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A Review on Corrosion of Steam Turbine.

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Abstract —*This review paper focuses on basics of corrosion, causes of corrosion and solutions of problems related to it. A steam turbine is governed by a wide range of mechanical and chemical properties. A large number of problems arise which try to manipulate these properties and thus need prevention. Major steam turbine problems, such as corrosion in steam turbine prevalence, effects, various causes, various methods of prevention of corrosion in running turbine, corrosion in a stationary turbine and methods of preservation are discussed. Some case histories of repair welding of steam generator components are discussed with special emphasis on details of repair welding of cracked steam turbine blades.*

Keywords* - *Steam turbine, corrosion, problems, turbine blade failure, effects of corrosion.

I. INTRODUCTION

A steam turbine is a machine used for generating mechanical power in rotary motion from the energyof steam at temperature and pressure above that of the available sink. In steam turbines, enthalpy of the steam is first converted into kinetic energy in nozzles or blade passages. The high velocity steam strikes the curved blades which changes the direction of flow of steam due to which a force is exerted on the blades fixed on a rotor and power is developed due to the rotation of the blades.The steam turbine is used as prime mover in steam power plants worldwide.

A modern steam turbine includes the following essential parts regardless of its rating or complexity:

- A casing or housing that contains the stationary blade system.
- A rotor carrying moving buckets (blades or vanes) either on drums or wheels, with journal
- Bearings at the ends of the rotor.
- A set of bearings, used in the casing to support the shaft.
- A governor and valve system for regulating the speed and power of the turbine

A steam turbine being a complicated machine with different parts is susceptible to failure due to many reasons some common problems face by steam turbine operated worldwide are due to vibration damages, erosion of blade profile, misalignment of rotors, fatigue failure of parts, deposition and corrosion. A prevalence of combination of one of more of these problems can cause the lowering of efficiency, loss of power output, reduction of turbine life or even catastrophic turbine failure.

The steam turbine is the most efficient engine for converting large amounts of heat energy intomechanical work. As the steam expands, it acquires high velocity and exerts force on the turbine blades. Turbines range in size from a few kilowatts for one stage units to 1300 MW for multiple-stage multiple-component units comprising high-pressure, intermediate-pressure, and up to three low-pressure turbines. For mechanical drives, single- and double-stage turbines are generally used. Larger modern turbines are multiple-stage axial flow units.

As a steam turbine is the most critical component of a steam-power plant, its proper and incident free working is important for being able to supply uninterrupted power to the consumers. This can be achieved by investigating various problems occurring in a steam turbine and finding a viable solution to them.One of the most important problem faces by steam turbines all over the world is of corrosion and in this paper we aim to review its occurrence, causes, effects and some solutions to the problem.

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II. CORROSION

Corrosion is the gradual destruction of materials by chemical and/or electrochemical reaction by a process, in which the pure material is converted to a chemically-stable form like its oxide, hydroxide, or sulfide due to its interaction with its environment. Corrosion is of various types and is generally categorized according to it root cause or major effect it produces.

Some common corrosion types are: Uniform attack corrosion or general attack corrosion, it is a common form of corrosion that is caused due to chemical reactions that results in the deterioration of the entire surface of a metal. Even though it is the most common form of corrosion it causes less damage as it is predictable and easy to manage.

Localized corrosion, it specifically targets one area of the metal structure and is further classified into:

1. Pitting which is a small hole that forms in the metal, due to de-passivation of a small region. This region becomes anodic, and the other part of the metal becomes cathodic, producing a localized galvanic reaction.

2. Crevice corrosion: it occurs at a specific location that is related with a stagnant micro-environment, like that is under gaskets, washers and clamps.

3. Filiform corrosion: it occurs under painted or plated surfaces when water breaches the coating and corrosion spreads out inside the structure of the substance.

Galvanic corrosion, it occurs when two or more different metals are in contact together in a corrosive electrolyte. A galvanic couple forms between the two metals, where one metal becomes the anode and the other the cathode. The anode corrodes and deteriorates faster, while the cathode does it more slowly than it would have otherwise.

Fretting corrosion, it occurs as a result of repeated wearing, weight or vibration on an uneven, rough surface. It results in pits and grooves and occurs on the surface. Fretting corrosion is often found in rotating and impact machinery, bolted assemblies and bearings. Stress corrosion cracking, it is the development of cracks in a corrosive environment. It can lead to sudden failure of normally ductile metals subjected to a tensile stress, especially at elevated temperature.

Corrosion in steam turbines

A steam turbine faces the worst possible environment regarding corrosion. This is due to the working conditions of a normal steam turbine which are high temperature, constant contact with water and air and high probability of facing concentrated chemicals due to evaporative concentration in the boiler. Turbine corrosion dependent on a combination of environmental effects like steam chemistry, it’s temperature, stresses, material properties, composition, and defects. Even pure water and wet steam can cause corrosion of turbine materials, chiefly in the rotor and disc parts.

Turbine environment plays a major role in corrosion during operation and layup. The distinctiveness of this environment is the phase fluctuations of the working fluid and the impurities carried by the steam (steam, moisture, liquid films, and deposits). Within the steam flow path and on the turbine component surfaces, the parameters governing corrosion, such as pH, concentration of salts and hydroxides, and temperature, can change within a wide range. Even though steam contamination concentrations are controlled in very low range, these impurities can concentrate on the fine surface of the turbine over repeated exposure.

Corrosion and steam chemistry

Steam is one of the most critical parameter that determines corrosiveness of the deposits and liquid films on turbine surfaces. Usually the low pressure turbine requires the lowest concentration of impurities in the cycle (in the order of parts per billion). Steam purity is governed by the purity of feed water as well as in the boilers by boiler water chemistry its pressure, and carryover. Factors that determine the corrosiveness of the steam are:

- Concentration of impurities from low ppb levels in steam to percent levels in steam condensatesand other deposits) resulting in the formation of concentrated aqueous solutions.
- Insufficient pH control and buffering of impurities by water treatment additives such asammonia.
- High velocity and high turbulence flow of low-pH moisture droplets (FAC).

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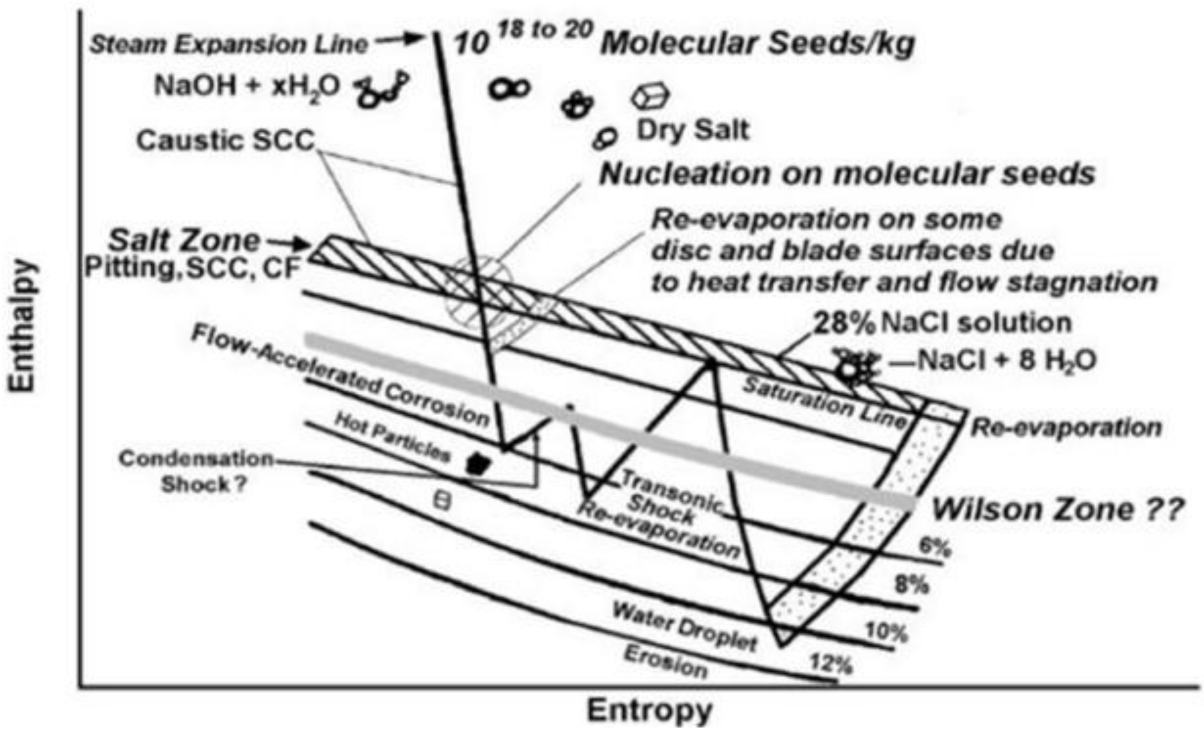

Figure 1: Mollier Diagram with LP steam expansion line and thermodynamic regions for impurity concentration and corrosion mechanisms.

The concentration of various impurities includes the following steps:

- Precipitation from superheated steam and deposition.
- Evaporation and drying of moisture on hot surfaces.
- Concentration on oxides by sorption.
- Non homogeneous nucleation of concentrated droplets and crystals on surfaces.

Some methods of preventing turbine corrosion through the control of steam parameters are:

- Reducing concentration of impurities in feed water.
- Turbine washing after chemical upsets to remove deposited impurities.
- Reduction or elimination of copper and its oxides and their corrosion effects by reducing oxygen concentration, working with an electrochemically reducing environment and a low ammonia concentration, or by replacing copper alloys with steel or titanium.

III. Design considerations for corrosion in steam turbines

Because of their extended life, steam turbines go through limited prototype analysis where the long-term effects of material degradation, such as corrosion cannot be fully replicated. With new turbine types, larger sizes, new power cycles, and water treatment practices coming fast in the last years, experience was short and limited, and problems developed, which need to be rectified and considered in new design and redesigns. While the turbine against corrosion is complex, there are five areas of design that affect turbine corrosion are mechanical design, physical shape, material selection, flow, thermodynamics and Heat transfer.

In new designs and redesigns of turbine components consideration of condensation and impurity behavior should be taken into considerations. To ensure a corrosion-free design, a corrosion specialist and a chemist should be consulted during the primary design activity.

The following should be considered in design of steam turbines:

- Stresses - The mechanical design concepts for avoidance of stress corrosion cracking should include an evaluation of the material corrosion properties and defects that influence an evaluation of the material corrosion

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properties and defects that influence susceptibility to SCC and CF, i.e., threshold stress, threshold stress intensity, crack growth rate, corrosion fatigue limit, pitting rate, and pit depth limit.

- Heat transfer and flow - Surface temperature resulting from heat transfer and flow stagnationshould be considered along with its effect on thermodynamic conditions of the impurities and water film at surfaces.
- Flow of moisture - To avoid flow-accelerated corrosion and water droplet erosion, the flowvelocity of wet steam should not exceed the allowable velocity specific to the materials and moisture chemistry. Regions of high turbulence should be avoided or higher chromium steels should be used.
- Crevices - Crevices can act as impurity traps and concentrators, facilitate formation of oxygen concentration cells, and may generate high stresses by the oxide growth mechanism. The worst crevices are those with corrosive impurities and metal temperature within the "salt zone".
- Galvanic effects - When dissimilar materials are coupled together, corrosion of both materialscan be affected by the associated shift in corrosion potentials into the stress corrosion cracking(SCC) or pitting regions. The more active of the two materials may suffer galvanic corrosion.
- Inspect ability - In designing turbine components, the question of inspect ability should beaddressed. In particular, crevices and high stress regions should be reachable using available inspection techniques.

Corrosion is highly dependent on the properties of the material used in the making of the parts. Hence here are some material considerations that reduce turbine corrosion:

- Replacement of higher strength NiCrMoV discs with lower yield strength (896 MPa) strengthdiscs.
- Repair welding of discs and rotors with Cr stainless steel weld metal.
- Freestanding and integrally shrouding of LP blades without crevices and structure with lower stresses.
- Using Titanium LP blades due to their corrosion resistant nature except for NaOH.
- New materials for blade pins and bolting that are resistant against SCC.
- Flow guides with double-ply expansion bellows - reduces impurity concentration, better SCCresistance.
- Moisture extraction to improve efficiency and reduce flow-accelerated corrosion (FAC) and water droplet erosion and use of alloy steels to reduce FAC.

Component	Material	Corrosion Mechanism
Rotor	CrMov, NiCrMoV low alloy steel forging	P, SCC, CF
Discs	NiCrMoV, CrMoV, NiCrMo low alloy steel forging, 12Cr weld repair	P, SCC, CF, FAC
Blades and shrouds	12Cr stainless steels, 15-5PH, 17-4 PH, Yi6-4, PH13-8Mo, Fe-26Cr-2Mo	P, SCC, CF
Tie wires	12Cr stainless steel (Ferritic and martensitic)	SCC, P, CF
Dovetail pins	CrMo low alloy steels, 5CrMoV, similar to ASTM A681 Grade H-11	SCC
Erosion shields	Stellite type 6B - weld deposited or soldered, same as blade	SCC, E
Stationary blades	304 SS, other stainless steels	SCC, LCCF
Shell and piping	Carbon steel	FAC,SCC
Expansion bellows	AISI Types 321 or 304 stainless steels, Inconel 600	SCC, LCCF

Table 1: Corrosion mechanisms in parts.

IV. PROBLEMS THEIR ROOT CAUSES AND SOLUTIONS

Steam turbine corrosion damage, particularly of bladesand discs, has long been recognized as a leading cause ofreduced availability (Scegljajev, 1983; McCloskey,2002; Sanders, 2001;Cotton, 1993; Jonas, 1985a, 1987; EPRI, 1981, 1998a).

Ithas been estimated that turbine corrosion problems costthe U.S. utility industry as much as one billion dollarsper year (EPRI, 1985b, 2001a; Syrett, et al., 2002; Syrettand Gorman, 2003; Jonas, 1986) and that the cost forindustrial turbines, which suffer similar problems, is even higher.

When a corrosion problem is discovered duringinspection or by equipment malfunction, the failuremechanism and the root causes are not always known.Even when the damage fits a description ofa well-known problem (disc or blade cracking),replacement parts may not be readily available and thedecision for what to do has to be made quickly. Themain objectives in handling identified and potentialproblems are maintaining safety and avoiding forcedoutages.

Experience shows that pits and ground-out stress corrosion cracks can remain in-service for several years, depending on stress and environment. However, components containing high-cycle corrosion fatigue cracks should not be left in-service. Procedures for prediction of residual life and determination of a safe inspection interval have been developed for all major failure mechanisms including SCC, CF, fatigue, FAC, and creep. The procedures for SCC of turbine discs (Clark, et al., 1981; EPRI, 1989; Rosario, et al., 2002), low cycle corrosion fatigue, and FAC (EPRI, 1996) have been successfully applied because all variables influencing these mechanisms can be reasonablypredicted or measured. However, life prediction for high cycle corrosion fatigue and fatigue has not been so successful because the vibratory stresses and the corrosiveness of the environment are usually not accurately known. Life prediction is based on results of inspection, fracture mechanics analysis of components with defects, and application of SCC and CF crack growth data. Time or number of load cycles to reach ductile or brittle fracture is predicted and a safety factor is applied to determine the time for the next inspection. In the procedure used by OEMs and Nuclear Regulatory Commission (NRC) for nuclear turbines for determining the inspection interval for turbine discs under SCCconditions, the safety factor of two was applied to the predicted time-to-failure.

Root Causes

SCC of discs (at keyways, bores, and blade attachments) is caused by a combination of high surface stresses, a susceptible material and operational and shutdown environments. Design-related root causes are the most important and prevalent. They include high surface tensile stresses and stress concentrations, and use of high strength materials.

Sources of stresses that contribute toSCC of discs include:
• Basic centrifugal load caused by rotor rotation. High concentration of centrifugal loads is locally caused byvariation in the gaps between blade and discrim attachment.
• Residual machining stresses.
•Vibratory stresses—interaction of SCC and corrosionfatigue. Also, vibratory stresses reduce the life of thecracked disc when the flaws reach a sufficient size thatfatigue becomes a dominantmechanism.

Steamchemistry root causes of SCC and CF cracking include:
•Operating outside of recommended steam purity limitsfor long periods of time; sometimes caused by organicacids from decomposition of organic water treatmentchemicals. Condenser leaks—minor but occurring over along period of time.
•Condenser leaks—major ingress, generally one seriousevent, and the system and turbine not subsequentlycleaned.
•Water treatment plant or condensate polisherregeneration chemicals (NaOH or H2SO4) leakdownstream.
•Improperly operated condensate polisher (operatingbeyond ammonia breakthrough, poor rinse, etc.).
•Shutdown environment: poor layup practices pluscorrosive deposits.Sodium hydroxide is the most severe SCC environmentencountered in steam turbines. The sources of NaOHinclude malfunctioning condensate polishers andmakeup systems and improper control of phosphateboiler water chemistry combined with high carryover.Many other chemicals can also cause SCC of low alloysteels. The chemicals used in turbine assembly andtesting, such as molybdenum disulfide (lubricant)andLoctite™ (sealant containing high sulfur), can accelerateSCC initiation (Turner, 1974; Newman, 1974).

Solutions

In most cases where material yield strength is 895 MPa, the solution to disc SCC is a design changeto reduce stresses at critical locations. This has been achieved by eliminating keyways or even disc bores (welded rotors) and by larger radii in the blade attachments. Higher yield strength (> 895 MPa) low alloy steel discs should be replaced with lower strength materials. The goal is to keep the ratio of the local operating stress to yield stress as low as possible, ideally aiming for the ratios to be less than 0.6. Minimizing applied stresses in this manner is most beneficial in preventing initiation of stress corrosion cracks. Once cracks begin to propagate, a reduction in stress may be only marginally effective unless the stress intensity iskept between11 - 22 MPa-m1/2. This is because of the relative independence of the crack growth rate over a broad range of stress intensities. For many rim attachment designs, such levels of applied stress intensity are impossible to achieve once an initial pit or stress concentration has formed. An emerging solution to disc rim stress corrosion cracking is a weld repair with 12%Cr stainless steel. Another solution has been to shot peen the blade attachments to place the hook fit region into compression. Good controlof the steam purity of the environment can help to prevent or delay the SCC. Maintaining the recommended levels of impurities during operation and providing adequate protection during shutdown can help minimize the formation of deposits and corrosive liquid films, and lengthen the period before stress corrosion cracks initiate.

Corrosion fatigue and stresscorrosion cracking of blades

LP turbine blades are subject to CF, SCC, and pitting of the airfoils, roots, tenons and shrouds, and tie wires (Holdsworth, 2002; EPRI, 1984c, 1984d, 1985c, 1985d, 1987c, 1991b, 1993b, 1994b, 1998d; Jaffe, 1983; Evans, 1993; Singh, et al.; BLADE-ST™, 2000). Figure 1 depicts the typical locations on an LP turbine rotating blade that are affected by localized corrosion and cracking.

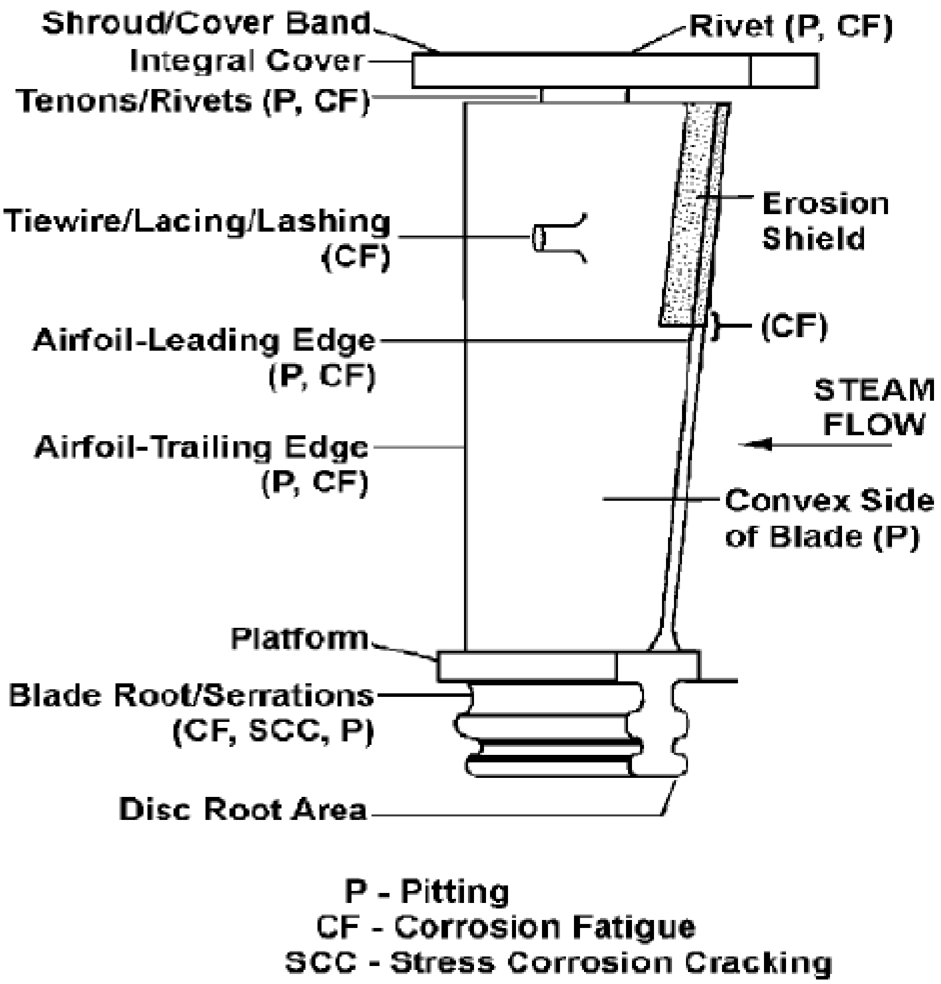

Figure 2:Typical Locations of Cracking and Localized Corrosion on LP Turbine Rotating Blades. There Has Also Been SCC and CF Cracking in the Tiewire Holes.

Missing Knowledge

It is estimated by the author that 70 percent of knowledge to solve and prevent corrosion problems in steam turbines is available. The percentage of available knowledge for understanding the effects of stress and environment is much lower than that for solving the problems, about 40 percent. The knowledge that is missing or needs improvement includes:

• Threshold stress required to initiate SCC in bladeattachments.

• Effects of steeple geometry (stress concentrations andsize) on SCC and CF.

• Effects of overloads during heater box and over speedtests on stress redistribution and SCC in steeples, bladeroots, and disc keyways.

• Effectiveness of grinding out SCC and CF cracks as acorrective measure.

• Effects of organic water treatment chemicals, andorganic impurities on SCC, CF, and pitting and composition of water droplets.

• Effects of electrical charges carried by water dropletson corrosion.

• Effects of galvanic coupling of dissimilar materials,such as the blade-steeple, on corrosion.

V. CONCLUSIONS

• Steam turbines can be a very reliable equipment withlife over 30 years and overhaul approximately every 10years. However, about 5 percent of the industrial andutility turbines experience corrosion and depositionproblems. Mostly due to LP blade and blade attachment(disc rim) corrosion fatigue or stress corrosion failures.

• The root causes of the blade and disc failures includedesign with high stresses, bad steam chemistry, and useof high strength materials.

• Other steam turbine problems include: low cyclethermal fatigue, pitting during unprotected layup andoperation, loss of MW/HP and efficiency due todeposits, water droplet erosion, flow accelerated corrosion, solid particle erosion by magnetite particlesexfoliated from superheater, turbine destructive overspeed caused by the control valves stuck open because ofdeposits in the bushings, and water induction-waterhammer.

• All the problems are well understood, detectable, andpreventable.Monitoring, inspection, and defectsevaluation methods are available. These methods includedesign reviews and audits of operation and maintenance,NDT, life prediction, vibration monitoring, vibrationsignature analysis, water, steam, and deposit chemistrymonitoring and analysis, valve exercise, and control ofsuperheater temperatures.

• Steam cycle design and operation influences turbineproblems by causing high steady and vibratory stresses, by thermal stresses related to load and temperaturecontrol, and by water and steam purity and boilercarryover.

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