HITACHI TURBINE TECHNOLOGY FOR NUCLEAR APPLICATIONS

Y. Yamashita[1], T. Kudo[2] and N. Akane[3]
[1] Hitachi, Ltd. Power Systems, Energy and Environmental Systems Laboratory, Hitachi, Japan
[2] Hitachi, Ltd. Power Systems, Hitachi Works, Hitachi, Japan
[3] Hitachi, Ltd. Power Systems, Nuclear Systems Division, Hitachi, Japan

Abstract

Hitachi has supplied more than 1200 steam turbines and generators in the past 70 years for both thermal and nuclear applications. Hitachi nuclear steam turbines have been applied to all major reactor types including BWR's and PHWR's (CANDU). Hitachi's recent experience has included supplying the steam turbines for Qinshan Phase III Unit 1 & 2 in China, powered by two CANDU 6 reactors, as well as several ABWR projects in Japan. Hitachi has focused significant R&D efforts on continuous improvement of nuclear steam turbine technology capitalizing on its continuous supply history and sound technical capability. This paper addresses some of the key developments and newest technologies to be employed for new-build nuclear projects, including the ACR-1000 and Enhanced CANDU 6, and focuses on longer Last Stage Blade (LSB) development, Continuous Cover Blades (CCB), and other enhancements in product reliability and performance.

1. Introduction

Hitachi has a long history providing steam turbine generators to both the nuclear and the fossil power industry. Many design features of steam turbines for nuclear power applications (herein referred to as "Nuclear Steam Turbines" or "Nuclear Turbines") are based on experience gained with turbine designs for fossil power applications (herein referred to as "Fossil Steam Turbines" or "Fossil Turbines"). However, there are specific operating conditions in nuclear applications that are not present in fossil applications, such as wet-steam and radiation, and there are conditions in fossil applications that do not have to be considered in nuclear applications, such as supercritical steam temperatures and pressures.

Hence, the steam turbine design experience from the fossil power industry has only limited applicability for nuclear installations, and vice versa. Not all experience gained with Fossil Turbines can be transposed to Nuclear Turbines.

2. Nuclear Turbines vs. Fossil Turbines

Nuclear plants operate at steam conditions at or around the saturation state. Thus, the turbines for nuclear plants are often designated "wet-steam turbines". In comparison, the steam cycle of a state-of-the-art fossil fired power plant involves highly superheated main steam, as well as superheated reheat steam. Moreover, steam pressures in Fossil Turbine cycles are much higher than steam pressures in Nuclear Turbine cycles, which result in significantly different steam volumes and thus, different equipment dimensions.

The combination of large steam mass-flow and relatively low initial steam pressure associated with Nuclear Turbines results in very large volumetric steam flow rates, thus requiring blades with large mean diameters and lengths. Due to these long blades, large size Nuclear Turbines are designed with half the rotor speed of a fossil steam turbine in order to maintain the blade tip speed within reasonable limits. For 60 Hz, the rotor speed of Hitachi Nuclear Turbines is 1800 rpm, and for 50 Hz, the rotor speed is 1500 rpm. This reduced shaft speed requires a four-pole generator as compared to a two-pole generator typically driven by Fossil Steam Turbines.

In addition to the differences in steam pressures and temperatures, the steam in BWR/ABWR power plants is slightly radioactive. Hence, radiation shields are required to protect operating personnel and consideration has to be given to the long-term effects of radioactivity on material properties. Last but not least, typical Nuclear Turbines are designed for base load operation, while Fossil Steam Turbines are typically designed for more frequent load changes. This impacts thermal stress analyses, life cycle evaluations, and material selections.

Figure 1 Nuclear Turbines vs. Fossil Turbines

3. Hitachi Nuclear Turbine Generator Experience

Hitachi's experience in Nuclear Steam Turbine technology extends continuously over a period of almost forty years. Hitachi's first Nuclear Steam Turbine was installed in 1972 at the Karachi Nuclear Power Station, a CANDU reactor plant owned by the Atomic Energy Commission of Pakistan. This 50 Hz, non-reheat turbine is a Tandem Compound machine with four exhaust ends and 23 inch last stage blades (TC4F-23). The rated output is 139 MW. It operates at a shaft speed of 3,000 rpm and at main steam temperature of 248C.

Hitachi has contracted twenty more Nuclear Steam Turbines since this first unit in Pakistan was placed into operation, twelve of which operate in the 60 Hz market. As of today, 18 Hitachi steam turbines are in operation at CANDU, BWR and ABWR nuclear plants worldwide, and one additional steam turbine is under construction.

The most recently completed Hitachi Nuclear Steam Turbine project is the Shika Unit #2 ABWR Nuclear Power Station, a Hitachi EPC project that was completed in 2006. It is the most recent ABWR Nuclear Power Plant to be commissioned in the world. Its 60 Hz, TC6F-52 inch Nuclear Turbine has a rated output of 1,380 MW and steam temperatures of 284C and 253C for main steam and reheat, respectively.

The Shika Unit #2 Project used Hitachi’s advanced construction technologies, including highly digitalized construction management, modularization, and open-top installation using large crawler cranes. These unique Hitachi construction features helped reduce the total plant construction time to 44 months from first concrete to fuel loading and start of commercial power, a reduction of nearly 20% over earlier BWR plants constructed in Japan. These revolutionary construction techniques also resulted in a cost reduction of about 40% for site construction activities over those of earlier BWRs.

Most of the construction modules developed for the Shika Unit #2 ABWR turbine island, as well as all other Hitachi project experience can be adopted for future Nuclear Projects.

4. Hitachi Nuclear Steam turbine Technology

4.1 Hitachi standard Nuclear Turbine Design

Hitachi’s standard ABWR nuclear steam turbine is a tandem compound, six-flow, reheat steam turbine. It consists of a double-flow HP section, and three double-flow LP sections. The turbine sections are of an impulse or quasi-impulse type design with high efficiency and high availability.

Table 1 Hitachi Standard ABWR Nuclear Turbine Parameters

Turbine Type	TC6F-52”, 4 Cylinders
Rated Output	1,380 MW Class
Exhaust Pressure	5kPa Class
Main Steam Pressure	6.8MPa
Main Steam Temperature	284C
Reheat Temperature	253C

Casings

The HP casings and LP inner casings are split at the horizontal centerline, with full metal-to-metal contact through careful turbine flange and tightening bolt design.
The turbine is keyed to the foundation in the axial direction at the thrust bearing in the middle standard and mid LP sections. The casings expand axially from these fixed points.

Rotor

The HP and LP rotors are made of machined solid mono-block alloy steel forgings. The rotors have no shrink fit wheel structures and no welds. Labyrinth type shaft glands are machined into each end of the rotors.

Blades

Short blades are machined from solid bar materials, and long blades, including the 52 in last stage blades are machined from die-forged materials. All blades are designed to be free from resonance vibration near rotating speed.

Nozzles and Diaphragms

All nozzle and diaphragms are of fabricated type, which consist of nozzle profile and outer and inner rings of the diaphragm. Spring-backed labyrinth type packings are provided to reduce steam leakage.

Packings

Shaft-seals are used to reduce the inter-stage steam leakage as well as leakage from the turbine. Spring-backed, segmented labyrinth packing rings with high and low teeth structures are fastened on the end portion of HP casings and restrict steam leakage flow.

4.2 Advanced Nuclear Turbine Technology Features

In Japan alone, Hitachi operates ten major research laboratories with a research and development staff of 8,000 highly trained professionals (including over 1,200 doctors), which has enabled Hitachi to continuously develop and bring new products and services to market.

In spring of 2007, Hitachi commissioned a new steam turbine testing facility for steam loading tests. (shown in Figure 2). The facility consists of a simplified scale power plant that includes steam generator, turbine, cooling towers and balance of plant equipment. Moreover, the facility includes an inverter motor generator to drive the turbine shaft during low load simulations, and flash tanks to simulate feedwater heater flashbacks. The facility was designed to perform turbine scale model testing at actual internal steam flow conditions and stress distributions. Among others, flow field simulations, centrifugal stress simulations, feed-water heater flash-back simulations, low load operation simulations, and load rejection simulations can be performed.

This steam turbine testing facility is without parallel in the world in terms of enabling all range of load operation and load rejection simulations amongst wide variety of operating and/or transient conditions. Now with the development of longer last stage blade, reliability under all range of load operation becomes more critically important, and Hitachi nuclear steam turbine can achieve higher reliability and efficiency through such validation processes in the design and prototype phase.

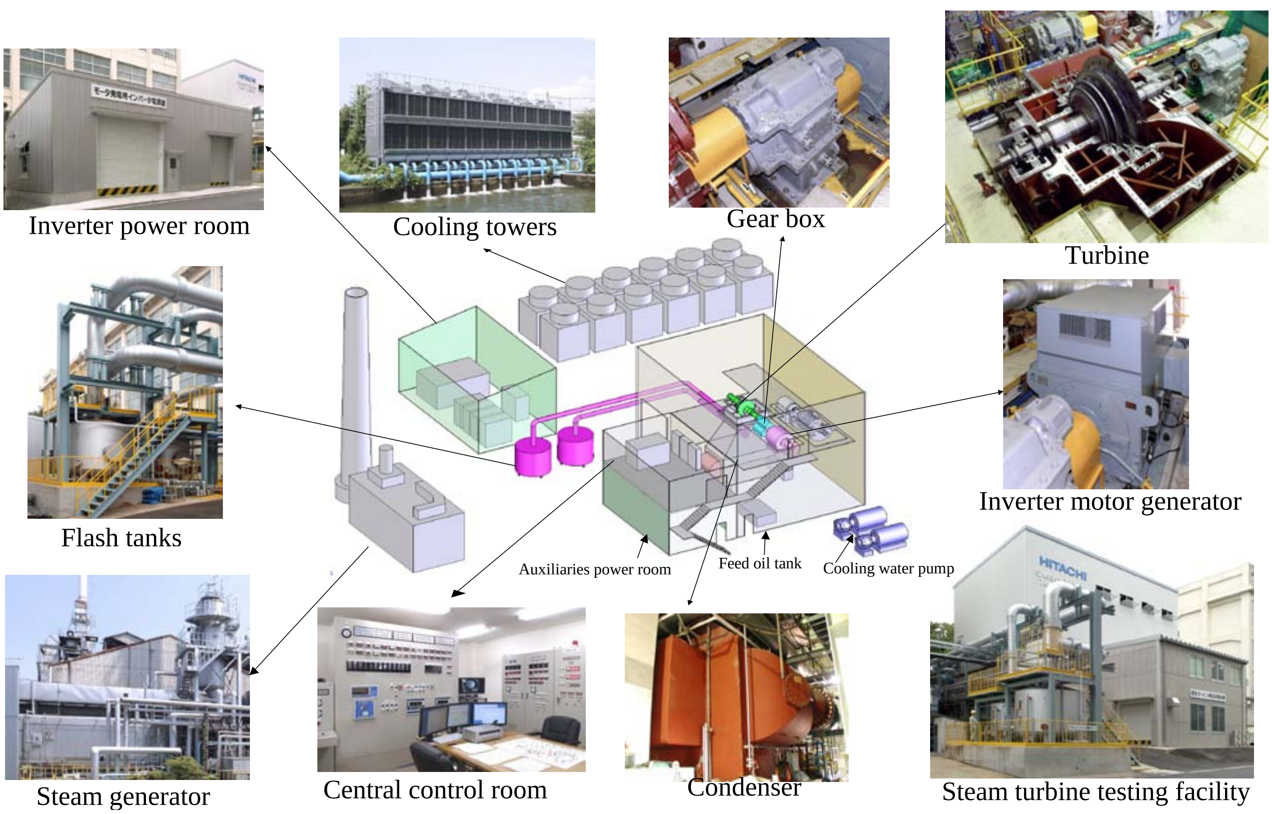


Figure 2 Hitachi Steam Turbine Testing Facility

4.2.1 Continuous Cover Blade (CCB) Design Technology for Nuclear Steam Turbine

Based on a number of cutting-edge design technologies of steam turbine, Hitachi has developed and is in the process of developing, a series of new blades for Nuclear Turbines featuring a Continuous Cover Blade (CCB) structure that offer better overall performance and superior strength and vibration characteristics. The CCB has been adopted from Fossil Turbines, where this mature technology has demonstrated an excellent operational track record, outstanding operating characteristics and high reliability since its introduction in 1991.

Hitachi's CCB design forms a continuously coupled blade structure to improve vibration characteristics relative to conventional designs. It also includes integral shrouds and mid-span supports to eliminate the reliability problems associated with tie-wires. (Figure 3)

Adjacent blades in steam turbines are generally linked together to provide greater rigidity and to reduce or dampen vibrations. The conventional blade assemblies design that were held together by shrouds and tie wires had a number of drawbacks, mostly related to stress concentration and assembly.

The CCB blades have contact surfaces (cover and tie boss) that are integral to the construction of the blade and therefore create significantly lower stress concentrations. Moreover, the untwisting of the blades during rotation, which is caused by centrifugal force, is restrained by the contact surfaces between blades. As a result, at rated shaft speed all of the blades are connected and interlocked to form a continuous ring of blades.

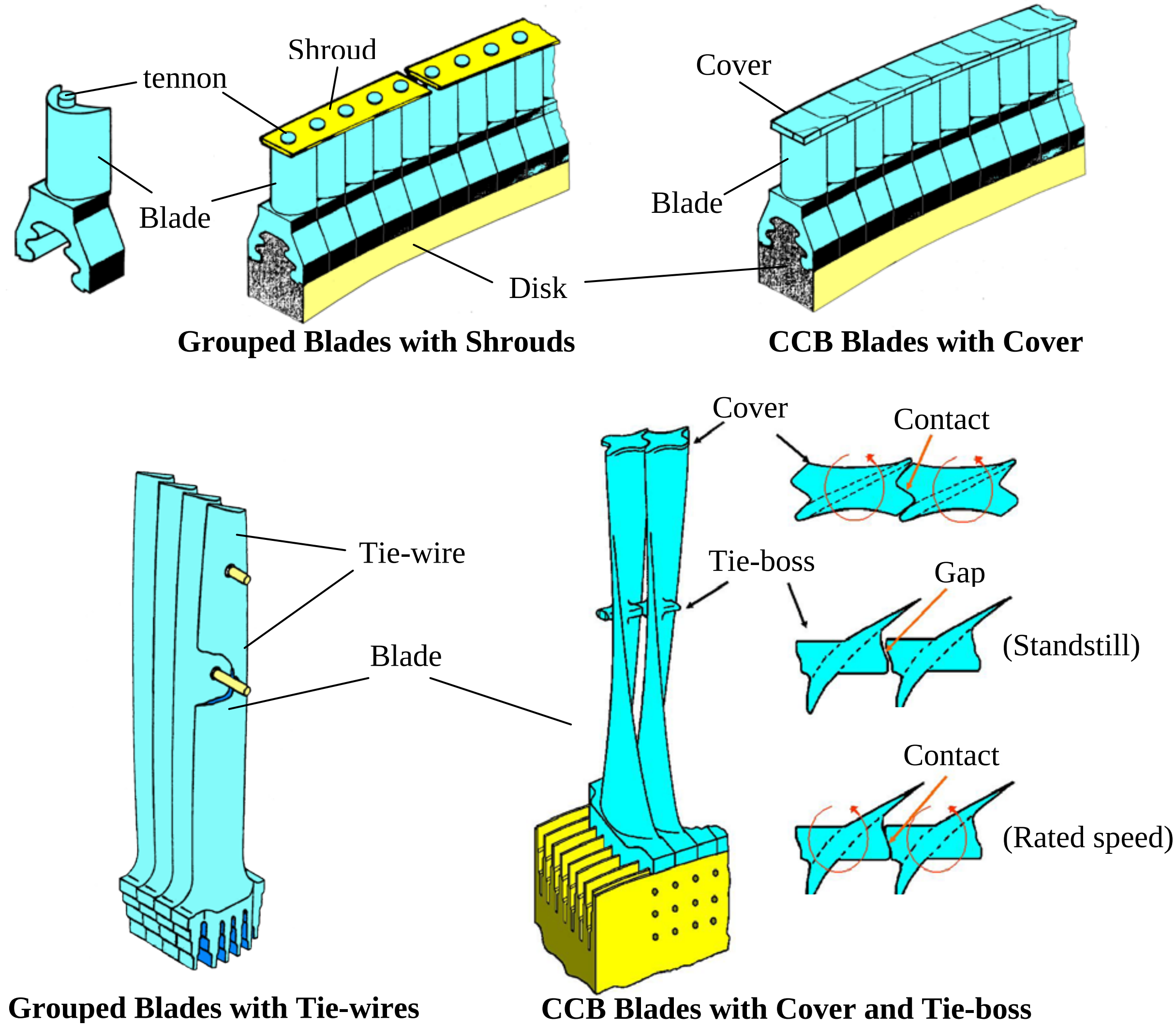


Figure 3 Conventional Blade Assemblies and Continuous Cover Blades

Table 2 summarizes characteristics of CCB in comparison with the conventionally grouped blade configurations, i.e., the CCB structure has better damping, fewer resonance points during rotation, more stable vibration characteristics (due to the interlocking of blades), reduced resonance stress levels, reduced random vibration stress levels, and suppressed flutter. Moreover, the CCB technology allows for the use of the high-low type radial fin as a tip seal (see Figure 4), which leads to a better labyrinth effect and hence, increased stage efficiency. Such high-low type radial fins are not feasible for conventional blade tip portions that have shrouds with protruding tenons.

Table 2 CCB Blade's Characteristics compared with Grouped Blade

Items	Characteristics
Strength and reliability enhancement	Better damping Reduced resonance stress levels Reduced random vibration stress levels Fewer resonance points during rotation More stable vibration characteristics Suppressed flutter Less stress concentration
Efficiency enhancements	Allowing for the use of the high-low type radial fin as a tip seal

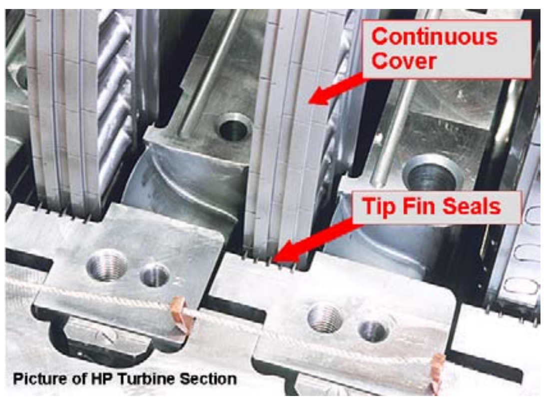


Figure 4 Continuous Cover Blade

4.2.2.1 Long Last Stage Blade

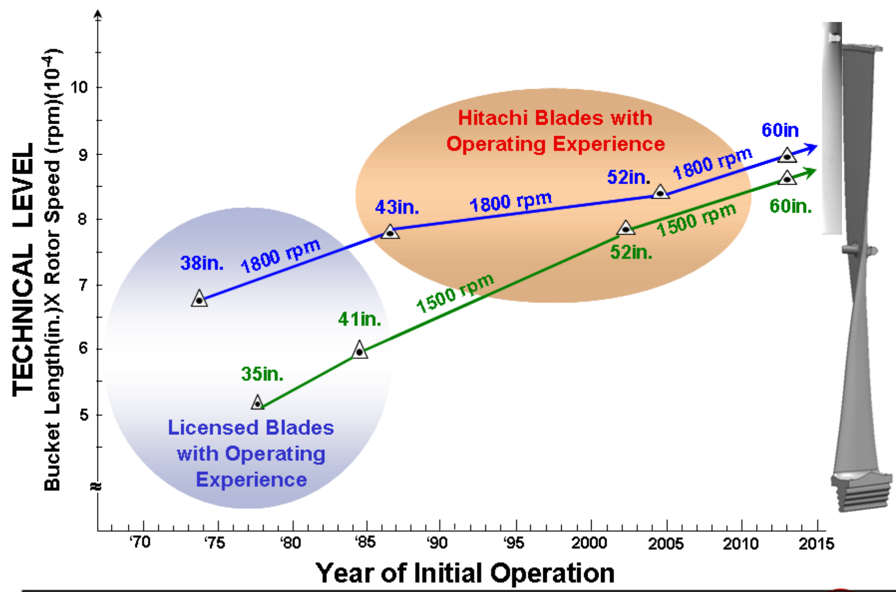
Long last stage blades produce approximately 10% of the total output of large steam turbines, and since they experience the largest centrifugal force, they are a critically important component affecting the performance and reliability of the overall product. The requirement for longer last stage blades results in larger steam flows and higher steam speeds, larger centrifugal forces, and various refined natural frequencies, thus requiring more advanced design technologies to optimize performance, strength and vibration characteristics of the blades.

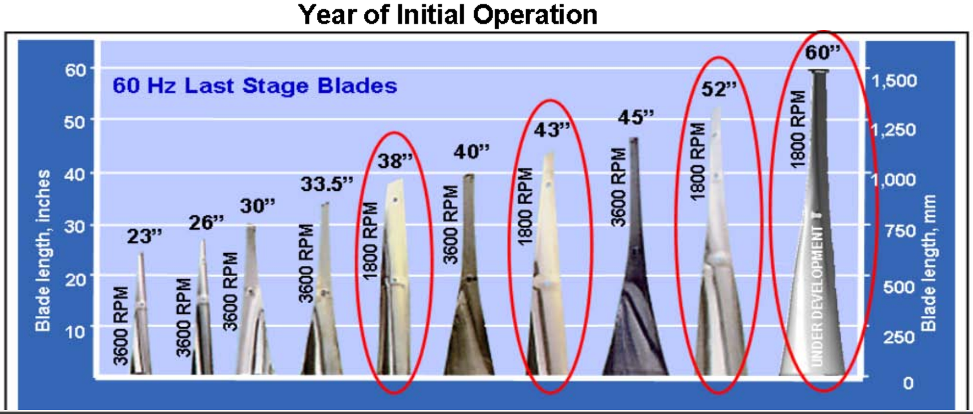
Since the early 1980's Hitachi has continuously developed new and improved last stage blades. As shown in Figure 3, Hitachi has operating experience with Nuclear Turbine last stage blade lengths of 38, 43, and 52 inches in the 60 Hz market (1800 rpm), and with 35,41, and 52 inches in the 50 Hz market (1500 rpm). Additional blade lengths are available for Fossil Turbines, as shown in Figures 5 5 and 66.

~~The next new last stage blade for Nuclear Turbine applications for 60 Hz applications is under developing. (Figure 3&4)~~

~~Turbine~~ Last stage blades are affected by a variety of exciting forces under operation, so improving vibration characteristics and damping are important. Due to reliability enhancement, CCB designs were applied for the next new last stage blade for Nuclear Turbine applications for 60 Hz applications. (Figure 7&8)
Newly developed blades are verified in the verification process shown in Figure 9.
In the next section, the results of verification test of Hitachi's newly developed 60Hz 60in last stage blade are described.

~~Hitachi's original technology "Continuous Cover Blade (CCB) structure" is described.~~





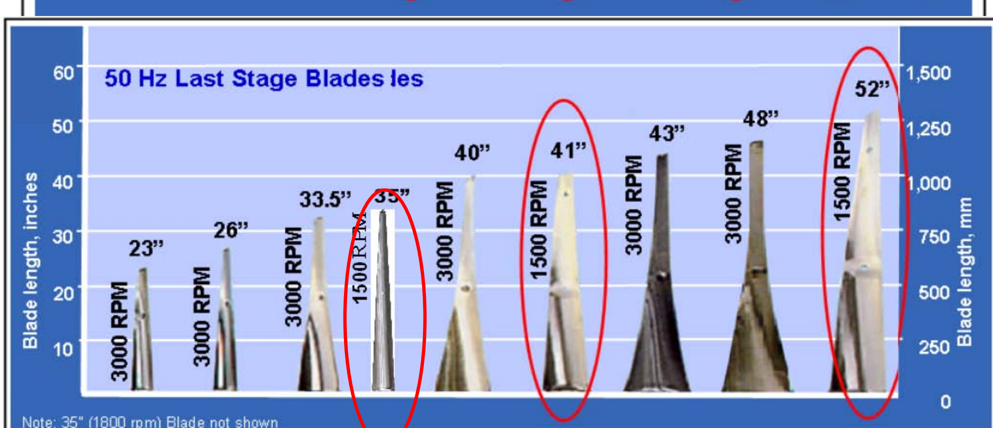


Figure 6 Hitachi 50 Hz Last Stage Blades
(Blades Applicable for Nuclear Turbines are marked)

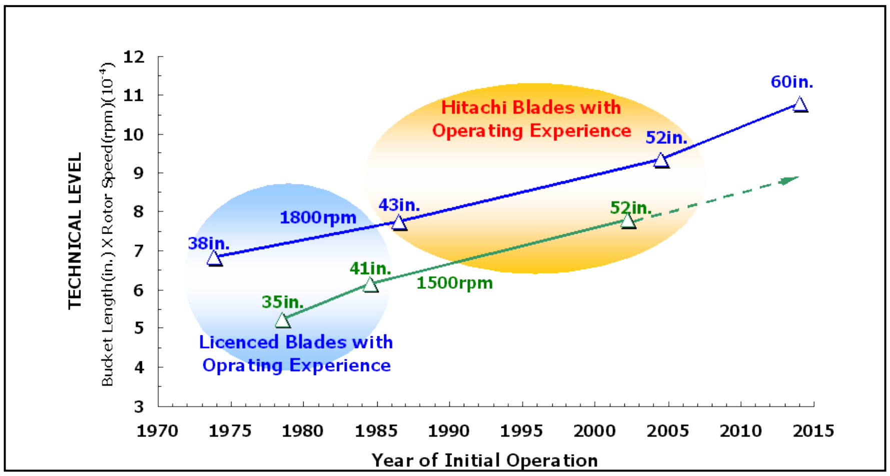


Figure ~~3~~ 7 Hitachi Last Blade Stage Blade Development for Nuclear Turbine

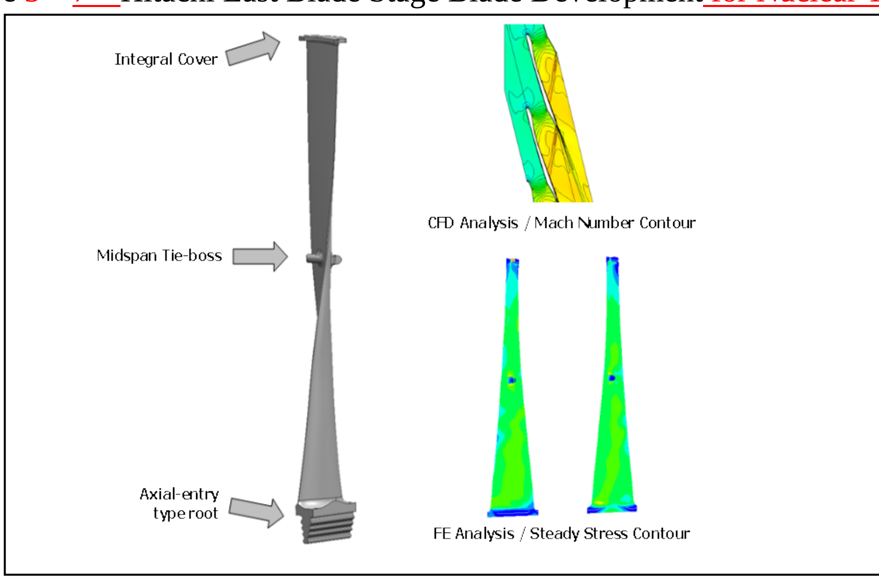


Figure 84 New 60 Hz Last Stage Blade

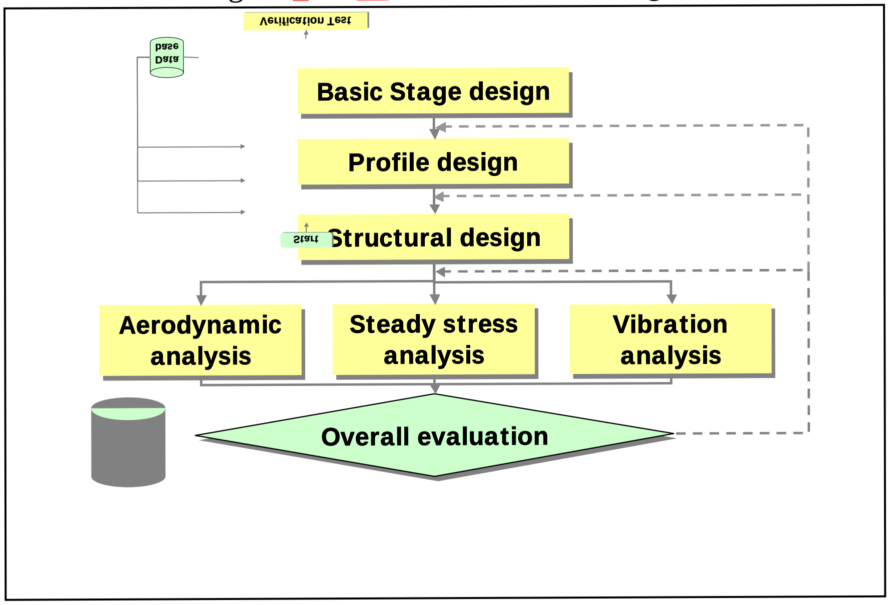
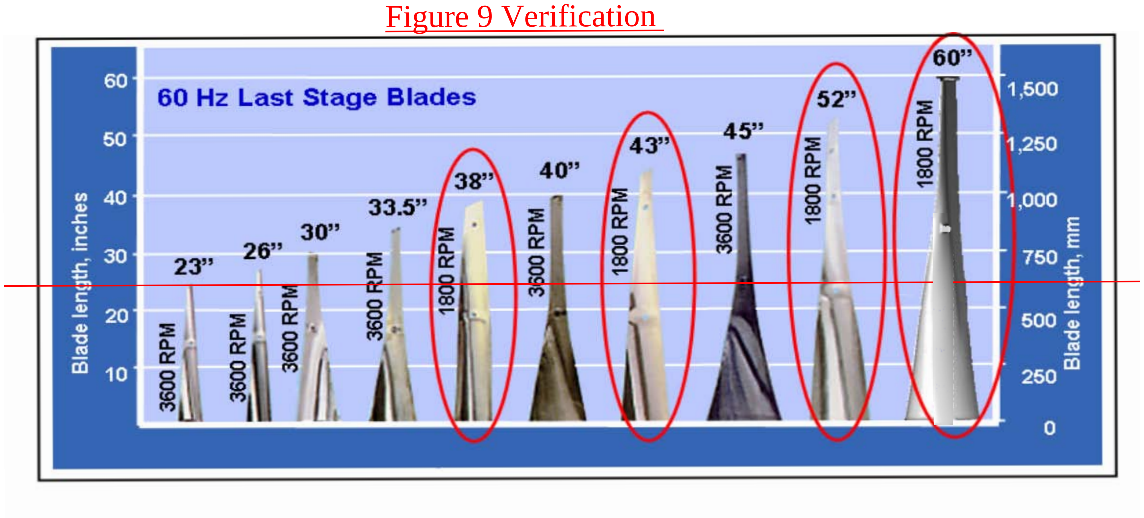
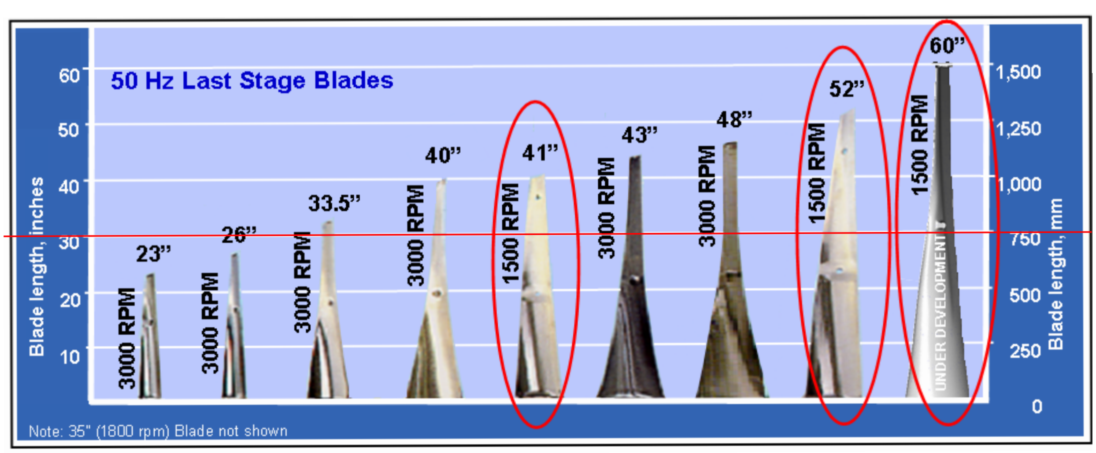


Figure 9 Verification



Process

Figure 5 Hitachi 60 Hz Last Stage Blades
(Blades Applicable for Nuclear Turbines are marked)



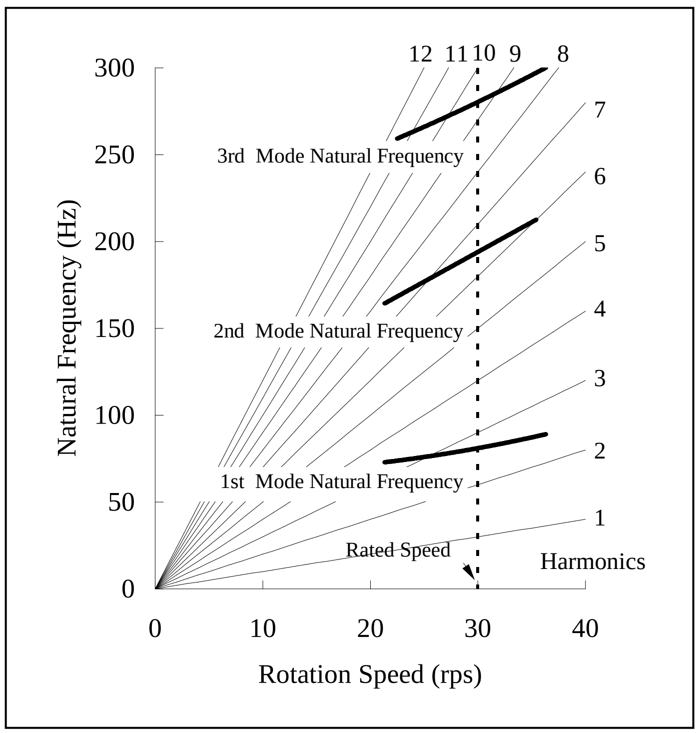
~~Figure 6 – Hitachi 50 Hz Last Stage Blades~~
~~(Blades Applicable for Nuclear Turbines are marked)~~

4.2.~~2~~3 Results of ~~Spin~~ Verification Test of 60Hz 60inch Last Stage Blade

Initial group of actual size new designed 60Hz 60inch LSB had been manufactured without any problems during production process. The spin test had been executed in test facility for verification of blade vibration characteristics such as blade natural frequencies in rotation and ~~dumping~~ damping ratio. The assembled blades on test rotor are shown in Figure ~~7~~10.

The vibrations of blades were measured by high sensitivity semi-conductor strain-gage that attached on blade profile surface. The signals from strain-gages were transmitted to stationary antenna from transmitter attached on the test rotor by telemetry system using the frequency modulation radio waves. The electromagnet was installed beside of blades to excite the blade vibration.

The data form spin test w~~ea~~re expressed in Campbell diagram ~~that~~ for ~~conformation~~ confirmation of blade vibration characteristics as shown in Figure ~~8~~11. The resonance points of new 60Hz 60inch blade were defined and resonance rotation speed were sufficiently ~~spread~~ far away from rated speed i.e. 30rps(1,800rpm). Also, ~~resonance~~ forced response analysis by FEA that reflected the actual vibration data from spin test was executed for checking the ~~alternative~~ dynamic stress in rated speed. From the result of analysis, the ~~alternative~~ dynamic stress is sufficiently low from limitation of high cycle fatigue of blade material. (Figure ~~9~~12)



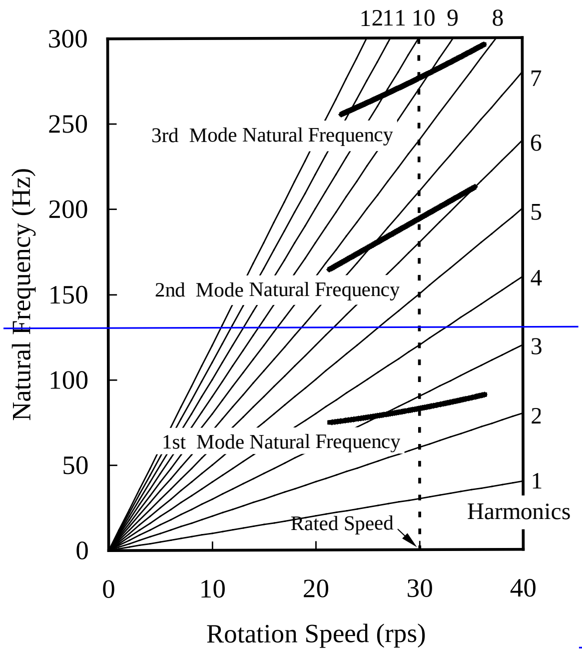


Figure ~~7~~ 10 Actual Size Test Rotor

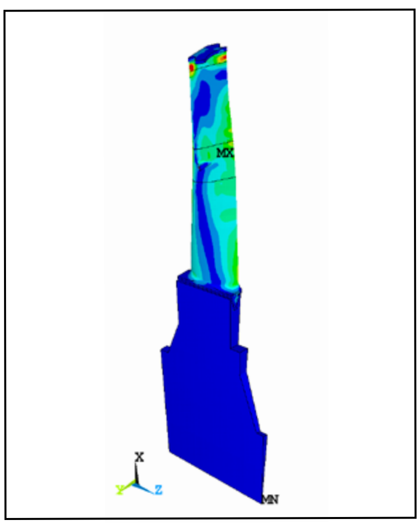


Figure 11 Campbell Diagram

Figure 12 Dynamic stress distributions by FEA

~~Figure 8 Campbell Diagram~~

Figure 9 Alternative stress distributions by FEA

4.2.2 Continuous Cover Blades (CCB)

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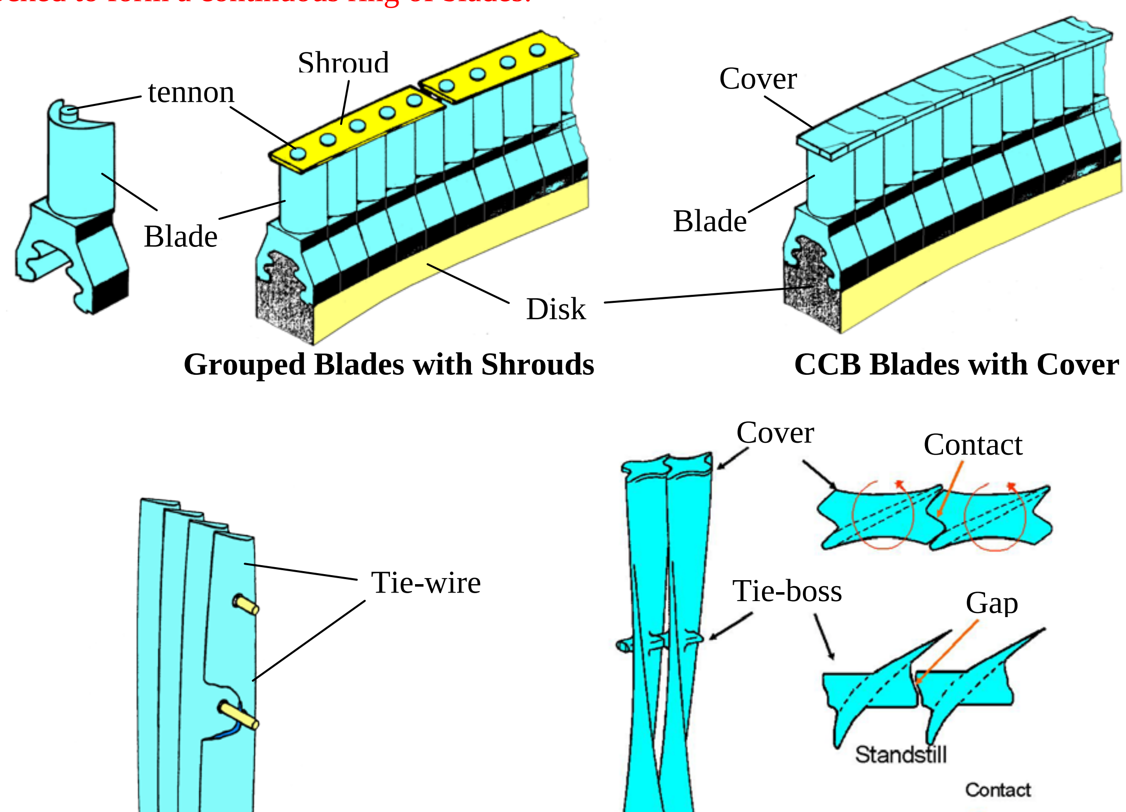

Grouped Blades with Tie-wires **CCB Blades with Cover and Tie-boss**

~~Figure 10 Conventional Blade Assemblies and Continuous Cover Blades~~

~~Table 2 summarizes characteristics of CCB in comparison with the conventionally grouped blade configurations, i.e., the CCB structure has better damping, fewer resonance points during rotation, more stable vibration characteristics (due to the interlocking of blades), reduced resonance stress levels, reduced random vibration stress levels, and suppressed flutter. Moreover, the CCB technology allows for the use of the high-low type radial fin as a tip seal (see Figure 11), which leads to a better labyrinth effect and hence, increased stage efficiency. Such high-low type radial fins are not feasible for conventional blade tip portions that have shrouds with protruding tenons.~~

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~~Items~~	~~Characteristics~~
~~Strength and reliability enhancement~~	~~Better damping~~ ~~Reduced resonance stress levels~~ ~~Reduced random vibration stress levels~~ ~~Fewer resonance points during rotation~~ ~~More stable vibration characteristics~~ ~~Suppressed flutter~~ ~~Less stress concentration~~
~~Efficiency enhancements~~	~~Allowing for the use of the high-low type radial fin as a tip seal~~

4.2.~~3~~ 4 Other Advanced Technology Features and Upgrades

Over the last several decades, Hitachi has continuously improved the STG design. Such improvements can be categorized into three general areas: strength/reliability enhancements, efficiency enhancements, and operation/ maintenance enhancements.

Strength and Reliability Enhancements

Strength and reliability improvements are those design changes that extend the life of the turbine through stronger, more robust components, such as Hitachi's centerline-supported diaphragms, advanced Electron Beam Welded (EBW) diaphragms, advanced mono-block rotor design, erosion prevention for last stage blades, and Continuous Cover Blades.

Efficiency Enhancements

Efficiency enhancements are those design changes that result in an overall turbine performance improvement, such as increased number of turbine stages; optimized degree of reaction stage versus impulse stage; balanced, highly loaded and advanced blade profiles; controlled and advanced vortex lean nozzles; Continuous Cover Blades with multiple fin seals; Elliptical Packings; and Diffuser Type Exhaust Hoods.

Figure 13 lists some of the major efficiency enhancements that have been implemented in Hitachi's turbine design.

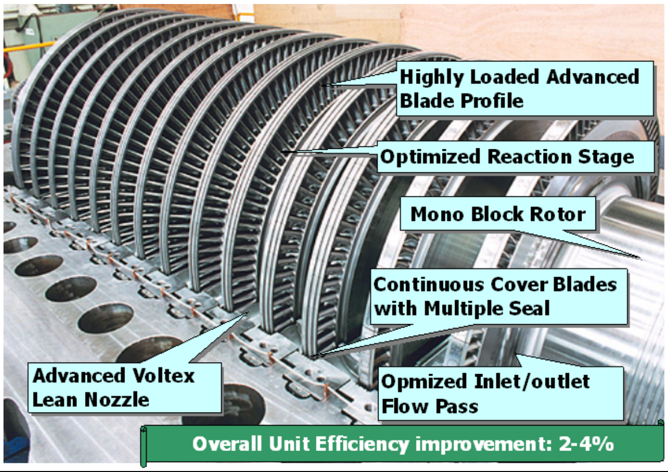
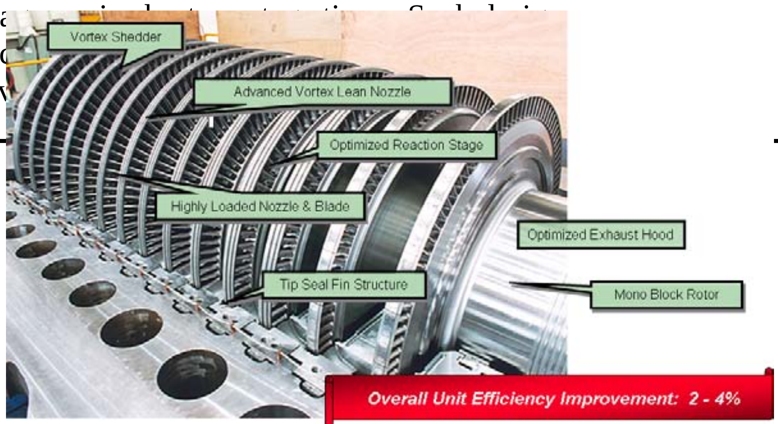


Figure 13 Efficiency Enhancement

Operation and Maintenance Enhancements

Operation and Maintenance (O&M) Enhancements are those design changes that result in longer intervals between scheduled maintenance outa
improvements include our advanced hydraulic
enhancements stated above also have a positiv



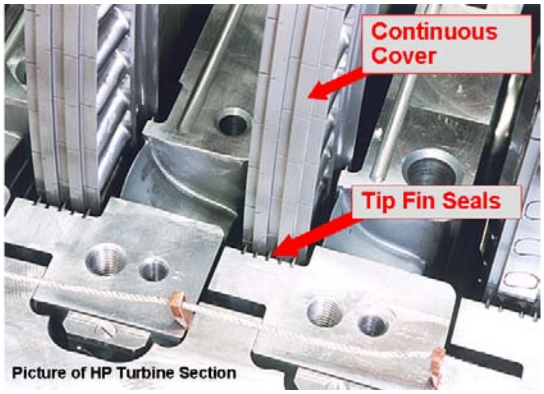


Figure 11 Continuous Cover Blade Figure 12 Efficiency Enhancement

5. Conclusion

Hitachi's Nuclear Steam Turbine Technology, which also leveraged lots of field experience, has been described. Also, Hitachi recognizes the important role nuclear power plays in global energy supplies, the cutting edge technology as represented by last stage blade and CCB is developed and being employed for improving efficiency and reliability of nuclear projects, especially the ACR-1000 and Enhanced CANDU 6 new-build. And commissioning of a new steam turbine testing facility is useful for that.

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