

## Failure Mechanisms Encountered in Geothermal Steam Service

Stephen Rowbotham, Olivia Chung, Monika Ko and Jessica Wong

Quest Integrity NZL Ltd., PO Box 38096, Lower Hutt 5045, New Zealand

[s.rowbotham@questintegrity.com](mailto:s.rowbotham@questintegrity.com)

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### ABSTRACT

Geothermal steam turbine rotors and blades operate at low pressure and temperatures and are constructed of hardware (rotors and diaphragms) derived from equipment used in nuclear power plants. The operating conditions encountered are aggressive when compared to steam chemistry prevalent in the closed system of conventional power plants. This paper reviews the typical steam path damage mechanism encountered during normal geothermal steam turbine operation and identifies remediation methods if any that are available to recover and continue to operate this critical equipment. Topics reviewed include: foreign and domestic object damage, scale formation, erosion mechanisms, rubbing, fretting, corrosion, vibratory stresses and fatigue, localised pitting and crevice corrosion and sulfide stress cracking.

### 1. INTRODUCTION

Currently twenty four countries have geothermal assets generating electricity. In August 2013 the worldwide geothermal industry generating capacity reached 11,765 MW with plans to add an additional 1,637 MW [1]. If the planned assets become operational by 2017 the global capacity will exceed 13,400 MW. It is estimated that the global geothermal resources still to be tapped could be in the order of 27GW.

Due to the environment pressures this “sustainable” resource will become more important in maintaining the energy supply to the areas where it is available. To maximise the availability of the critical equipment the power plant engineer needs to understand the likely failure mechanisms that can occur to the rotating plant as these are normally the largest capital expenditure with long lead times for replacement if sudden and unexpected failures are encountered.

This paper will concentrate on degradation mechanisms generated by the operation and exposure of the rotor, blades, diaphragms and seals to the geothermal operating conditions in the steam path. It must be noted that these conditions will change depending on the geochemistry of the resource and therefore blanket answers cannot be applied across the whole geothermal sector with individual site specific solutions required. This variation in steam – water, gas and impurity content is shown in Table 1.

The steam path damage mechanisms encountered in the rotating steam path parts include:

1. Operational Events
  - a. Foreign Object Damage / Domestic Object Damage
  - b. Solid particle erosion (abrasion)
  - c. Scale formation
  - d. Surface deposits
  - e. Component rubbing / fretting
  - f. Fretting Corrosion High Cycle Fatigue
  - g. Low cycle fatigue
  - h. Vibration
2. Damage induced by Environment / Water in the Steam Path
  - a. Sulfide Stress Cracking
  - b. Moisture –impact erosion
  - c. Blade trailing edge erosion
  - d. Wire drawing erosion
  - e. Water washing erosion

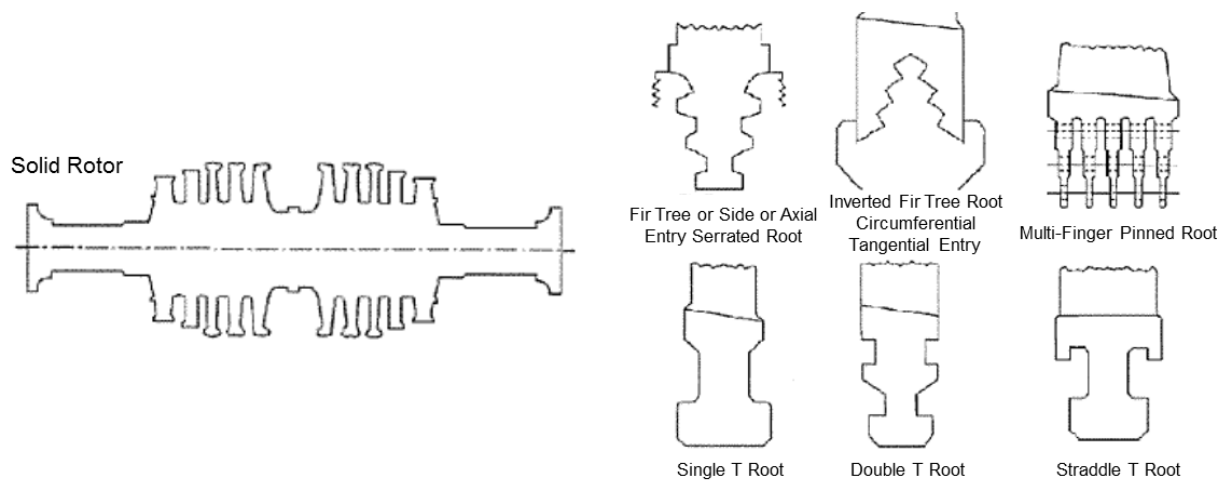
This paper reviews the mechanisms encountered - further reading on each mechanism is recommended.

**Table 1: Variation in steam-water, gas and impurity content at five example geothermal resources.**

Location		Geyser U.S.A		Matsukawa Japan		Kakkado Japan		Cerro Prieto Mexico		TIWI Philippines	
Steam Quality %	H <sub>2</sub> O	98.05-99.51		99.40-99.80		99.85-99.97		99.08-99.78		98.43-99.16	
	Gas	0.49-1.95		0.20-0.60		0.03-0.15		0.22-0.92		0.83-1.67	
Gases Content Vol%	H <sub>2</sub> S	1.69-2.99		12.9-17.7		9-26		20.9		0.8-2.57	
	CO <sub>2</sub>	63.5-69.3		79.3-85.2		65-87		79.1		96.64-98.63	
	Bal	37.69-34.89		1.7-4.2		0.5-15		-		0.37-4.4	
		Condensate	Hot Water	Condensate	Hot Water	Condensate	Hot Water	Condensate	Hot Water	Condensate	Hot Water
Condensate and hot water (ppm)	pH	6.5	6.7-7.3	4.4-4.9	4.4-5.3	6.0-6.4	8.8-9.1		5.8-6.6	4.2-5.9	7.5
	K	-	-	0.3-3.0	120-300	0.1-0.28	55-67		631-2031	0.07-0.37	830
	Na	-	-	0.8-5.0	152-360	0.27-0.72	460-501		4406-7764	0.05-3.0	4400
	Mg	<1	-	<2.1	4.7-14.5	<0.1	0.01-0.02	-	-	0.02-0.20	0.19
	Ca	<1	-	<1.6	12.8-28.8	Trace	5.8-9.0	-	259-359	0.02-0.20	85.0
	Fe	<0.1	-	0.45-17.8	235-630	0.01-0.05	0.06-0.09	-	-	<0.31	0.31
	Al	-	-	<2.0	6.5-28.6	0.01-0.04	0.14-0.64	-	-	Tr-0.20	0.14
	Si	0.71	-	0.83-4.7	273-566	0.22-0.52	256-364	-	179-1458	0.02-1.72	345
	Cl	39	-	3.3-6.7	4.3-13.8	1.9-3.4	625-685	-	928-14934	0.91-173	8970
	SO <sub>4</sub>	229	-	2.0-40	1188-1856	0.24-0.83	64-82	-	4.9-62	13.2-53.7	46.5
	CO <sub>2</sub>	-	-	12.4-51	4.3-6.5	14.40	Trace	-	42-494	106-108	-
	H <sub>2</sub> S	5-10	30-205	10-52.2	1.7-3.3	25-58	2.1-3.4	-	24-165	6.0-8.9	-

## 2. GEOTHERMAL ROTORS

The most common rotors used for geothermal steam turbines are solid rotors as shown in Figure 1. The steam path can be single flow or double flow. The blade fixings on the rotor can be single T-hook, double T-hook or straddle T-hook, fir tree (axial entry), straddle root fir tree (circumferential or tangential entry) and multi finger pinned root. In most cases the earlier stages (HP to IP ) are normally found to be of the T-hook type with the LP blades being a combination of fir tree straddle root and the last row (largest blades on rotor) are fir tree or multi fingered pinned root.



**Figure 1: Typical construction of geothermal rotor (image on left illustrated a geothermal solid rotor with posts- double flow) and blade fixing options.**

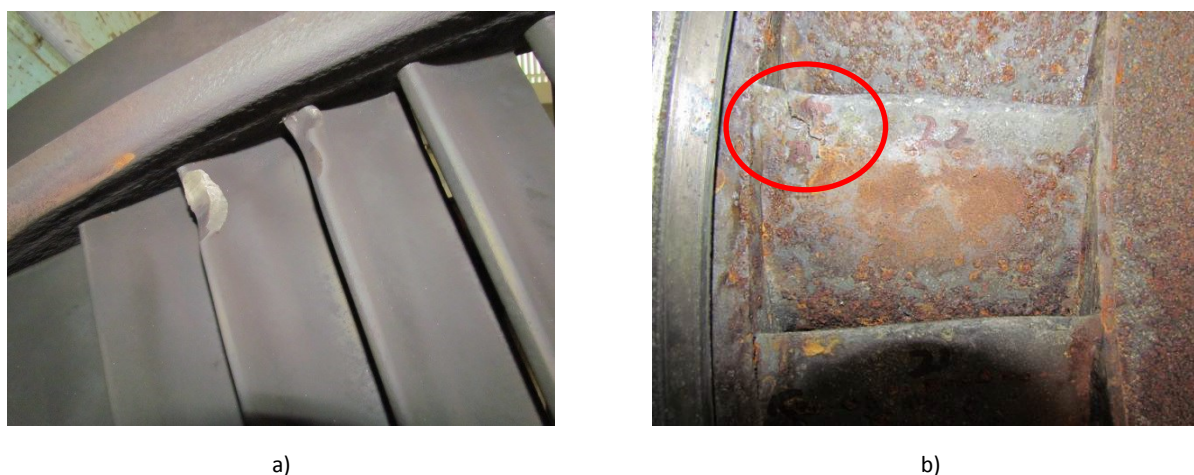
The materials of construction found in geothermal rotors are commonly:

- |                              |                                   |
|------------------------------|-----------------------------------|
| • Rotor material             | CrMoV, NiCrMoV, 410               |
| • Blades and Diaphragm vanes | 410 /403, 15-5PH, 17-4PH, Ti6Al4V |
| • Tie wires                  | 410 /403                          |
| • Dovetail pins              | CrMo low alloy steels             |
| • Erosion shields            | Brazed on Stellite Type 6B        |

### 3. DAMAGE MECHANISM DUE TO OPERATIONAL EVENTS

#### 3.1 Foreign Object Damage / Domestic Object Damage

Object damage is caused by particles carried within the steam flow from the steam field pipeline, released particles from the steam path components (domestic) and drop in metallic items left in the steam path following an overhaul (foreign). Foreign object damage can be seen on all stages of the rotor. When debris enters the steam path it will collide with the rotating blades and stationary vanes producing impact craters. The craters formed can vary in size and the degree of damage generated depends on the size of the particle, its composition and the section size and stiffness of the impacted component.



**Figure 2: a) Domestic Object Damage. Leading edge of stationary diaphragm vane shown and b) rupture/ cracking associated with foreign object damage.**

If the debris is associated with the failure of a component on the rotor with a section of the component released (domestic) the piece is likely to be large and may produce significant damage to the impacted part, see Figure 2.

If the debris is large enough it will be trapped between the stationary vanes and rotating blades resulting in extensive damage to the rotating components. The fragments that are trapped at a seal can act like a machining tool trepanning the rotating blades or the rotor. The release of components on the smaller blades and stationary components may not be detected by the vibration sensors allowing significant consequential damage to be generated before the unit is tripped.

This damage mechanism can be an initiator of consequential (domestic) damage in relation to other mechanisms occurring in the steam path. The damage can be rated as follows:

- Peening type damage.
- Deformed diaphragm vane leading and trailing edges.
- Large surface craters and tears.
- Massive craters and material rupture damage.
- Domestic debris trapped between stages.

#### 3.2 Solid Particle Erosion (Abrasion), Scale Formation and Surface Deposits

Solid particles and scaling phenomenon are of major concern in geothermal power plants and control of the solid particles in the steam entering the steam path and scale formation is paramount. They can affect old or new plant with rapid degradation generated to the seals, blades, diaphragms and the main rotor body. In geothermal plants the scale formed is primarily quartz / silicon together with traces of heavy metals. In some cases the steam is water washed in the high pressure steam line by injecting water which scrubs the silica from the steam. In other cases the solids are separated by scrubbers located near the power station. The build-up of the deposits can be extensive and lead to abrasion wear on the main body of the rotor and diaphragm, gland seals (see Figure 3) and casing. This again can go undetected with the onset of damage being indicated by changes in pressure readings or inspection. Solid particle erosion will normally manifest itself on the outer regions of the stationary vanes. The rotating blades do not normally exhibit the same level of degradation to that seen on the stationary vanes, however; due to the rotational stresses present the effect of the damage generated on the integrity of the blades or coverbands can be significantly greater when compared to the stationary components.



**Figure 3: Solid particle erosion to gland seals.**

The particulate deposits can lead to blockages to drains which can adversely affect the gland seal areas. If material is lost from the trailing edges of stationary vanes, the steam discharge angle can be affected changing the dynamics of the subsequent blade row together with a loss in efficiency.

### 3.3 Component Rubbing / Fretting (Corrosion and Fatigue)

Axial and radial clearances of the steam path components are strictly specified to increase the efficiency of the units and minimise steam leakage around the outer edges of the blading (coverbands). Rubs can occur as a result of high vibration on start-up, shut down, during an overspeed event or when significant failure of the unit occurs resulting in a significant unbalance. The rubs can be associated with historic events and may not lead to further degradation, see Figure 4a. If the contact on the coverband is severe it can result in damage to the tenon heads leading to the release of the coverband and eventually the blade aerofoil due to fatigue. If the thrust bearing is damaged large axial movements can occur resulting in damage to more of the steam path components. Rubbing on the casing can occur and is normally associated with excessive overspeed, high vibration (radial movement) and when the casing is distorted.

Fretting induced corrosion damage and material loss occurs without the need of a corrosive species and is caused by the movement of two surfaces nominally in tight contact. Once the fretting has started it can develop into fretting fatigue.



**Figure 4: a) Groove cut into coverband by diaphragm seal and b) area of material stiction and subsurface cracking**

It can be seen on the lacing wires on the later stages in the steam path where the lacing wire passes through a drill hole in the aerofoil section of the blade. It can also be seen on blade root load bearing surfaces and on the vertical side faces of blades as they move between each other leading to areas of stiction and cracking, see Figure 4b. This mechanism can be the cause of significant damage as failure of the latter stages of blades will liberate larger debris into the steam path (domestic object damage).

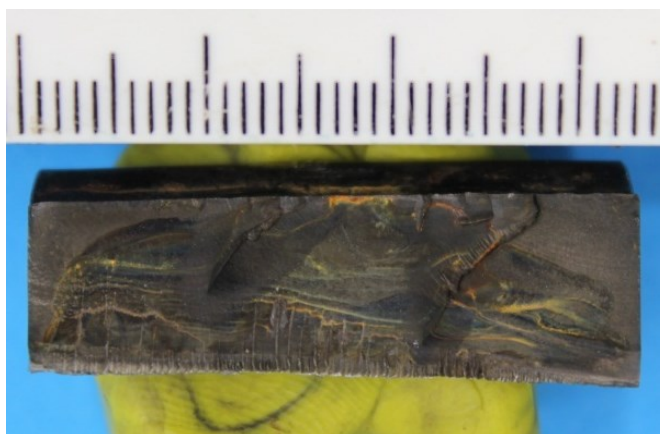
### 3.4 Fatigue Failures

The rotor steels and martensitic blades and vanes will fatigue crack if subjected to cyclic stress above their fatigue limit (endurance limit) which for rotor steels is approximately 50% of the ultimate tensile strength (UTS) and for martensitic grade 410 is approximately 65% of the UTS. Below these stress levels fatigue crack initiation and propagation should not be encountered. However, surface effects can act as stress raisers increasing the applied stress to exceed the endurance limit. This is especially true of changes in section profile and when surface pitting and fretting has occurred. Once a crack has initiated the crack growth rate will follow the fatigue crack growth model used in materials science and fracture mechanics. The basic formula is:

$$\frac{da}{dN} = C\Delta K^m \quad (1)$$

Where  $a$ ,  $N$ ,  $C$ ,  $\Delta K$ ,  $m$  are crack length, number of load cycles, material constant  $C$ , range of the stress intensity factor and material constant  $m$ , respectively.

Fatigue initiation and propagation are dependent on the presence of external forces or introduced features sufficient to initiate a defect of the critical size which when subjected to cyclic loading will grow. One of the most common operation features which can adversely affect the blades is the blade damping. If the design of the rotor is such that a component is exposed to energy impulses (passing frequency) close to one of its natural frequency and no damping is present then cracking will be induced.



**Figure 5: Fatigue failure of blade root fixing. Multiple initiation sites found.**

When high cycle fatigue is the main damage mechanism the surface will exhibit a crystalline appearance with beach markings (arrest lines) visible indicating when the cyclic stress cyclic was stopped during operation, see Figure 5. Low cycle fatigue is designated as requiring less than 10,000 cycles to cause failure, it is most commonly found in conventional steam turbines and is associated with thermal gradient changes during start-up /shut down. It can be seen on geothermal turbines but due to the lower operating temperatures and the units being predominately base load the effect is reduced.

### 3.5 Vibration

The blades on the rotor are most susceptible to high cycle fatigue and are subjected to stresses caused by the vibratory stimulus developed within the steam path during service. The vibration magnitude varies along the rotor and is affected by the frequency and magnitude of stresses present on each row of blades. The rotor can be considered as having high, intermediate and low pressure steam path excitation forces. These are associated with several vibrational stress sources specific to each pressure zone, see Table 2.

**Table 2: Steam path exciting forces, harmonic and typical sources.**

Section of Rotor	Harmonic	Typical Vibrational Stress Sources
High Pressure (HP)	High per rev (40x)	Nozzle tolerance limits
		Upstream wake degeneration
		Structural turbulence
Intermediate Pressure (IP)	Nozzle passing frequency (NPF)	Nozzle wakes
	2x NPF	Diaphragm harmonics
	3x NPF	Diaphragm harmonics
Low Pressure (LP)	One per rev	Relative displacement nozzles to blade
	Two per rev	Diaphragm joints
	Multiple/rev	Structural supports in steam flow path
	Medium/rev	Diaphragm harmonics Aeroelastic disturbances
	High/rev	Nozzle turbulence harmonics Upstream wake degeneration Structural turbulence

Of all the vibrational effects listed in Table 2 the most common cause of damage is the effect of nozzle impulse which is generated by distortions in the steam /liquid flow which produces a pressure pulse on the rotating blade. If this pulse is close to the natural frequency of the blade then resonance will occur. It is important that when diaphragms are reworked the throat thickness of the vanes is maintained.

#### 4. DAMAGE INDUCED BY ENVIRONMENT / WATER IN THE STEAM PATH

##### 4.1 Sulfide Stress Cracking (SSC)

The operating environment in the steam used in geothermal power generation contains significant levels of  $\text{H}_2\text{S}$  and other acidic gases such as  $\text{CO}_2$  and boric acid, together with heavy elements such as arsenic (As) and antimony (Sb). The presence of  $\text{H}_2\text{S}$  is of concern as brittle SSC failures may occur. It has been found that SCC requires three conditions to be met for cracking to occur. These are the environment, stress level and material properties (high strength steels). It is possible to reduce the likelihood of SSC if the requirements of ANSI/NACE MR 175/ISO 15156-1/2/3(2009) are applied. The cracking behaviour of rotor steels and the martensitic stainless steels commonly used when exposed to  $\text{H}_2\text{S}$  is controlled by the complex interaction of several parameters, including the following:

- Chemical composition, tensile strength, heat treatment, microstructure and surface finish.
- Partial pressure of  $\text{H}_2\text{S}$  or equivalent dissolved concentration in the water phase.
- Acidity of the water phase (pH).
- Chloride or Halide ion concentration.
- Level of oxygen (normally low but if present can give synergistic Chloride Stress Corrosion Cracking).
- Exposure temperature.
- Pitting resistance of the material in the service environment.
- Galvanic effects.
- Applied stresses.
- Exposure time.

The three main factors are:

- Partial pressure of  $\text{H}_2\text{S}$  if this is less than 0.3 kPa (0.5 psi) it is considered unlikely that SSC will occur in normal materials used in rotor steels and blades. It must be noted that for high strength alloys with yield strength above 965MPa can crack at this partial pressure.
- Material properties and heat treatment of the material should be such that the material exhibits a hardness of  $\leq 22$  HRC. It has been found that materials with hardness below this value are unlikely to suffer SSC.
- Applied stresses, in most cases the rotors used in geothermal application are low stress items and hence SSC is unlikely. During operation the original applied stress can be increase by degradation mechanisms, such as localised corrosion, introducing stress concentration factors resulting in an increased risk of SSC.

By managing the three main factors the risk of SSC can be minimised.

##### 4.2 Moisture Induced Damage

Most steam entering the high pressure section of a geothermal rotor will contain small amounts of water. The moisture portion of the mixture increases as the steam passes through the initial stages of the expansion increasing to the highest level at the low pressure section blading (approx. 12%), see Figure 6.

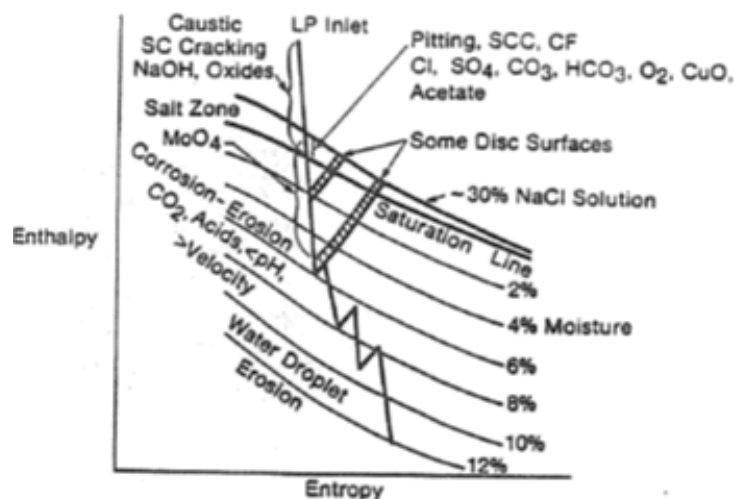


Figure 6: Mollier Diagram showing typical expansion line through a steam turbine.

##### 4.2.1 Impact Erosion

This is the most common form of water damage found on the steam path componentry. For it to occur the moisture must be present in sufficient quantities for water droplets to form and collect. This normally occurs on stationary component surfaces in areas where the water formed cannot be drained. Once the water has collected at sufficient levels, droplets are then released from the solid surfaces and enter the steam path and causes impact damage to the leading edges of the following blades, see Figure 7a. Water removal is of paramount importance in extending the life of the rotating blades. In the later stages of the rotor the blades normally have drainage grooves extending along the suction side of the leading edge, see Figure 7b. The coverband does not extend over the leading edge area allowing the water to be thrown into the water catcher belt designed into the rotor casing / diaphragm.





**Figure 7: a) Water impact erosion on leading edge of rotating blade and b) water drainage grooves on suction side of leading edge.**

After prolonged operation localised loss of material can remove the profile of the drainage grooves. Where this is likely to occur, the addition of an erosion shield (hard facing material inserts brazed into the leading edge on the suction side) should be considered. Erosion shields are normally specified for areas where the water content is such that drainage grooves would not cope with the loading. The erosion shield, normally extends down the leading edge on the suction side to a position where the tangential velocity for the blade is below the velocity where erosion is expected to be generated typically 240 to 250 m/sec, see Figure 8a. If erosion is found below the erosion shield extending the shield on replacement blades should be considered or changing the moisture flow patterns on the diaphragms upstream to alleviate the problem.

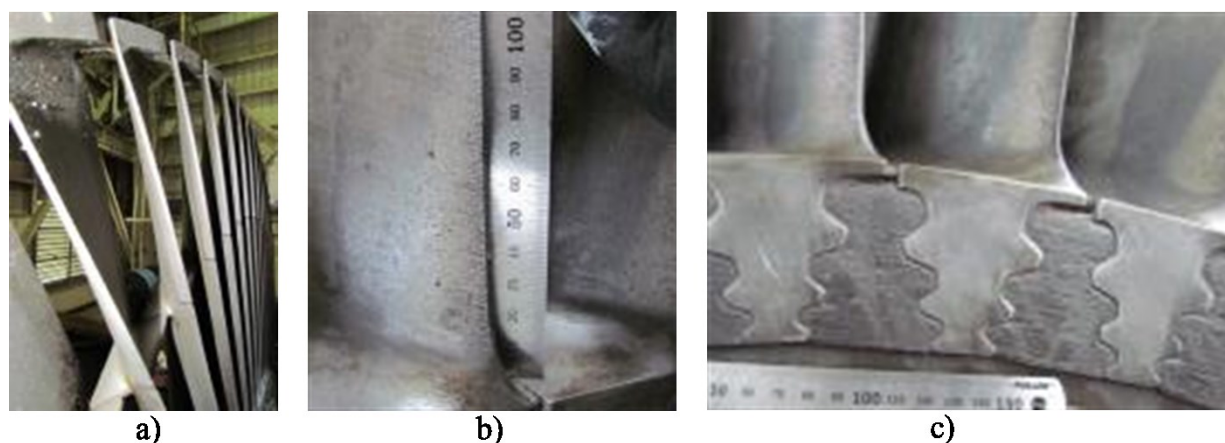
#### 4.2.2 Blade Trailing Edge Erosion

This is normally found on the last stage of blades and occurs on the discharge face of the lower half of the blade suction surface side. The damage is normally seen on the inner diameter a short distance from the root platform and set back from the trailing edge, see Figure 8b.

The erosion is typical of a gouging action, over time the discharge edge will become thinner introducing a stress concentration on the blade near the principal stress location on the blade aerofoil, which can generate a crack and subsequent blade failure. It is important that these areas are inspected to detect any changes in the pattern of erosion damage and the depth / extent.

#### 4.3.3 Water Washing Erosion

This is a form of erosion which causes micro ruptures of the material surface as water flows over the metallic surfaces at high velocity. It can be seen on the rotor blade root fixings, see Figure 8c, coverband edges, tenon heads and diaphragm inner and outer ring surfaces. This can affect seals areas which will require repair work to be completed before return of the unit to service.



**Figure 8: a) Erosion shield on leading edge suction side, b) trailing edge erosion and c) water wash erosion on rotor blade root fixing.**

## **CONCLUSIONS**

The damage mechanisms discussed cannot be entirely avoided in geothermal operations. Efforts to minimise the risk of occurrence can be made in relation to the particulates in the steam but it is likely that even with the best practice, failures will be encountered; this is especially the case as the assets age. It is important therefore that the plant engineering team are knowledgeable on the mechanisms in play, the cause of each mechanism and the steps required to reduce the risk of unexpected failure occurring.

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