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UPGRADING AND LIFE EXTENSION TECHNOLOGIES FOR GEOTHERMAL STEAM TURBINES

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ABSTRACT

In some aging geothermal steam turbines, the increased steam consumption is found out due to time deterioration of the turbine parts, mainly caused by erosion, corrosion damages or deposits of impurities on the steam paths. Furthermore, the heavy damage due to stress corrosion cracking or corrosive fatigue damage, etc. are observed on rotors, blades and other parts and components.

On the other hand, in other units, the turbine output capacity decreases according to aging decrease of geothermal well pressure, that is, inlet steam pressure of turbine.

Under these circumstances, it is required that upgrading and life extension for reliability and performance on geothermal steam turbines, particularly the existing ones. And as the effective utilization of geothermal energy is important from the point of view of decreasing carbon dioxide on environment problem, these technologies can, needless to say, be applied to new geothermal projects a well as the existing ones.

This paper describes development and application of advanced steam path design such as nozzle and blade for improving reliability and performance, and of advanced rotor design and material including overlay coating technology for improving reliability and extending life. And also it describes uprating of the existing units in opposition to aged decreasing in the inlet steam pressure.

1 INTRODUCTION

Fig. 1 and **2** show an overview and a longitudinal cross section of the 60MW class geothermal steam turbine, and the major specification of a 66MW geothermal steam turbine is shown in **Table 1**. In order to provide a stable power supply, high operational flexibility and high reliability are requisite conditions, and , at the same time, effective improvement of efficiency and scaling up are also very important and fundamental factors for the geothermal steam turbines.

On the other hand, geothermal fluid, which operate steam turbines in geothermal power plants, contain several impurities and non-condensable gases as shown in **Table 2**. The chemical compositions of geothermal steam are quite complex and vary for each plant location.

As the geothermal turbines are driven by such geothermal fluid and continuously exposed to corrosive gases and impurities contained in the steam, there occurs several problems special to geothermal plants from a viewpoint of reliability and performance as listed in **Table 3**. Under these circumstance, reliability and performance of geothermal steam turbines have to be ensured in consideration of the following technological features.

- The inlet pressure and temperature of geothermal steam are relatively in low level, so some devices and constructions such as drain catcher and erosion protection, etc. are needed to reduce drain on the blades, erosion and wetness loss.
- Gases such as hydrogen sulfide (H_2S), carbon dioxide (CO_2) are highly corrosive and promote corrosion heavily, so the corrosion-resistant material and the SCC-resistant material are to be selected.
- Geothermal steam contains non-condensable gases in large amount compared with that of fossil thermal power plant, so the large capacity gas removal system is needed to keep the turbine exhaust pressure low level.
- The thermodynamic state of the gas-mixed steam is different from that of the pure steam, so the gas-mixed considered steam table is needed to estimate the turbine efficiency correctly.
- Geothermal steam contains various solid particles which cause solid particle erosion and scale deposits, so the countermeasures such as SPE-resistant design and material, separator, periodic overhaul and washing operation, etc. are needed to reduce the damage.

The followings describe some of the recent development and application technology which are based on the operating and maintenance experience for a lot of existing geothermal steam turbines.

2 STEAM PATH DESIGN AND ADVANCED TECHNOLOGIES

Geothermal fluids contain non-condensable gases, of which a major portion is carbon dioxide. The amount of non-condensable gases in the flashed steam is several percent in mass fraction. Among geothermal power stations presently operating, some units utilize geothermal steam which contains relatively high amounts of non-condensable gases, of which about 98 percent is CO_2, as shown in **Table 2**. The presence of such non-condensable gases in the steam, particularly the wet steam, affects the steam path flow pattern and efficiency due to the different fluid characteristics between the pure steam and the gas-mixed steam.

On the other hand, scale deposits problem in geothermal steam turbines often occurs on the steam path components. It is well known that such scale deposits in steam turbines is caused by silica (SiO_2), calcium-carbonate ($CaCO_3$) and others, dissolved in the geothermal brine. The solid particles which vary from silica, calcium-carbonate, etc. are carried by the steam and accumulate on the surface of nozzles and blades. The scale deposits induce two forms of loss. One is the loss associated with the roughness on the vane surface, causing a frictional drag effect, and the other is the loss associated with the clogging of the throats of the nozzle and blade passages. Furthermore, the scale deposits cause unbalance of the rotor, which induces an increase of rotor vibration problem.

2-1 Fluid characteristics of gas-mixed steam

We have already established the equations of state of steam mixed with non-condensable gases to design the steam path and to estimate the thermodynamic efficiency of the geothermal steam turbines accurately. The accuracy of these equations were confirmed by the element tests, the model turbine test and the field tests, and the calculation method has already been applied to the actual design of the geothermal turbines [(1)(2)].

2-2 Advanced steam path technologies

Fig. 3 shows the generating mechanism of the complex secondary flow vortex in the vane passage, which leads to loss of steam energy. This phenomenon is caused by fluid viscosity in the boundary layer of flow passage, and is typical the inner and outer side wall of nozzles and blades. The advanced flow pattern (AFP) shown in **Fig. 4** is one of the advanced steam path design to match the suitable aerofoil profiles and to improve the efficiency, and minimizes the loss by distributing the largest portion of steam to high efficiency zone as well as by shifting the streamlines near the side walls strongly toward the walls at the exit and eventually reducing the secondary flow losses. We have realized this steam path design with assistance of computerized three dimensional flow analysis in conjunction with the experimental approach. Nozzles and blades are excellently designed and precisely manufactured to three dimensional shape to realize high performance [(3)(4)].

Fig. 5 shows the snubber blades, of which aerofoil and tip cover are manufactured from a single forging or a bar material, have several important characteristics that contribute to the enhanced reliability and performance of the blading. Elimination of tenon and shroud structure removes a corrodent trap and reduces stresses at junction between blades and shrouds. It naturally excludes the possibility of erosion damage on the tenons sometimes observed in the conventional geothermal steam turbines. The integral covers are butted together between adjacent blades and, thus, the entire blading assembly in essence performs as a 360 degrees continuous shroud. These continuously coupled integral covers form a circumferential boundary of the steam path and provide an optimal interstage sealing with a minimum of leakage losses. And the blade tip leakage control of the conventional turbine stages has utilized a single fin as the structural constraints of the tenon and shroud configuration did not allow other arrangement, but snubber blades with integral cover enable the application of the improved blade tip leakage controls, as shown in **Fig. 6.** And also, the contact between adjacent covers limits the amplitude of vibration and produces high damping when stimulating steam forces work. The blades are, therefore, highly resistant to vibratory excitation. In addition, as the blades are not mechanically connected each other, they can be dis- and re-assembled easily when it is required. This leads to better maintenability and saving of maintenance cost in the future operation.

In some of the conventional nozzle design, the large numbers of nozzle partitions, that is small nozzle profile, are being selected to avoid resonance with the rotating blades. Under combination with the snubber blades, however, it is allowed to choose smaller numbers of partitions, that is large nozzle profile, as they have excellent damping against vibratory excitation. Large nozzle partitions are robust and less sensitive regarding the effect of deposits, that are quite often observed in the conventional geothermal steam turbines, on the turbine performance and power.

2-3 Other advanced systems

In some geothermal steam turbines which are occurred severe scale deposit problem on the steam path components, the water washing system is effective method for scale deposit removal. Adequate small sized and quantitative water droplets which are sprayed from the main steam inlet of the geothermal steam turbine can directly remove the scale deposits on the steam path surface of the nozzles and blades during normal operation.

3 DEVELOPMENT AND APPLICATION OF GEOTHERMAL TURBINE MATERIAL

It is extremely important to evaluate metallurgically the material corrosion behavior such as general corrosion, stress corrosion cracking and corrosion fatigue strength in the field tests using actual geothermal steam, because the geothermal steam chemistry is significantly varied in different geothermal power plants. We have carried out many field tests in domestic and overseas for many years, and accumulated data base has been utilized and contributes to make further improvement of turbine material for reliability, combined with the design consideration including lowering stress level and structural modification for corrosion and erosion, etc.

3-1 Rotor material

For the rotor material of the geothermal steam turbines, first of all, suitablely balanced combination between mechanical strength and material toughness is required under the condition of the large centrifugal force and corrosive steam. And also high metallurgical quality is required throughout large rotor forgings. In addition, good resistance to corrosion and stress corrosion cracking is further important for the geothermal steam turbine rotor material. The low alloy CrMoV steel forging had been succeeded in fully used over twenty years for geothermal steam turbine rotors which are employed less than the 23 inches class last stage blades, but from the further reliable needs with increasing turbine output, the cleaner CrMoV steel forgings with higher toughness has been developed. This modified CrMoV steel forgings have already been applied for the geothermal steam turbine rotors which employ larger than the 26” inches class last stage blades as well as less than the 23” inches class.

The fundamental material property depends on chemical composition, heat treatment and processing on manufacturing rotor forgings. Therefore, the required chemical compositions and impurities in CrMoV steel are controlled during steel making process to achieve the good combination of strength and toughness. Strict control of raw materials and modern steel making technology such as ladle refining process and vacuum carbon deoxidization are adopted for the modified CrMoV steel rotors to reduce impurities such as sulfur and phosphorus, and their segregation. Its chemical composition is shown in **Table 4**. And, as the result of optimized heat treatment process, higher toughness and finer microstructure can be obtained by using lower quenching temperature and faster quenching rate than the conventional low alloy CrMoV steel. **Fig. 7** shows the improvement of toughness, that is FATT and notch impact absorbed energy in charpy impact test, due to the modification of heat treatment and chemical composition of CrMoV steel [(5)(6)].

The modified CrMoV steel rotor is also confirmed to have the good resistance to stress corrosion cracking. High metallurgically cleanliness and fine micro structure of the modified CrMoV steel rotor accomplish the low susceptibility to stress corrosion cracking and the low crack propagation rate with the improved toughness. To suppress stress corrosion cracking, the surface treatment of rotor such as shot peening and aluminum coating is also confirmed to be quite effective in the actual machines.

And also, **Fig. 8** shows the design consideration for rotor construction to decrease the stress level by using the wider wheel dimensions, larger shaft diameters and larger R-contour of the wheels, etc. In addition, the shot peening is applied to increase fatigue limit of the rotor material on the R-contour portions of the wheels, and the cobalt base spray coating is applied to protect corrosion and erosion on the gland and nozzle packing portions of the rotor. Moreover, there is the 12Cr steel rotor which has the best advantage in the corrosive environment for the geothermal steam turbines. This technology for the geothermal steam turbine rotors is contributing to high reliability and life extension, together with the design consideration including lowering stress level and structural modification. The journal portion of the 12Cr steel rotor is required to be covered with the low Cr steel, because the journal surface of the high Cr steel is susceptible to damage, that is gauling damage, due to direct support on the bearing. Therefore, two kinds of the structures on the rotor journal portion are employed as the established technology, one is the shrunk-on sleeve type and the other is the welding overlay type.

3-2 Blade material

For the blade material, the 12Cr steel having high corrosion resistance has widely been used. Field corrosion fatigue tests of the 12Cr blade steels were carried out at several domestic and overseas geothermal power stations, and the test results are summarized as shown in **Fig. 9**. Field corrosion fatigue data are scattered and spreaded owing to different steam chemistry of each test site, and corrosion fatigue strength has not apparent endurance limit although the definite endurance limit exists in the air test. These tendency of geothermal corrosion fatigue strength is similar to these of other corrosion fatigue behaviors which are tested in sea water or other corrosive environments [(6)].

Therefore, the blade design of the geothermal steam turbines is considered based on these material properties in the geothermal corrosive steam to decrease the stress level by using the wider blade and the snubber blades, etc.

4 TURBINE UPGRADE FOR AGED DECREASING IN INLET STEAM CONDITION

Some geothermal steam turbines are forced to decrease in their output capability according to aging decrease of their inlet steam pressure, that is their geothermal well pressure. Investigation and studies are performed for degradation of ground water resources as well as geothermal exploration and exploitation, but the turbine steam path modification also employed as one of countermeasures for the aged decreasing in turbine output capability. Modification design is taken enlargement of steam path areas into consideration of matching to degradated steam pressure of geothermal well and , at the same time, applying the advanced steam path technologies such as AFP and snubber blades, etc. Modification is generally based on the replacement of such parts as nozzles and blades directly related to the turbine output capability, but actual modification work of the existing units is carried out in various restrictions, in comparison with a new turbine design, due to structural and practical restrictions.

The scope of part renewal is determined after evaluating unit operational planning, predicted forecast degradation of geothermal steam condition, required expense and economical gain, etc. **Fig. 10** shows the steam path modification experience of 50MW class existing geothermal steam turbines in accordance with aged decreasing in the inlet steam condition.

5 CONCLUSION

A number of countries are engaged in geothermal exploration, exploitation and progress geothermal development projects. In order to provide a stable power supply without increasing carbon dioxide on global environment problem, high reliability and high maintainability are requisite conditions for the geothermal steam turbines. At the same time, effective improvement of efficiency and uprating of the geothermal steam turbines are also very important and fundamental factors.

Under such circumstances, we continue efforts to design and manufacture the reliable and efficient geothermal steam turbines and their auxiliary equipments based on a lot of existing geothermal units experience.

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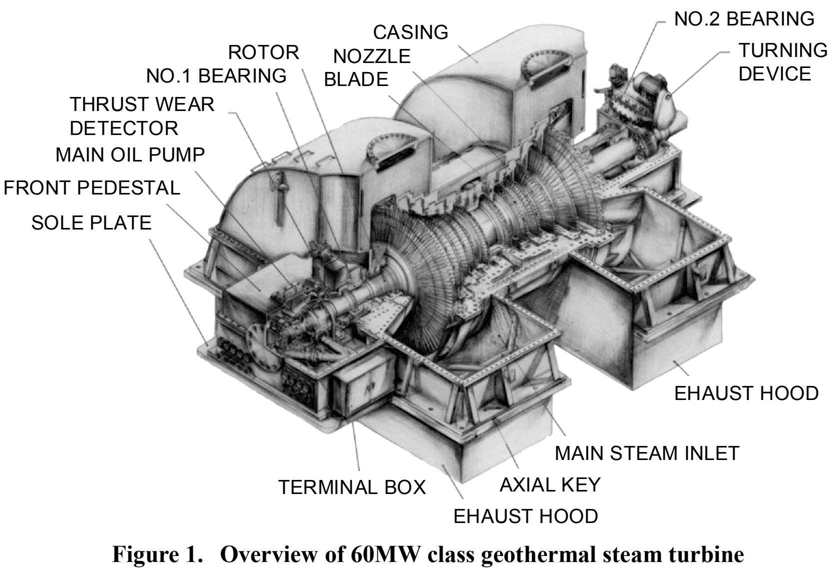

Figure 1. Overview of 60MW class geothermal steam turbine

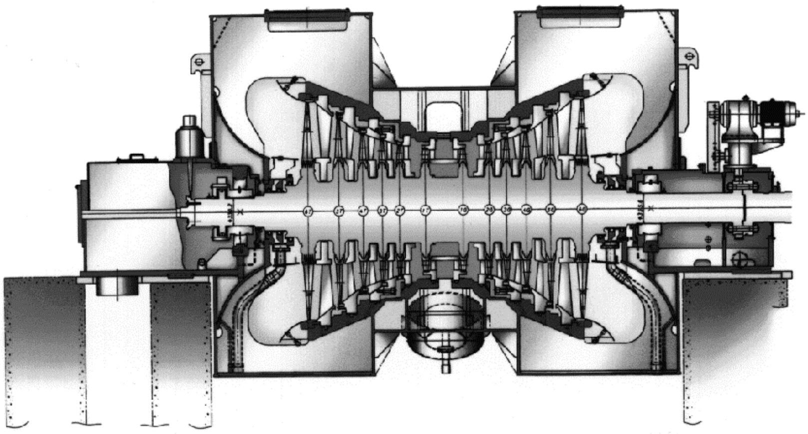

Figure 2. Longitudinal cross section of 60MW class geothermal steam turbine

Table 1. Major specification of a 66MW geothermal steam turbine

Type	Single casing double flow type
Rated output	66,000 kW
Speed	3,600 rpm
Inlet steam condition	5.5 kg/cm^{2}a, 156 deg C
Exhaust pressure	0.09 kg/cm^{2}a (2.6"Hg abs)
Last stage blade height	660.4 mm (26 inches)
Control system	EHC (Electric hydraulic control)

Table 2. Chemical compositions of geothermal steam

NATION	JAPAN		U.S.A.	PHILIPPINES	MEXICO
POWER PLANT	MATSUKAWA	MORI	GEYSERS	TIWI	CERROPRIETO
(Vol %)					
Steam	99.4～98.8	94.6～96.5	98.1～99.5	92.8～98.3	99.6
Gas	0.2～0.6	3.5～5.4	0.5～1.0	7.2～1.7	0.1
Gas Composition (Vol %)					
H_2S	12.9～17.7	0.5～1.0	1.69～2.99	2.22～2.74	24.0
CO_2	79.3～85.2	97.9～98.2	63.5～69.3	97.0～97.5	76.0
H_2	～0.28	0.02～0.07	12.7～14.7		
N_2		0.47～0.58		0.26～0.28	
CH_4	～1.15	0.52～0.62	11.9～15.3		
Hot Water					
PH	4.35～4.85	5.55～5.74	6.65～7.25	3.9～5.2	8.35 (Ave)
K (ppm)	180～190	0.01～0.02		0.15～34.6	0.58 (Ave)
Na	280～300	0.04～0.1		0.03～18.8	1.29 (Ave)
NH_3			134～567		
SiO_3	795～990	0.08～0.2		0.09～15.9	
HCO_3		730～1276	483～3388	1.87～15.0	
SO_4	1780～1800	4.2～4.3		3.2～8.3	6.8 (Ave)
Cl	9.2～17.7	0.1～0.3		0.02～17.9	5.6～21.4
H_2S	10～52	12.8～27.6	30～205	2.6～8.9	1850～ 3600

Table 3. Characteristics of geothermal steam

Item	Problem	Countermeasure
Wet steam	• Moisture impact erosion of moving blade • Wetness loss	• Installation of drain catcher and erosion protection
Corrosive gas and impurity	• Corrosion of turbine parts • Stress corrosion cracking of turbine parts	• Corrosion-resistant material • SCC-resistant material
Non-condensable gas	• Estimation of gas-mixed steam characteristics • Increase of turbine exhaust pressure	• Adoption of gas-mixed considered steam table • Installation of gas extraction equipment
Scale	• Solid particle erosion • Scale deposits	• SPE-resistant design and material • Installation of separator • Large profile steam path design • Washing operation • Periodic overhaul

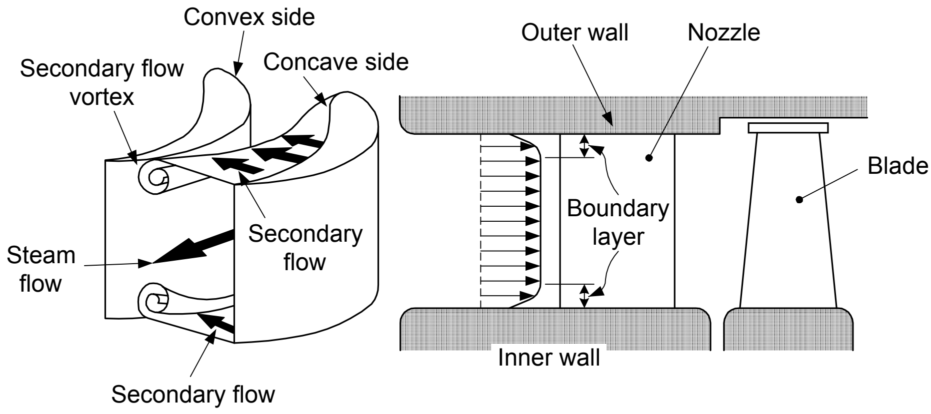

Figure 3. Mechanism of secondary flow loss in steam vane passage

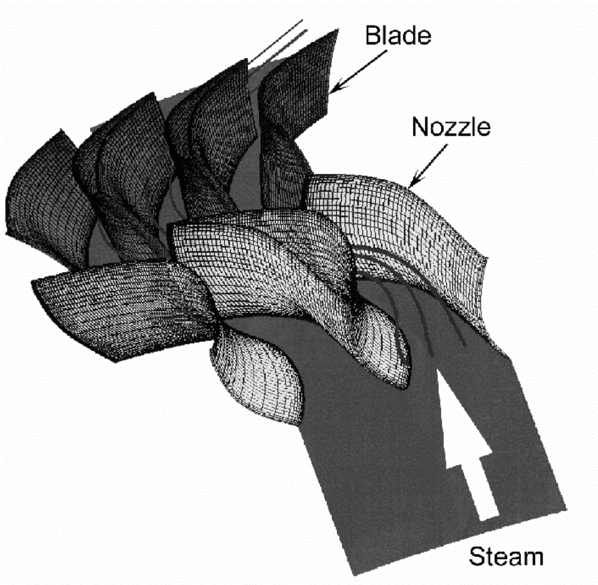

Figure 4. Advanced flow pattern (AFP) design

Figure 5. Snubber blades in steam turbine

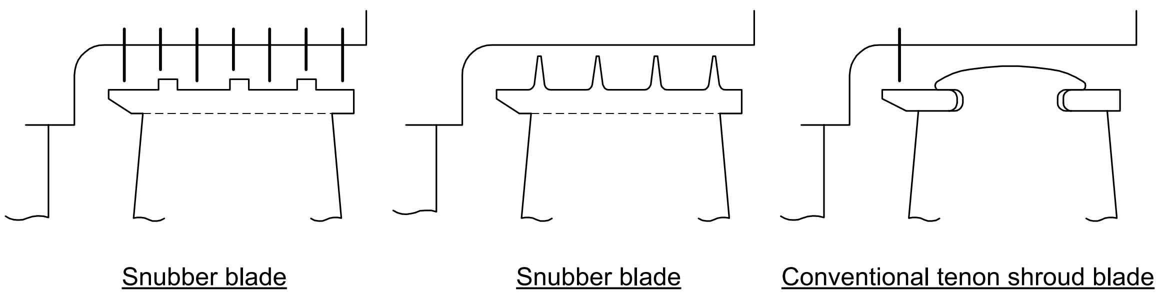

Figure 6. Comparison of tip fin structure

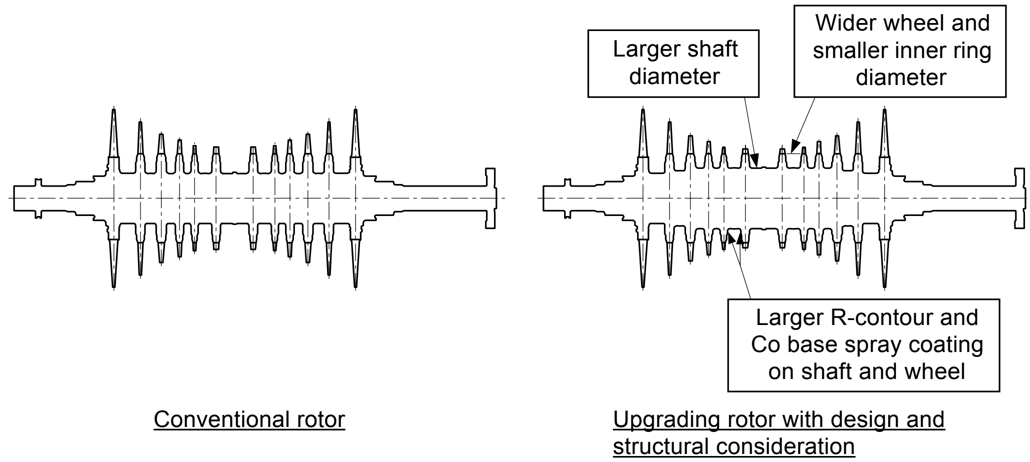

Figure 8. Comparison between conventional and upgrading geothermal steam turbine rotors

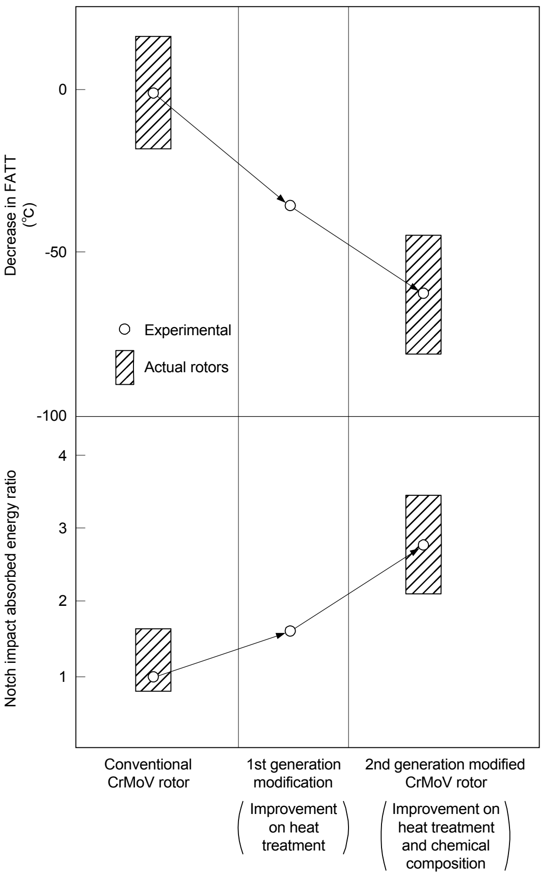

Figure 7. Improvement of metallurgical toughness in CrMoV rotor

Table 4. Chemical composition of modified CrMoV rotor for geothermal steam turbine

	Chemical composition (wt %)									
	C	Si	Mn	P	S	Cr	Ni	Mo	V	Fe
Modified CrMoV rotor for geothermal steam turbine	0.26 ~ 0.33	Max 0.10	0.65 ~ 0.85	Max 0.015	Max 0.018	0.90 ~ 1.20	Max 0.60	1.10 ~ 1.50	0.20 ~ 0.30	Bal

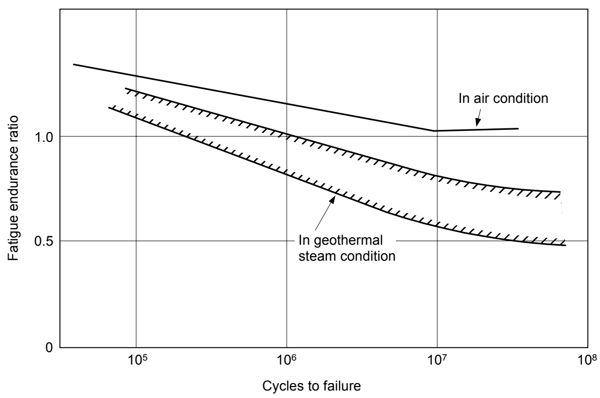

Figure 9. Field corrosion fatigue test result of 12 Cr steel

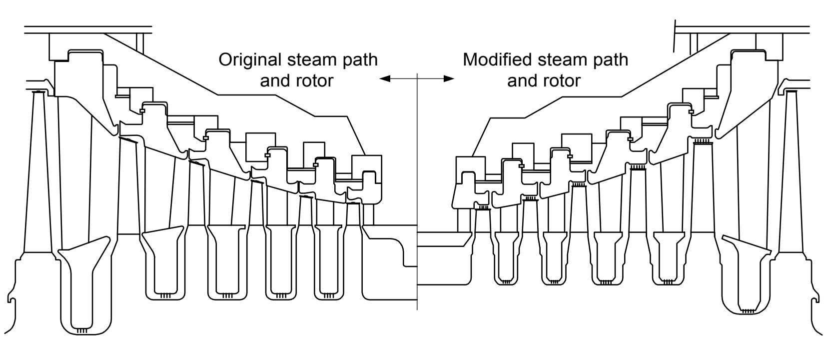

Figure 10. Comparison between original and modified steam paths and rotors in a 50MW existing geothermal steam turbine