Hitachi Turbine Generator Technology for Nuclear Applications

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1. Nuclear Turbines vs. Fossil Turbines

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.

Both the Nuclear Power Industry and the Fossil Power Industry utilizes multiple variations of steam cycles. For the purpose of the this report, the steam turbine design for an Advanced Boiling Water Reactor (ABWR) nuclear power plant is compared with the steam turbine design for a large state-of-the-art fossil fired power plant.

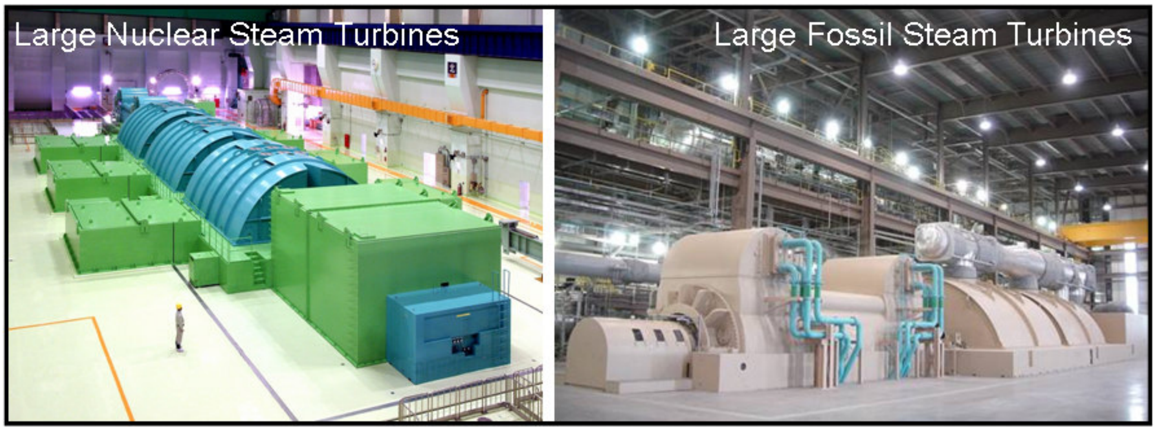

Figure 1 – Nuclear Turbines vs. Fossil Turbines

1.1. Operating Conditions

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 results 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, 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 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. Hence, the turbine material selection is not the same for Nuclear Turbines and Fossil Turbines.

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.

1.2. Design Challenges

The operating conditions and therefore the damage mechanisms for Fossil Steam Turbines versus that for Nuclear Steam Turbines are very different.

Table 1 compares the relevance of steam path damage mechanisms for the two steam turbine types. The table clearly indicates that technical design issues important to Fossil Steam Turbines vary significantly from that of Nuclear Steam Turbines. Some of the issues of critical importance to a nuclear steam turbine are of little concern to a fossil steam turbine.

Damage Mechanism	Fossil Turbine	Nuclear Turbine
Creep and Creep-fatigue in Blades and Attachments	**Secondary**	**Uncommon**
Solid Particle Erosion	**Critical**	**Uncommon**
Surface Deposition	**Critical**	**Uncommon**
Fatigue in LP Blades	**Critical**	**Secondary**
Fatigue in HP Blades	**Secondary**	**Secondary**
Localized Corrosion	**Secondary**	**Critical**
Corrosion Fatigue	**Secondary**	**Critical**
Stress Corrosion Cracking in Disc-Rim Attachments	**Critical**	**Critical**
Stress Corrosion Cracking in Blades	**Secondary**	**Secondary**
Water Droplet Erosion	**Critical**	**Critical**
Water Induction	**Critical**	**Critical**
Flow-Accelerated Corrosion	**Secondary**	**Critical**
Fretting	**Secondary**	**Secondary**
Notes: “Critical”: indicated damages commonly found or presenting a major problem when found “Secondary” indicates damages that can be found but present a lesser problem “Uncommon” indicates damages uncommon to have occurred in this type of turbine		

Table 1 – Steam Path Damage Mechanisms

Water droplet erosion (WDE) of the rotating blades is one of the most important factors influencing the operating reliability of Nuclear Steam Turbines and thus, a determining factor for design configurations. The WDE hazard mainly depends on the steam wetness and circumferential speed of the rotating blades, sharply increasing with the latter. The enormous volumetric steam flow rates and resulting large mean blade diameters and lengths of Nuclear Turbines aggravates the WDE problem.

Another challenge with Nuclear Steam Turbines is that they involve a more complex manufacturing process and are far more labor intensive during manufacturing. Nuclear Steam Turbines require heavier machining facilities, larger manufacturing areas, and necessitate the use of more up-to-date technologies than that of large Fossil Steam Turbines.

2. Hitachi Nuclear Turbine Generator Experience

Hitachi's experience in Nuclear Steam Turbine technology extends continuously over a period of almost fourty 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 478 ˚F.

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, PWR, BWR and ABWR nuclear plants worldwide, and three additional steam turbines are under construction. Figure 3 graphically illustrates Hitachi's Nuclear Turbine experience.

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, TC-6F-52 inch Nuclear Turbine has a rated output of 1,358 MW and steam temperatures of 543 ˚F and 487 ˚F for main steam and reheat, respectively.

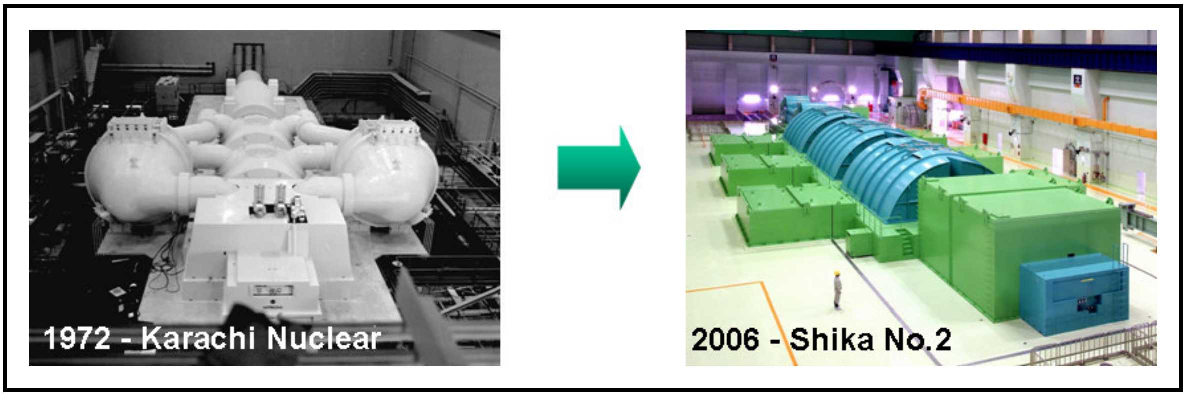

Figure 2 – Hitachi's first Nuclear Turbine and Hitachi's most recent Nuclear Turbine

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.

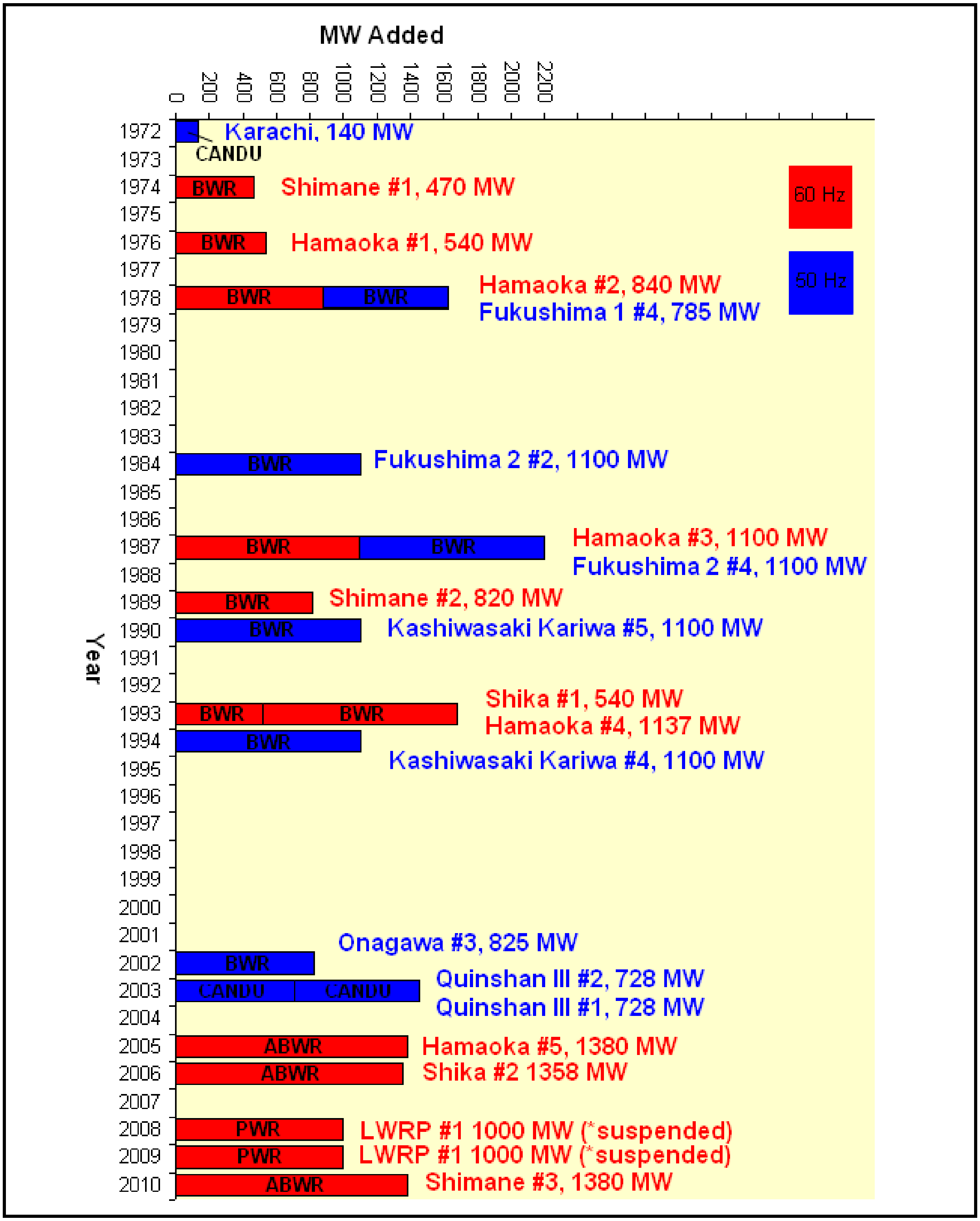

Figure 3 - Hitachi Nuclear Steam Turbine Experience

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Figure 4 shows the Hitachi nuclear steam turbine experience in comparison with other BWR turbine suppliers' experience. It is to be noted that only one BWR steam turbine supplier other than Hitachi has turbine operating experience in both the 60 Hz and the 50 Hz market, and only Hitachi has operating experience of a 52 in last stage blade in the 60 Hz BWR nuclear turbine market. Moreover, Hitachi is the only BWR turbine supplier that has continuously been involved in nuclear steam turbine projects over the last decade, and Hitachi is the only BWR turbine supplier who is currently involved in nuclear projects in the 60 Hz market.

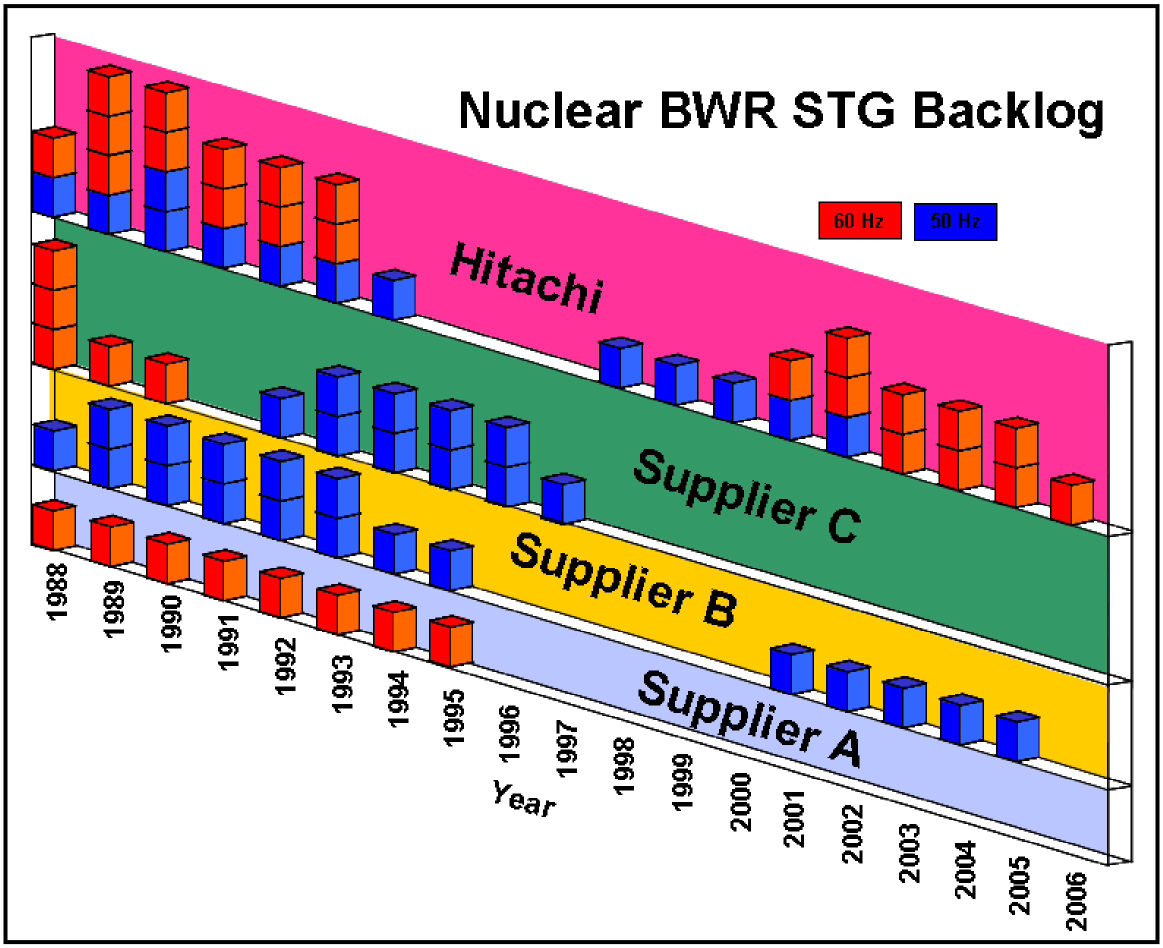

Figure 4 - BWR Nuclear Steam Turbine Projects

2.1. Hamaoka Unit # 5 Incident

The most recent Hitachi Nuclear Turbine design improvements are based on experience from a blade failure at Hamaoka #5 that occurred in 2006.

2.1.1 Outline of the Incident

On June 15, 2006, Hamaoka Nuclear Power Station Unit 5 was in operation at constant thermal output when an alarm was generated for “Excessive Turbine Vibration”. As a result, the turbine tripped and the reactor shut down automatically. Upon opening the LP turbine B (BLP) casing it was found that a blade of the L-2 stage, the third stage from the exhaust, had become detached from the rotor.
Detailed inspections revealed that the forks and pins of the L-2 stage blade root structure were damaged and examination of the fracture surfaces confirmed the presence of signs of high-cycle fatigue.
Hitachi responded to the blade failure by applying every resource to define, diagnose and resolve the problem for our customer. Eight months after the incident, in February 2007, Hamaoka # 5 went back online.

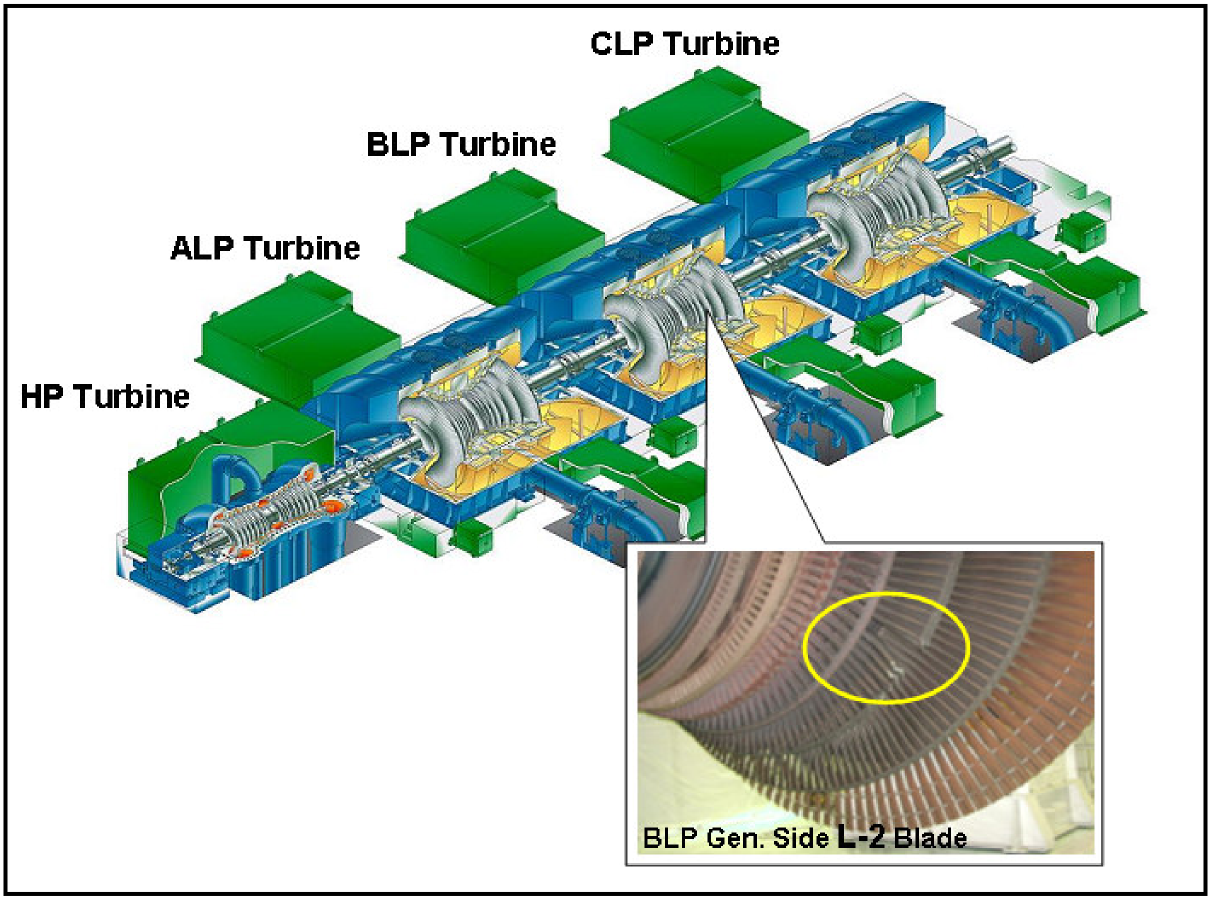

Figure 5 – Hamaoka #5 Blade Failure

2.1.2 Root Cause

Detailed damage analysis revealed that the high-cycle fatigue was the result of stress caused by superposition of Random Vibrations and Flashback Vibrations during the low load test operation.

Random Vibrations

Random Vibrations are irregular oscillations that occur in blades as a result of steam turbulence within the turbine. They occur when the turbine is under no load or at low load operation. Based on Hitachi design experience, considerable Random Vibrations are frequently found in turbine stages L-0 and L-1 and are taken under consideration as part of the blade design process. The L-2 blades, however, are typically not subject to Random Vibrations and therefore, Random Vibrations were not considered as part of the L-2 blade design for Hamaoka #5. Upon simulation of the internal flow at Hitachi's Steam Turbine Testing Facility, it was found that due to Hamaoka's large steam turbine capacity the L-2 blades are also potentially subject to Random Vibration force, a phenomenon that had not been observed on other Hitachi steam turbines.

Flashback Vibrations

Flashback Vibrations are caused by wet steam that enters the turbine through the feedwater extractions nozzles during a load rejection. This reverse flow of extraction steam into the turbine is caused by the pressure drop in the turbine that occurs when the steam flow is stopped or significantly reduced. For Hamaoka Unit #5 the feedwater heater #2 steam extraction piping is located just upstream of the L-2 blades and hence, the L-2 stage was subject to Flashback Vibrations.

Superposition of Random and Flashback Vibrations

Based upon simulation of the Hamaoka #5 steam turbine's internal flow at Hitachi's Steam Turbine Testing Facility the Random Vibration force or the Flashback Vibration force alone was found not to be sufficiently large to cause the severe blade damage that occurred. However, Flashback Vibrations and Random Vibrations can occur simultaneously and superposition of both vibration forces causes unexpected and excessive stress to the blade fork area that was not taken under consideration during detailed design. Figure 6 illustrates the excessive stress levels due to superposition of Random Vibrations and Flashback Vibrations. This strong, combined vibration force to the L-2 blades resulted in fatigue cracking of the blade fork during commissioning and subsequently progressed to severance of the blades from turbine rotor disc.

2.1.3 Damage Mechanism

Initial turbine operation, in particular the 20% load rejection test, followed by no-load turbine operation, represented ideal conditions for the parallel occurrence of Random Vibrations and Flashback Vibrations. It is highly likely that the fatigue cracking in the L-2 blade root initiated during these initial functional tests, during which the cumulative fatigue ratio exceeded the critical fatigue ratio and cracks initiated in the fork area of the blades.

After the initiation of the initial fatigue crack, the stress due to Random Vibrations at low load operation and Flashback Vibrations at the load rejection tests caused further propagation of the initiated cracks, and finally, on June 15, 2006 the residual area of the fork was unable to withstand the centrifugal force imposed on the blades, and fork and pins ruptured.

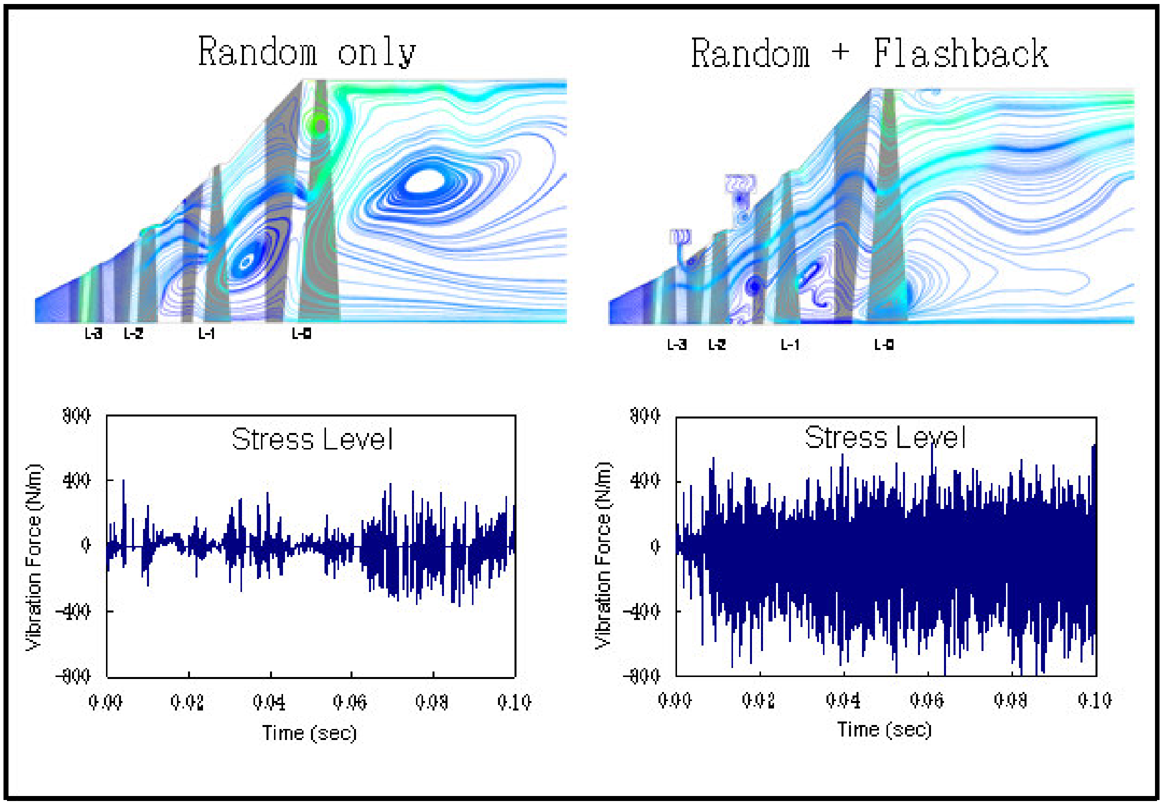

Figure 6 – Random Vibrations and Flashback Vibrations

2.1.4 Improved Design

As a result of the Hamaoka #5 experience, a new set of L-2 stage blades was developed with higher damping structure and optimum rigidity to withstand the Random Vibrations during low load operation and the Flashback Vibrations during load rejection. The following design improvements have been implemented in Hitachi's standard ABWR TC6F-52 turbine design.

1. New L-2 blade with Continuous Cover Blade structure with integral shroud.

2. Improved L-2 stage nozzle for optimized stage flow under consideration of low load operation and minimization of turbulent flow conditions.

3. Change from single-extraction nozzle structure to two-extraction nozzle structure for extraction line #5. The two-extraction nozzle results in more uniform flashback flow.

Scale model turbine testing and full size rotation testing based on the improved design have been completed and the reliability of the new design has been verified by Hitachi and approved by the Japanese government and electric utilities. Figure 7 shows a drawing of the new L-2 Continuous Cover Blades.

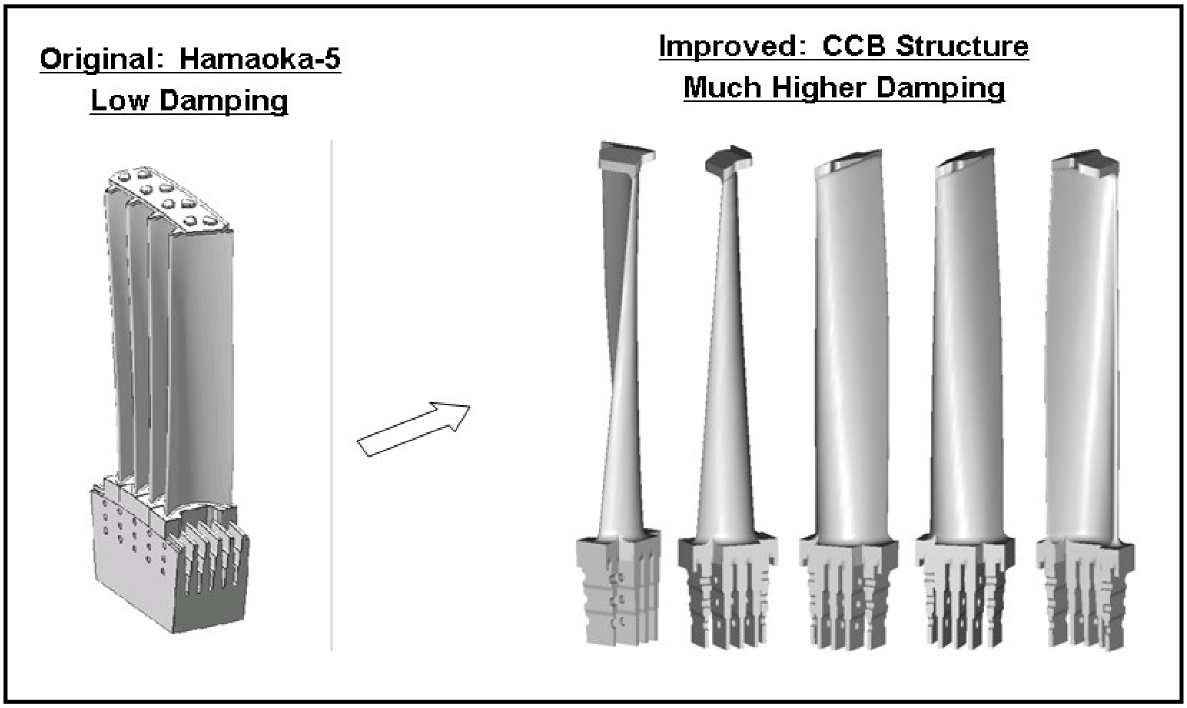

Figure 7 – New L-2 Blade with Continuous Cover Blade Structure

3. Hitachi ABWR Steam Turbine Technology

3.1 Hitachi Standard ABWR Turbine Specification

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.

Hitachi Standard ABWR Nuclear Turbine Parameters	
Turbine Type	TC6F-52", 4 Cylinders
Rated Output	1,380 MW Class
Exhaust Pressure	1.5 in HgA Class
Main Steam Pressure	970 psia
Main Steam Temperature	543 ˚F
Reheat Temperature	487 ˚F

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 HP casing can be disassembled by means of four oil jacks being located at the vicinity of the four casing corners. The LP outer casing can be disassembled by means of jacking bolts.

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. The HP rotor includes couplings for governor device and main oil pump and bearing collars for No. 1 and No. 2 journal bearings, as well as thrust bearing. The LP rotors also include bearing collars for Nos. 3-8 journal bearings.

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. Blades in the last three LP turbine stages (L-0, L-1, L-2) are attached to the rotor disc with a fork type fixture, while all other blades have tangential-entry type fixtures.

Nozzles and Diaphragms

All nozzle 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. Hitachi uses advanced Electro Beam Welding Processes to minimize heat deformations during manufacturing and to maximize reliability of the nozzle diaphragms.

Bearings

The eight journal bearings are self-aligning, elliptical over-shot type, horizontally divided, spherically seated bearings. Jacking oil ports are provided on the lower half of No. 3 through No. 8 bearings for smooth turning operation.

The thrust bearing is located between the HP and the A-LP section. It is of a tapered land type.

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 structure are fastened on the end portion of HP and LP casings and restrict steam leakage flow.

Turbine Auxiliary Equipment

Hitachi uses world-wide sourcing of auxiliary equipment. For US projects, Hitachi will maximize the use of auxiliary equipment suppliers located in the US and will comply with US standards, such as the ASME pressure vessel code and HEI standards for pressure vessels and heat exchangers, respectively.

3.2 ABWR Steam Cycle

Figure 8 shows a schematic of a typical ABWR steam cycle. Saturated Steam from the Reactor Pressure Vessel is supplied to the HP turbine where it expands to reheat pressure, thereby producing usable work. Upon exiting the HP turbine the reheat steam is supplied to the Moisture Separator and Reheater (MSR) where moisture is removed and the steam is superheated to reheat temperature. The energy required in the MSR to superheat the reheat steam is supplied from main steam and from an HP turbine extraction. Upon exiting the MSR, the superheated steam is sent to the LP turbine sections, where it is expanded to condenser pressure, thereby producing additional useful work. The steam is condensed in the condenser and the condensate is pumped back to the reactor through a set of four LP heaters and two HP heaters that elevate the feedwater temperature to reactor inlet temperature. The energy required by the feedwater heaters to heat the feedwater is supplied from HP and LP turbine extractions and from the MSR steam discharge.

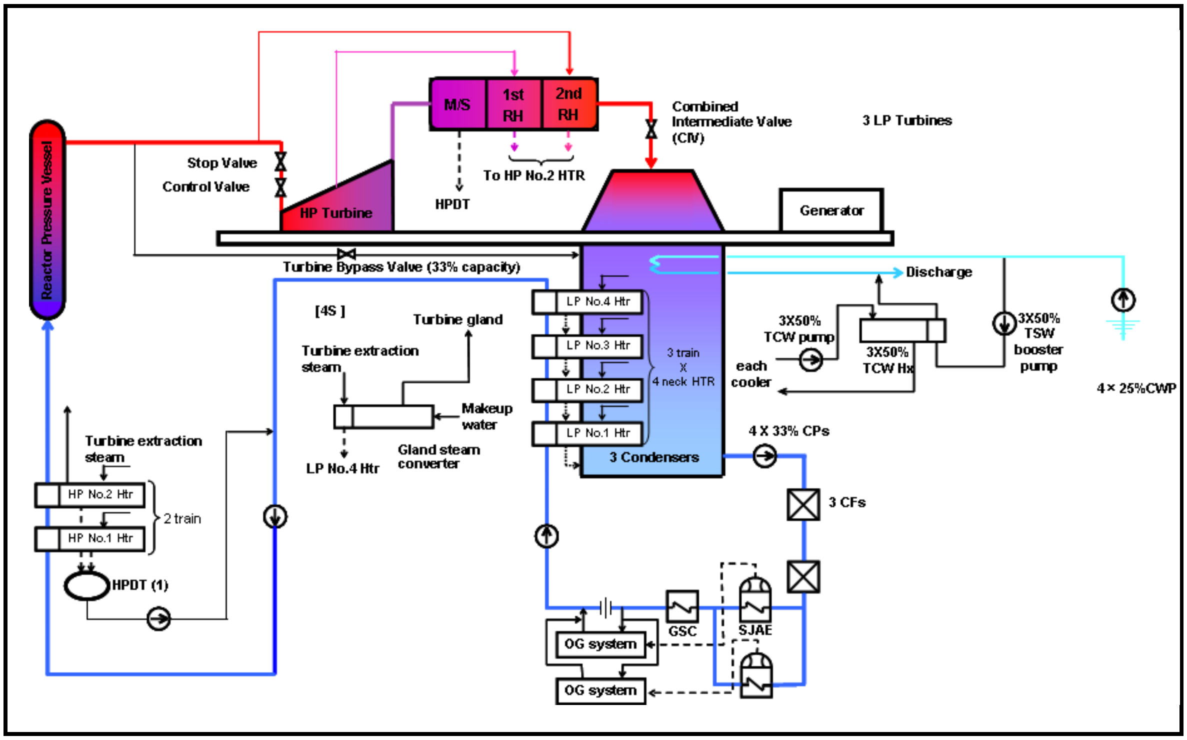

Figure 8 - Schematic of a typical ABWR Steam Cycle

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3.3 Hitachi Research – Advanced ABWR Turbine Technology Features

In Japan alone, Hitachi operates ten major research laboratories with a research and development staff of 8,000 highly trained professionals. As a result, Hitachi continuously develops and brings new products and services to market, such as the world's largest mono block turbine rotors that were conceived and first produced by Hitachi.

In spring of 2007, Hitachi commissioned a new steam turbine testing facility for steam loading tests (Figure 9.) The facility consists of a simplified small scale power plant that includes steam generator, turbine, cooling towers and balance of plant equipment. Moreover, the facility includes an inverter motor 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. The turbine currently installed in the facility is a scaled model of the actual Hamaoka #5 ABWR LP Turbines that was used to improve and verify the L-2 blade design.

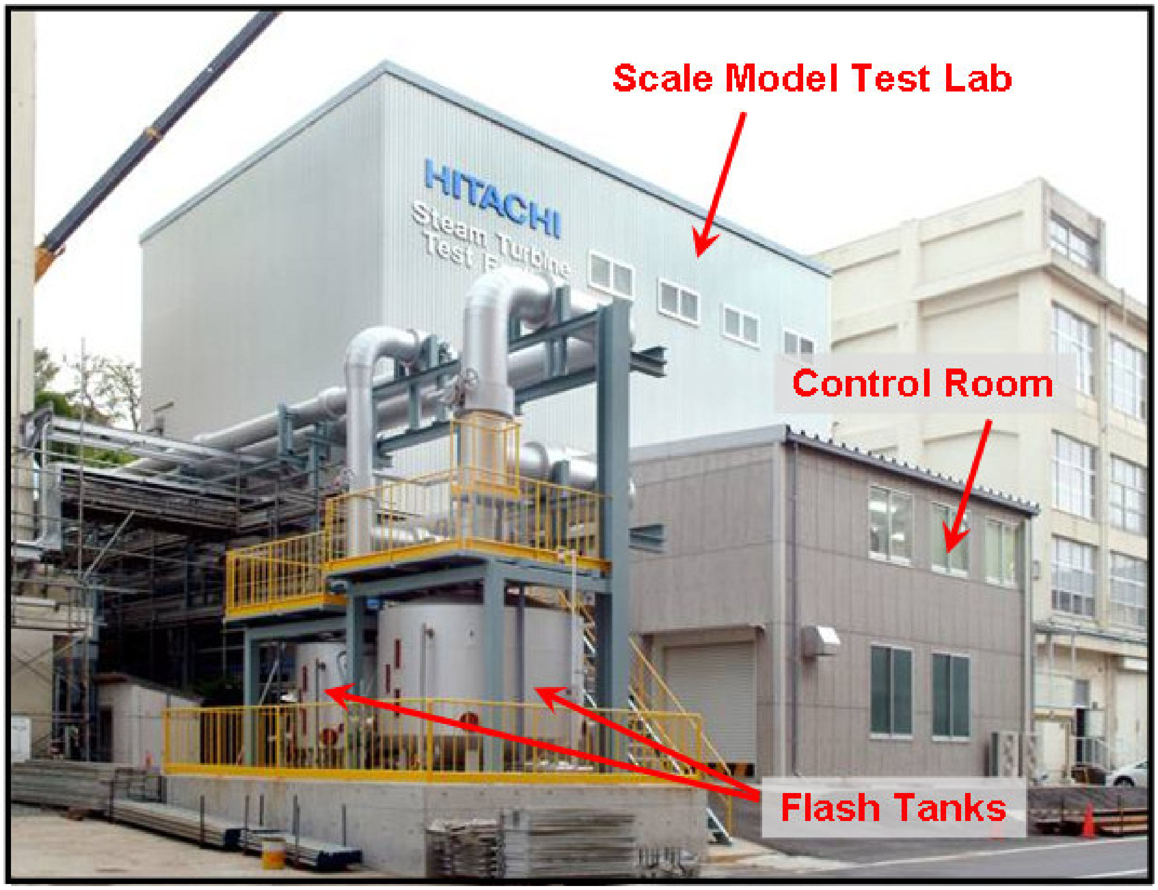


Figure 9 – Hitachi Steam Turbine Test Facility

3.3.1 Long Last Stage Blades

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 10, 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 12 and 13.
The next new blade designs offered by Hitachi for Nuclear Turbine applications will be the 60 inch last stage blade for 60 Hz applications (Figure 11.), followed by the same blade length for 50 Hz applications. Development of this new blade is in progress and is expected to be completed in 2013.

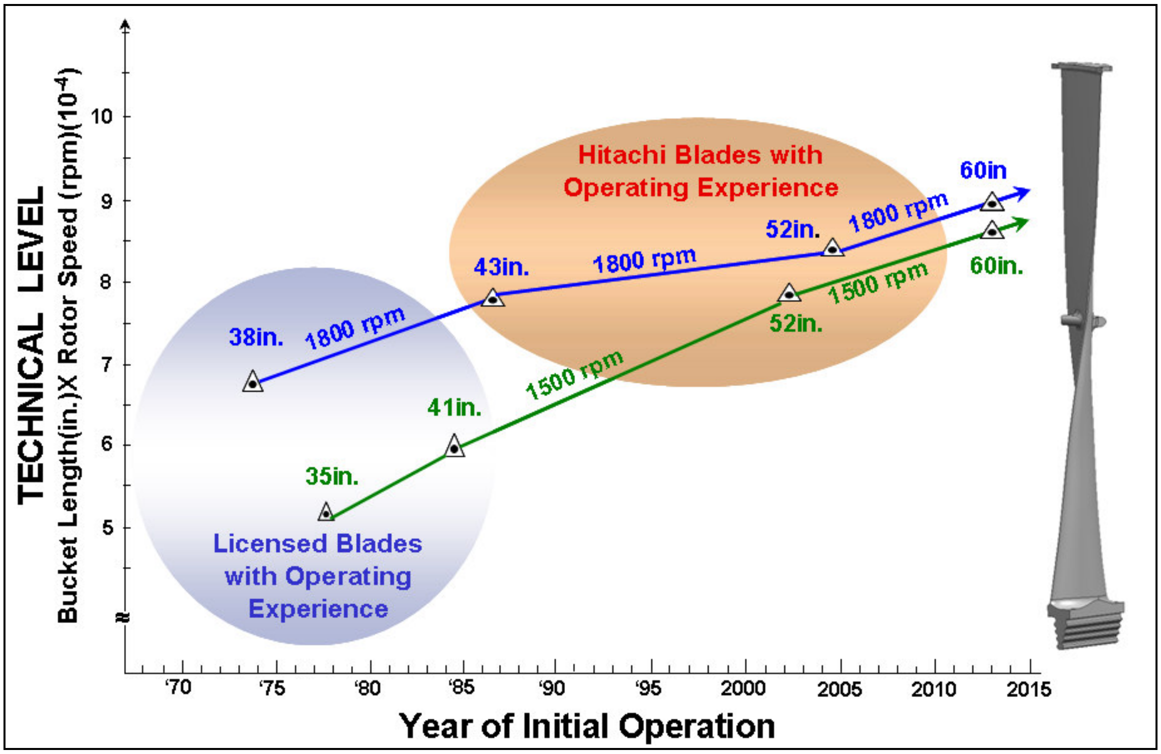
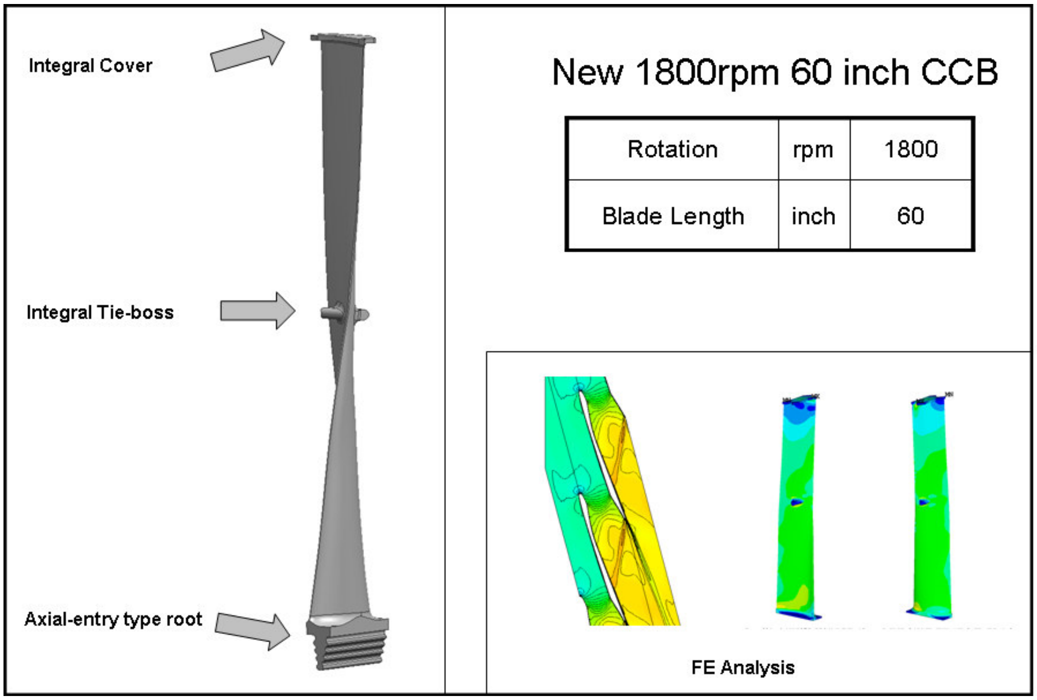


Figure 10 – Hitachi Last Stage Blade Development



New 1800rpm 60 inch CCB

Rotation	rpm	1800
Blade Length	inch	60

Figure 11 –New 60 Hz Last Stage Blade

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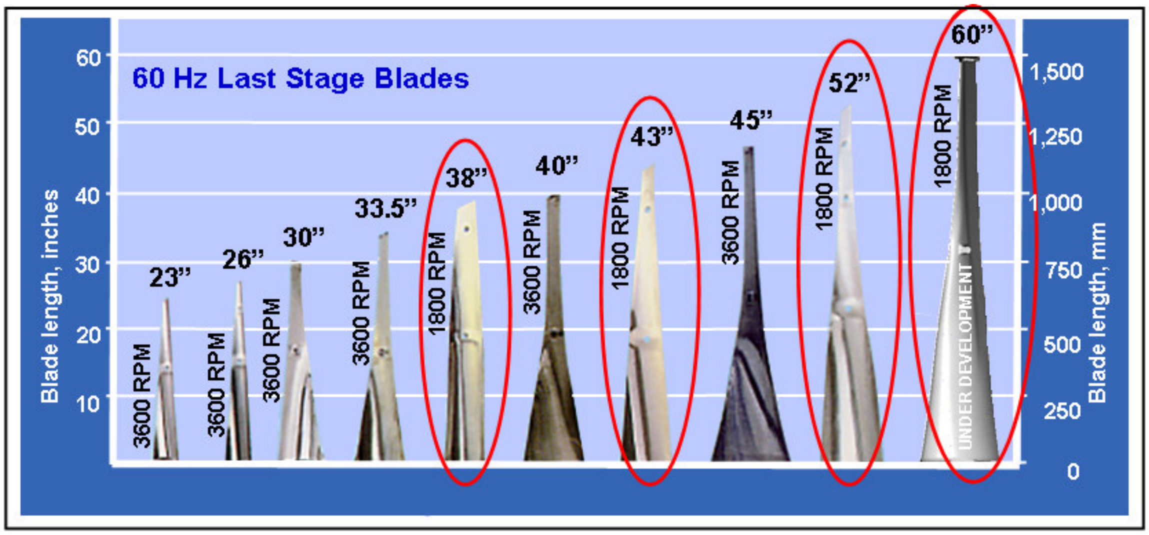


Figure 12 – Hitachi 60 Hz Last Stage Blades
(Blades Applicable for Nuclear Turbines are marked)

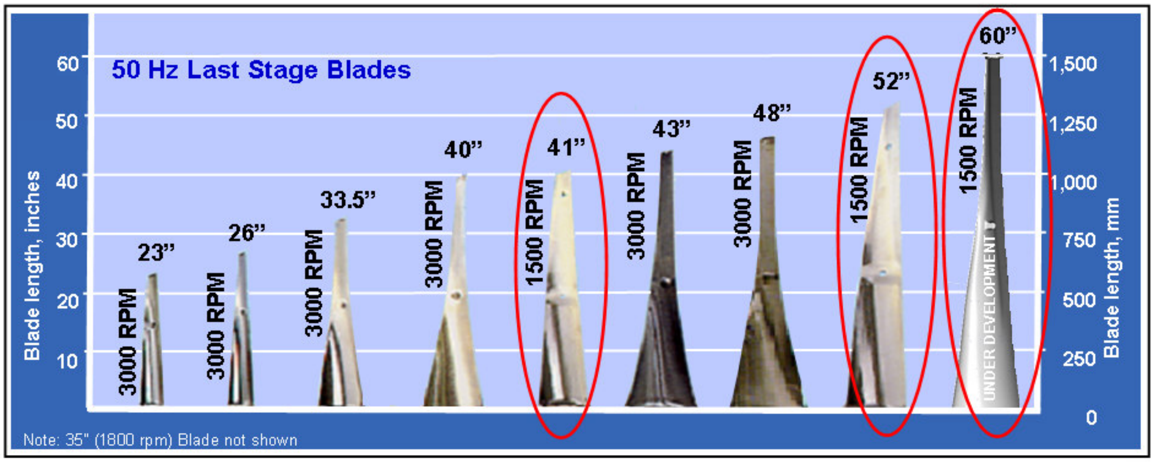


Figure 13 – Hitachi 50 Hz Last Stage Blades
(Blades Applicable for Nuclear Turbines are marked)

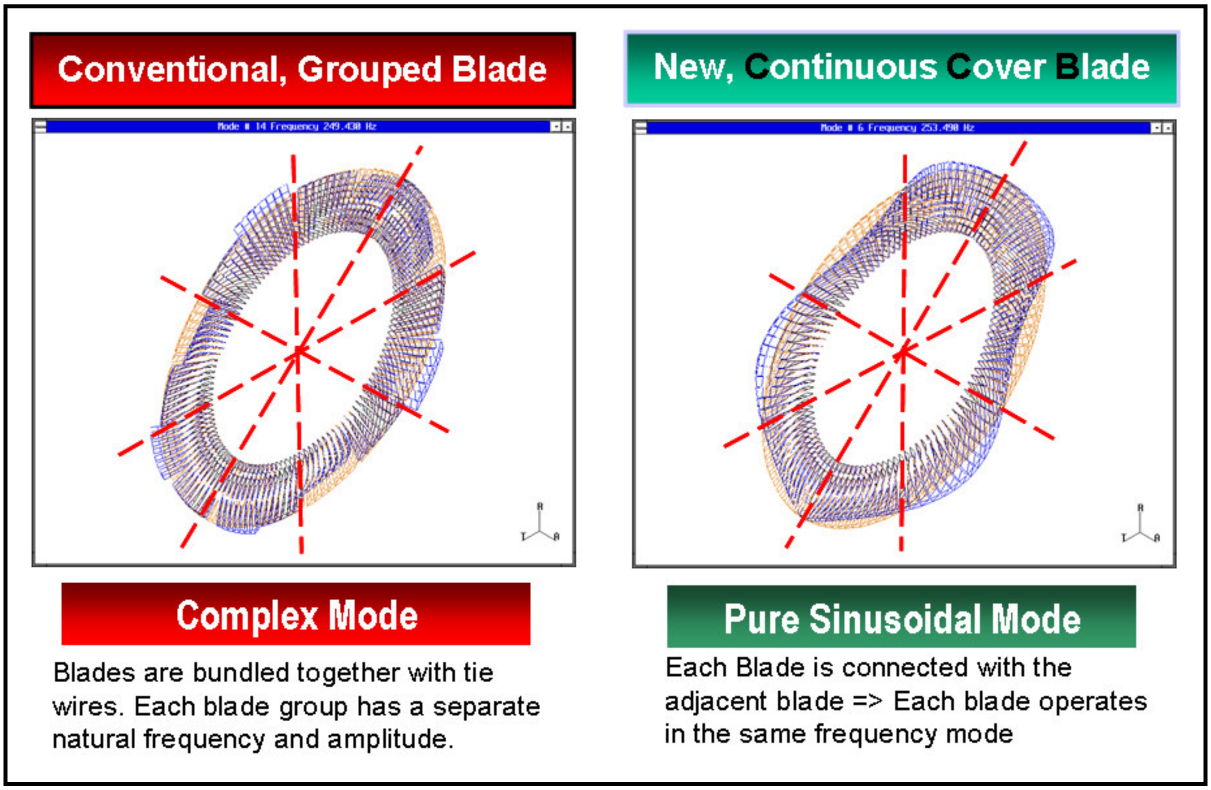
3.3.2 Continuous Cover Blades (CCB)

Based on a number of cutting-edge design technologies, 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 and axial type blade roots that offer better overall performance and superior strength and vibration characteristics. The CCB and axial type root technology 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 older designs. It also includes integral shrouds and mid-span supports to eliminate the reliability problems associated with tie-wires.

Adjacent blades in steam turbines are generally linked together to provide greater rigidity and to reduce or dampen vibrations. The old blade assemblies that were held together by tenons, caulked 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 pre-twisted 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.



Blades are bundled together with tie wires. Each blade group has a separate natural frequency and amplitude.

Each Blade is connected with the adjacent blade => Each blade operates in the same frequency mode

Figure 14 – Last Stage Blade Vibration Mode Characteristics

In comparison with the conventionally grouped blade configurations 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 15), 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.

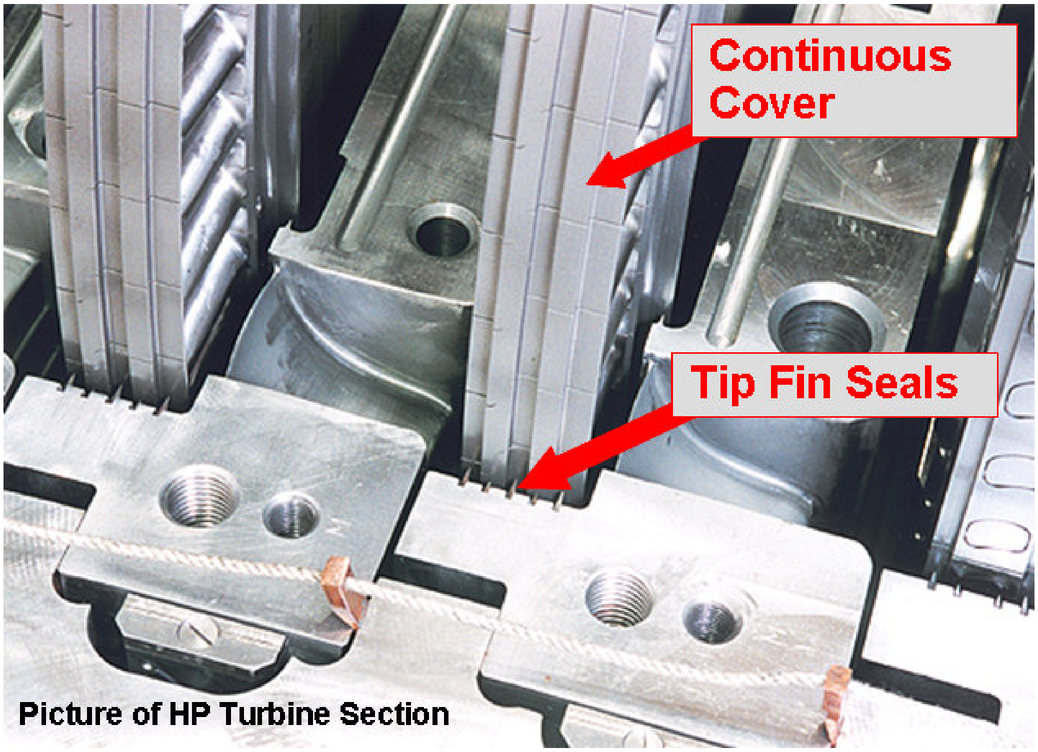


Figure 15 – Continuous Cover Blades

3.3.3 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: efficiency enhancements, strength/reliability 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 steel 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 laminar blade profiles; controlled and advanced vortex lean nozzles; Continuous Cover Blades with multiple fin seals; Elliptical Packings; and Diffuser Type Exhaust Hoods.

Figure 16 lists some of the major efficiency enhancements that have been implemented in Hitachi's turbine design.

Operation and Maintenance Enhancements

Operation and Maintenance (O&M) Enhancements are those design changes that result in longer intervals between scheduled maintenance outages or in shorter outage times. Such design improvements include our advanced hydraulic bolt tightening technology and topless alignment. The strength and durability enhancements stated above also have a positive impact on the O&M intervals.

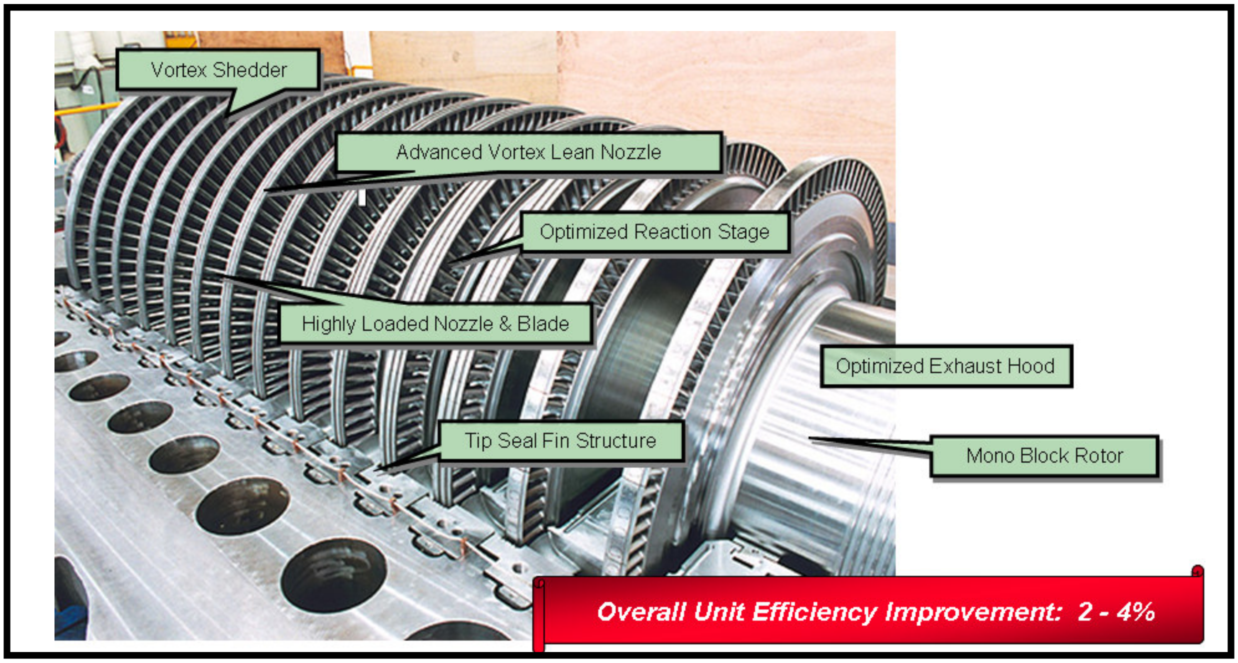


Figure 16 – Efficiency Enhancements

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