47TH TURBOMACHINERY & 34TH PUMP SYMPOSIA
HOUSTON, TEXAS | SEPTEMBER 17-20, 2018
GEORGE R. BROWN CONVENTION CENTER

KNOW YOUR TURBOMACHINERY'S OPERATING ENVIRONMENT!

David Linden
President
D.H.Linden Associates, Inc.
Denver, NC, USA

David Linden is President of D.H.Linden Associates, Inc. He has 44 years of experience in the Turbomachinery Industry and specializes in the areas of Turbomachinery design and reliability. Mr. Linden has experience in the design, application, repair and operation of axial and centrifugal compressors, gas expanders and gas and steam turbines. Mr. Linden has worked for a number of Turbomachinery Manufacturers including Conmec, Inc., Dresser Rand Co., General Electric Co., Ingersoll Rand Co. and Westinghouse Electric Co. He has authored fifteen technical papers for various technical forums including the ASME and Turbomachinery Symposiums and coauthored the book "Expanders for Oil and Gas Operations"- McGraw Hill - 2014. He has been a member of ASME, ASTM, NACE and a contributor to the API 687 Rotor Repair sub-committee.

ABSTRACT

This paper discusses the importance of knowing the operating environment that the Turbomachinery will be operating in. The lack of proper definition in the design phase can result in the manufacture of machinery that cannot perform or survive in the actual operating environment. Not accounting for detrimental environment factors in the design and environment degradation are two of the most common causes of Turbomachinery component failures.

While the effects of the Turbomachinery environment are quite broad and reaching, this paper is intended to highlight the importance of knowing and controlling the environment in and around the machinery to assure maximum reliability. Several examples of environment degradation failures are discussed to highlight the complexity of the problem and how it reaches across all types of Turbomachinery. Suggestions are made as to what the Turbomachinery operators and manufacturers can do to minimize the potential for Turbomachinery environmental degradation and failures.

INTRODUCTION

Turbomachinery mechanical reliability is highly dependent on many diverse engineering inputs that include the quality and thoroughness of the unit design, manufacturing, operation and operating environment. Each aspect is equally important and not addressing the details of any of these areas is likely to lead to poor machinery reliability and availability.

Design

For Turbomachinery to be highly efficient and structurally sound, the basic design of the machinery must be sound. With the many years of operating experience and the tremendous advances in analytical design and analysis tools, the quality of the Turbomachinery designs has vastly improved. Analytical tools such as Finite Element Analysis (FEA) allows the prediction of steady state, dynamic and transient stresses to be calculated with a high degree of accuracy. Component and system vibratory characteristics can also be accurately predicted, and designs optimized. Similarly, Computational Fluid Dynamics (CFD) and advanced Aerodynamic Design Packages have allowed a greater understanding of the gas dynamics and greatly improved Turbomachinery capabilities, efficiency and overall performance. Advanced Rotor Dynamic analytical tools have allowed a greater understanding of the rotor operating characteristics and have led to improved bearing designs, rotors less sensitive to unbalance and external stimuli and overall well-behaved rotor operating characteristics. There is no doubt that these analytical design and analysis tools have greatly reduced the number of Turbomachinery problems due to the basic unit design. These analytical tools have also allowed today's Turbomachinery to be pushed to greater capabilities than ever before. More flow, higher head, higher speeds, pressures, temperatures and efficiencies are being achieved in fewer stages and in much smaller casings. With the increased aero and structural loadings, these designs often have lower structural margins, require higher strength materials (which may have lower corrosion resistance) and make them more susceptible to environmental degradation.

Condition *– Manufacturing and Maintenance*

The condition of the machinery is critical in assuring unit reliability. As originally manufactured or after the unit has been in operation, is the equipment in a condition that assures it will meet and maintain the originally intended structural and vibration margins? The condition is very much depended upon the quality of the initial manufacture, as well as the maintenance and repair practices used. Advanced manufacturing methods, standards and tooling have improved the quality of the Turbomachinery parts and overall unit assemblies. Improved quality inspection standards and techniques have helped to assure that the machinery parts are of the highest quality and meet the design requirements and intent.

Operation

Turbomachinery operation has a major affect on its reliability and overall life. It is important to assure:

- That the machinery is being operated within the specified operating and design parameters?
- There are adequate control systems and operator training in place to assure proper operation?
- There is an adequate Health Monitoring system and program in place to assess the machinery's condition?
- There is a formal Performance Monitoring program in place to detect performance degradations?

Unit operations is generally a combination of automated controls and human input. The human factor is and will likely continue to be a significant part of the Turbomachinery operations. It is good to see that over time, better operator training, closer monitoring with more accurate instrumentation and advanced controls have greatly reduced the number of operational upsets that can affect the Turbomachinery reliability.

The area that continues to cause the most Turbomachinery operational and reliability problems continues to be the auxiliary equipment (lube oil, gas and oil seals, guide vane actuation, surge, cooling, cleaning equipment, condensate removal, inlet filters, etc.). It is imperative that these systems be properly designed, operated, maintained and supported. The automation of the auxiliary systems has been helpful in reducing their influence on Turbomachinery reliability.

Proper unit operation is obviously critical in assuring that the Turbomachinery is operated within the specified design requirements and conditions.

Environment

Despite all the advances in Turbomachinery design, manufacturing and operation, the industry does continue to have major in-service component failures. Many of these failures are related to the operating environment of the Turbomachinery. Environmental conditions (both internal and external) can lead to the deterioration of the machinery to a point where the original design margins are compromised, and the risk of component failures increases significantly. Turbomachinery environmental degradation is the primary subject of this paper.

OBSERVATIONS

Environmental degradation is generally considered to be a negative change in physical condition of or a deterioration to the machinery that adversely effects the unit's performance, operating characteristics and even the structural reliability. Environment degradation occurs when the machine's local external or internal environment has unknown or unexpected contaminants that can cause adverse operating conditions to form or occur in and around the Turbomachinery. Abrasion, deposition, foreign material build-up, erosion and corrosion are the most common forms of environment degradation.

Component deterioration associated with corrosion and/or erosion are two of the most common causes of Turbomachinery failures. These types of failures occur in all types of Turbomachinery including centrifugal and axial compressors, steam and gas turbines and radial and axial gas expanders. Each type of machine has its own unique environmental conditions and potential problems. Unfortunately, the damage often occurs with little or no forewarning. The failure of critical components such as vanes, impellers, blading or disks have catastrophic consequences, often causing damage throughout the various stages or even throughout the entire machine. Unit emergency shut downs, plant shut downs, repairs and production losses all have major economic impacts to the plant operation and often create both major safety and environmental events.

Environment degradation continues to occur throughout the industry due to a failure of Turbomachinery operators and manufacturers to recognize beforehand a potential problem. If a detrimental condition is known and identified, steps can be taken to mitigate the effects and changes can made to the machinery to make it more forgiving of the adverse operating conditions. Examples of mitigation steps include:

Corrosion: If the machinery's operating environment is known to be corrosive, upgrade materials more resistant to the environment can be utilized. In addition, the material's manufacturing methods, chemistry, quality and heat treatments can be changed to make the material more corrosion resistant. Corrosion coatings can also be used to reduce the corrosion damage. If possible, the source or conditions that lead to the formation of the corrosive compounds can be reduced or eliminated.

Deposition/Fouling: Inlet filter systems can be very effective in reducing the amount of foulants entering the machinery. Smooth and continuous or even the polishing of the flow path can reduce the amount of deposition. Slippery or low adhesion coatings can be incorporated into the designs. Flow path cleaning procedures can be incorporated into the unit operation.

Erosion: Erosive wear of Turbomachinery is best prevented by the reduction of the amount and size of erosive particles or liquid droplets. Particle and droplet extraction helps to reduce the surface damages. The use of erosion resistant materials and/or coatings can be used to reduce the effects of the erosive environment.

Machine Design**:** The machinery's flow path can be designed to reduce the potential for erosion or deposition. The unit's structural margins can be increased to minimize the effects of surface damage and the reduction in materials capabilities.

Auxiliary Equipment: Auxiliary equipment can be installed to reduce the effects of the environment. Examples of such equipment include particle separators to reduce solid particle erosion, inlet filters to reduce flow path fouling, deposition, erosion and corrosion, liquid separators to reduce flow path erosion and corrosion and online cleaning systems can be utilized.

If there are mitigation measures that can be taken to reduce the harmful effects of environmental degradation, why aren't they more commonly used? Unfortunately, in too many cases, environment degradation problems are not identified, understood and addressed before they become a major problem. The problems are often identified only after significant periods of unit operation and often after the Turbomachinery is out its warranty period. The most common cause of environment degradation is due to critical informational gaps that existing between the Turbomachinery manufacturer and the owner/operator of the equipment.

The Original Equipment Manufacturer (OEM) is in a very competitive business environment and is trying to supply a piece of equipment that will do the job at the lowest cost. Building the equipment with more exotic materials, special manufacturing methods, extra coatings, higher stress margins, more stages, etc., all add to the manufacturing cost of the equipment. Unless the specialty needs are fully defined up front in the design stage, standard designs will be provided when a custom design maybe required. Like the machinery manufacturer, the end use is also in a very competitive business environment and is trying to construct, upgrade or expand a plant at the lowest cost possible. When the rotating machinery equipment costs represent a substantial portion of the plant construction costs, the lowest cost equipment becomes attractive. Detailed comparisons of all bids must be made to assure that all the proposed equipment is suitable for the application. If one manufacturer is providing an upgraded or more conservative design, its costs are likely to higher and that bid could be noncompetitive. More effort must be made in evaluating the merits and technical details of the bids being offered and assuring that all the bids are satisfactory and address potential adverse operating conditions.

The process designer, EPC contractor, machinery manufacturer and owner operator all need to spend more time and effort in defining potential adverse environmental conditions before the equipment is quoted and designed. Unless the Turbomachinery specialty needs are fully defined up front in the design stage, standard designs will be provided when a custom design maybe required.

EXAMPLES OF TURBOMACHINERY ENVIRONMENTAL DETERIORATION

The following examples are intended to highlight the complexity and diversity of Turbomachinery environmental deterioration and show how the problems occur in virtually all Turbomachinery applications:

DEPOSITION/FOULING

Flow path Deposition or Fouling is the accumulation of debris in the flow passage of an impeller or blading. It is caused by the adherence of particulate to the rotating and stationary flow path components. Almost all Turbomachinery operate in environments that have entrained particulates or gaseous compounds that can combine in the flow path and develop into flow path foulants. The particulate that causes fouling is generally very fine and typically less than 2 microns in size.

External foulants are ingested into the machinery from the local environment. They can be of the form of fine dust, dirt, rust or scale from ductwork or inlet systems, structures or upstream equipment, airborne salts from the ocean, cooling tower emissions or other process units, insects, organic matter such as plant pollens or seeds, or even inorganic pollutants from the surrounding area of the compressor or turbine. While inlet filter systems help to reduce the ingestion of external foulants, many inlet filter systems are not effective in removing very small (<1.0 microns) particulate or the gaseous contaminants. The ingestion of liquids or the formation of condensate in the inlet or the flow path can accelerate the amount of deposition since it can become the "glue" that sticks the particulate together and to the flow path surfaces.

Figure 1- Axial Compressor Flow Path Fouling

Internal foulants are formed inside the Turbomachinery inlet system or within the equipment itself due to the changes in gas pressures and temperatures. Examples of internal foulants are the formation of polymeric materials inside of Ethylene cracked gas compressors, Ammonium Chloride fouling in Reformer recycle compressors or Ammonia Sulfate formation in industrial air compressors. Severe fouling can occur in just a matter of days of operation. Deposits of these types cause significant production losses, increased unit maintenance and shortened service life. Flow path fouling is often very detrimental to the operation and reliability of Turbomachinery:

- Fouling leads to a roughening of the flow path surface finish that reduces the aerodynamic efficiency.
- The deposits can build up sufficiently to change the flow area/capacity of the stage. This can lead to reductions in both stage and overall unit capacity, efficiency, surge margin and pressure drop or loss.
- The deposits can create rotor unbalance and vibration.
- The deposits often contain corrosive compounds that cause corrosion of the base materials.
- The deposits can create local environments that are conducive to creating failure mechanisms in the base materials.

An example of a heavily fouled axial air compressor can be seen in Figure 1. Compressor performance losses of more than 5 percent in efficiency and capacity occurred from this fouling in only several months of operation. While it was initially concluded that the slippery, oil like substance on the blading was bearing housing oil leakage into the compressor, detailed deposit analysis revealed the black substance to be fine particulate (process catalyst) bound to the blading by Ammonia Sulfate that formed from gaseous ammonia and air borne salts. The deposits were found to occur mainly in the first four stages of the fifteen-stage compressor.

In many applications, flow path fouling can be greatly reduced by utilizing a well-maintained inlet filter system. A properly designed inlet filter can prevent the ingestion of airborne liquids (ice, rain, snow, etc.) and abrasive particles (dirt, dust, salt, etc.).

Online and offline washing or abrasive cleaning of a flow path can also be effective in removing existing flow path deposits and restoring the Turbomachinery performance. The use of flow path antifouling coatings has also been effective in reducing flow path fouling. These specialized coatings are often very corrosion resistant as well.

Figure 2 – Heavily Fouled Industrial Steam Turbine Rotor

Condensing and non-condensing steam turbines are particularly susceptible to flow path deposition and rotor corrosion problems. Figure 2 shows a heavily fouled mechanical drive turbine. It is interesting to note the heavy fouling on the first three stages of this turbine and minimal deposits can be seen in the fourth stage where the steam turns wet and washes off the water-soluble deposits. Common sources of impurities found in industrial steam turbines include make up water, process chemicals, combustion products, corrosion products, condenser water and air leakages, water treatment chemicals and demineralizers. Hydroscopic salts such as sodium hydroxide in the steam system deposit throughout the turbine flow path. Wet sodium hydroxide tends to adhere to the turbine metal surfaces and can entrap other impurities such as silica, metal oxides and phosphates. When these salts absorb moisture, such as when the super-heated steam becomes saturated and condenses in the turbine, aggressive acids can be formed and create a highly corrosive environment. Corrosion issues tend to be more prevalent in industrial steam turbines due to turbine operation at lower pressures and temperatures that cause wet and saturated steam conditions, the turbines operate over wider speed and load ranges, the poor purity and quality of the steam from industrial plant boilers and the lack of closed cycle steam systems that require higher feedwater make up and introduce higher levels of dissolved impurities.

EROSION

Unlike flow path deposition where fine particles adhere to the flow path surfaces, larger particles ingested into Turbomachinery can be very abrasive and cause erosion damage to the machinery flow paths. Erosion is the result of gas entrained particles or moisture droplets being accelerated to high velocity in the Turbomachinery flow path and impacting the surfaces of the flow path. Figure #3 is an example of heavily eroded inlet edges of centrifugal compressor impeller vanes. The vanes have been worn from the ingestion of air borne particulate in a steel mill environment. Some corrosion pitting can also be noted on the vanes. The source of the erosive particulate was a nearby slag pit that quickly overloaded from the compressor inlet filter system. Impeller failures have occurred due to the vane thinning and corrosion damage similar to that shown.

Figure 3 - Centrifugal Compressor Solid Particle Erosion

Flow path erosive wear effects the Turbomachinery performance as well as the mechanical reliability. Performance degradation is the result of the erosion causing a roughening of the flow path surfaces. A deterioration of the of the flow path surface finish results in increased frictional losses and an overall reduction the aerodynamic efficiency. Flow path geometric changes caused by erosion can also result in efficiency losses due to changes in the gas path dynamics, aerodynamic loadings, stage loadings, flow capacity, pressure drop or rise, and increased seal leakages.

Flow path geometric changes due to erosion can also change the structural and vibrational characteristics of the components. If the shape of the blades or vanes are change sufficiently, the component operating stresses often increase, and local stress concentrations can be created. The material loss can also change the shape of the component sufficiently to change the naturel frequencies of the component. As blade and vane leading and trailing edges wear, there is also a thickening of the edges, which can result in stronger nozzle wakes which in turn create stronger and uneven flow excitations to the adjacent stages. Uneven material wear can also result in rotor unbalance and vibration.

Solid Particle Erosion

Solid particle erosion is the loss of base material that results from the repeated impact of solid particles. Erosion can occur as the result of the particle machining away the base material, an impaction of the surface with consequential deformation and a shattering and/or spalling of the base material surface. Particle size, shape, impact angle and velocity all have strong influences in the base material erosion rates. Two examples of solid particle erosion can be seen in Figures 4 and 5. Figure 4 is an example of very heavy solid particle erosion of the rotor blades in a FCC hot gas expander. Hard and abrasive process catalyst is carried over from the process and can be very erosive to the expander flow path. With proper process operation and the use of properly designed and operating particle separators, the FCC expander can operate for more than 40,000 hours continuously with only minor erosion damage. This is despite the expander ingesting more than 100 lbs. (45 kg) per hour of the particulate throughout the entire operating period. Process upsets or problems with the separation equipment can increase the amount and sizes of catalyst carryover. In the case shown in Figure 4, a problematic particle separator has allowed the catalyst carryover to increase in particle size from less than 10 microns to more than 80 microns. The aluminum silica-based catalyst is very abrasive and eroded the expander blades in only a few weeks of operation. Erosion of this magnitude greatly reduces the power produced by the expander and the blade structural integrity becomes questionable. The heavy erosive wear changed the geometric shape of the blades, which in turn changed the flow path aerodynamics, the resulting stress distributions, created stress risers in critical regions of the airfoil and changed the blade natural frequencies.

Figure 4 – Expander Rotor Blade Erosion - Process Catalyst

Figure 5 is an example of steam turbine flow path solid particle erosion. Feed water contaminants and scale from the exfoliation of boiler tubes are common sources of solid particles in steam systems and are very erosive to the nozzle block and impulse stages of the turbine. Solid particle

Figure 5 - Steam Turbine Flow Path Solid Particle Erosion

erosion is highly depended upon the abrasive makeup, density, quantity, size, shape, velocity and impact angle. The surface wear can be the result of surface polishing, material extrusion, surface cutting, tearing or brittle fracture.

Solid particle erosion damage is best prevented or minimized by reducing the amount of particulate being carried over into the Turbomachinery. This is often done with cyclonic particle separators, screens, strainers and inlet filters. The flow path aerodynamics often can be redesigned to reduce the number of particle impactions and change the particle impact angles. Finally, erosion can be reduced by utilizing erosion resistant materials, erosion shields and coatings on the flow path components most susceptible to the erosion.

Figure 6- Steam Turbine LP Blade liquid droplet erosion

Liquid Droplet Erosion

As the working gases change pressure and temperature throughout turbine and compressor flow paths, condensation can occur, and liquid droplets form. The impaction of the droplets can be very erosive to the flow path components. Figure 6 shows an example of leading edge, water droplet erosion on low pressure steam turbine blading. Unlike solid particle erosion, water droplet erosion is often the result of the rotor blade impacting the slower moving liquid droplet. The erosion is most commonly found on the low-pressure blades that operate with saturated or wet steam. Liquid droplet erosion can also be the result of intentional injection of a liquid into a flow path to clean flow path foulants. The liquid droplets often remove small amounts of the base material and create pits, voids and microcracks in the surfaces. In corrosive environments, the microcracks can be initiation sites for fatigue cracking.

Liquid removal upstream and within the Turbomachinery flow path is the best way to reduce the effects of liquid droplet erosion. Similar to solid particle erosion, liquid droplet erosion can be reduced by utilizing erosion resistant materials, shields and coatings on flow path components most susceptible to the erosion damage.

CORROSION

The number one cause of Turbomachinery component deterioration and failures is corrosion damage. The damage is obviously the result of the environment the machinery is operating in. Common fluids and gases that cause corrosion difficulties include: fresh, distilled, salt and runoff waters, steam condensate; rural, urban, industrial, marine and tropical atmospheres; gases such as steam, chlorine, ammonia, oxygen, sulfur oxides and fuel; mineral acids such as nitric, sulfuric, hydrochloric and organic acids such as acetic, formic and citric. Turbomachinery corrosion damage can occur from a variety of corrosion mechanisms:

General Surface Corrosion is a uniform corrosive attack over the surface of the part and generally not a problem. Oxidation is a generic form of surface corrosion. Surface corrosion can be beneficial on many materials and is depended upon to prevent further corrosion. This is particularly true in high-temperature alloys that form metal oxides on the surfaces that acts as a barrier to other types of corrosion.

Crevice or Contact Corrosion results when a more aggressive environment is locally created in tight spaces or cavities. Blade attachment, shrouds, riveted components, impeller or wheel fits, spacer regions and even piping connections are all areas susceptible to crevice corrosion.

Erosion Corrosion is the result of a combination of an aggressive chemical environment, the presence of an abrasive media and high fluid surface velocities. Surface erosion causes the removal of surface protective films or coatings and allows corrosion to occur in the base material. It is often associated with multiphase flows.

Exfoliation Corrosion is subsurface corrosion that begins on a clean surface and spreads below it. It differs from pitting in that the attack has a laminated appearance. Exfoliation corrosion is often the source of erosive particulate entering the Turbomachinery flow path.

Fretting Corrosion is a rapid corrosion that occurs at the interface between contacting and highly loaded metal surfaces when subjected to slight vibratory motions. Protective surface films are often broken down and result in the exposure of the base material to the corrosive environment. This type of corrosion is most common on bearing surfaces such at the contact surfaces of axial compressor and turbine blading attachments or centrifugal impeller and coupling hub fits to a shaft.

Galvanic Corrosion is an electrochemical action of two dissimilar metals in the presence of an electrolyte and an electron conductive path. It occurs when dissimilar metals are in contact. A current flow between the metals results in the corrosion of one of the metals in the couple. Proper material selection and the use of component coatings can prevent galvanic corrosion.

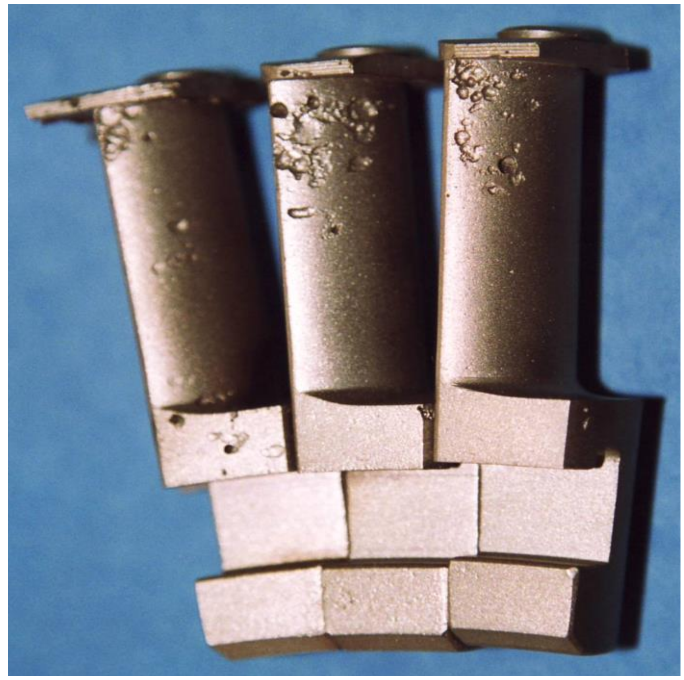

Figure 7 – Severe Steam Turbine Rotor Blade Pitting

Intergranular corrosion is a type of corrosion that results from the preferential corrosion of the grain boundary phases in an alloy. Intergranular corrosion is common in high temperature environments and can assist to drive corrosion and cracking rapidly into the base material.

Leaching is the removal of an element(s) in an alloy. The depletion of the leached element results in a base material chemistry change that can greatly reduce the material capabilities. High temperature corrosion products and scales are often found to have high concentrations of the leached element. Nickel and Chromium are two elements that commonly leach from the base materials and form oxide and sulfide corrosion products in highly alloyed gas turbine materials.

Pitting corrosion is the local formation of corrosion by which pits, holes, cavities or crevices are produced in the surface of the base material. Pitting corrosion often occurs as the result of corrosive compounds laying on the part surfaces and creating a locally aggressive environment under the deposits. An example of severe pitting corrosion on steam turbine rotor blades can be seen in Figure 7. Pitting corrosion can readily be a crack initiation point in Turbomachinery components and therefore considered to be more dangerous than general surface corrosion. Pitting corrosion is also more difficult to detect, predict and design against. The effects of pitting corrosion can be seen in Figure 8. A 40 percent reduction in fatigue strength/stress amplitude can occur from general surface corrosion without pitting, while more than an 80 percent reduction in stress amplitude can occur as the result of pitting corrosion.

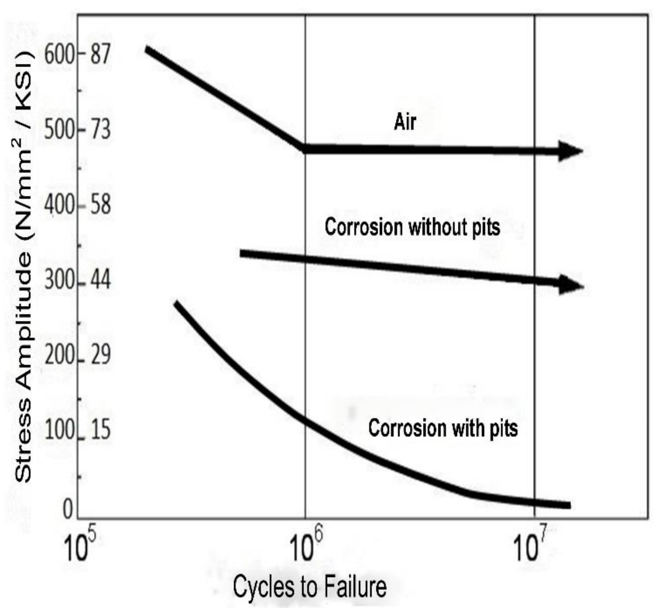

Figure 8- Effect of Corrosion Pitting on Fatigue Life of a 400 Series Stainless Steel Courtesy of Elliott Co.

Corrosion Assisted Failures:

High cycle fatigue failures are the most common failure mode in Turbomachinery rotors due to the rotor components operating at significant steady state and dynamic stress levels. Steady state stresses are the result of centrifugal and gas bending loads. The dynamic/alternating stresses are the caused by non-steady gas forces, strong exciting harmonics of rotational speed, nozzle wakes, partial arc nozzle admissions, flow instabilities and even system resonances (component and assembly). Material property degradation and component deterioration due to the operating environment greatly increases the probability of a component fatigue failure. Several corrosion related failure modes commonly found in Turbomachinery are:

Stress Corrosion Cracking

One of the most common modes of Turbomachinery component failures is Stress Corrosion Cracking (SCC). Stress Corrosion Cracking is the initiation and propagation of cracks in steels subject to the combination of high mean surface stresses, a susceptible material and operation in a specific corrosive environment. Figure 9 shows an example of Stress Corrosion Cracking in a 12 percent Chromium Stainless Steel steam turbine blade attachment. While the environment is a major contributor, the designed related causes are very important and controllable by the machinery designer. Design related causes include high steady and/or vibratory stresses, the use of materials susceptible to SCC, the use, manufacturing method and heat treatment of high strength materials, the material composition, quality and the surface treatments.

Figure 9- Stress Corrosion Cracking of Steam Turbine Blade Attachment

Many of the commonly used stainless steels used in turbomachinery are particularly susceptible to SCC where chloride and other halide ions are present even at very low levels (ppm). In these environments, relatively minor surface damage caused by this distinct type of corrosion can initiate and propagate cracks at stress levels well below the endurance limit of the material in a clean air environment.

Steps taken control Stress Corrosion Cracking include:

- Reducing component operating stress levels (both steady state and concentrated) at critical locations.
- Remove or reduce stress concentrations.
- Improve component fit up to prevent non-uniform loadings.
- Reduce components vibratory stresses to prevent corrosion fatigue.
- Judicious material selection, manufacturing processing, heat treatment and surface treatments.
- Shot peening the critical regions to place the surface stresses in compression.
- Reducing and monitoring of gas impurities.
- Utilizing corrosion resistant surface coatings.

Sulfide Stress Cracking

A similar corrosion assisted failure mode is Sulfide Stress Corrosion (SSC). SCC and SSC are similar in several aspects in that both require three simultaneous conditions to be problematic: stress levels above a threshold level, material susceptibility and a corrosive environment. While Chlorides are the problem in cases of SCC, Sulfur is the problem in the cases of SSC. In many chemical or petrochemical plants, Hydrogen Sulfide is present along with Chlorides. The presence of sulfur and chlorides can create a very aggressive corrosive environment in the Turbomachinery. These acidic conditions make the base materials very susceptible to Sulfide Stress Cracking. The critical stress levels for failure are highly dependent upon the acidity of the environment. As the environmental pH reduces below 5.0, the critical stress level for crack initiation can be reduced to less than 50 percent of that in a neutral environment. While most manufacturers follow the requirements specified in NACE MR0103 and MR0175 for the prevention of Sulfide Stress Cracking, it may not be enough to prevent failures in the more aggressive environments. Acidity levels as lower than 3.0 have been measured in some Turbomachinery installations.

Corrosion Fatigue

Corrosion Fatigue (CF) is a special case of stress corrosion cracking that is caused by the combined effects of cyclic stress and corrosion. CF is a common failure mode of Turbomachinery components. Figure 10 shows fatigue cracking in multiple 12 percent Chromium Stainless Steel axial compressor rotor blades. The damage from corrosion fatigue is greater than the sum of the damage from both cyclic stresses and the corrosion. It is characterized by a lowering of the fatigue strength of the base material and occurs in virtually all metals commonly used in Turbomachinery. Figure 11 shows how dramatically the fatigue strength of a material can be degraded in even mildly corrosive environments. The stress level at which a material would be expected to have an infinite life is lowered significantly or even removed completely. Contrary to a pure mechanical fatigue, there is no fatigue limit load in corrosion assisted fatigue. Corrosion fatigue is best prevented by lower the component cyclic stresses and/or by corrosion control.

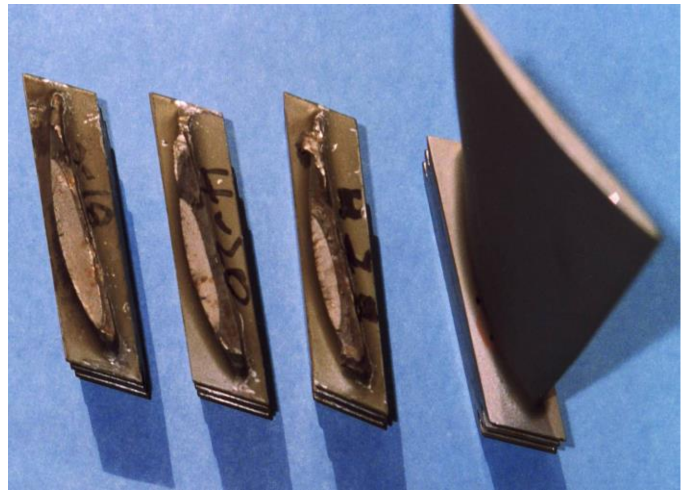

Figure 10 - Axial Compressor Corrosion Fatigue

Material Capability Reduction

In addition to the obvious component physical deterioration from corrosion, the operating environment can degrade the other base material structural and vibrational capabilities. Properties such as tensile strength, impact strength, threshold stress intensity, fracture toughness, stress rupture, creep strength, and endurance limit (fatigue strength) can all be affected by the machinery's operating environment. Material tensile, creep and rupture strength reductions of more than 20 percent have been confirmed in numerous environmental studies. As Figure 11 shows, the fatigue strength of 12 percent Chromium Steel alloys in aggressive aqueous environments can be reduced by more than 70 percent.

Too often the investigation of the machinery operating environment is only carried out after a machinery problem is experienced or identified. Machinery failures are very costly and present major safety and environment risks. It is also very important that generalized plant or industry experience not be the sole basis an individual plant's Turbomachinery design, construction and operation. The extrapolation of operating experience from an industry or from plant to plant can be dangerous since each installation has its own unique ambient and operating conditions, feed sources, feed contaminants, product make, installed equipment, plant layout, etc. While the effects of many operating environments (such as steam turbine chemistry or the presence of hydrogen sulfides in chemical plants) have been extensively researched and are well documented, *every Turbomachinery installation is unique and specific measures need to be taken to identify potential and quantify the severity of environment*. Site specific designs must be developed to account for the actual operating conditions the Turbomachinery will be subject to.

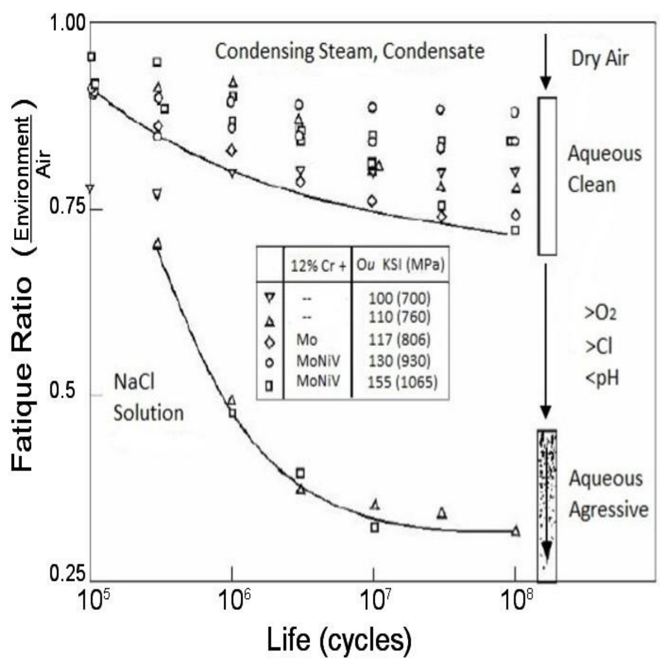

Figure 11 - Effect of Various Aqueous Environments on Material Fatigue Strength – Courtesy of Elliott Co.

Shut Down Corrosion

While corrosion damage often occurs during unit operation, significant corrosion damage can also occur during unit down periods, contiguous shutdown and start up periods and even during the storage of used rotors after removal from the unit. Shut down corrosion is generally the result of contaminates and deposits remaining on the flow path components after the unit has been removed from service. During these shut down periods, the deposits hydrate from process gas condensation, steam condensation or even local environmental humidity. Once hydrated, the local environment in and around the deposits experience the formation of very aggressive acids. Significant local corrosion damage can occur very rapidly. Figure 12 shows extensive corrosion pitting on a rotor blade from residual nitrous oxide deposits hydrating and forming aggressive acids during a Nitric Acid Gas Expander shut down.

Figure 12 – Shut Down Corrosion Pitting on a Nitric Acid Expander Rotor Blading

To minimize the shutdown corrosion potential, the machinery internal environment should have the moisture levels maintained below 40 percent (RH). Since even the ambient conditions often contain moisture above that level, additional measures need to be taken to protect the Turbomachinery. Some commonly used methods used to minimize shut down corrosion include:

- Cleaning the flow path during normal operation, the shutdown process or immediately upon shut down.
- Draining of condensation during the shutdown of the equipment.
- The elimination of moisture following a shut down.
- The use of casing purges to reduce the moisture levels or eliminate the presence of oxygen. This has been accomplished with dehumidified air, hot dry air, or the use of inert or non-reactive gases such as helium or nitrogen.
- The use of dehumidifying air systems.
- Alkaline washing of surfaces.
- The selection of corrosion resistant materials and coatings.

One of the most neglected areas of Turbomachinery maintenance is the proper handling and the storage of rotors removed from service. A widespread practice in many installations is to hold the “old or run” rotor on site until such time the spare rotor is installed and operational. Since most major turnarounds last approximately one month, the run rotor can experience significant corrosion damage in that brief period. After rotor removal, it is very important to clean the rotor as soon as possible and to keep it in a dry safe location. The following work scope is recommended to prevent shut down corrosion on critical machinery components:

- Immediately upon opening the machinery, visually inspect and photo document the condition of the flow path.
- Immediately take deposit samples throughout the entire flow path of the unit, as well as the inlet and discharge systems.
- Remove and clean the rotor and stationary hardware to prevent deposit hydration and shut down corrosion. Store in a dry protected environment. Visually inspect the parts for signs of wear, tenaciously attached deposits or corrosion products, corrosion or distress. The condition of the cleaned components should be photographed and well documented.
- Evaluate the components for their suitability for reuse as emergency, short term or long-term operation.
- Prepare the components for Non-Destructive Inspection. Visually, Dimensionally and Non-Destructively Inspect the machinery components. Qualified and experienced inspection personnel must be utilized since many types of corrosion develop surface scales that are continuous, diffused or penetrated the base materials and can hide or mask sub-surface corrosion damage and cracking. A detailed inspection report should be prepared.
- The owner/operator and manufacturer should jointly work together to determine what work scope required to fully evaluate and restore the components to a zero or near zero-time condition. This step is extremely important since part deterioration may appear to be relatively minor at this point, although if allowed to continue, additional damage in the next operating campaign may increase the potential for an in-service problem.
- All environmental degradation measures used in the initial component manufacturer, must be full restored. This is particularly true for polished high stresses regions, shot peened areas, coatings, etc.
- All work must be performed to defined standards and by qualified and experienced shop facilities and personnel.

CASE STUDIES

Several Case Studies are presented to show both the severity and diversity of environment degradation throughout the Turbomachinery Industry.

CASE Study 1 - Steam Turbine Rotor Blade Failure

Erosion of steam turbine blades due to the impaction of water droplets can cause serious performance losses and major mechanical reliability issues (including airfoil failures). Water droplet erosion occurs in the stages where the steam conditions are such that the steam becomes saturated and condensation occurs (below the Wilson Line). This obviously occurs in the LP/discharge stages of the turbine. The condensation collects on the flow path surfaces and larger water droplets form and are carried through the flow path with the gaseous steam. Low velocity water droplets leave the upstream nozzle trailing edge and impacting the rotor blade leading edges on the suction side of the blades.

Figure 13 shows surface damage to the last stage of a condensing steam turbine. The erosion gouges are on the suction side of the leading edge of the blades. The gouges eventually served as crack initiation regions and resulted in through airfoil cracking. Continued operation of the subject turbine would have likely resulted in an airfoil tip separation.

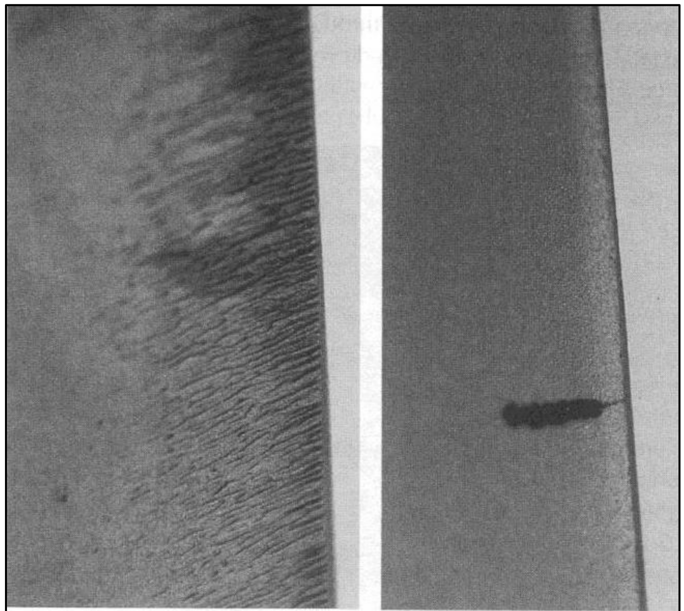

Figure 13 – Steam Turbine Rotor Blade Cracking from Trailing Edge Erosion

Figure 14 shows the airfoil section velocity diagram for both the steam and water droplets. It can be seen that the water absolute velocity (C_{water}) is less than 20 percent of the steam absolute velocity (C_{steam}). While the resulting steam relative velocity (W_{steam}) matches the blade metal inlet angle, the water relative velocity (W_{water}) impacts the blade adversely at a high negative incidence angle.

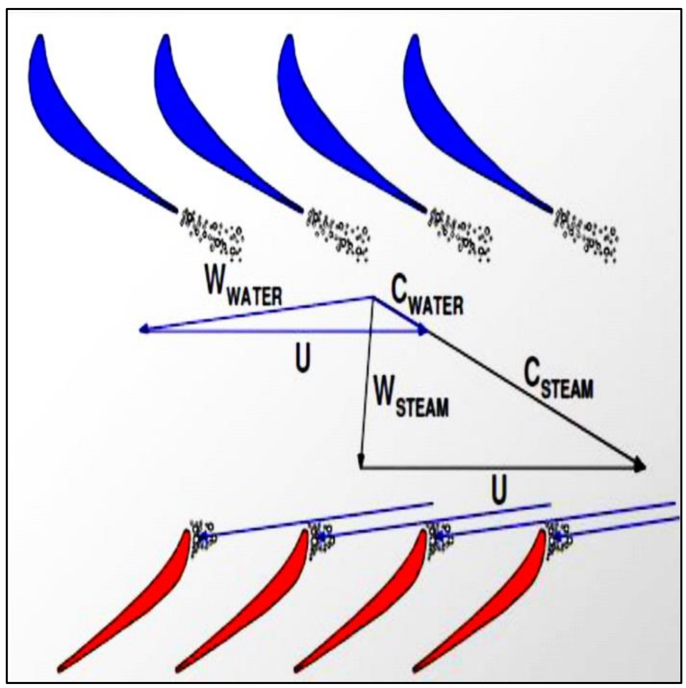

Figure 14 – Stage Velocity Diagram for Steam and Water

The base material erosion mechanism is complex with the water droplets initially causing shallow craters. The accumulation of impacts over time results in overlapping impact craters, surface work hardening, the delamination of the plastically deformed layers and local fracturing. Water droplet erosion can be reduced in several ways including:

- The internal reduction of moisture within the turbine via building extraction slots and stage drains in all wet stages.
- Adding water suction slots to stators.
- Utilizing a more erosion resistant flow path design.
- Utilizing more erosion resistant blade materials such as hardened 12 percent Chromium alloys and Titanium.
- Hardening the leading edges of the blades via heat or laser surface treatment.
- Hardening the loading edges of the with erosion resistant coatings or shields (Stellite).

Case Study 2 – Axial Compressor Rotor Disk and Blade Failures

An industrial axial flow air compressor installed in a coastal refinery location, experienced repeated rotor failures in less than a year of operation. One of the events included the failure of a low alloy steel third stage rotor disk after only fifteen months of service. Figure 15 shows the loss of a large triangular section of the disk outer surface. The dove tail failure resulted in the release of a rotor blade that caused extensive damage throughout the entire compressor flow path. After installing the spare rotor, the unit operated only ten additional months before a 400 Series stainless steel third stage rotor blade failed.

Figure 15 – Axial Compressor Rotor Disk Stress Corrosion Cracking Failure

Examination of the rotors showed heavy flow path deposits on all stages despite the use of a modern inlet filter system. Corrosion damage to the rotor blading, variable stator blading and rotor disks was found primarily in the first four stages of the compressor. These stages experienced the greatest deposition and corrosion damage due the operation of these stages in a wet environment.

Both the disk and rotor blade failures were found to be the result of corrosion fatigue. Corrosion pits were found in the corners of the dove tail slots in the rotor disk and fretting damage was found on the attachments of the rotor blades. Multiple crack initiation points were observed and resulted in a larger crack being developed and propagating through the components until the final overload occurred.

Deposit and inlet filter capture analyses showed foreign materials with similar chemistries. Chemical analyses revealed both insoluble mineral elements such as aluminum, silicon and iron, as well as water soluble contents such as chlorine, sulfur and fluorine. Compound analysis and corrosion testing revealed that aggressive acids were being formed in the compressor and that very few materials would be able to provide the required services life.

Extensive environment testing was conducted to determine the source of the deposited materials and corrosive compounds. Inlet filter analysis revealed that the filters were effective in removing particulate greater than 5 microns in size and some of the air borne sea salts. The analysis also revealed that the salts collected in the inlet filter migrated through the filter media over time and were being washed through the filters during periods of high humidity and precipitation. The inlet filters were found to be ineffective in removing gaseous contaminants that travel through the filter and formed the compounds that led to the aggressive acidic conditions in the compressor. An extensive corrosion prevention program was implemented to prevent future in-service failures. Some of the product upgrades and practices included:

- Redesigning the blade attachments to reduce the operating stress levels and concentrations in the rotor disks.
- Component upgrades included refining the rotor disk chemical composition, manufacturing methods and heat treatments.
- Utilizing a multilayer corrosion resistant coating on the rotor disks.
- Shot peening the rotor blade and disk attachment regions.
- Upgrading the compressor blade materials including the use of Titanium blades in the stages most susceptible to corrosion.
- Reducing the level of contaminants by changing the inlet filter media to improve the filter efficiency.
- Changing out the filter media more frequently to prevent the migration of salt through the elements.
- Performing periodic online compressor flow path cleaning to remove harmful deposits.
- Installing corrosion probes in the compressor flow path to monitor the corrosion potential inside the compressor.
- Drying the compressor internals during shut down periods.
- Immediate cleaning of the compressor components during a unit turnaround.

Since the implementation of the product and operational upgrades, the compressor has operated successfully for more than 20 years without another failure.

Case Study 3 – Centrifugal Compressor Impeller Failure

After many years of successful operation, a multistage industrial centrifugal compressor began to experience multiple impeller vane failures. Three impeller failures occurred in both new and existing used spare rotors in less than 10,000 hours of operation. These failures resulted in compressor flow path damage, high rotor vibrations, unscheduled plant shut downs, costly repairs and extended plant down time. The failures occurred in both high strength alloy steel and 12% chromium impellers. Figure 16 shows one of the damaged impellers with a large section of missing vane. The failure analysis team performed extensive:

- Structural design reviews
- Impeller vibration and modal analyses
- Aerodynamic and performance analyses
- Surge/stall analysis
- Gas composition testing and analysis
- Process conditions review
- Operating history review
- Metallurgical destructive testing
- Erosion and corrosion assessment

Figure 16 - Centrifugal Compressor Impeller Vane Failure

Findings of the analytical investigations revealed that the first stage impeller was operating with moderately high stresses. While no evidence of impeller resonant conditions were found, the vane dynamic stress levels were also moderately high.

The operational review showed that the compressor in more recent times was operating near its maximum speed and flow capabilities. No evidence of operation outside the operating envelope were identified. The moisture separator used in the inlet of the compressor was found to have deteriorated performance due to fouling and increased loadings. Evidence of environment degradation was noted on the first stage impeller. Liquid droplet erosion and corrosion were found on the leading edges of the impeller vanes. Multiple crack initiation points were found on the impeller vane leading edges with the cracking initiating from corrosion pits. Corrosion assisted fatigue was found to be the primary driver of the cracks. Corrosion in the cracks helped to drive the cracks further into the base material.

The process review and metallurgical reviews revealed that the compressor inlet condensate had significant levels of Acetic and Sulfur bearing acids. The condensate pH could have been as low as 2.8. The impeller failures were attributed to be the result of Stress Corrosion Cracking (SCC) and/or Sulfide Stress Cracking (SSC). The root cause was found to be the result of changes in the process operation that lead to the reduction in compressor inlet pressure and temperature, the formation of increased condensation, fouling of the moisture separator and an overall change to the first stage impeller operating environment. A number of design changes were made to the process equipment and compressor to address the adverse operating environment:

- Replacement impellers were redesigned to reduce the operating stresses and stress concentrations.
- Replacement impellers were manufactured from low alloy and 12% Chromium steels in accordance with NACE MR0175 and MR0103 guidelines for corrosive environments.
- Critical regions of the impellers were shot peened.
- The impellers were coating with a polytetrafluorethylene (PTFE) fouling and corrosion resistant coating.

Operational changes were also made to the unit to reduce the aggressive acids in the compressor inlet. The liquid separation equipment upstream of the compressor was cleaned and upgraded. The compressor inlet pressure losses were reduced. The compressor inlet temperature was maintained at a higher level to reduce condensation and acid formation.

The design, manufacturing, operational and environmental changes were successful in preventing further impeller failures.

Case Study 4 - Gas Turbine Rotor Blade Failures:

Gas Turbines are complex Turbomachines that push the limits of machinery design in many ways. They experience the operational issues of high volume, high pressure ratio air compressors, the complexity of combustion dynamics and the many material issues of high temperature turbines.

Unique to the gas turbine are the many issues associated with the high stresses and temperatures in the turbine flow path. Most notable are the material limitations including tensile, low and high cycle fatigue, impact, creep and rupture strengths. The high temperature operation gives rise to very complex material kinetics.

Figure 17 – Gas Turbine Salt deposits and Hot corrosion damage (Courtesy of Sulzer)

Environmental degradation of the gas turbine comes in many forms. Corrosion remains as one of the primary causes of gas turbine failures. Many of the corrosion problems are the result of unit operation and the ingestion of foreign materials that can lead to and accelerate corrosion. The effects of high temperature corrosion can resemble both fouling and erosion because some types of hot corrosion cause a buildup of corrosion products on the turbine part, while others cause metal to be stripped away. Figure 17 shows heavy hot corrosion damage on the turbine rotor blades. While gas turbine corrosion takes on many forms, several of the more common types of corrosion damage that occur in the hot section of the turbine include:

Oxidation is a chemical reaction between oxygen and metal components and forms a metal oxide over the part surfaces. The high operating temperatures in a gas turbine greatly accelerate the oxidation process of the base materials. While general surface oxidation/passivation can aid in preventing of high temperature corrosion, excessive oxidation can greatly deteriorate the condition of the turbine components.

Hot corrosion is a rapid form of corrosive attack that is generally associated with alkali metal contaminants, such as sodium and potassium, reacting with sulfur in the fuel to form molten sulfates. The presence of only a few parts per million (ppm) of such contaminants in the fuel or the equivalent in the air is sufficient to cause hot corrosion. There are two distinct forms of hot corrosion that are related to the ingestion of salts. They are commonly referred to as Type I and II hot corrosion.

> ***Type I (high temperature) hot corrosion*** occurs in a temperature range of 1,500 to 1,700ºF (816 to 927ºC) in the presence of sodium sulfate (Na_2SO_4). Sodium sulfate is generated in the combustion process as a result of the reaction between sodium, sulfur and oxygen. Sulfur is present as a natural contaminant in the turbine fuel. Type I corrosion is characterized by intergranular attack, sulfide particles and denuded zones of the base material.
>
> ***Type II (low temperature) hot corrosion*** occurs in a temperature range of 1,100 to 1,400ºF (593 to 760ºC) and requires a significant partial pressure of SO_2. It is caused by low melting point eutectic compounds resulting from the combination of sodium sulfate and some of the alloy constituents such as nickel and cobalt. Type II corrosion can be very aggressive if the conditions are right and is characterized by a layered type of corrosion scale.

Sulfidation is a chemical reaction between the turbine base materials and sulfur in an oxygen containing atmosphere. Sulfur enters the turbine in the combustion air or the fuel. Whereas oxide scales can be protective, metallic sulfide scales are not protective and often lead to a rapid rate of surface degradation.

Foreign materials enter the gas turbine from the inlet air, combustion fuel and water or steam injection sources. Common contaminants in gas turbines include sodium and potassium chloride salts, sulfur and heavy metals such as vanadium and lead. The lines of defense against most types of hot corrosion are similar: Reduce the contaminants, reduce the component operating temperature, use corrosion resistant materials and apply corrosion and deposit resistant coatings.

Case Study 5 – FCC Gas Expander Failure:

Numerous expander rotor blade and disk failures have occurred at different installations that were all found to have conservatively designed expanders and operations within typical expander design parameters. Most of the failures were the result of a combination of corrosion and creep fatigue. Puzzling was that some expanders did not fail with major corrosion damage like that shown in Figure 18, while other expanders failed with very minor corrosion damage.

Environment testing, and operational analysis shows that FCC expanders operate through a wide range of operating parameters. Figure 19 shows both the range of operating inlet temperatures as well as the flue gas make up for the two types of FCC operation. While the complete combustion mode of operation would be expected to produce more high temperature corrosion due to the higher operating temperatures, the greatest number of expander blade failures have occurred in the incomplete combustion mode of operation. The greater number of FCC expander failures in the incomplete combustion mode is attributable to the flue gas composition and is illustrated in the Phase Equilibrium Diagram for Chromium and Nickel in Figure 20. Due to the lower partial pressure of oxygen in the incomplete combustion mode, Chromium and Nickel Sulfides have a greater tendency to form. These phases are unstable and tend to leach the Nickel out of the base material and create crack prone Chromium Sulfides in the surface of the base material. As the oxygen levels increase above 1.25 percent in the flue gas, more stable and protective Chromium and Nickel oxides form on the surfaces of the base material and cracking is less likely to occur.

The base material selection was also found to be significant in determining why some expanders with similar structural and vibration margins failed with minor corrosion damage while other expanders did not fail despite major corrosion damage. Laboratory testing of the base materials revealed that many of the nickel base super alloys have significantly lower crack threshold levels in the FCC environment than that in a heavily oxidizing environment (O_2 levels above 15 percent) like that of a gas turbine.

Rotor Corrosion in FCC expanders is best prevented by:

- Running cleaner feed stocks
- Operation with increased oxygen content
- Minimizing flue gas and catalyst contaminations
- Expander material selection and heat treatment
- Utilizing corrosion resistant rotor coatings
- Reducing the expander rotor operating temperatures
- Making the rotor local environment more oxidizing

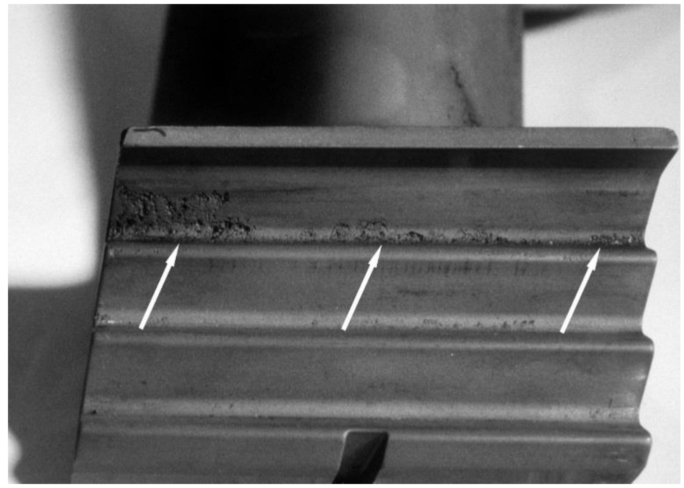

Figure 18 – FCC Expander Blade Attachment Corrosion

Operating Parameter	Incomplete Combustion	Complete Combustion
Flue Gas Temperature	1,100 to 1,275°F (593 to 690°C)	1,275 to 1,425°F (690 to 774° C)
Gas Composition -	Wgt %	Wgt %
Nitrogen	70.0	73.0
Oxygen	0.0 – 1.5	1.5 to 5.0
Carbon Monoxide	7.0	0.0
Carbon Dioxide	10.4	14.0
Water	12.5	11.0
Sulfur (SOx)	50 to 1,500 ppm	

Figure 19 – FCC Expander Operating Environment

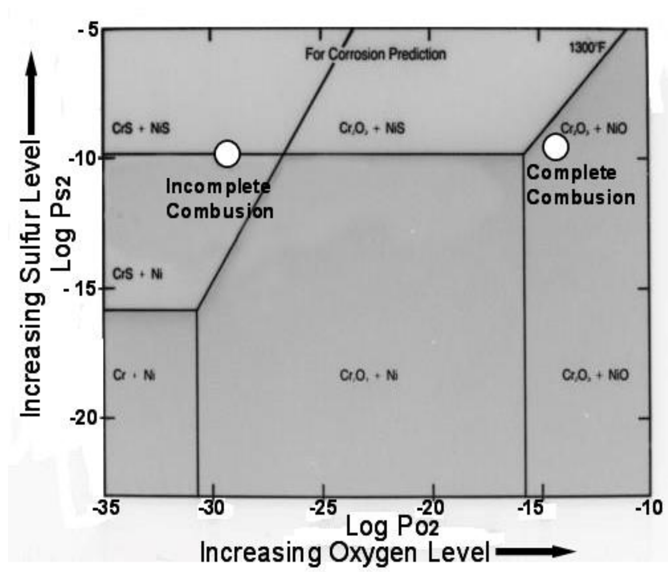

Figure 20 – FCC Environment Phase Equilibrium Diagram

WAYS TO AVOID ENVIRONMENT DEGRADATION OF TURBOMACHINERY

As highlighted in the various case studies and throughout this paper, Turbomachinery environmental degradation is very complex. No industry, application or type of Turbomachinery is unaffected. Since environment degradation of the machinery continues to remain at the top of the list as a reason for many equipment failures, more effort must be taken to reduce its occurrence. Turbomachinery operators must recognize that over time, the likelihood of machinery degradation continually increases from both normal wear and environment degradation. The risk of an equipment problem is constantly increasing over time and owner/operators must continually work to minimize those risks.

Turbomachinery failures can best be avoided by identifying and remediating potential environmental degradation mechanisms up front, before they occur. This is obviously far more desirable than initiating a remediation program after a unit failure. The following recommendations can assist both the equipment operator and manufacturer in reducing the potential for Turbomachinery Environmental Degradation and the associated operational problems and risks.

Owner/Operators Involvement

Machinery Design

It is critically important that the owner/operator knows and understands the Turbomachinery design and capabilities. Detailed analytical studies should be conducted prior to the delivery of the machinery in all major aspects of the design including structural, vibrational, aerodynamic, performance, rotor dynamics, metallurgical, operational, etc. If these analyses have not been provided by the machinery manufacturer, they should be performed and provided. The owner/operator should participate in all design reviews, the analytical work should be properly documented and the results made readily available to those responsible and involved in the Turbomachinery reliability. Detailed design reviews should be conducted prior to the purchase of new equipment and prior to any change in the operation or modification of existing equipment. The design reviews should include plant operational, maintenance and technical personnel, corporate engineering support, equipment manufacturer support and independent technical support from experienced industry specialists. The operation of a sound and proven design is the first step in assuring reliable Turbomachinery.

The process designer, EPC contractor, machinery manufacturer and owner/operator all need to spend more time and effort in defining potential adverse environmental conditions before the equipment is quoted and designed. Unless the Turbomachinery specialty needs are fully defined up front in the design stage, standard designs will be provided when a custom design maybe required.

The owner/operator should recognize that the machinery manufacturer may not be fully familiar with the nuances or specialty operations associated with the process application. This is not unexpected since the machinery manufacturer's expertise are in the equipment design and not the process design and process designers are often reluctant to share the process proprietary design details. Start up and shut down conditions, turn down rates, maximum operating conditions, process gas variations, fuel gas compositions and variations, seal and cooling gas quality and sources, feed stock variations and contaminants, the use of process catalysts or environment additives, etc. all need to be fully identified.

Management of Change (MOC)

When changes are planned or occur in the process operation, the owner/operator needs to:

- Re-evaluate the current condition of the existing equipment and determine if it is suitable for the new operating conditions.
- Evaluate if the change in operation will affect not only the capacity and efficiency, but also the operating pressures and temperatures.
- Evaluate how the rotor dynamic, structural and vibration margins of the Turbomachinery will be affected by the changes.
- Evaluate if the operational changes will change the gas compositions, states or level of contaminants.
- Identify if the rates or degree of environment deterioration will change and/or require additional remediation measures or more frequent maintenance and refurbishment.
- Define if equipment auxiliary equipment needs to be modified.
- Define the new operational limits.

- Work with the manufacturer as required to develop custom designs or parts to maximize the machinery performance, structural margins and minimize environmental degradation and maintenance.
- Make operators aware of any adverse operating conditions and how to avoid them.

Machinery Operation

It is important to recognize that the site-specific operation and machinery operating conditions are the responsibility of the process designer and owner/operator. The owner/operator obviously know their process operations, site conditions and their specific needs better than the machinery manufacturer. It should also be recognized that the owner/operator may not fully understand the subtleties of Turbomachinery design and all the conditions in the operating environment that may affect the machinery reliability. By providing the everyday operational conditions, needs and ranges, the Turbomachinery manufacturer can better address any those conditions and is often an excellent source of operational experience and technical information.

To prevent start up or operational problems, there is a need for more upfront site analysis. Site surveys and evaluations should be periodically conducted to identify potential sources of environmental contaminants. This is particularly true if there are changes or modifications to the surrounding plant equipment or operating units. Examples of environment contaminate sources include cooling towers, process vents or reliefs, sewer or dirty water vents and openings, flue gas stacks, boilers or combustion turbine exhausts, fugitive emissions from other process units, sulfur or slag pits, site proximity to a marine environment, power station, chemical plant, etc.

Machinery Condition

The monitoring and evaluation of the Turbomachinery performance and supervisory equipment over time is critical in assessing the condition of the machine and identifying problems as they develop. If adverse environment conditions are identified, measures should be taken to monitor and minimize those conditions. In addition to the normal supervisory equipment monitoring, additional online monitoring and testing might include site air or gas sampling, inlet filter or strainer capture analysis, process gas, fuel, feed and condensate sampling. If possible, install and periodically check corrosion coupons. Sample and analyze flow path deposits at every opportunity. Evaluations should be conducted during the unit operation, as well as during the shutdown periods. The operating experience, condition and age of the machinery all enter into determining the turnaround and inspection requirements. While extended unit operating goals are very desirable from a plant economic perspective, the Turbomachinery must not be pushed to a point were reliability and safety is compromised.

During a unit shut down and inspection, it is critical to protect the machinery from shut down environmental degradation. If the Turbomachinery is to be disassembled, the critical components should be immediately cleaned, inspected and stored appropriately. If the Turbomachinery is not going to be disassembled during the unit shut down, appropriate steps need to be taken to keep the unit warm and dry to prevent shut down corrosion

Critical during a unit inspection is to evaluate the most recent operational experience and inspection results to identify problem areas and determine if the equipment is capable of achieving the next operating goal. The equipment refurbishment work scope needs to be sufficient to assure it will meet the operating goals. All too often, after a successful run, there is a desire to operate the equipment harder and for a longer operating time. It is important to identify if the partially deteriorated component will be able to operate safely and reliably with similar additional or greater deterioration during the next operating campaign. Critical aspects of the machinery design must be zero timed (restored to a new or near new condition). For example, when machinery parts are coated and depend upon that coating to prevent environment degradation, the evaluation of the coating life is critical since many coatings are sacrificial and their life and capability to resist corrosion or erosion maybe inadequate in the worn state and for an additional or longer operating campaigns. The owner/operator must budget appropriately for restoring the equipment to the required degree needed to minimize the risk associated with environment degradation.

Turbomachinery Manufacturer Involvement

The manufactures and owner/operators of the Turbomachinery must work closely and cooperatively throughout the life of the equipment to assure maximum unit reliability. With more open, direct and earlier dialog, the machinery manufacturers can contribute significantly in reducing the number of environmentally related failures.

Machinery Design

The Turbomachinery manufacturers need to be more involved in supporting the owner/operator of equipment both pre and post order. The manufacturer can assist in many ways:

- Share all (both the good and the bad) of the operating experiences of the proposed equipment in similar operating environments, plants and throughout the industry. Manufacturers tend to not share negative operating experiences.
- Develop more industry specific, knowledgeable experts that can assist in identifying potential problems associated with a given application.
- Advise the machinery owner/operator of areas of potential problems and how those problems can be adverted. This needs to be done early in the machinery design phase to prevent machinery order cost adders and schedule delays.
- Participate in site walk downs to aid in identifying potential environment conditions that might be averse to the machinery.
- Participate in site environment testing. Assist in evaluating the test results.
- Provide product upgrades that will enhance the structural and vibration margins of the machinery components as well as the environment resistance. While improvements in unit efficiency and capacity, as well as the lowering of machinery costs are desirable, reliability improvements are just as, if not more important.
- When potential detrimental environment conditions have been identified, provide more conservatively designed Turbomachinery. This includes accounting for the machinery material property reductions, upgrading material capabilities, adding part surface enhancements, lowering structural and vibration margins, reducing stress concentrations, etc.
- Provide methods to reduce potentially harmful environment conditions. This would include recommendations in the areas of process and machinery control, inlet gas filtering, moisture removal, etc. Filter design and change out recommendations should be made basis the actual site environmental testing.
- Provide both design and hardware provisions in the machinery for online or offline cleaning.
- Provide provisions for online environment testing including gas sampling, condensate capture and corrosion monitoring.
- When machinery is to be rerated, re-assess the potential changes to the environment, machinery structural and vibration margins and evaluate the auxiliary equipment performance (i.e. filters, moisture separators, condensate drain provisions, etc.).

Machinery Operations

The Turbomachinery manufacturers can assist in the monitoring and evaluation of the Turbomachinery performance and supervisory equipment over time. Experienced personnel knowledgeable with the machinery design can provide valuable input in assessing the condition of the machine and identifying problems. The manufacturer often has the expertise in evaluating the environmental conditions and what steps can be taken to minimize those conditions. This type of support requires a strong relationship between the manufacturer and the owner/operator.

Turbomachinery manufacturers need to supply more detailed and complete operating instruction manuals. Many instruction manuals are “generic” and not tailored to the actual site installation and operation. This is especially true for auxiliary drivers such as start up or helper steam turbines, gear boxes, motors, generators, etc. The failure of the auxiliary equipment is often more likely to cause a Turbomachinery train or Plant shut down, as the main equipment. The Turbomachinery operating instruction manuals need to be provided early in the machinery manufacturing cycle to allow the owner/operator to assure compatibility with the process operation. The manuals are often supplied at the end of the manufacturing cycle and the machinery operating requirements may already in conflict with the process operating requirements. Changes to the process, Turbomachinery, controls and operations made late in the manufacturing or construction cycle are very costly and often have significant negative consequences to the project resources and schedule.

Machinery Condition

Turbomachinery manufacturers can greatly assist owner/operators in evaluating end of run equipment and hardware during unit turnarounds. This is best done by the manufacturer providing for each piece of machinery, detailed disassembly and reassembly instructions, required component and assembly drawings, handling instructions and procedures, cleaning procedures, inspection procedures, acceptance criteria, refurbishment and repair procedures, and shipping, storage and preservation procedures.

The machinery manufacturer must provide the necessary technical expertise to properly evaluate the machinery components.

The use of generalized inspection and repair procedures is not recommended since each machine design is unique. Without intimate knowledge of the design, materials of construction, structural and vibration margins and levels, unit operations, operating environment, etc., one cannot with confidence assess the condition of the components and their suitability for repair, refurbishment and/or reuse.

SUMMARY/CONCLUSIONS

Major Turbomachinery reliability issues continue to exist throughout all industries and applications. Environment degradation of the machinery continues to remain at the top of the list as the reason for equipment failures. It was the intention of this paper to highlight how common the problems are, the severity and diversity of the problems and how all types of Turbomachinery are affected. Steps can be taken by both the user and manufactures of the machinery to reduce to occurrences and magnitude of environment degradation. Turbomachinery reliability can be greatly improved if environmental degradation can be identified up front and the appropriate steps taken to mitigate it.

REFERENCES:

Dowson, P., 2011, "Development of Anti Fouling Type Coatings for Centrifugal Compressor and Industrial Steam Turbines", Hydrocarbon Processing

Dowson, P., Bauer, D., and Laney, S., 2008, "Selection of Materials and Material Related Process for Centrifugal Compressors and Steam Turbines in the Oil and Petrochemical Industry", 37th Turbomachinery Proceedings

Drosjack, M., Linden, D., Singh, M., 2014, "Expander for Oil and Gas Operations: Design, Applications, and Troubleshooting", McGraw-Hill

Filho, O., Donda, M, and Ramalho, E, 2012, "Hydrate Occurrence in Centrifugal Compressor Systems", 41st Turbomachinery Symposium

Forsthoffer, W., 2001, "Do as I Say" (The effect of the process on Turbomachinery Reliability). 30th Turbomachinery Symposium

Forsthoffer, W, 2005, "Principals of Rotating Equipment"

Hamed, A., Tabakoff, W., 2006, "Erosion and Deposition in Turbomachinery", Journal of Propulsion and Power, Vol 22

Henhorene, M., 2005, "Fundamentals of Corrosion", Carpenter Technology Corp.

Jonas, O and Machemer, L, 2008, "Steam Turbine Corrosion: Problems and Solutions", 37th Turbomachinery Symposium

Kua, R., Brun, K. and Mokhtab, S., 2011, "Gas Turbine Compressor Blade Fouling Mechanisms, Pipeline & Gas Journal.

Kurzs, R., Mecher-Homji, C., Brun, K., 2014, "Gas Turbine Degradation", 43rd Turbomachinery Symposia

Kurzs, R., Brun, K., Makhatab, S., 2011, "Gas Turbine Compressor Blade Fouling Mechanisms"

Linden, D., 2008, "Corrosion Control in Industrial Axial Flow Compressors", 30th Turbomachinery Symposium

Linden, D., 2011, "Long Term Operating Experience with Corrosion Control in Industrial Axial Flow Compressors", 40th Turbomachinery Symposium

McCloskey, T., 2002, "Troubleshooting Turbine Steam Path Damage Mechanisms", 31st Turbomachinery Symposium

Schilke, P., 2004, "Advanced Gas Turbine Materials and Coatings", GE Energy Publication GER-3569C.

Wang, Q., Houston, R., Pasinetti, E., 2001, "Centrifugal Compressor Impeller Stress Corrosion and Corrosion Fatigue Case Study", Corrosion 2001 – Paper 01238