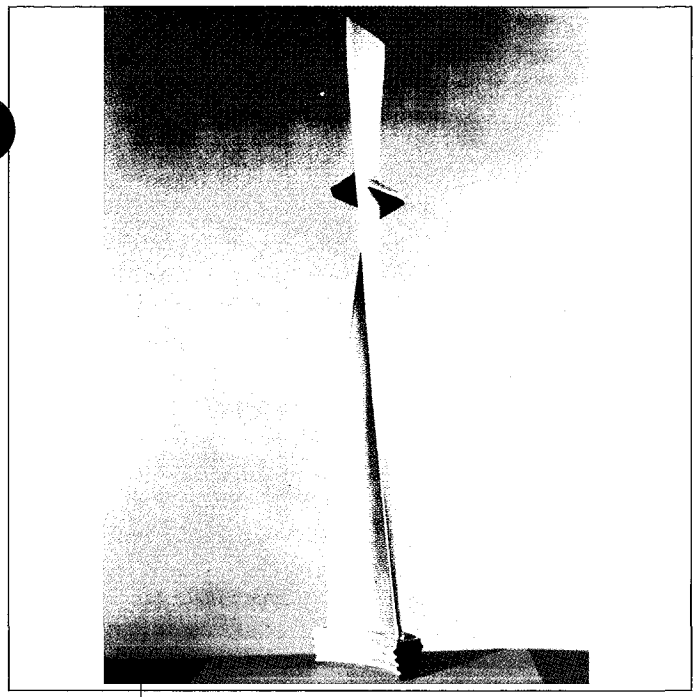

Fig.8 SONGS 47" Last Stage L-0 Blade

The original LP exhaust hoods presented a significant restriction to the steam exhausting from the last stage blade annulus because of their curved shape and short axial steam space (Fig.3). This restriction was removed by the design and installation of new generously sized hoods and exhaust flow guides (Fig 4), designed using state of the art computational fluid dynamics analysis tools.

The MWe improvement guaranteed by ALSTOM Power was contractually required to be attributable to the LP retrofit only, for nominated terminal conditions, including constant reactor thermal power. As well as accounting for the improvements in steam path design as outlined above, the guarantee also included a figure for degradation recovery of the existing LP turbines. The performance improvements (compared to the original LP turbine design) are detailed in Table 1.

Table 1 - Contributions to Performance Improvement

	Generator Output Increase %
Modern fixed and moving blade profiles, and Optiflow design.	1.1
Steam path flare (integral shrouds)	0.1
Improved moving blade tip and diaphragm gland sealing	0.3
Longer L-0 blade	0.15
Exhaust hood optimization	0.5
LP degradation recovery	0.15
Total	**2.3**

Performance Test Plan

SCE specified inclusion of a performance test provision in the contract to assess performance change of the turbines. Utilities facing similar retrofit should consider a test which can provide the following benefits:

- Meaningful contractual warranty,
- Accurate performance gain assessment,
- Early identification of the possible retrofit problems,
- Increase OEM focus on maximizing possible performance gain during design and manufacture,
- Very useful byproduct is overall plant conditions analysis which helps to identify any inherited performance problems, such as leaking valves, heat exchanger problems or inaccurate instrumentation

Technical Difficulties

It was clear that the test needed to be accurate enough to achieve the established objectives. All reasonable efforts were made to decrease uncertainties as high uncertainties could diminish or even eliminate completely all of the potential benefits. For example, there would be no reason to perform a contractual test with an uncertainty of say 10 MWe, when trying to measure a 10 MWe improvement.

There is no easy way to assess relatively small performance changes even under the best theoretical conditions. It is very common to obtain significantly different results when two measurements are taken on the same turbine generator set one or two days apart, even without parameters changing. It would become more complicated in real life when Pre and Post modification tests may be performed six months apart, as various uncertainties increase significantly and new variables need be taken into account. Some major uncertainty contributors are listed below:

- Instrument drift
- Instrument calibration between the tests
- Equipment aging and degradation
- Outage repairs (i.e. steam path, leaking valves, MSR, heaters)
- Operating parameters change which station has control of (live steam pressure, blowdown flow. gland steam flow, reactor power, power factor, heater bypass, etc.)
- Operating parameters change outside of the station control, such as condenser backpressure, heat exchanger efficiency.
- Impact of other major equipment modifications, such as HP turbine steam path modifications or SG pressure change.
- Steam cycle isolation.
- Unidentified leaks.

It would appear that the best method to assess efficiency improvement resulting from the LP turbine replacement would be to perform a full scale ASME PTC-6 Performance Test which provides the most accurate

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information about the components performance with a minimum uncertainty. However there are significant problems with such an approach. The major obstacle is the significant cost involved. Furthermore, it is a common practice for all major OEMs to guarantee relative MWe improvement, not absolute post retrofit MWe, because a significant part of the aged plant equipment is not impacted by the retrofit and is outside of the OEM's control. Therefore, two full scale PTC-6 tests, one before and one after the retrofit would be required to answer the main question of what MWe improvement was achieved. This would double the cost making a full scale test approach even more expensive.

In our case SCE and ALSTOM Power agreed that high accuracy could be achieved without the expense of full scale PTC-6 tests. Particularly it was agreed to perform back-to-back alternative tests per ASME PTC 6-1, relying on less measurements and analytically accounting for all changes and modifications made during the implementing outage and all other factors listed above.

Plant-vendor Agreements

All major agreements between SCE and ALSTOM Power were reached in advance during the contract negotiating phase. The Performance Test Plan was developed later and approved by both parties in order to formalize all details, most issues were treated per Test Code recommendations. Following are major components of the Test Plan:

- Test timing.
- Credits for non LP turbine outage modifications.
- Instrumentation details
- Plant isolation details
- Data collection details
- Prevailing conditions during each test run
- Data reduction
- Test acceptance criteria
- Data corrections
- Cycle loss calculation methodology

Two items from the above list are of particular interest. The first is test timing. In order to minimize uncertainties resulting from the instrumentation drift it was agreed that the Pre Test would be performed within 90 days prior to the Outage and Post Test would be performed no later than 90 days after the Unit returns to full power operation. The goal, however, was to perform a Post Test earlier, to further decrease instrumentation drift effects. Another point of interest is data correction. It was agreed that any deviations of the test conditions which could not be eliminated, such as condenser vacuum would be normalized using accepted correction curves. The main question, however, was how to handle additional plant modifications such as SG pressure reduction, condenser modifications and especially HP diaphragms modification, described above. All these changes were outside of the original scope of work and it was expected that they could have impact on the overall result of up to 20-25 MWe.

As HP diaphragm replacement was not part of the original LP turbine retrofit contract, its impact needed to be separated from the LP turbine retrofit impact. The problem was that in addition to calculated HP MWe impact value, the HP retrofit had significant uncertainty which depended on the diaphragms manufacturing tolerances and therefore could be fairly high. A solution was found using the fact that there is strong theoretical correlation between the diaphragm area and upstream pressure, therefore it became possible to calculate corrections to the test data by measuring HP 1st stage pressure before and after the outage. It should be noted, however, that these additional variables increased overall test uncertainty.

One more interesting issue was of how to assess the performance gain from the new generously sized exhaust hoods and aerodynamically designed diffusers (see Fig. 4), which were the part of the original contractual performance warranties. The hoods and diffusers were installed separately two years before the LP rotors replacement outage. The expected performance gain for this part, provided by ALSTOM Power was 0.5% (see Table 1), which corresponds to 5.5 MWe of overall electrical output. Such a small performance improvement could not be reliably measured. However, as SONGS noticed significant output increase using station instrumentation and other secondary indications, it was agreed to account for 5.5 MWe output improvement without further testing.

Test Uncertainties

The alternative test produces higher uncertainties than the full scale ASME PTC 6 test. Ref. 4 states that expected test results for steam turbines operating predominantly within the moisture region have an uncertainty of about 3/8% for the full scale test and 1/2% for the alternative test. Half a percent uncertainty would correspond to 6 MWe for the Pre test and 6 MWe for the Post test in the SONGS case, resulting in overall test result uncertainty as high as 12 MWe. This extremely high uncertainty would make the full scale test approach less suitable for contractual purposes.

It is important to note that test uncertainty is not the same as test tolerance. Test uncertainties are statistical values calculated in such a way that they bound real test results in 95% of the cases. If an arithmetic sum of the Pre and Post test uncertainties were used for back-to-back tests, the theoretical probability of the overall test result being outside of this range would be even smaller. This is because Pre and Post test results would need to be significantly biased in the opposite directions to make this happen. The probability of such an event is negligibly small as shown below using probabilistic range of 95 to 99.5%
$P = 2*(0.025)*(0.134) = 0.0067$ (0.67%).
Test tolerances on the another hand are negotiated commercial

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values which are used for warrantee purpose only. There is no good answer as to what value should be used in each particular case. Some authors even stated that the tolerances should not be applied to modify test results [Ref 5, page 227]. We believe that these values are subject of contractual negotiation which should be closely tied to other contractual issues. For this reason this subject is left outside the scope of this paper.

It was realized that it was necessary to decrease test uncertainties to more reasonable values in order to have meaningful data. Overall test uncertainty depends upon the cycle uncertainty or how well operational conditions are assessed, in addition to overall instrumentation uncertainty which in turn depends upon individual uncertainties (i.e. measurement errors) of the specific parameters. Test uncertainty of each particular instrument or parameter has two components:

♦ Systematic or fixed bias error,
♦ Random or precision error

The benefit of the back-to-back test methodology is that all bias errors are cancelled out as long as a number of special provisions is taken. Therefore, only the random error and cycle uncertainties remain. This makes accurate testing much easier. However, additional steps needed to be taken to achieve further test uncertainty reduction. The following approaches and solutions were used:

♦ Eliminate systematic (bias) uncertainty, leaving random uncertainty only [Ref 6. page 21]. The same instruments were used for the Pre and Post test without additional calibration between the two tests. Instrument drift between the tests was verified, however no calibrations were performed.
♦ Identify major contributors and improve accuracy for their measured values, using more accurate instruments. It was agreed to use main steam flow measurements instead of feedwater flow to avoid significant uncertainty resulting from possible feedwater venturi fouling. Additionally, high accuracy instrumentation was used to measure generator electrical output and power factor, final feedwater temperature, condenser vacuum, and first stage HP turbine pressure.
♦ Increase number of critical instruments (some installed by ALSTOM Power and some by SCE), taking statistical credit by averaging data obtained from multiple instruments. Electrical output was measured by 2 independent power analyzers, final feedwater temperature was measured by 4 independent instruments, using 2 additional permanent station instruments as reference points, condenser vacuum was measured at 9 different locations using a total of 18 instruments (6 new condenser vacuum basket tips per Code [Ref. 4] were installed in addition to three existing station instruments), and 1st stage HP turbine pressure was measured by 4 independent instruments.
♦ Collecting more raw data by increasing frequency readings, the number of data collection periods and duration of these periods. Each test consisted of two successive two hour test periods. Data for all critical parameters were collected every 1 minute, resulting in 240 raw data points for each critical parameter.
♦ Controlling operating parameters and keeping them steady. It was necessary for the SONGS operators to keep primary and secondary cycles in a stable and steady condition, using following limits as a guideline:

o Generator electrical output ±3 MWe
o Steam generator pressure ±4 psi
o Reactor power ±0.25%
o RCS reference temperature ± 0.5°F

♦ Keeping Post test conditions as close to Pre test operating conditions as possible eliminating extra variables.
o Isolate Steam Generator blowdown. (Unfortunately, plant chemistry conditions would not allow us to shut off blowdown during the Post Test).
o Condenser makeup was isolated
o Reactor power was kept the same for both tests
o Secondary plant alignment including number of operating pumps, feedwater heater levels, emergency dump valves position was kept the same.
o Condenser backpressure maximum value was limited in order to minimize vacuum correction
♦ Decreasing overall test confidence level from 99.3% to a more reasonable value of 95%

The overall uncertainty of the test was calculated based upon the above considerations and it was concluded that the value of ± 0. 17% with a confidence level of 95% could be achieved for each test. This corresponds to the overall back-to-back test uncertainty of approximately ± 3.5 MWe with confidence level of 95% which was believed to be adequate for this particular test purpose.

Measured Improvements

The pre test on SONGS 2 was performed 65 days before the planned Outage. The intention was to have enough time to repeat the test if things did not work out as intended. Everything went as planned and a baseline was established.

The first Post retrofit estimation was performed five days after SONGS 2 reached full load. This estimation was performed for the primary purpose of obtaining a quick assessment of the performance changes. Corrected LP turbine MWe improvement was calculated to be 23.2 MWe. It was felt at that time that five days could be not enough time to stabilize all parameters and to identify all potential cycle leaks. In addition, test timing was not optimal due to an unusually high number of variables such as extremely high vacuum, high SG blowdown flow, abnormal auxiliary steam alignment, etc. All these factors resulted in the large correction factors, increasing overall test uncertainty. In order to decrease the uncertainties, the Post test was repeated three more times 12, 55, and 85 days after the outage completion. The results obtained during all four Post retrofit tests were normalized to design conditions using the correction curves and formulae. All four Post retrofit tests, performed under very different operating conditions, provided very close results. This gave us a high confidence level in the obtained results. The difference between the

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Pre and Post tests electrical outputs provided documented performance improvements as shown below. See table 2.

Table 2 SONGS Unit #2, Pre- And Post- Cycle 10 Outage Retrofit Test Data

	PRE-TEST	POST-TESTS			
Test date	10/27/98	3/2/99	3/9199	4/22/99	5/23/99
Reactor Power (%)	100.00	99.90	100.09	100.11	100.06
Measured Elec. Power Corrected to 100% MWt	1161.033	1175.209	1173.192	1171.621	1168.344
SG Pressure (psia)	872.21	830.62	817.01	806.40	804.89
1st Stage Press-Corrected to 100% MWt (psia)	783.74	706.61	707.15	708.92	708.81
1st Stage HP Pressure Correction (MWe)	NA	21.365	21.213	20.723	20.754
Condenser Vacuum Correction (MWe)	3.834	-12.403	-10.887	-7.024	-3.142
SG Blowdown Correction (MWe)	0.000	3.100	3.100	2.320	2.320
Auxiliary Steam Correction (MWe)	0.000	1.200	1.200	0.000	-0.800
Miscellaneous Corrections (MSR outage repair, Leakages, Steam Traps, Power Factor) MWe	0.850	0.480	0.525	0.300	0.650
Normalized (corrected) MWe	1165.717	1188.950	1188.344	1187.941	1188.126
NET LP Turbine MWe Gain for each test	N/A	23.232	22.627	22.223	22.409
Average MWe Gain Due to LP Turbine Retrofit		**22.62 MWe**			

Conclusions

1. The methodology and technology discussed in this paper can be applied at nuclear power plants with a need to replace or modify their turbines. Significant performance gains can be achieved, with relatively straightforward verification, while simultaneously addressing long term equipment maintenance concerns.
2. The new ALSTOM Power HP turbine diaphragms reduced 1st stage pressure by 74 psi with a respective reduction in Steam Generator pressure from 872 psia with Valves Wide Open to 830 psia with some remaining throttling on the Governor Valves. This pressure reduction was greater than was anticipated allowing SG temperature and pressure to be dropped further by fully opening the turbine inlet valves. Thus, optimum Steam Generator life extension operating conditions were achieved without additional plant modifications with performance limiting consequences.
3. Installation of the new ALSTOM Power "Optiflow" LP Turbines have effectively improved SONGS 2 electrical output by 22.62 MWe versus the 21.5 MWe anticipated. Further, the generous exhaust hoods and modern diffusers, installed ahead of time, have accounted for an additional 5.5 MWe improvement. Therefore the overall LP retrofit improved SONGS 2 electrical output by 28.1 MWe.
4. As a side benefit, numerous existing problems with plant equipment and instrumentation were identified as a result of the performance testing. For example, a significant difference of 3.485 MWe was noticed between the test quality Power Meter installed for the tests and installed plant instrumentation. Resolution of these issues has helped to further improve plant electrical output and efficiency.

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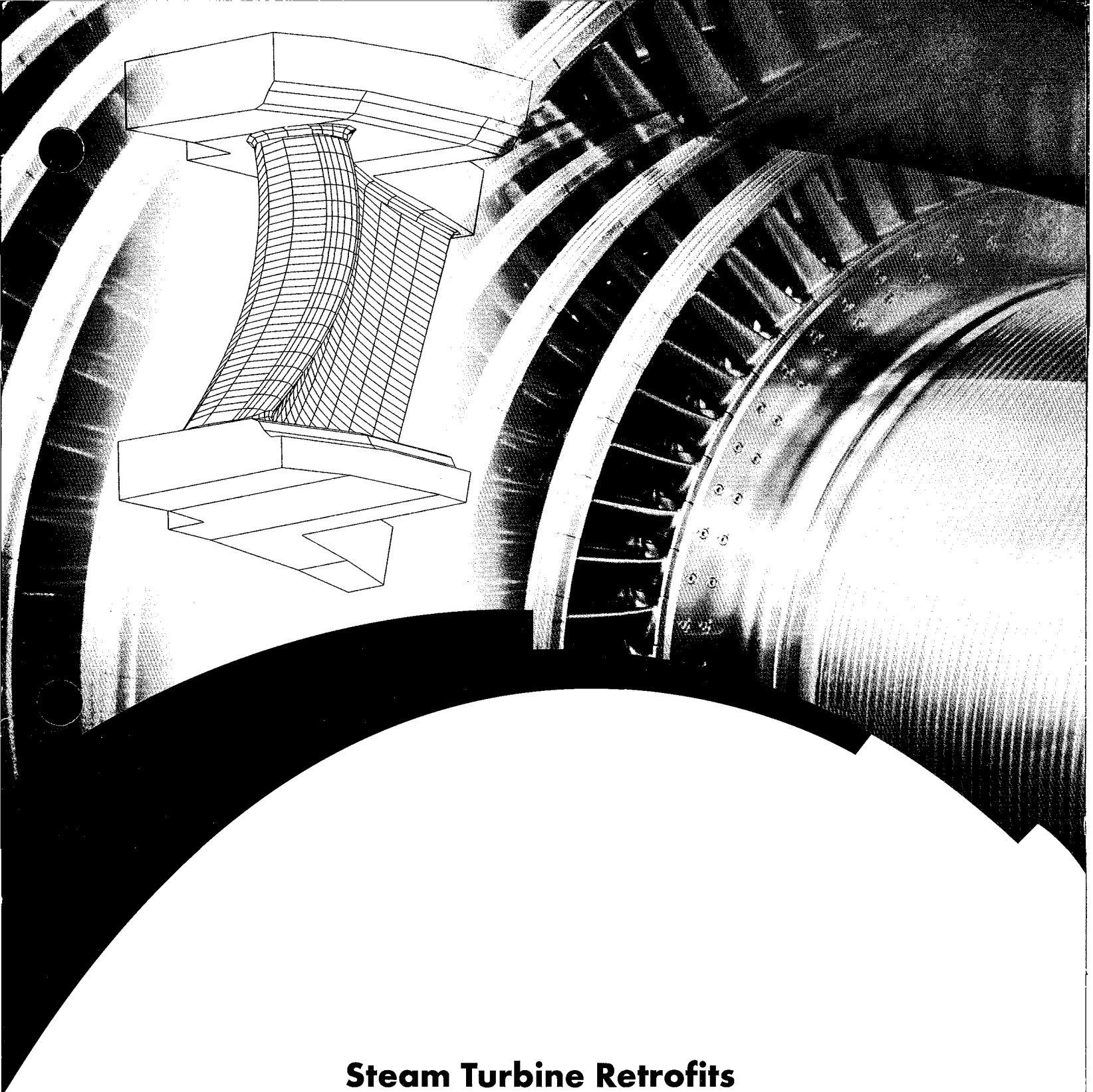
ALSTOM

ALSTOM Power - Newbold Road, Rugby. CV21 2NH. England
Tel: +44 (0) 1788 57111 Fax: + 44 (0) 1788 531700



Steam Turbine Retrofits

ALSTOM

Power

Steam Turbines

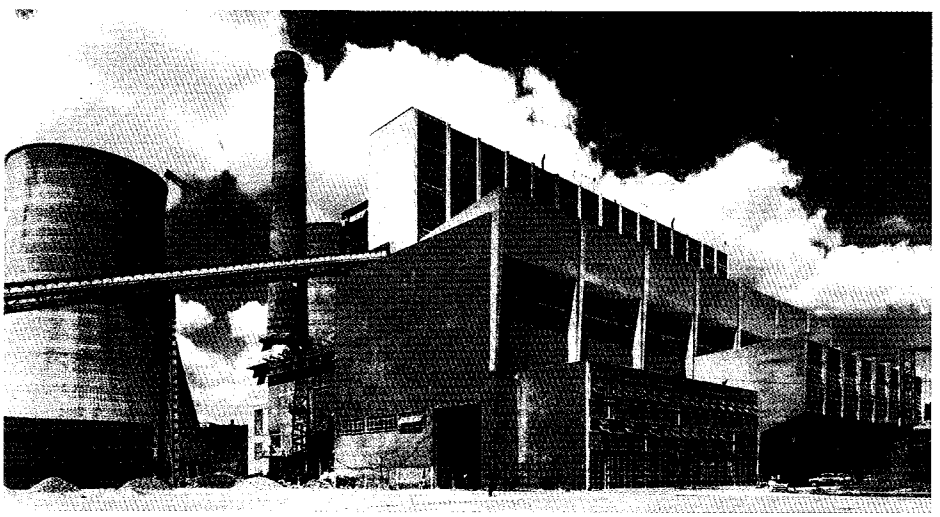
IP7_006346

Why Retrofit?

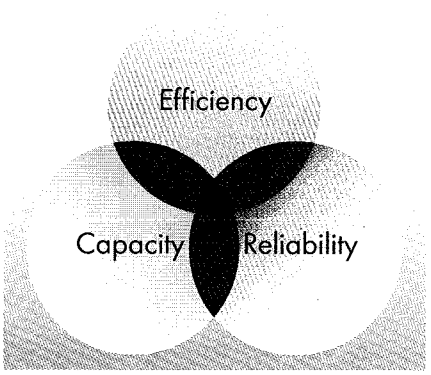
Need for modernization

Drastic changes are taking place in many of the world's electricity markets with the introduction of deregulation, supply exchanges and new standards for environmental emissions.

These changes combined with an aging generating fleet and the increased demand for power in many countries have created a growing need for modernization, repowering and the life extension of existing generating plants.



Retrofit drivers



Enhance efficiency

The improvement in unit heat rate has become the strongest retrofit driver in many countries.

Deregulation and the introduction of more stringent environmental regulations have placed new challenges on power plant operators. These changes have resulted in competitive markets for electricity and a strong drive to reduce generating costs and emissions.

Retrofitting of existing steam turbines with the latest steam path technology offers attractive returns on investment with a reduction in fuel costs and plant emissions.

Increase capacity

Increased demand for power and the high market price during peak periods are powerful drivers for increasing the MW capacity of existing generating plants. A steam turbine retrofit offers the most cost effective means of increasing capacity in many cases.

Improve reliability

Many older types of steam turbines suffer from reliability problems requiring frequent and extensive repairs or component replacement. Even without major operational problems, a unit with high service hours represents an availability risk as it reaches the end of its lifetime.

Retrofitting solves all existing maintenance and lifetime problems.

Retrofit or refurbishment?

If the plant operator selects a refurbishment solution, existing components are renovated or replaced with components of similar design. This will overcome the plant degradation and lifetime problems but will not provide increased performance.

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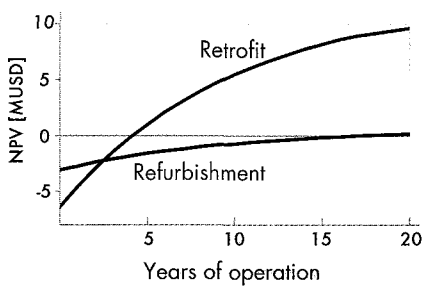
A case study

A comparison is made between retrofit and refurbishment of a 300 MW steam turbine, with respect to initial investment, payback period and net present value. It has been assumed *that steam path and rotor of the* double-flow low-pressure cylinder are replaced.

	Refurbishment	Retrofit		
Project Data				
Initial Capacity	298.0			MW
oad Factor	85.6			%
utput Increase		2.0	10.0	MW
Final Capacity		300.0	308.0	MW
Project Cost		3.3	6.5	MUSD
Economic Environment				
Power Sales Price	25.0			USD/MWh
Discount Rate	10.0			%
Evaluation Period	20			years
Additional Income		0.375	1.875	MUSD/year
Project Evaluation				
Net Present Value		0	9.69	MUSD
Payback Period		20	4.5	years

The retrofit solution has a significantly shorter payback period.



If the plant operator selects an ALSTOM retrofit solution, steam path components of improved design incorporating state-of-the-art technology are installed, bringing the turbine performance up to the level of a new unit.

In addition to overcoming plant degradation and lifetime issues, the retrofit solution will provide improved performance, maintainability and operational flexibility. Furthermore, only a retrofit design can be optimized to match changed plant operation loading requirements including boiler or reactor capacity changes.

Retrofit - the preferred solution

The potential for improvement in efficiency or output combined with the ensuing environmental benefits and lower generation costs generally makes retrofit the preferred solution.

Although a retrofit may require a higher initial investment compared with refurbishment, the difference is usually recovered in a short period of time and provides a distinct economic advantage over the longer term.

Each project is different

When evaluating the benefits of retrofitting, each project will be unique with its own combination of market and local factors to consider.

These factors include total project costs, potential efficiency and capacity improvement, projected electricity and fuel price and unit capacity factor. Additional factors will be reduced maintenance costs, increased availability, reduced environmental emissions and improved operational flexibility.
In competitive electricity markets the economic benefits of retrofitting are leading to units of less than 10 years of age being replaced.

Definition from IEC code (#60953-3)

"Retrofit is the change of turbine hardware to improve thermal performance"

6.9.1 Deterioration of turbine performance on retrofitted components

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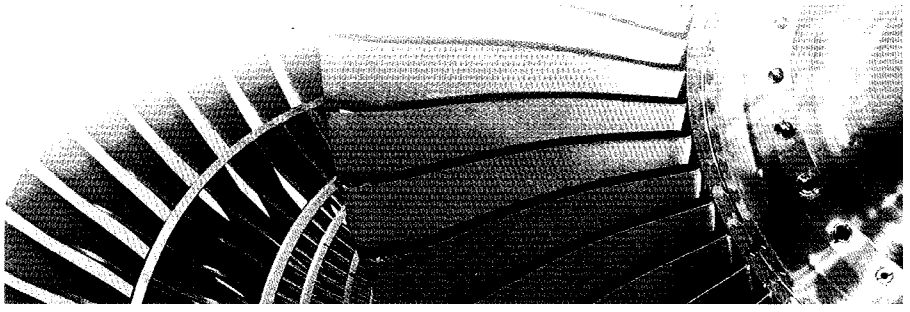
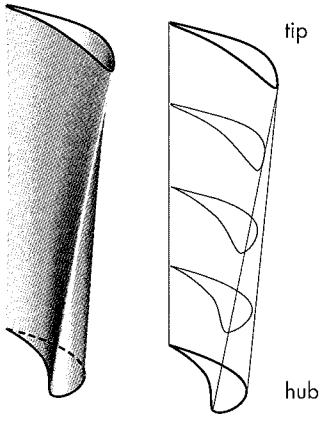
Progress in Technology



Low pressure rotor with free-standing last stage blades

Steam turbine development

Important steam turbine technology achievements have been made in the areas of steam path, frame architecture, component design and material development. Persuing bespoke solutions by a holistic approach involving mechanical, aerodynamic and manufacturing aspects has allowed ALSTOM to offer industry-leading steam turbine designs.



Shape and orientation of the latest generation blade profiles are optimized between hub and tip.

Removing efficiency barriers

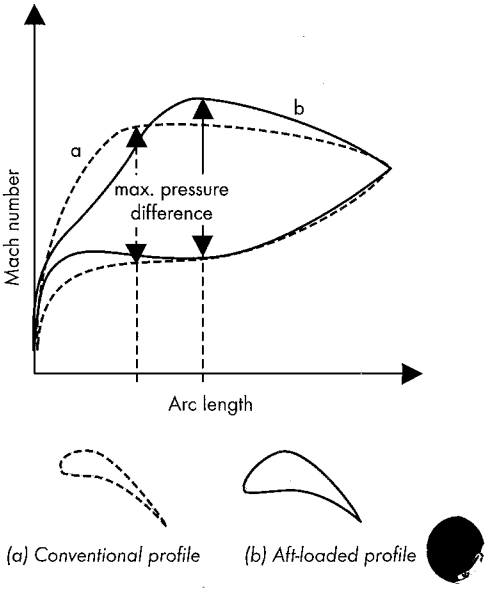
Development and introduction of three-dimensional (3D) blading allowed many of the traditional stage efficiency limitations to be overcome. With 3D-blading, the blade profile (cross-section at a given height) and blade shape ('stacking' of profiles between hub and tip) are optimized with respect to reducing steam flow causing secondary losses.

During the 1990's Computational Fluid Dynamics (CFD) techniques using models allowed computer simulated blade testing and resulted in significant efficiency advances.

Advanced blade profiles

Advanced aft-loaded profiles have been introduced that make the passage loading more uniform and produce a smaller pressure difference at the leading edge between the concave side and the convex side of the blades. This results in reduced secondary flow losses at blade hub and tip.

The latest generation of blades has twisted profiles that follow the incident steam direction, since orientation of the steam flow to the blades varies between hub and tip. This ensures the optimum effect of aft-loading along the entire length of the blade.



The smaller pressure difference at the leading edge leads to optimized steam flow and reduced secondary losses.

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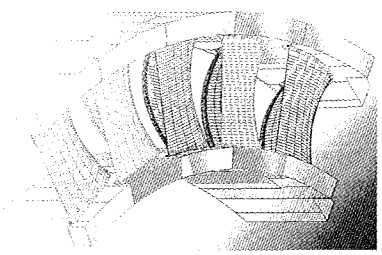
Refined sealing

ALSTOM's 'controlled flow' stationary blades have a twist in their shape that enlarges the throat area at mid-height of the steam passage, guiding the steam flow away from the high-loss end-wall regions.

These developments have produced the highest levels of performance available today.



Controlled flow diaphragm blades with enlarged throat area at blade mid-height

Improved gland seal mechanisms significantly reduce leakage, which is particularly important for the short HP and IP blades.

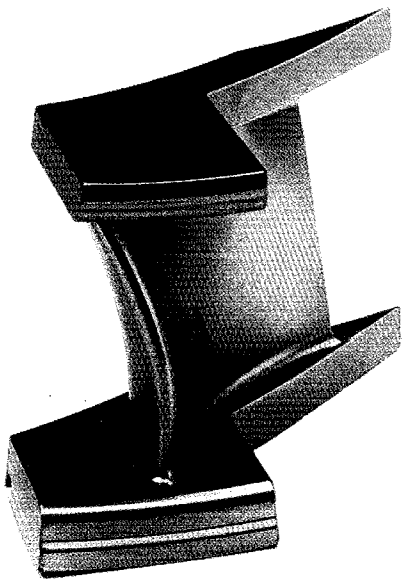
The most effective gland fin geometry of the inter-leaved type is applied throughout at blade tips and shaft glands. Constructional features, which assure annular concentricity, preserve the small clearances and maintain performance during prolonged operation.

Application of advanced minimum clearance sealing such as abradable packing and brush seals now provide options for further reduction of losses on short height stages.

Enhanced blade hub and tip shapes ensure smooth merging of the leakage steam into the next row, so avoiding flow disruption.

2 x 1200 MW nuclear power station in the USA

Progress in Technology



Latest generation fixed blade with fully optimized profile

Improved mechanical integrity

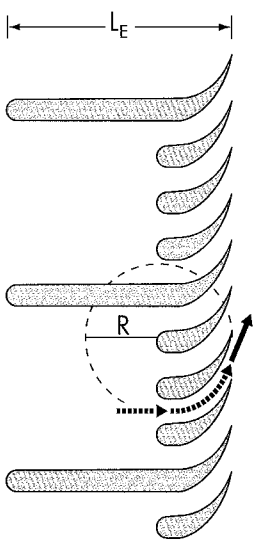
Progress with finite element dynamic stress calculations allows the elimination of existing weaknesses in old designs and in potential new designs ensuring mechanical integrity of the retrofit solutions.

Stress corrosion cracking (SCC) in turbine rotors and solid particle erosion (SPE) in HP and IP turbines are two examples of design-inherent problems that are solved with retrofitting. ALSTOM retrofits also eliminate problems with material fatigue, rotor instability, internal steam leakage and casing distortion.

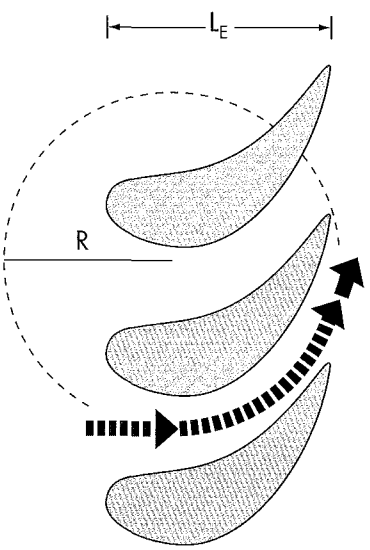
Limiting solid particle erosion

SPE occurs in certain HP and IP blade designs with narrow fixed blades with strongly curved profiles.
Solid particles contained in the steam impact with the typically thin blades and cause severe local erosion, resulting in significant loss of efficiency.

ALSTOM blade designs feature moderately curved steam paths with larger blade profiles and more robust trailing edges, allowing most solid particles to pass harmlessly through the turbine. Any erosive particles that impinge do so with reduced momentum and onto thicker trailing edges, thereby limiting SPE to a minimum.



- Flow turns sharply
- Particles hit trailing edges
- Thin blade trailing edges
- Vulnerable to erosion



- Flow turns gently
- Particles remain within flow
- Robust blade trailing edges
- Resistant to wear

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Eliminating stress corrosion cracking

SCC occurs in turbine components, particularly nuclear low-pressure turbine rotors when three key parameters are present in a critical combination. These parameters are material yield strength, stress loading and temperature. Critical values are frequently reached at blade root attachments, rotor side-faces, and disc bores and keyways of shrunk-on disc rotors.

In ALSTOM rotors of welded disc or mono-bloc design, the rotor does not suffer the high stresses associated with shrunk-on discs. Furthermore, ALSTOM rotors are designed to operate with material of much lower yield strength. Therefore, the critical combination of high-strength material, high local stress loading and temperature cannot occur in ALSTOM rotors.

Advanced materials

New high temperature alloys developed in recent years are used in retrofits for blading, rotors and casings. Their higher strength at mid and high temperatures allow compact solutions with greater operational flexibility. Improved materials for low temperature applications have also been introduced.

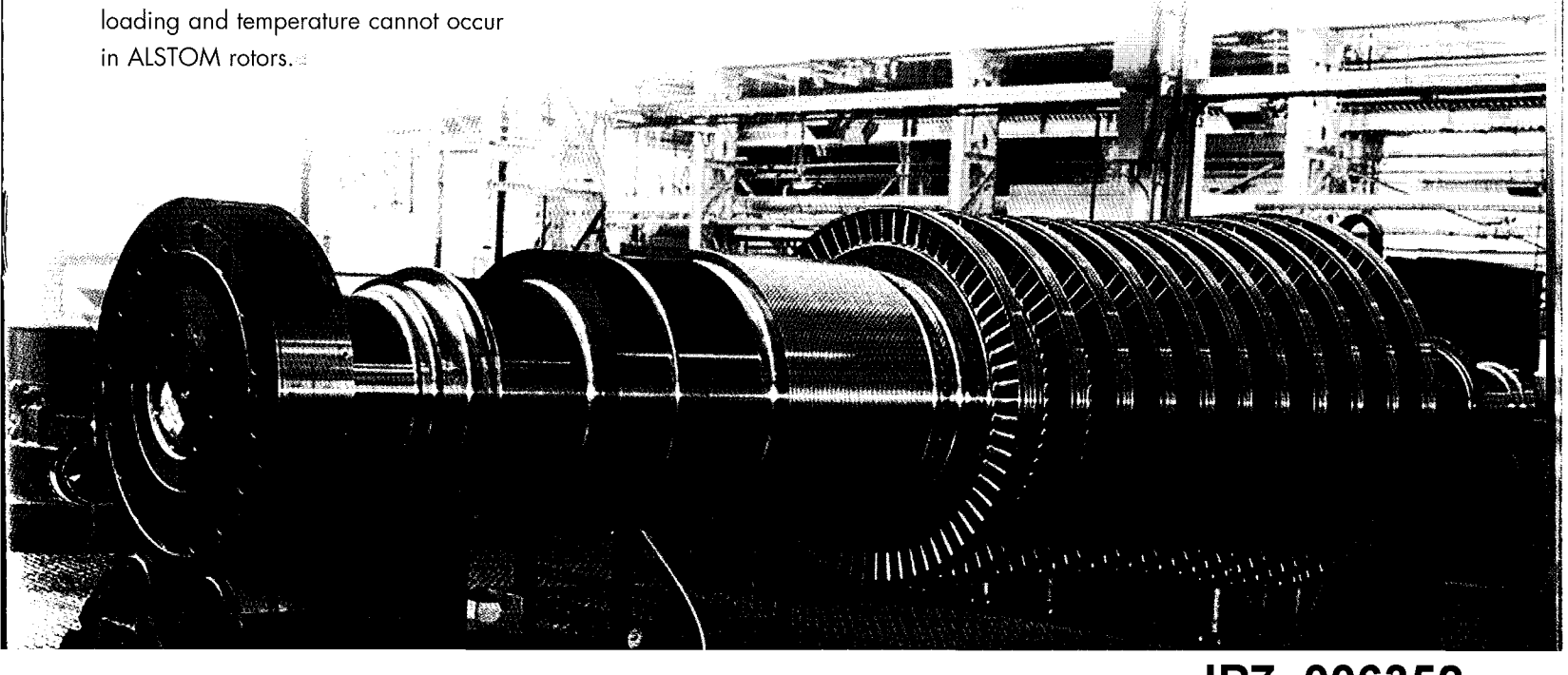
ALSTOM has been a leading participant in international collaborations to develop advanced materials and has also carried out its own extensive research particularly for welded rotors.

Materials with improved weldability combined with high fracture toughness and hardenability have been introduced.

In combined cylinders, welded solutions allow the combination of materials with optimum properties in different parts of the rotor.

For nuclear applications a variety of materials of proven long-term capabilities are available.

Retrofit HP turbine rotor during manufacture for a 660 MW unit in the UK



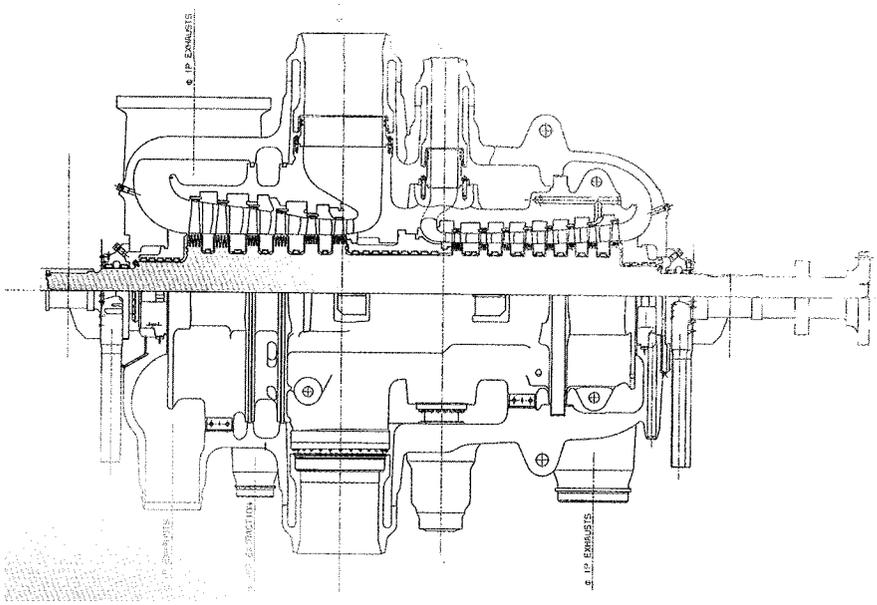
Innovation and Optimization

Design philosophy

ALSTOM retrofit designs aim to achieve the highest performance improvements and the best mechanical integrity.

These designs, incorporating the technology developed for the latest generation of steam turbines, lead to innovative concepts - such as changing double flow to single flow - providing a significant performance gain.

Care is taken to incorporate special customer requirements and to minimize impact on the plant operating parameters, making the retrofit virtually invisible for the operator.



Complete HP/IP cylinder retrofit for a 574 MW unit in the USA

Optimized plant retrofits

As supplier of both steam turbines and boilers, ALSTOM is able to perform a complete plant assessment.
Optimize Plant Retrofit (OPR) solutions optimize the water/steam cycle, matching steam turbine and boiler to maximize output or efficiency.

Unique range of solutions

ALSTOM brings together the leading technologies for reaction and impulse design. This unique capability allows the choice of reaction or impulse solutions irrespective of the original technology. ALSTOM can offer retrofit applications for all types of steam turbine supplied by any manufacturer.

IP7_006353

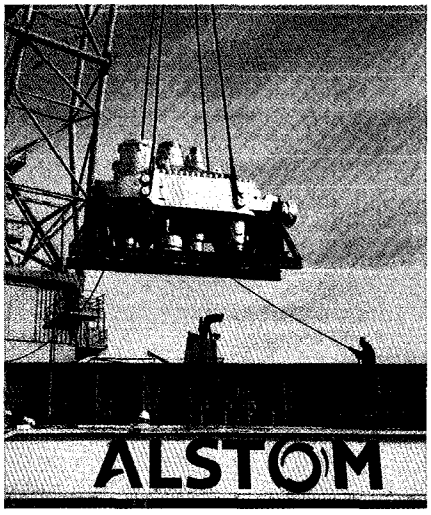
Project execution

On-site measurements are carried out on non-OEM equipment before finalizing design parameters.

Components typically are shipped in less than 14 months. They are installed as drop-in modules requiring minimal adjustment at site. Installation is achieved within a normal scheduled outage.

ALSTOM's site installation service is tailored to the customer's requirement. It can vary from the provision of technical direction working with the customer's installation contractor to the complete turnkey installation.

ALSTOM provides a performance guarantee irrespective of the selected installation arrangements.



Shipment of complete retrofit module

Customer support

ALSTOM provides dedicated customer support for the life of the supplied equipment.

A global customer service organization is located in all major countries with local service shops.

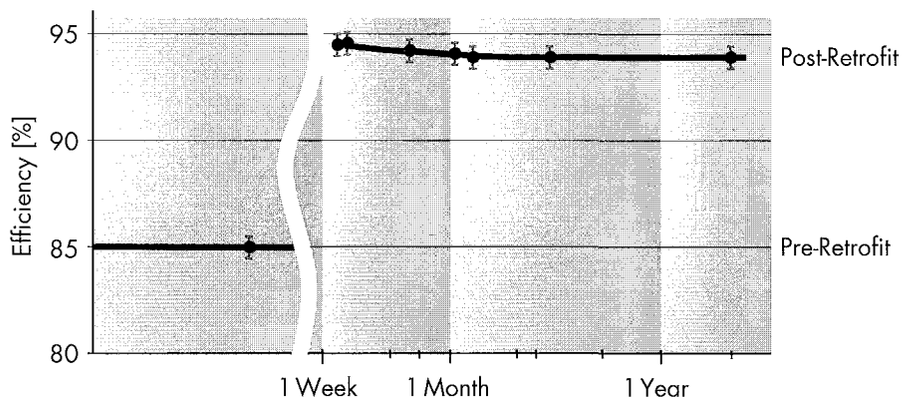
Detail of LP turbine rotor with flow optimized blades

Customer Benefits

Sustained efficiency improvement

Typical increase in cylinder efficiency achieved by an ALSTOM retrofit is 6-9%, resulting in unit heat rate improvement of up to 3%. Special design features ensure that the improvement is sustained.
ALSTOM now offers plasma nitriding of the steam path components to further increase sustainability of performance.

Performance measurements after HP-Retrofit of five 660 MW units in UK

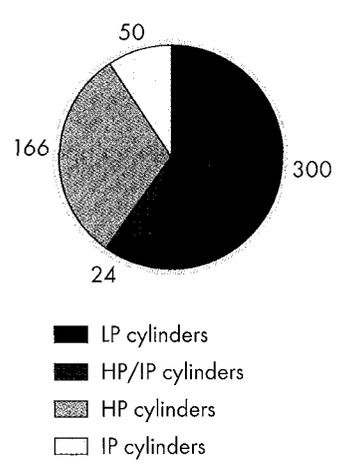


Reduced maintenance

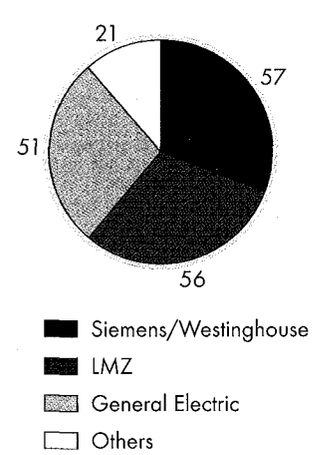
A retrofit supplied by ALSTOM offers high turbine availability and reliability resulting in significant savings in maintenance costs. Turbine inspection requirements after a retrofit are typically at intervals of 100,000 operating hours.

Extensive retrofit experience

Close to 550 turbine cylinder retrofits have been supplied in total, making ALSTOM the world's most experienced supplier. Of these, 400 were installed in the last decade alone, with over 150 for installation on non-OEM turbines.
An extensive range of proven nuclear and fossil retrofit solutions has been developed for all the main international steam turbine manufacturer's designs - including technologies originating from General Electric, Westinghouse and Leningrad Machine Works (LMZ) - and is available for the benefit of the customer.



Total retrofit experience 540 cylinders



Non-OEM retrofit experience 185 cylinders

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ALSTOM retrofit advantages

Improved turbine efficiency and plant heat rate

Sustained performance

Reduced fuel consumption and emissions

Increased MW capacity

Increased revenues during peak demand

Reduced maintenance

Maintenance problems eliminated

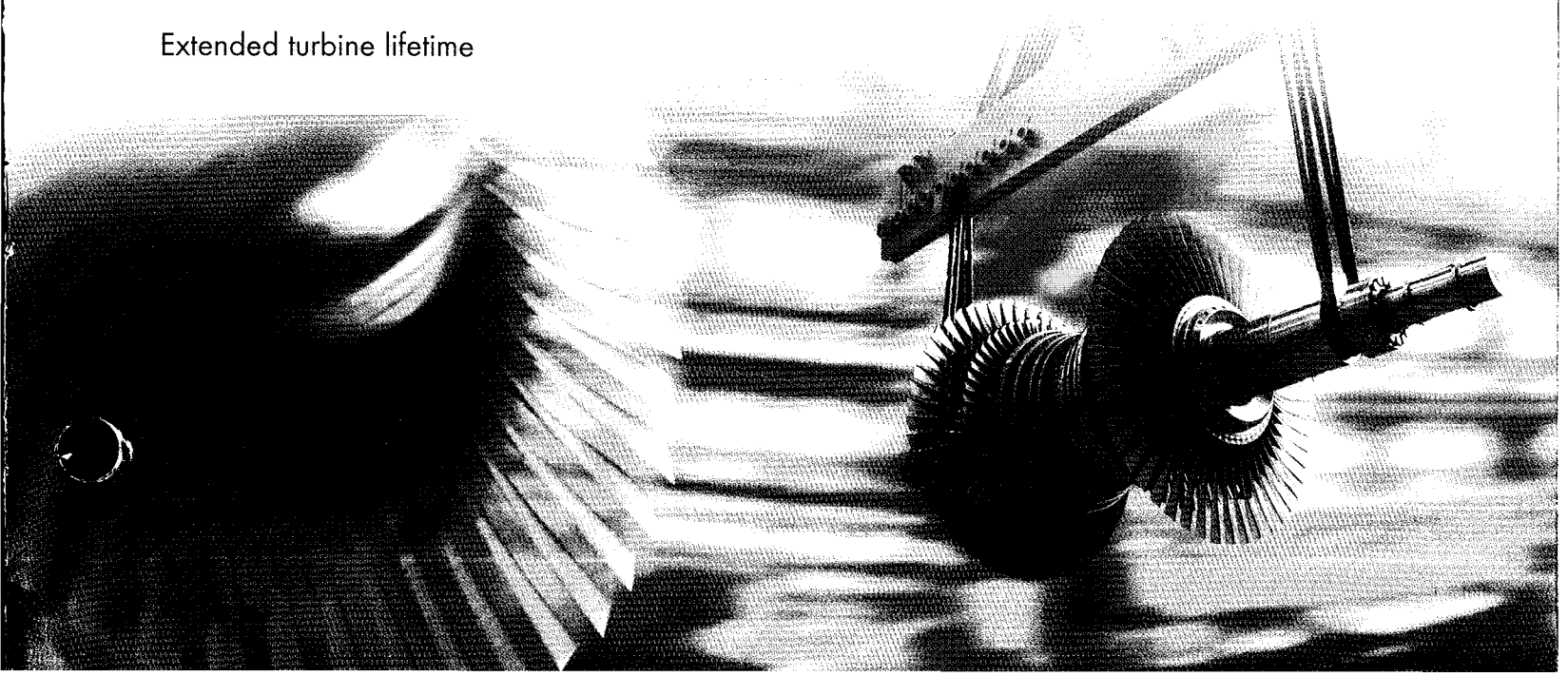
Extended turbine lifetime

ALSTOM project characteristics

Performance guarantee

Installation during regular outage

Low pressure rotor during manufacture



werbeagentur **akzent** D-Mannheim, Tel. +49 621 86 202 45

ALSTOM

ALSTOM (Switzerland) Ltd, Brown-Boveri-Strasse 7, CH-5401 Baden/Switzerland
www.power.alstom.com

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