# NEW TECHNOLOGIES OF SYNTHESIS GAS COMPRESSOR DRIVE STEAM TURBINES FOR INCREASING EFFICIENCY AND RELIABILITY

by
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## ABSTRACT

Recently, synthesis gas compressor drive steam turbines have required upgrading to increase efficiency and reliability for saving both operation and maintenance costs in many ammonia plants. This paper introduces the latest practical technologies to achieve very high performance. Examples include a highly unique assembly of integral shrouded blades, a new profile design procedure for both fluid loss reduction and increased strength against high-speed and high-stage power. Finite-element and computational fluid dynamics analysis results of new blades and nozzles are discussed while comparing experimental data from a cascade test and a rotating blades shaker test. These results are shown in terms of actual loss distribution, efficiency measurement, and vibration/stress mode on rotating blades including design criteria. Other useful applications of new technologies to reduce steam leakage and increase last stage blade performance are introduced. These involve modification of the exhaust casing and a new turning device.

In particular, high speed and high loading are inevitable in synthesis gas compressor drive steam turbines. In order to improve operation reliability considering these factors, a special cooling design is applied for the thrust bearings to reduce the pad metal temperature. The results of this analysis and basic experimental data are discussed in detail.

Furthermore, examples of actual job applications are explained, and high-speed balancing, mechanical running test, and site performance test results are shown.

## INTRODUCTION

Synthesis gas compressor drive steam turbines are the most important rotating equipment in the field of methanol and ammonia plants. They are specially designed to cope with high speeds (exceeding 10,000 rpm) and high output powers (up to 40,000 kW) and have been applied as both end drive machines for high-pressure (HP) and low-pressure (LP) compressors. In the process of these plants, efficiency improvement is achieved through such means as a chemical catalyst, and as a result the required maximum power tends to decrease to less than 30,000 kW. Thus the efficiency of these turbines is focused on the design of the plant in order to minimize the margin on heat and flow balance for the most cost effective solution. In contrast, large capacity plants for methanol or new fuel are under consideration in a case study. For these mega plants, the synthesis gas compressor drive steam turbines with large output powers (exceeding 50,000 kW) will be required and realized in the near future. In this sense, these synthesis gas compressor drive steam turbines have to be continuously improved and upgraded to increase their efficiency and reliability for saving both operation and maintenance costs.

As a starting point to this improvement, the performance of several existing extraction-condensing turbines actually in operation undergoes detailed analysis of their high-pressure and low-pressure sections. According to the analysis results, practical countermeasures are considered including the application of newly developed nozzles and integral shrouded blades (ISB) for speed control stage having mostly high-stage power. In this paper, the process of key components development is introduced by showing the results of finite-element analysis (FEA), computational fluid dynamics (CFD) analysis, lab evaluation tests, actual application, and performance evaluation based on onsite data.

## STRATEGY OF MODIFICATION

The cross section of synthesis in a gas compressor drive steam turbine and the key features for improvement are shown in Figure 1 to make the concept of modification clear. The smooth flowpath from the inlet governing valve diffusers through HP and LP sections to the exhaust casing is designed by CFD in order to minimize losses. The first stage generates a maximum 12,000 kW and accounts for the greater part of the total output power. For this stage, the combination of nozzle and ISB with developed profiles is applied to increase stage efficiency dramatically, as explained later in this paper. The ISB with advanced profile is used for all other stages. In particular, the last stage has a bow nozzle to decrease secondary flow losses. In addition, a slant labyrinth seal is applied in the high-pressure side and extraction portion. This special seal can decrease the leakage by about 30 percent. The journal and thrust bearings have large thrust forces, high-pressure intensity, and heat load due to high-speed friction losses. For the purpose of decreasing metal temperature, back metal cooling for pads and copper back pads are applied. The latest material coating technology is used for improving reliability for long-term operation. A special coating is applied to the first stage nozzles and LP section blading to prevent solid and drain erosion.

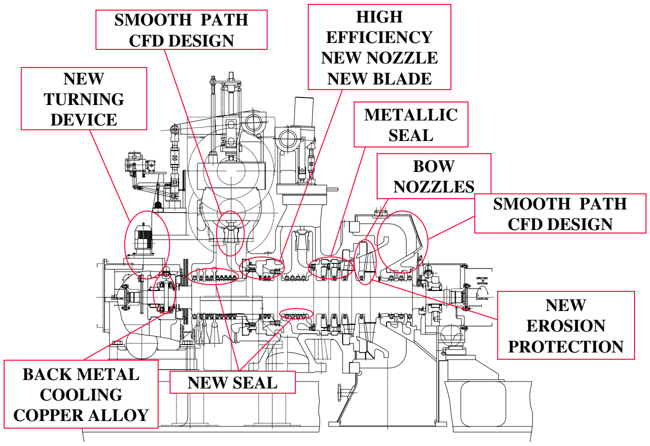


*Figure 1. Strategy of Modification.*

## DEPTH ANALYSIS OF PERFORMANCE

A synthesis gas compressor drive steam turbine in actual operation at site was chosen for a case study, and a detailed performance analysis was carried out to make a loss map, considering the HP and LP sections separately.

### *Loss of Flowpath Through Nozzle and Blade*

The calculated loss distribution for each stage is shown in Figure 2. From these analysis results, in the case of conventional nozzle and blade, the first stage of speed control stage accounts for a large part of the total loss, which consists of leaving loss, tip leakage loss, nozzle, and blade loss related to their profiles. The third stage of extraction pressure control stage loss is smaller than the first stage, but stage loss distribution ratio is almost the same—and these kinds of losses have to be minimized. For efficiency improvement, these control stages will be highlighted and the matching of nozzle and blade will have to be improved to prevent flow separation, flow velocity deceleration, and tip leakage. This will be achieved by profile modification and reaction control as shown in Figure 3. For decreasing losses effectively, the secondary flow loss of the nozzle and blade is considered as shown in Figure 4. The conventional blades shrouded by tenons have very high centrifugal forces for high-speed synthesis gas compressor steam turbines, and the nozzles are designed to have large gauging in order to minimize the blades height. For these large gauging nozzles, the profile cannot be optimized, and the nozzle exit velocity angle into the blade is so large that the stage overall efficiency tends to decrease. In the case of large stage power and large steam flow, this height restriction becomes critical, and to increase the blade strength, the application of ISB is one of the most important countermeasures.

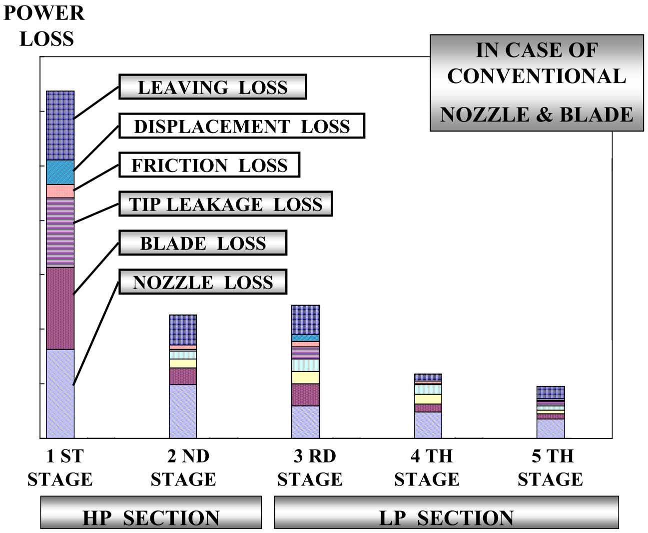


*Figure 2. Actual Loss Analysis.*

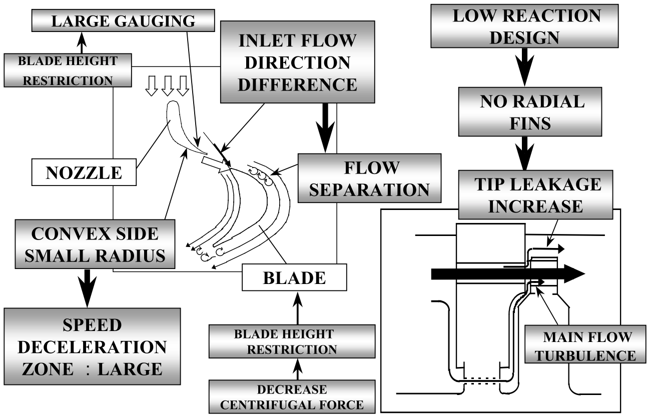


*Figure 3. Conventional Nozzle and Blade.*

### *Casing Internal Leakage*

Except for nozzle and blade losses, internal leakage through the split surface of diaphragms inside the casing will be considered in order to evaluate the turbine performance practically. The expected leakage ratio for each stage and related portion is described in Figure 5. According to leakage flow rate and energy level, the leakage from the HP section and extraction portion apparently affects the overall turbine efficiency.

Based on the results of the above loss and performance analysis, reaching the target of performance improvement is addressed as shown in Figure 6.

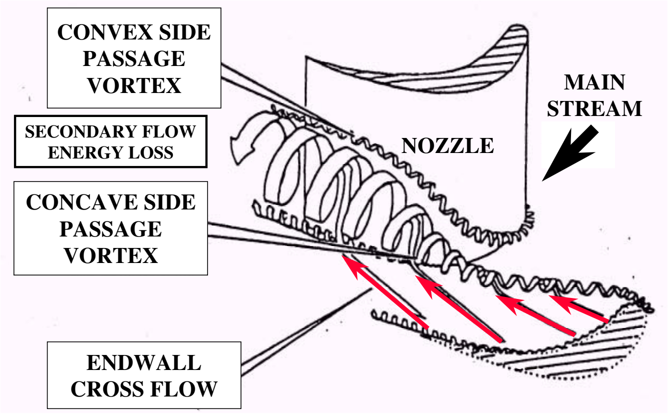


*Figure 4. Secondary Flow Pattern of Nozzle.*

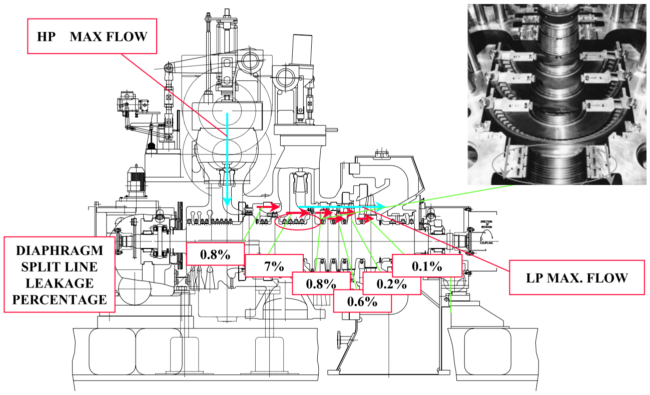


*Figure 5. Diaphragm Split Line Leakage.*

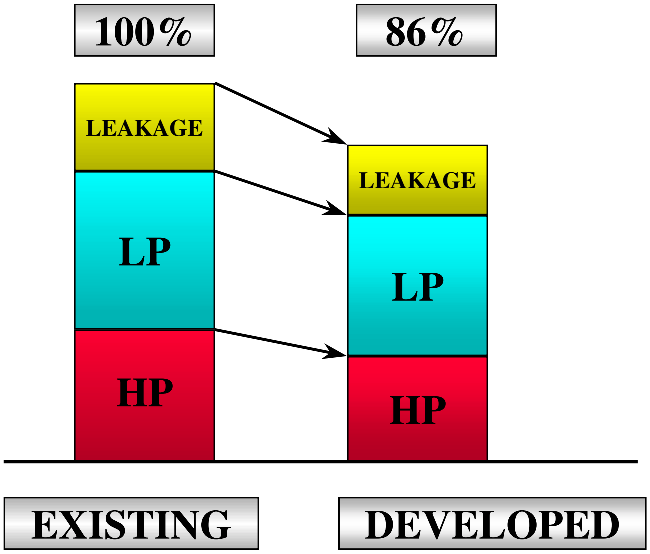


*Figure 6. Loss Decrease.*

## PRACTICAL COUNTERMEASURES

The latest practical technologies to achieve high performance are set out in the following pages of this paper. These include a unique assembly of integral shrouded blades, a new profile design procedure both for fluid loss reduction, and increase of strength to cope with high-speed and high-stage power. Other useful applications of these new technologies are also studied to reduce steam leakage and increase last stage blade performance involving bow nozzle and exhaust casing modifications. On the other hand, in order to improve operation reliability, a special cooling design is applied for high loading thrust bearings to reduce the pad metal temperature, and a new turning device is installed for easy maintenance. For long-term operation, special heat treatment of nozzles and ceramic coating of blades are applied to prevent solid and drain erosion.

## HP SECTION

### *Newly Developed Nozzle and Blade*

From loss analysis results in the case of conventional nozzle and blade, the first stage of speed control stage accounts for a large part of the total loss. For efficiency improvement, this speed control stage will be highlighted to optimize the matching of nozzle and blade by profile modification. A CFD analysis is carried out to find the points to be improved and the resulting three-dimensional (3D) steam stream line is shown in Figure 7. As a result of this analysis, an outline of nozzle and blade modifications required can be seen listed in Table 1.

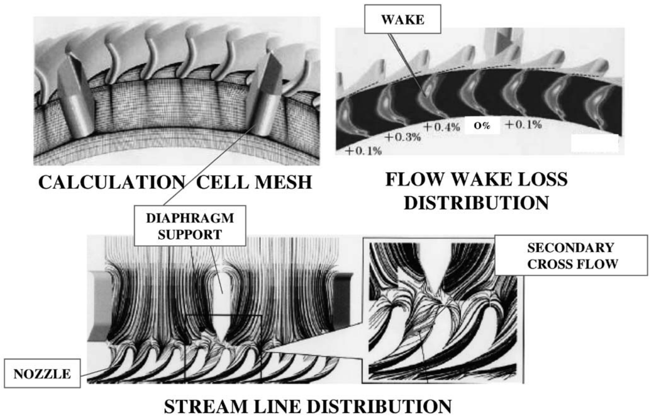


*Figure 7. Profile Design CFD Basis.*

*Table 1. Newly Developed Nozzle and Blade Design Direction.*

- **NOZZLE**
  - **GAUGING OPTIMIZATION**
  - **HIGH ASPECT RATIO**
  - **PITCH/CHORD RATIO OPTIMIZATION**
  - **PROFILE MODIFICATION CFD BASIS**
- **BLADE**
  - **ASPECT RATIO OPTIMIZATION**
  - **PROFILE MODIFICATION CFD BASIS**
  - **SECONDARY FLOW & PROFILE LOSS MINIMIZATION**
  - **ISB APPLICATION**

Figure 8 shows the difference in the Mach number distribution between the conventional and newly developed stages. The newly developed nozzle and blade can control steam flow, and the Mach number distribution around the throat becomes uniform. Consequently, the fluid dynamics loss can be totally eliminated. The integral shrouded blade is applied with a large safety margin to cope with the large centrifugal and excitation forces, as well as to decrease the tip windage loss without tenons. A particularly unique feature of the ISB is how each blade shroud makes contact with the next one at its tip. The mechanism of this tip shroud contact is explained in Figure 9. The blade is inserted into the disk groove in an inclined state, with some clearance at the tip. As the rotor speed increases up to minimum governor speed, the blades are forced up by the moment of centrifugal force, and their shrouds tightly contact together.

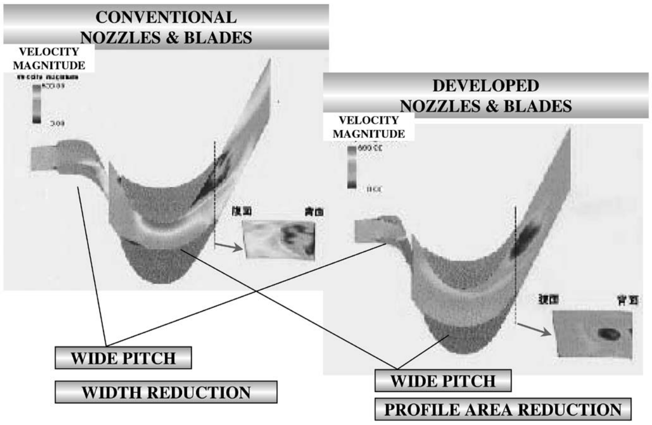


Figure 8. First Stage Flowpattern Analysis.

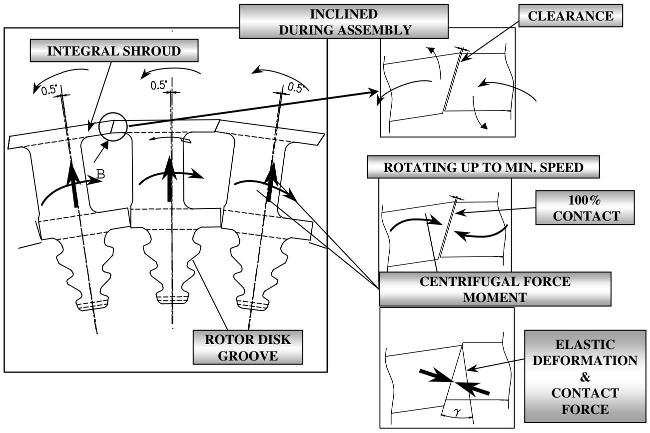


Figure 9. Mechanics of ISB Grouping.

*FEA Results of Blade Static and Dynamic Stress*

In the mechanical design condition of maximum rotation speed (12,000 rpm) and output power (12,000 kW), operating at the expected temperature, the FEA is carried out, and blade static stress and dynamic vibration stress for each vibration mode are respectively calculated as shown in Figure 10 and Figure 11. According to these calculated static and vibration stresses, the design point is plotted on a Goodman diagram as shown in Figure 12.

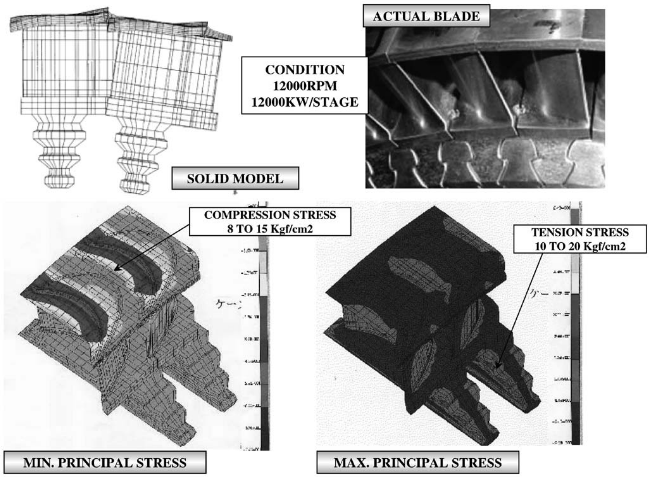


Figure 10. ISB Static Stress Analysis.

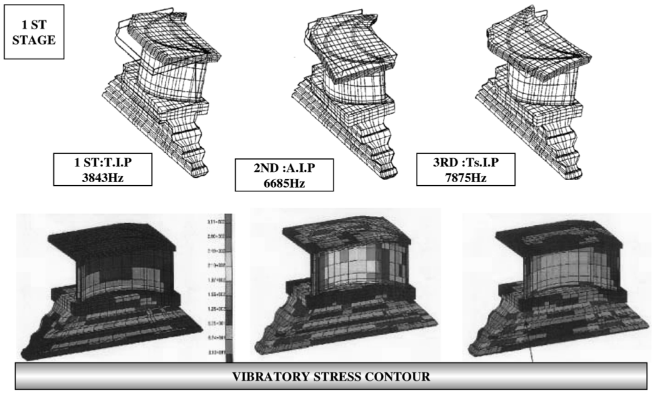


Figure 11. ISB Vibration Analysis.

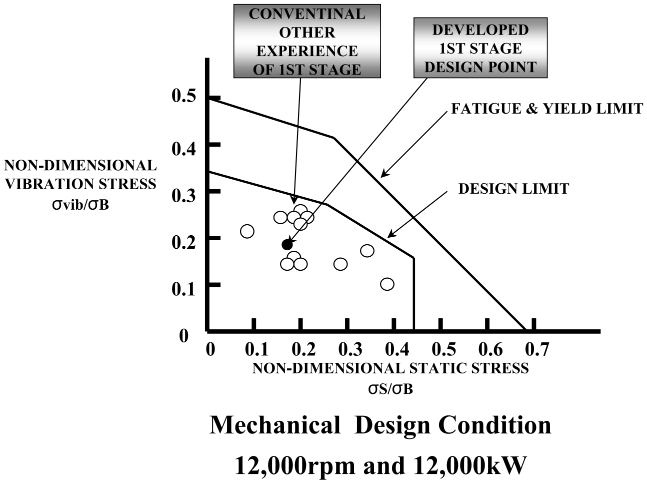


Figure 12. Goodman Diagram.

*Cascade Test*

The cascade test is conducted to measure the actual loss distribution of nozzles and blades along the direction of their height using actual real size nozzles and blades in a stationary condition with conventional and newly developed profiles, as shown in Figure 13. The velocity as a vector and static pressure are measured with a five-hole probe to compare the loss distribution between the conventional and the newly developed nozzles and blades. Figure 14 shows the relationship between the nozzle loss coefficient and Mach number. The loss coefficient distribution along the high direction for nozzles and blades is shown in Figure 15 and Figure 16, respectively. The results of this cascade test confirm that the loss coefficient can be decreased by application of newly developed nozzles and blades. In particular, the secondary flow loss close to the wall at the base and tip of the profile decreases remarkably, and the average loss decrease through the profile is more than 10 percent.

*Rotating Performance Test*

The diaphragm with the newly developed nozzle and the test rotor with the newly developed ISB are prepared for a rotating performance test in order to measure the actual overall efficiency combining the effects of these nozzles and rotating blades. A cross

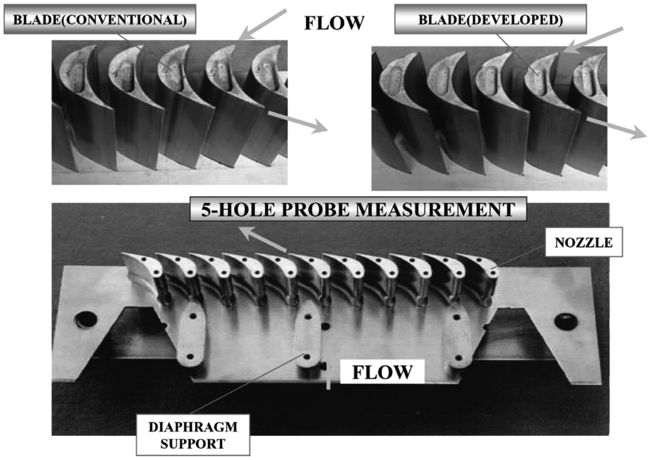


*Figure 13. Setup for Cascade Test.*

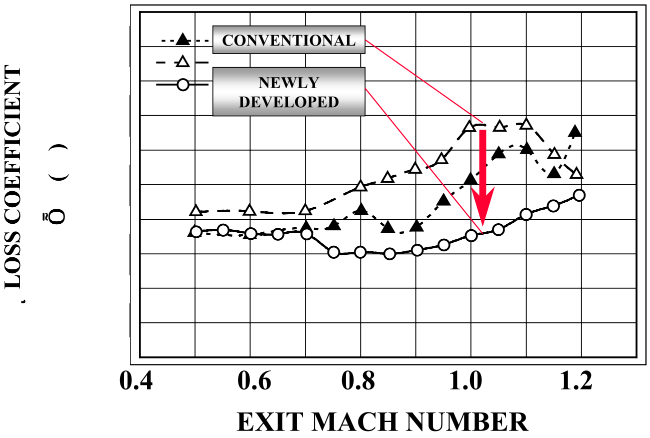


*Figure 14. Measured Data Nozzle Profile Loss Decrease.*

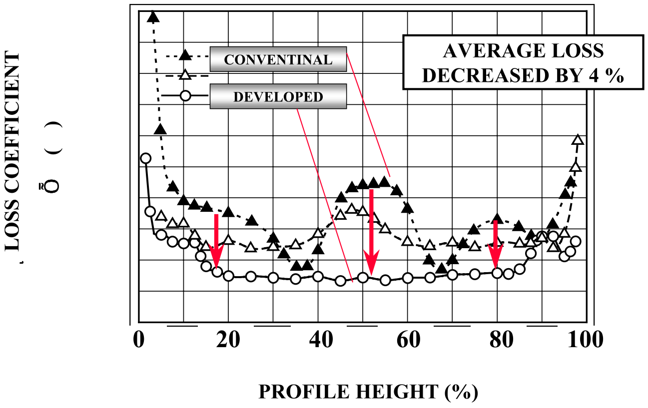


*Figure 15. Loss Decrease Measured Data Nozzle Total Loss Distribution.*

section of the test rotor is shown in Figure 17 and a photograph and schematic of the test setup are shown in Figures 18 and 19, respectively. Figure 20 gives the typical basic measured data and shows the relationship between the velocity ratio and overall efficiency. The results of this rotating performance test confirm that this newly developed stage can improve the stage efficiency by more than 10 percent relative to the conventional stage.

### *Blade Excitation Test of Newly Developed ISB*

The newly developed ISB for speed control stage and intermediate stage is actually assembled in the test rotor, to measure the

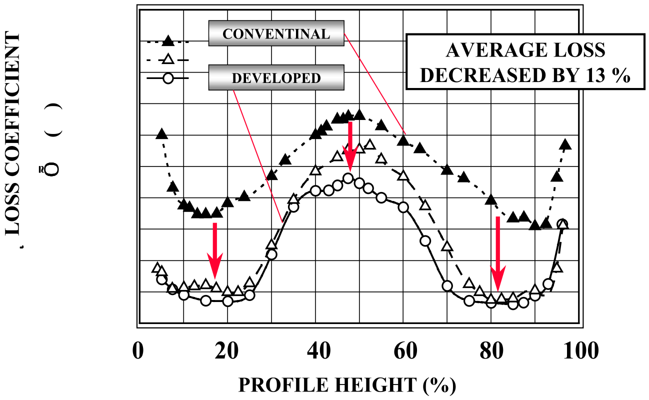


*Figure 16. Loss Decrease Measured Data Blade Total Loss Distribution.*

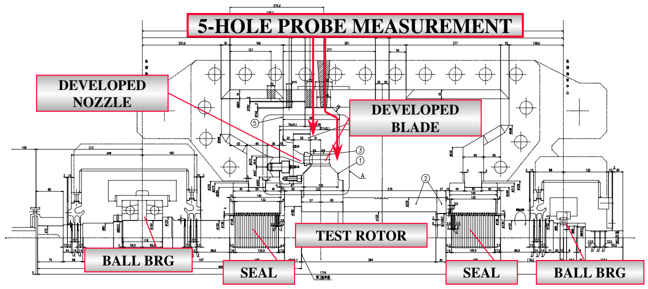


*Figure 17. Cross Section of Test Rotor.*

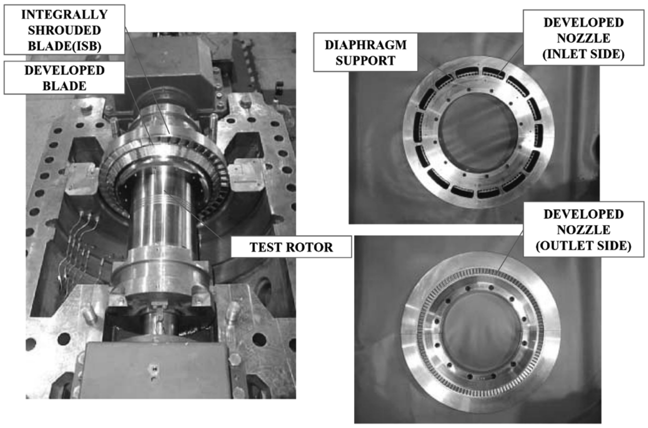


*Figure 18. Setup for Rotating Performance Test.*

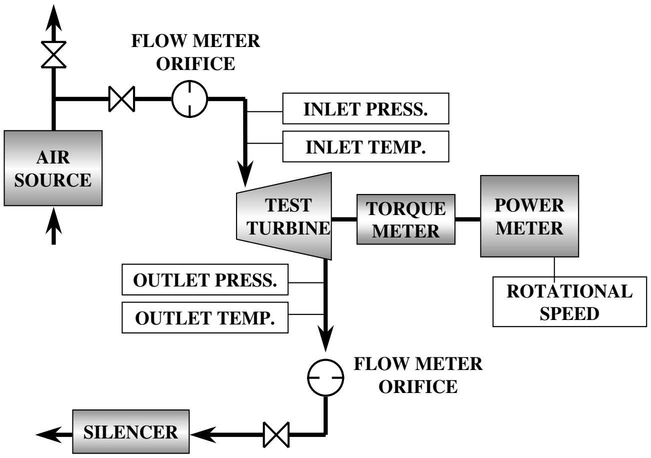


*Figure 19. Schematic of Setup for Rotating Performance Test.*

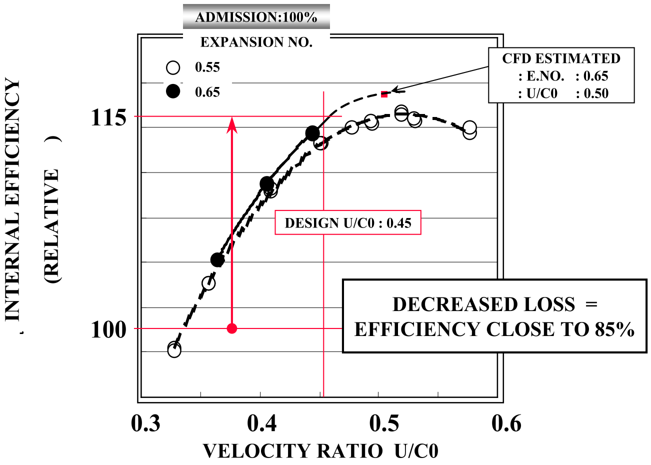


*Figure 20. Measured Internal Efficiency for First Stage.*

static and dynamic/vibration stresses compared with the conventional tenon grouped type blade, at the blade root and profile, using air jet nozzle excitation as shown in Figure 21. Before this rotating blade excitation test, a blade-hammering test in a stationary condition is conducted in order to identify each natural frequency and vibration mode in both freestanding blade and integrally shrouded blade conditions. Figure 22 shows the relation of frequency and compliance on hammering, and the vibration response peak of the freestanding blade is clearly observed at each basic natural frequency corresponding to tangential in phase mode (TIP), axial in phase mode (AIP), and torsional in phase mode (TsIP). In contrast, ISB does not have any vibration response peak. TIP and TsIP modes completely disappear due to the effect of integrally and continuously shrouded boundary condition in a circumferential direction.

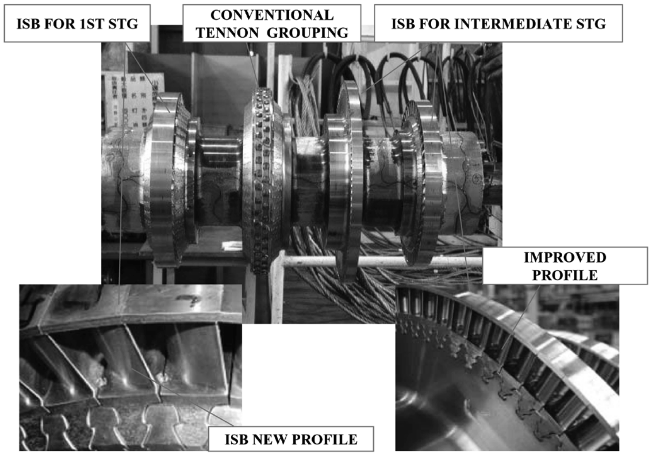


*Figure 21. Test Rotor for Blade Excitation.*

The test rotor setup for blade excitation is shown in Figure 23. The strain gauges are bonded on the profile surface and root where the peak vibration stress is expected according to the FEA calculation results. The telemetric measuring system is practically applied and transmitters with batteries are installed. Several air jet nozzles are set up in order to excite the blades according to the number of harmonics required as a test condition.

The successfully measured data during coasting up to a maximum continuous speed of 12,000 rpm are analyzed, resulting in a very interesting Campbell diagram (a typical one is shown in Figure 24). In the case of ISB, the TIP mode vibration observed in a freestanding blade has completely disappeared, and the vibration amplitude of other modes is equally decreased. Through these sequentially carried out tests, it can be demonstrated that the newly developed ISB has tough response characteristics against external excitation forces.

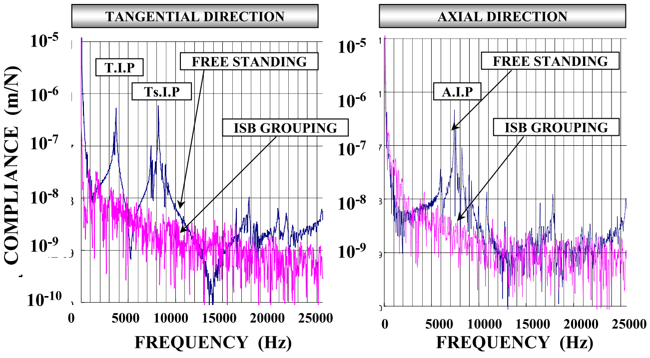


*Figure 22. Blade Hammering Test Data.*

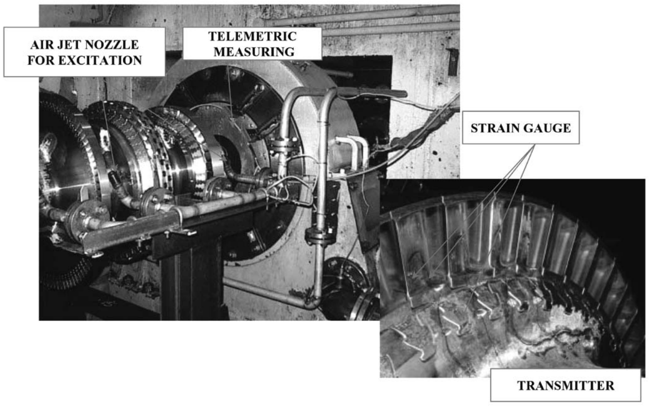


*Figure 23. Setup for Rotating Blade Excitation Test.*

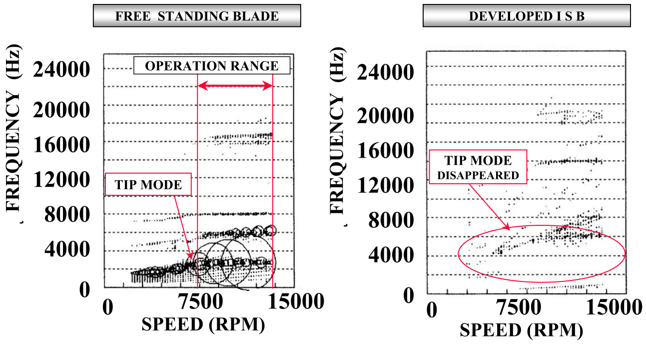


*Figure 24. Rotating Blade Shaker Test Data.*

## LP SECTION

Practical improvements to increase the efficiency for the LP section are proposed as listed in Table 2.

### *Bow Nozzles for Last Stage*

Bow nozzles applied in the last stage can decrease the secondary flow loss due to the effect of nozzle fluid force depressing endwall cross flow at the base and tip, as illustrated schematically in Figure 25. This bow nozzle design has been applied to the synthesis gas compressor turbines of a methanol plant, and a photograph of an actual diaphragm with bow nozzles is shown in Figure 26.

### *Loss Decrease for LP Casing CFD Basis*

The flow condition after the last stage blades tends to have so much affect on the overall efficiency of the LP section that the flow

*Table 2. Efficiency Improvements for LP Section.*

- **NOZZLE**
  - **BOW NOZZLE FOR LAST STAGE**
- **BLADE**
  - **HIGH EFFICIENCY PROFILE ISB**
- **DIAPHRAGM**
  - **METALLIC STATIC SEAL**
- **INTERMEDIATE LABYLINTH SEAL**
  - **HOLDER MODIFICATION**
- **LP CASING**
  - **FLOW GUIDE FOR LAST STAGE**

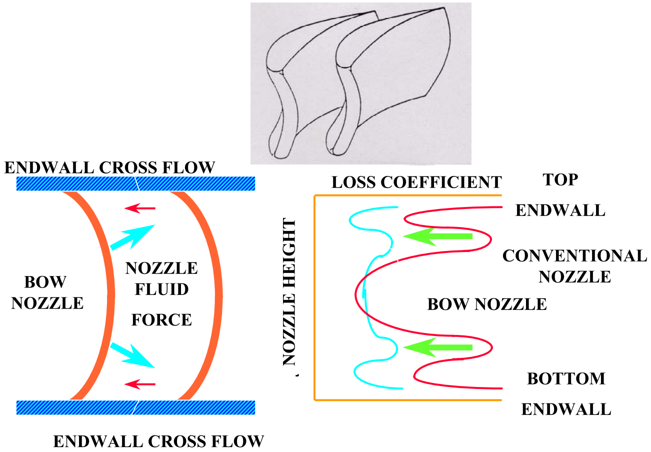


*Figure 25. Loss Decrease of Bow Nozzle.*

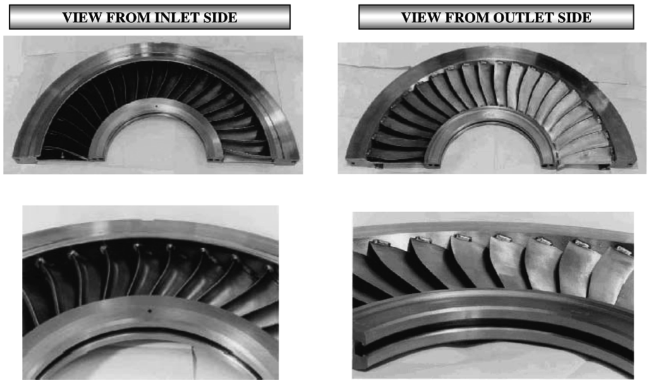


*Figure 26. LP Last Stage Bow Nozzle Diaphragm.*

pattern and pressure recovery have to be analyzed in detail to consider how the LP casing and flow guide can be designed to reduce losses. As shown in Figure 27, the inside of the LP casing is modeled to generate mesh for CFD, and calculations result in the illustrated streamline pattern. It can be seen that this streamline is very complicated due to a flow direction change from an axial direction to vertically down. Mach number contour and flow vector distribution are shown in Figure 28. As this CFD calculation result shows, a flow separation zone can be seen around the tip area downstream of the last stage blades, and each corner of LP casing has a local flow reduction zone and flow speed acceleration zone that basically generate the loss. As two possible countermeasures, fitting a flow guide to suit the expected flow pattern and changing the shape of the LP casing are considered.

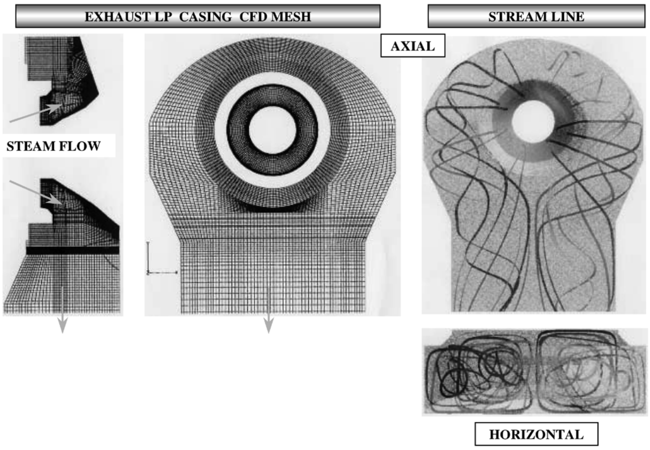


*Figure 27. Loss Analysis for LP Casing (Stream Line).*

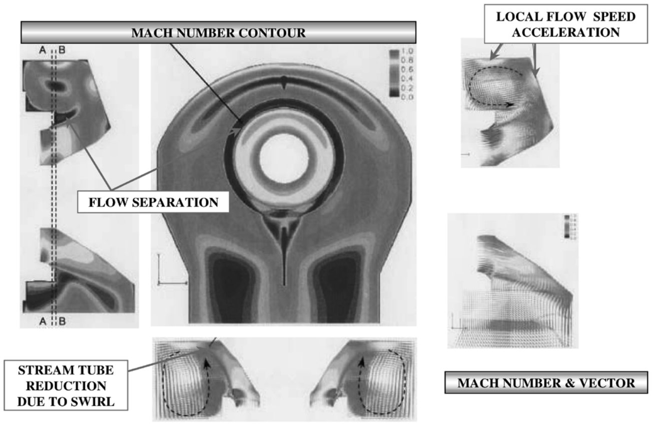


*Figure 28. Loss Analysis for LP Casing (Mach Number).*

## ACTUAL APPLICATION

The improvements explained above are actually applied on new turbines and modification of existing turbines as part of revamp projects, in the process of manufacturing and operation in the plant and onsite. Basic and main tests are then carried out, and finally a site performance test is conducted to evaluate the efficiency improvement and the characteristics of the newly developed nozzle and ISB.

### *High-Speed Balance Test*

The newly developed ISB is applied to high-temperature (exceeding 500°C [932°F]) and high-pressure (exceeding 100 ata) inlet steam backpressure turbines to evaluate the efficiency easily for domestic jobs. After completion of a low-speed dynamic balance, a rotor high-speed balance test is carried out. Stable rotordynamics having a very low vibration (less than 10 µm peak-to-peak) can be confirmed without any additional balancing and any vibration change during coasting up and down. In addition, a blade-hammering test is done as a natural frequency check and integrally grouped condition check.

### *Mechanical Running Test*

According to the job specification, a mechanical running test is successfully conducted in the shop and plant. And the same stable rotordynamics as those shown in the high-speed balance test are confirmed at hot condition.

## ACTUAL CASE STUDY OF PERFORMANCE IMPROVEMENT AT SITE

In the case of a new turbine consisting of new nozzles and ISB, a performance test is carried out, and the results confirm that steam consumption is the same as the expected steam flow based on actual operating conditions with more than a +3 percent margin. The overall efficiency calculated from the inlet and backpressure exhaust temperature is almost the same as that expected, based on thermodynamic calculations.

In the case of a turbine modification as part of a revamp, the performance evaluation is done before and after modification from data measured at site. Figure 29 shows which items are actually modified and illustrates the limitations to these modifications. The limiting factors to such a revamp include reuse of the rotor, blade root, and casing. However, even under these modification constraints, with the application of a new profile and countermeasures against internal leakage, steam consumption can be decreased and improved by more than 3 percent, and the effect of these improvements can be confirmed at site.

From these results, it is verified that the improved synthesis gas compressor steam turbines have effective performance gains and stable operation, as shown in Figure 30.

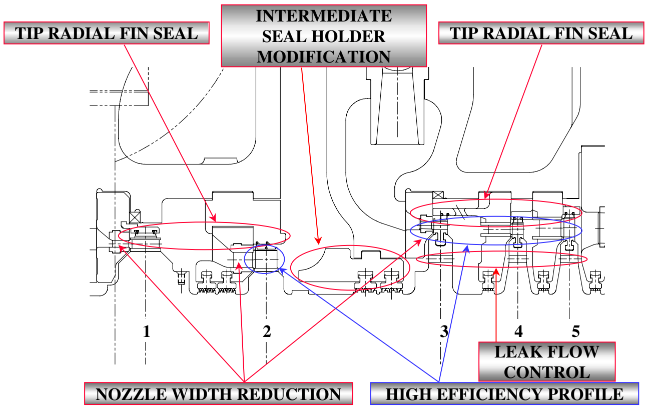
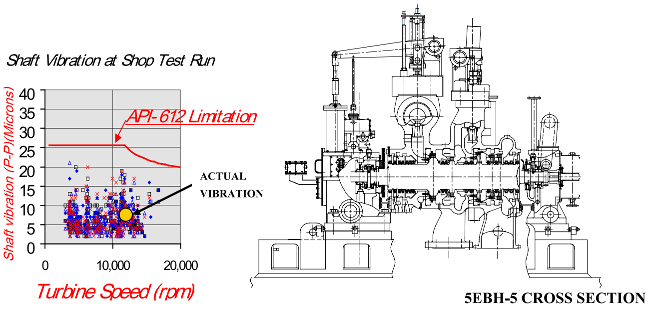


Figure 29. Actual Modification.



**JOB NAME : MITSUBISHI CHEMICAL KUROSAKI**
**AND OTHER 3 JOBS( EXTRACTION CONDENSING)**
**TURBINE MODEL : 5EBH-5 BACK PRESSURE TYPE**
**POWER : MAX 12104 kW**
**ROTATION SPEED : 10988 rpm**
**STEAM CONDITION : INLET 131ata×520℃×180Ton/Hr,**
**EXTRACTON 38ata, EXHAUST 1.8ata×40Ton/Hr**
**ROTOR VIBRATION : 5 μm p-p to 7 μm p-p**
**EXTRACTION TEMPERATURE : 376℃ (<DESIGN 380℃@NORMAL)**
**INLET STEAM CONSUMPTION : +3% MARGIN (GOOD)**
**OPERATION PERIOD : 12 MONTHS**

Figure 30. Site Performance Test Results.

## INCREASED RELIABILITY FOR LONG-TERM OPERATION

In order to improve operation reliability, a new turning device is used for easy maintenance and a special cooling design is applied for the thrust bearings to decrease the pad metal temperature. For erosion protection, several kinds of special heat treatment and coating are applied to the nozzles and blades.

## NEW TURNING DEVICE

This new turning device is highly unique, as shown in Figure 31. A four-stage gear without a worm gear and motor are assembled as one unit, which can be easily removed from the turbine for maintenance. The final gear is automatically engaged to the rotor wheel by the combination of slow inching and pushing motions. Gear slow inching is achieved using an inverter, switching logic, and electric resistance for power supply current reduction.

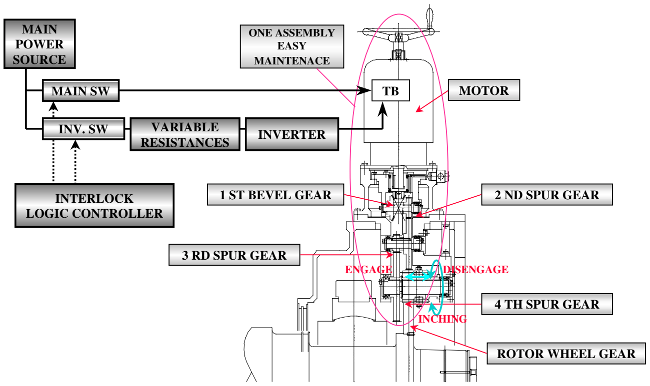


Figure 31. Assembly of New Turning Device.

### *Special Cooling for Bearings*

The journal and thrust bearings have large thrust forces, high-pressure intensity, and heat load from high-speed friction loss. For the purpose of decreasing the metal temperature, back metal cooling for pads and copper back pads are applied. As a typical example for the thrust bearing, Figure 32 shows the difference between conventional and the newly improved bearings. An additional oil cooling flow jet is put on the surface under each pad. The effect of pad temperature decrease due to all the modifications, including equalizing function improvement, is remarkable and can be seen in Figure 33.

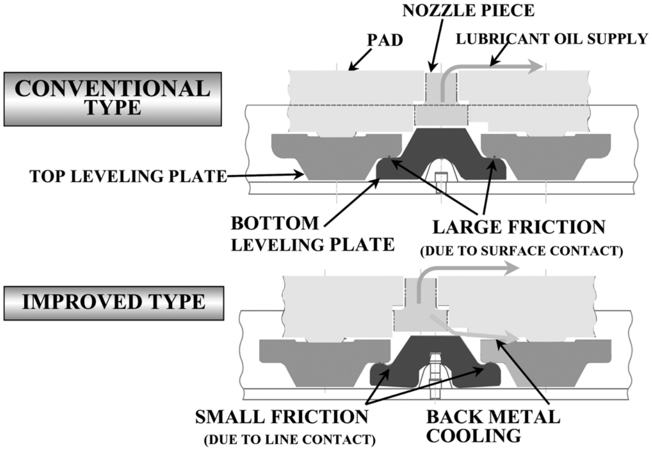


Figure 32. Improved Thrust Bearing.

### *Special Coating for Erosion*

As an example of the latest technology developed to improve the reliability for long-term operation, special heat treatment and coating can be applied for the first stage nozzles and LP section blade to prevent solid and drain attack erosion, as shown in Table 3. In particular, boronizing diffusion heat treatment with a very

- **DIRECT LUBE AND NON-FLOOD TYPE**
- **IMPROVED LEVELER**
- **COPPER ALLOY BACK METAL**
- **OFF-SET PIVOT**
- **BACK METAL COOLING**

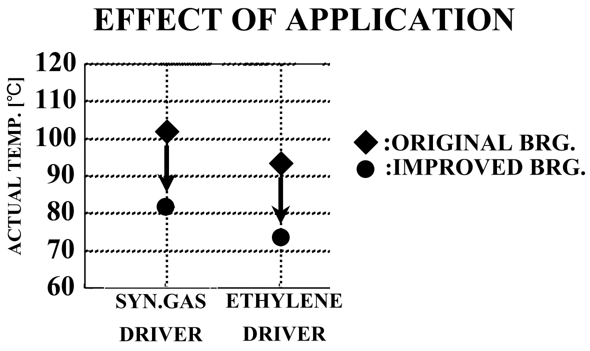


*Figure 33. High Reliability of Thrust Bearing.*

high hardness coating layer is applied for nozzles to prevent solid particle erosion and, as explained in Figure 34, the effect of this boronizing is confirmed with actual applications to achieve long-term operation.

*Table 3. Classification of Coating.*

| PHENOMENA | SOLID PARTICLE EROSION(SPE) | DRAIN ATTACK EROSION(DAE) |
|---|---|---|
| MECHANISM | PLASTIC | DUCTILE |
| TEMPERATURE | HIGH | LOW |
| APPLICABLE COATING | • BORONIZING<br>• PLASMA SPRAY | • ION PLATING<br>• PLASMA SPRAY<br>• STELLITE PLATE BRAZING<br>• PTA (Plasma Transfer Arc) |
| APPLICATION | NOZZLES<br>BLADES<br>DIAPHRAGM | NOZZLES<br>BLADES<br>DIAPHRAGM |

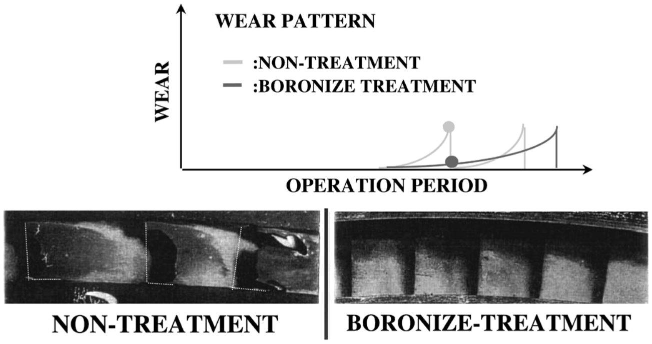


*Figure 34. Effect of Boronize Treatment.*

## CONCLUSION

This paper has presented the latest practical technologies to achieve high performance and improve operation reliability for synthesis gas compressor drive steam turbines. The results outlined herein verify that effective performance gains can be produced through the application of these technologies based on detailed analysis, experiments, and evaluation for onsite performance tests.

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