Proceedings of the Fortieth Turbomachinery Symposium
September 12-15, 2011, Houston, Texas

# Long Term Operating Experience with Corrosion Control in Industrial Axial Flow Compressors

by
David Linden
President
D.H.Linden Associates, Inc.
Allentown, PA, USA

David Linden is President of D.H.Linden Associates, Inc. He has 37 years of experience in the turbo machinery industry. Mr. Linden has worked at a number of Original Equipment Manufacturer's including Conmec Inc., Dover, Dresser Rand Co., General Electric Co., Ingersoll Rand Co. and Westinghouse Electric Corp. Mr. Linden specializes in the areas of Turbomachinery design and reliability. Mr. Linden graduated with a BSME from Rutgers University. He is the author/coauthor of ten technical papers for various ASME and Turbomachinery Symposiums. Mr. Linden is a member of ASME, ASTM, NACE and a contributor to the API 687 Rotor Repair sub-committee.

## ABSTRACT

One of the primary causes of flow path failures in industrial axial flow compressors has been attributed to or is related to corrosion damage. Over the years, a number of corrosion mitigations have been utilized by various manufacturers and users. This paper summarizes several long term monitoring and assessment programs that evaluated the effectiveness of the mitigation steps and makes recommendations for future operation. The monitoring programs included detailed metallurgical analyses of corroded stator and rotor blades, material captured in inlet filter pads, flow path deposits and corrosion coupons. The hardware was examined at various run time intervals that ranged between 2 to 12 years. When possible, corrosion damage was mapped and quantified. The hardware was then returned to service and later re-evaluated in the exact same locations after the additional operating time.

## INTRODUCTION

This paper summarizes comprehensive corrosion studies carried out in seven industrial axial flow compressor installations. The operating experience of five FCC (refinery) main air blower applications and two lake side steel mill main air blower applications are the subject of this paper. Of interest, was the steel mill air quality and corrosion experiences were very similar to those measured in the refinery applications.

The purpose of these studies was to determine what are the causes of flow path (rotor blades, stator vanes and rotor drum or disk) corrosion and when does the corrosion damage cause risk to the compressor reliability or significant performance deterioration. Additional goals of the evaluations were to determine if the noted corrosion in these compressors could be minimized or eliminated via metallurgical upgrades of the rotor. Long term reliable operation of the compressors is critical to successful process operation.

All of the studied compressors were existing installations that were initially started between 1960 and 2003. In addition, all of the subject compressors had experienced at least a one rotor (blades and/or disc) failure in which rotor corrosion was either the cause or a major contributor to the failures.

The basic methodology of the corrosion monitoring started by base-lining the condition of new hardware being installed into the compressors. Periodic assessment of the compressor hardware was then made via in-place crawl in inspection during unit shut downs, borescopic inspections during quick unit shut downs and unit disassembly at major turnarounds. In addition, several of the compressors were modified to accept online removable corrosion coupons.

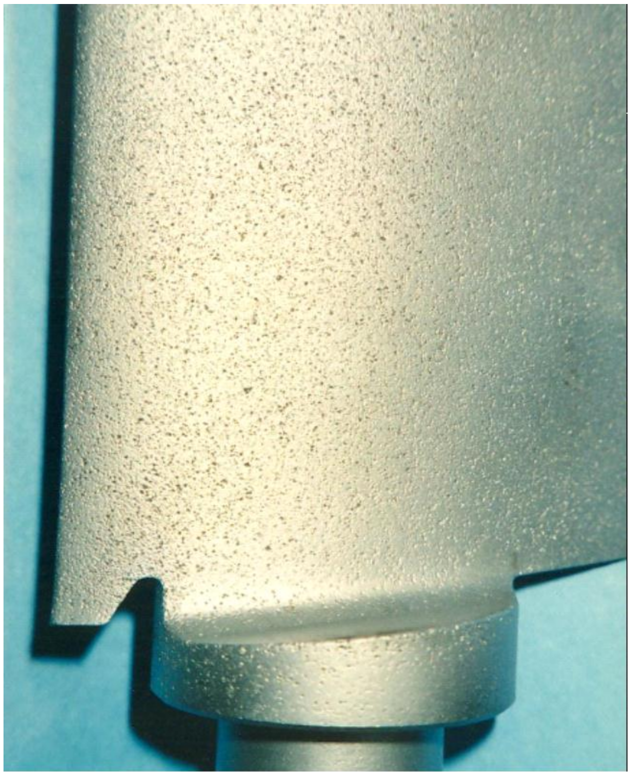

**Figure #1 – Corrosion Pitting of 410 SS IGV after 36 months of service**

**Figure #2 – General and Pitting Corrosion of 403 SS First Stage Rotor Blades after 24 months service**

## CORROSION:

Compressor flow path corrosion can be divided into two basic types; General and Localized.

- General Corrosion is a uniform corrosion in which the metal corrodes at a fairly constant rate over the entire surface of the part.

- Localized Corrosion is where only a small area of the metal surface is affected, although the rate of corrosion in this small area is often very high. Examples of localized corrosion include inter-granular corrosion, stress corrosion cracking, pitting and crevice corrosion.

Pitting corrosion has been found to be the more significant corrosion in industrial axial flow compressors. The pits are often the crack initiator in blade fatigue failures. Pitting in stainless steel materials that are apparently immune to attack by certain solutions, can fail by corrosion occurring in localized areas. The cause of this local corrosion is related to material build ups on the surface of the material. The area in or immediately under the deposit can form a local environment that is oxygen deprived. Oxygen on the surface of the stainless steel metal is required to maintain the corrosion resistant surface film. In addition, the localized corrosion can be further accelerated by the creation of aggressive acids.

Compressor general and local corrosion is generally the result of moisture containing salts and the formation of aggressive acids collecting in and around the deposits and on the blade and vane surfaces. During normal operation air borne moisture is present in the inlet stages the compressor. The moisture is the result of fog, rain, snow, humidity, etc. Addition moisture drops out of the air due to the rapid air acceleration and lowering of the air pressure in the first several stages of the compressor. Water as a liquid often exists in the first five stages of the compressor. As the air gets compressed and heated up in the later stages of the compressor, the water turns into a vapor and operational corrosion significantly decreases.

Figures #1 and 2 show how severe the flow path corrosion can be. Figure #1 shows a cleaned Inlet Guide Vane (IGV) after 37 months of service. Heavy pitting can be seen over the entire part. These IGVs were manufactured from 410 Stainless Steel (SS) bar and were uncoated. Figure #2 shows severe rotor blade corrosion (403 Stainless Steel) and rotor disk corrosion (4340 alloy steel) after only 24 months of service. The rotor blades experienced both a generalized corrosive attack as well as corrosion pitting. The pitting on the blades exceeded 0.125” (3.2 mm) in diameter and penetrated into the base material more than 0.030 in (0.8 mm).

## MATERIALS:

| Trade Name | Typical Industry Specification | Nominal Chemistry | Relative Corrosion Resistance |
|---|---|---|---|
| | | | |
| Alloy steel (Disc Material) | AMS 6414<br>AISI 4340 | Fe, 1.8Ni, 0.8 Cr, 0.25 Mo | 2 |
| 403/410 SS | AMS 5611<br>AMS 5609 | Fe, 12 Cr | 1 |
| 420 SS | AMS 5621 | Fe, 13 Cr, 0.35, C | 1 |
| 300 SS<br>321/347 | AMS 5645<br>AMS 5646 | Fe, 18 Cr, 10 Ni | 5 |
| 15-5 | AMS 5658 | Fe, 15 Cr, 5 Ni, 4 Cu | 3 |
| 17-4 | AMS 5643 | Fe, 17 Cr, 4 Ni, 4 Cu | 3 |
| Carpenter Custom 450 | AMS 5763 | Fe, 15 Cr, 6 Ni, 1.5 Cu | 3 |
| Irrubigo | N/A | Fe, 25 Cr, 5 Ni | 4 |
| A-286 | AMS 5735 | Fe, 25 Ni, 15 Cr, 2 Ti | 4 |
| Inconel 718 | AMS 5663 | Ni, 19 Cr 17 Fe, 5 Cb,3Mo | 4 |
| Titanium | AMS 4928 | Ti, 6 Al, 4 V | 5 |

**Table #3 – Summary of Commonly Used Compressor Flow Path Materials**
Corrosion Resistance: 1 - Low, 5 - High

The above Table #3, shows that a variety of materials have been utilized in industrial axial flow compressors, as well as in the compressor section of gas turbines. For many years, the industry standard for rotor and stator blades has been the 400 series (12% Cr) stainless steels. The 400 Series Stainless steels offer good strength, ductility and moderate corrosion resistance. Unfortunately, these materials have not held up well over extended (>4 years) periods of operation, particularly in environments significant Salts, Sulfur, or Fluorine. High pressure ratio compressors, such as those in a gas turbine, utilize the above high nickel and nickel base alloys. These high nickel alloys are used in the later stages to accommodate the increased operating temperatures of the gas turbine compressor.

*Bare 403or 420 Stainless Steel* – Under most refinery and steel mill environments, uncoated 403, 410 and/or 420 SS was found to develop significant surface pitting in less than 2 years of unit operation. The corrosion was found to be quite severe at the end of run (typically 4 years of operation) and major blade refurbishment or replacement is usually required.

*Austenitic Stainless Steels (300 Series)* – The higher Chromium (18%) and Nickel (10%) content of the 300 series SS makes these materials very corrosion resistant to the corrosive environments of the industrial axial flow compressors. Unfortunately, the 300 series SS do not have the mechanical strengths that are required for compressor rotor blading, and therefore, are not typically used for rotating components. The 300 Series SS have been utilized, and are the industry standard for most stationary vanes.

*Duplex Stainless Steels* – A number of hardenable duplex stainless steels have been utilized to provide increased corrosion resistance. Carpenter Custom 450, 15-5 and 17-4ph are examples of the duplex stainless steels. These materials provide increased tensile strength without sacrificing stress corrosion resistance. Substantial increases in the high cycle fatigue and corrosion fatigue strength are also achieved with these materials when compared to 403 SS. Superior corrosion resistance is achieved due to the higher chromium and molybdenum contents. These materials have been found to be very effective for environments where the acidity is greater than 4.5 pH. For more aggressive environments, even the duplex SS have experienced pitting corrosion during operating periods of less than 2 years. The following Figure #4 is an example of significant pitting damage on the inlet stage vanes and rotor blades of an FCC air blower.

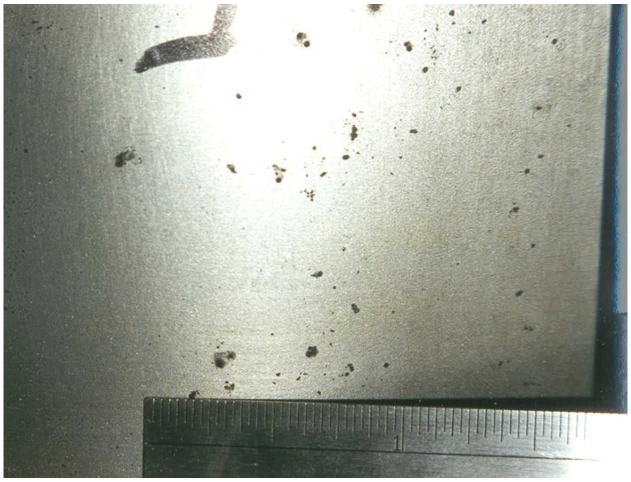

**Figure 4 – Bare CC 450 Blading**
Note: Surface Pitting after 18 months of operation

*Super Alloys* – High Nickel or Nickel based super alloys are generally not used in industrial axial flow compressors since the discharge temperatures are typically under $500^o$ F ($260^o$ C). The need for high temperature strength and the lack of corrosion in the later stages of the compressor do not justify the high costs of the super alloys. None of the monitored compressor in this paper utilized super alloy blading.

*Titanium* – Aircraft engine experience and laboratory testing suggested that Titanium blading might be a good choice of material for the industrial air compressor. Indeed, operating experience has confirmed that the Titanium material had superior corrosion resistance than that of the Duplex and 400 Series SS alloys.

These corrosion evaluations suggest that the Titanium material corrodes in a different manner than the other blade materials. The Titanium material appears to achieve a self-limiting corrosion pit depth, i.e. after an initial pit formation, the pits did not continue to penetrate into the base material over time.

## BLADE COATINGS:

Flow path coatings have been successfully applied to industrial axial flow compressors for many years. The coatings have been found to be very corrosion resistant to many industrial atmospheres and often have positive effects on compressor performance. Several types of coatings have been successfully applied:

*Electroless Nickel and Nickel Cadmium* – Nickel base coatings have been used successfully for many years in industrial axial flow compressors. Even in a thin coating thickness, they exhibit excellent corrosion resistance in sea salt environments and provided good erosion resistance. Service experience has shown that the Nickel based coatings were not found to hold up in the more severe industrial applications where the surface deposits where highly acidic (pH<6.0). Nickel Cadmium coating use has also been on the decline in recent years due to the environmental toxicity of the Cadmium metal.

*Aluminum Ceramic* – Extensive (> 40 years) operating experience also exists with the use of Aluminum Ceramic Coatings. These coatings are usually sprayed on to the blades with a chromate and phosphate corrosion inhibitor, cured in an oven and burnished to promote electrical conductivity. Corrosion protection continues despite holidays or defects in the coated surface due to the galvanic potential making the Aluminum in the coating sacrificial. The Aluminum Ceramic coatings have been found to provide good corrosion protection for both high salt and acidic environments.

While the coatings have provided excellent corrosion protection to compressor flow path components, the life of the coatings has been found to be limited due to erosion. This is particularly true of compressors that do not have effective inlet filtration and where there is a large ingestion of particulate matter into the compressor.

*Base Material Compatibility* – In these corrosion studies, it was found that not all compressor base materials are capable of being coated. Problems were encountered in the coating of some of the Duplex SS materials. In the highly acidic salt environments, the coatings were found to be separating/de-bonding from the base material. Detailed metallurgical investigations showed the deterioration in coating bond strength was attributable to galvanic couplings created between the coating and base material.

## FIELD GAS TESTING AND MONITORING:

In all tested compressor installations, air quality measurements were taken in order to identify the source of the various corrosion contributors. The field measurements were helpful and often identified the major sources of corrosive species. It should be recognized that they represent a single point in time and the gas measurements and ambient conditions were found to vary significantly over time and were often seasonal. The field measurements did consistently find significant levels of Potassium and Sodium Salts, Sulfur and Ammonia in all installations.

All installations also exhibited significant levels (greater than 25 percent of the sample) of air borne particulates such as road dust, Iron, Copper and Zinc Oxides. As would be expected, the FCC applications showed significant levels of FCC catalyst, while the Steel Mill applications showed high levels of slag pile particulates.
High levels of sea salts were found in all coastal installations, although many non–coastal installations were also found to have high levels of salts. The source was usually a local water cooling tower.

## FLOW PATH DEPOSITS:

Flow path deposition has found to vary significantly throughout the compressor flow path.

*Inlet Stages* – Inlet stage flow path deposition is generally found to be a wet oily type deposit. The deposit is often mistakenly identified as oil leakage from the compressor bearing housing since it is wet and oily in appearance. Detailed chemical and compound analysis found that these deposits are almost always Ammonium Sulfate rather than a hydrocarbon. In addition, salt deposits are often present as can be seen as the white colored crystal deposits in Figures #5 thru 7.

*Mid Stages* – The middle stages of the compressor were often found to have the heaviest flow path deposits. The middle stage deposition is due to the increasing air pressure and temperature that vaporizes the liquids in the air. Some of the compressors experienced a deposition of wash solution residual solids in the middle states and the re-deposition of washed deposits from the inlet stages.

*Discharge Stages* – The later stages of the compressor generally experience dry powdery deposits as can be seen in Figure #7. While these deposits are of similar chemistries to the earlier stage deposits, they do not cause in-service corrosion of the blade materials due to the stages operating dry.

It should be noted, that the same type of aqueous corrosion experienced in the inlet stages, can be seen in the later stages, if the compressor were shut down and idle for a period of time or if the rotor is left un-cleaned and in a humid or moist environment.

Major compressor performance deterioration can result from flow path deposits. Flow capacity and pressure reductions of more than five percent are common and can be in excess of ten percent.

**DEPOSIT CHEMICAL & COMPOUND ANALYSIS:** Whenever possible, flow path deposits were removed from the compressor inlet casings, corrosion coupons and compressor flow path components for analysis. Throughout the twelve year evaluation period, over 80 compressor deposits were collected and analyzed. The following Table #4 summarizes the results of the various deposit chemical analyses. It can be clearly seen that Iron and Sulfur made up a major portion of most flow path deposits. Chloride salts were also very common, particularly in the coastal installations.

A common finding throughout the various compressors tested was the presence of Ammonium Sulfate. Ammonia and sulfur oxides enter the compressor as a gas, and then

| Element | Minimum weight. % | Maximum weight. % | Typical (average) |
|---|---|---|---|
| Sodium | 2 | 19 | 5 |
| Aluminum | 1 | 21 | 8 |
| Silicon | 0 | 35 | 10 |
| Sulfur | 22 | 68 | 32 |
| Chlorine | 2 | 26 | 10 |
| Potassium | 0 | 5 | 2 |
| Calcium | 0 | 8 | 3 |
| Iron | 6 | 68 | 42 |
| Copper | 0 | 10 | 1 |
| Zinc | 0 | 12 | 1 |

**Table #4 Deposit Analysis Results** – Weight Percent

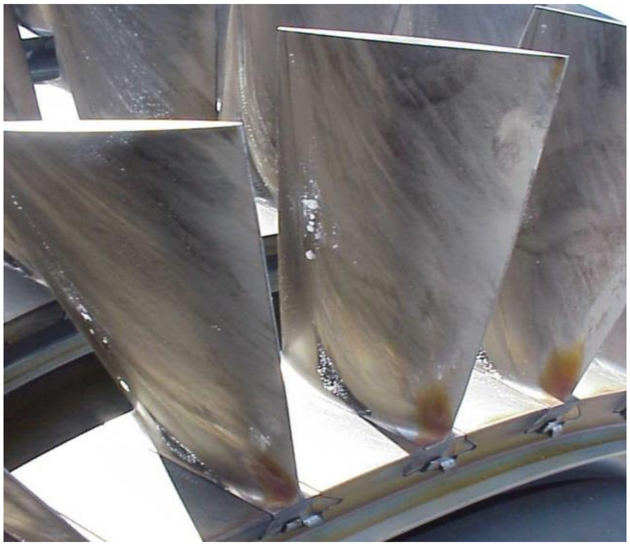

**Figure #5 - 1st Stage Blade Deposits**

**Figure #6 - 8th Stage Deposits**

**Figure #7 - 15th Stage Deposits**

precipitate as ammonium sulfate or iron-potassium ammonium sulfate on the inlet guide vanes, rotor blades, and stator blades. Ammonium cations can be replaced by potassium, iron, sodium, copper and zinc. Corrosion occurs when the moisture quantity is high enough to condense on the blade surface and is in contact with these compounds.

In the presence moisture, the Ammonium Sulfate can create an acidic condition with a water saturated pH as low as 4.5. The presence of chlorides in the deposits, appears to promote the formation of crystalline compounds. Specifically, a Hexahydrate formation of the sulfate. The formation of an Iron (Potassium or Zinc) Ammonium Sulfate Hexahydrate was often found to deposit in the inlet of most compressors. These crystalline compounds were found to be extremely acidic, with a water saturated pH's as low as 2.5. In some compressors, the Hexahydrate compounds made up as much as sixty percent of the deposit weight.

Generally after the fifth stage of the compressor, the Hexahydrates dehydrate due to the higher temperature of the compressed air. The higher temperature destroys the crystalline compounds and reduces the corrosive potential in the stages where the operating temperature is above 220$^{o}$ F (100$^{o}$ C).

The most corrosive environments were created when high levels of Chlorides (> 500 ppm) and/or Fluorides (> 1000 ppm) were present in the inlet air. Alkylation plants are generally the source of the Fluorides.

## CORROSION EVALUATIONS:

*Corrosion Coupons* – The use of corrosion coupons provided a way of monitoring corrosion potential and the progression of the corrosion over time, without having to disassemble the compressor or interrupt the process operations. The coupons were typically installed 45 degrees off of the vertical centerline in the top half of the stator casing, and upstream of the inlet guide vanes. The coupons were round in shape and had a small penetration into the compressor flow path.

The cylindrical coupons included a milled flat that faced toward the discharge side of the compressor and tend to accelerate deposit deposition due to the downstream flow separation. Figure #8 shows two "as found" corrosion coupons after several years of service. In this example, the cleaner/top coupon was bare Titanium, while the second coupon was an Aluminide Coated Alloy Steel. It can be seen that the Titanium coupon experienced virtually no visible signs of corrosion. Figure #9 shows a close up of the same coupons after a light solvent cleaning. The bare alloy steel material shows significant general corrosion/oxidation, while the coated regions

**Figure #8 – As received Titanium (top) and Coated Alloy Steel (bottom) Corrosion Coupons**

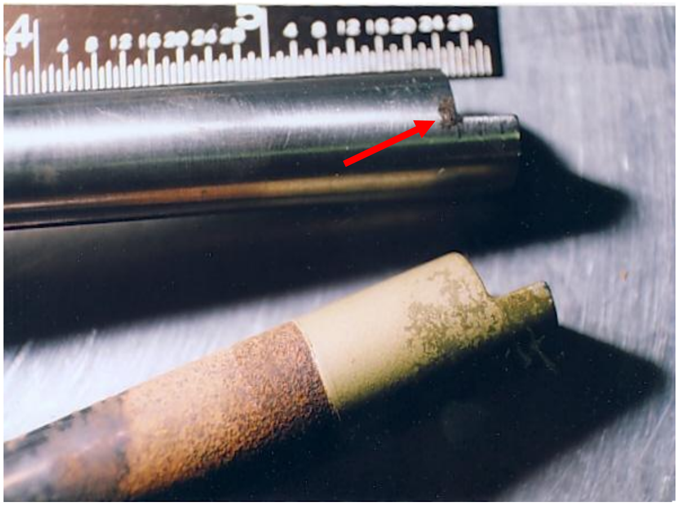

**Figure #9 - Close up of Corrosion Coupons**

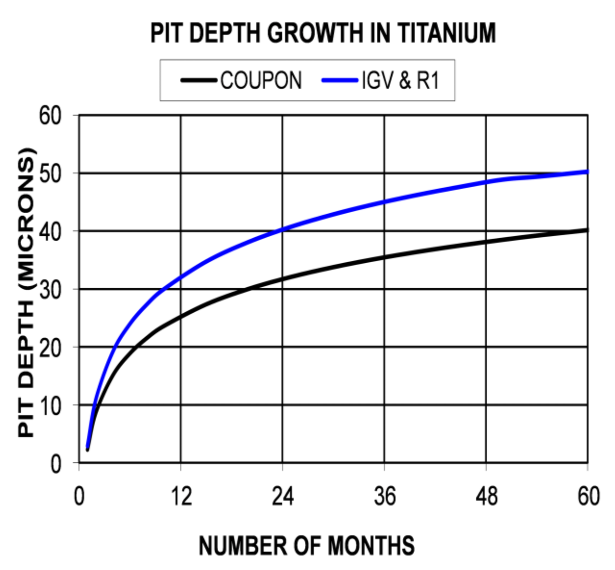

**Figure #10 Pit Depth Measurements** – Probe vs. Blade show some deterioration of the Chromate top coat. From the evaluation data, it can be seen that compressor corrosion coupons do show the same corrosion potential and characteristics as the actual blading. The corrosion coupons tended to show somewhat less corrosion which could be attributable to the lower operating time (coupons were removed for approximately one month each year), the cleaning and minor polishing during the evaluations and the location being favorable for cleaning during compressor online water washing.

*Stator Vanes and Rotor Blades* – The actual flow path blading required a significant amount of work to evaluate the blade for corrosion due to the complexity of the shape and often more numerous corrosion pits. Evidence of corrosion was generally most severe on the leading edge of the airfoils, although it could be found over the entire blade/vane airfoil (reference Figure #3) and attachment region. Figure #11 shows significant corrosion pitting on the leading edge (near the base) of a rotor blade airfoil after 18 months of service. Corrosion pits as large as 0.025 inches (0.64 mm) in diameter by 0.015 inches (0.38 mm) in depth were noted in this compressor.

*Inspection Procedure* - The nondestructive inspections and corrosion pit studies were conducted similarly on both the corrosion coupons and the actual flow path components:

- The parts were visually inspected and the condition photo-documented.
- A binocular microscope was used to survey the as received surfaces and deposits.
- Macro and micrographic records were made of the interesting areas.
- Corrosion deposits were removed from the surfaces using an electrically conductive carbon tape with adhesive on both sides.
- Deposits were analyzed in the scanning electron microscope by Energy Dispersive Spectroscopy for a semi-quantitative analysis of chemical elements.
- Light microscopic observations of surfaces were made and wherever possible, corrosion damage was mapped.
- The major crystalline chemical compounds in the deposits were identified via X-ray Diffraction techniques.
- The examined hardware was cleaned in water or acetone with a soft bristle brush and visually inspected.
- Light microscope photomicrographs of representative corrosion pits and corrosion products were obtained.
- The most interesting areas of the surfaces were surveyed using a metallurgical microscope.
- Significant pits were mapped, dimensional inspected and photographed.
- Pits were cleaned with acetone and replicated with cellulose tape to obtain a permanent record.

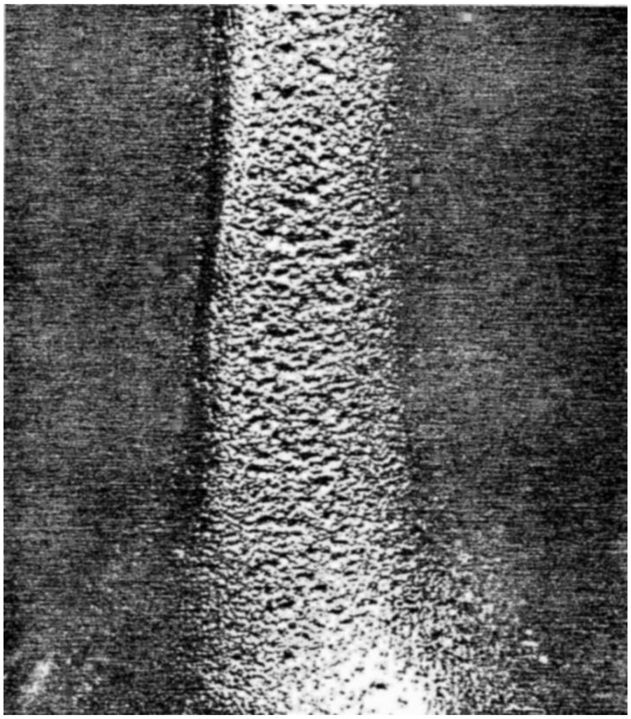

**Figure #11 – 403SS Rotor Blade Leading Edge Pitting-**8X

**PIT DEPTH SURVEYS:**

Pit Depth Surveys were conducted to monitor corrosion activity and to monitor the progress of the pitting over time. Mapping of significant corrosion pits to hard surface features allowed the researchers to return to the same pits at subsequent evaluations. The pit depths were found to vary throughout the compressor as can be seen in Table #12. This data represents a single compressor that operated for three, two year (6 years total) operating periods with the different blade materials as listed.

| Stage | Run #1<br>403 SS | | Run #2<br>CC 450 | | Run #3<br>Titanium | |
|---|---|---|---|---|---|---|
| | Mils | Micron | Mils | Micron | Mils | Micron |
| 1 | 10 | 250 | 3 | 76 | 2 | 50 |
| 2 | 22 | 560 | 8 | 200 | 2.4 | 61 |
| 3 | 17 | 430 | 6 | 150 | 2.3 | 58 |
| 4 | 11 | 280 | 4 | 102 | 2 | 50 |
| 5 | 10 | 250 | 5 | 127 | 1 | 25 |
| 6 | 3 | 76 | 1 | 25 | - | - |
| 7 | 3 | 76 | 2 | 50 | - | - |
| 8 | 2 | 50 | 0.5 | 13 | - | - |
| 9 | 1 | 25 | - | - | - | - |
| 10 | 0.5 | 13 | - | - | - | - |

**Table #12 - Maximum Corrosion Pit Depth by Stage**

24 month operating periods

The pit depths were measured with an optical depth micrometer or a light metallurgical microscope at a magnification of 2OOX. The pit depth measurement accuracy is estimated to be +/-0.0002 inches (5 microns).

The corrosion damage measured in all of the tested compressors was found to be most severe in the front end of the compressor. Typically the most severe corrosion was found in the 2nd and 3rd stages. The front end corrosion is the result of the foreign materials that deposits on the blading in the front end of the compressor. The inlet air experiences sub-atmospheric conditions that causes various air borne corrosion species and additional water to separate and deposit in the flow path. As the air is further compressed in the latter stages, the air temperature and pressure increase to a point where the liquids become gaseous and do not form the aggressive acids that cause the corrosion.

Basis the pit depth surveys, a number of interesting observations were made:

- *Alloy Steel* - The alloy steel rotor body or disk material experienced more general surface corrosion and less pitting. Unfortunately, when pitting occurred, it was typically located in critically stressed regions such as in the blade attachment. This appeared to be related to deposits building up in this confined area and promoting a crevice corrosion attack.

- *400 Series Stainless Steel* - The 400 Series Stainless Steels typically experienced both a general corrosion and pitting (reference Figures #1&2). The harder/higher strength versions of the alloy experienced much more severe corrosion. At times it was difficult to determine the pitting corrosion rate since the general corrosion removed surface material and caused the pit depths to appear to be less than previous readings. When evaluations were made on a corrosion coupon, the diameter of the coupon was also monitored to determine the general corrosion rate as well as the pitting corrosion rate. Shallow machining marks on the corrosion coupons were beneficial in evaluating the general corrosion rate and locating previously noted pits.

- *300 Series Stainless Steel* – The 300 Series Stainless Steels used for stationary vanes were found to have excellent corrosion resistance and no significant corrosion was noted in any of the compressor inspected.

- *Duplex Stainless Steels* - The Duplex Stainless Steels (Custom 450) materials experienced little general surface corrosion, but limited and more aggressive pitting attack (reference Figure #4). The Duplex Stainless Steels did provide significantly more corrosion protection than the 400 Series Stainless Steels in environments where the deposit acidity was greater than a pH of 4.5. The Duplex Stainless Steel appeared to have a corrosion pit growth rate between one half to one third that of the 400 Series Stainless Steel. The pitting occurred only in the most severe corrosive environments when the deposit acidity was between a pH of 3.0 to 4.5.

**Figure#13- 1st& 2nd Stage Titanium Blades** - 48 months

- *Titanium* – While used in a limited number of compressors, the Titanium blades showed excellent corrosion resistance in all applications including the most severe. Figure #13 shows the condition of first and second stage Titanium blades after 48 months of service. The subject blades were returned to service for another four year operating campaign. The pit depth evaluation of the subject blades showed both very minor general and pitting attack. Titanium compressor blades typically showed a general corrosion attack of less than 1.0 mils (25 microns) in depth and a pitting corrosion attack of less than 3 mils (76 mm). The Titanium attack was found to occur in the first 24 months of service and then had virtually no progression or worsening over the additional operating time. This phenomenon can be seen illustrated in Figure #14. Of all the materials monitored, the Titanium experience the least corrosion damage and appears to be a good choice of material for the more highly corrosive applications.

A comparison of the pit depth growth in three blade materials can be seen in Figure #14. This data is for a specific compressor installation and the data represents that compressor's operation in its unique operating environment and at a given time period. The data shows the different corrosion pit growth rates for 403 Stainless Steel, Carpenter Custom 450 (1050 HT) and Titanium. Similar data was generated for the various compressors analyzed in this study. The different compressor corrosion pit depth growth and their characteristics are obviously site specific. While the pit depth growth rates varied between the different analyzed compressors, the relative corrosion rates and characteristics of different materials was the same. Between all seven compressors the pit depth growth rate varied approximately +10 to -25%.

Armed with a Structural Analysis and Fracture Mechanics Data, limits on pit depth can be established for each compressor and individual compressor component lives can be predicted. These types of analyses are obviously machine specific.

*<u>Coatings</u>* – Evaluated compressors that utilizing rotor and flow path coatings used Aluminide Coatings with an inorganic top coat such as Sermatech's 5380 DP coating system. In general, the coatings were found to be very corrosion resistant to even the most severe environments. While the coatings offered excellent corrosion protection, they did deteriorate over time:

- After approximately 11/2 years of operation, the coating often exhibited micro-cracking in the surface seal/top coat. While extensive top coat surface cracking was noted, it did not appear to reduce the corrosion protection of the coating.

- Many units experienced erosive wear of the airfoil coating. Significant coating loss (both the top and base coats) occurred along the leading edge and just forward of the trailing edge of the airfoils. The erosive wear was experienced mainly in the first two or three stages of the compressor. It appears that the erosive media is centrificated outward in the flow path and ever decreasing wear patterns occur in the tip region of the subsequent stages. Coating erosive wear was most prevalent in compressors that did not have effective inlet filtration systems.

- General coating top coat wear/deterioration was found to occur with operating time. A general loss of top coat and eventually base coat occurs, leaving an orange peel looking characteristic.

- In the most severe (highly acidic) applications, coating delamination was found in the rotor disks under the blade attachments (See Figure #16). This deterioration was attributed to a very aggressive crevice corrosion in the attachment region.

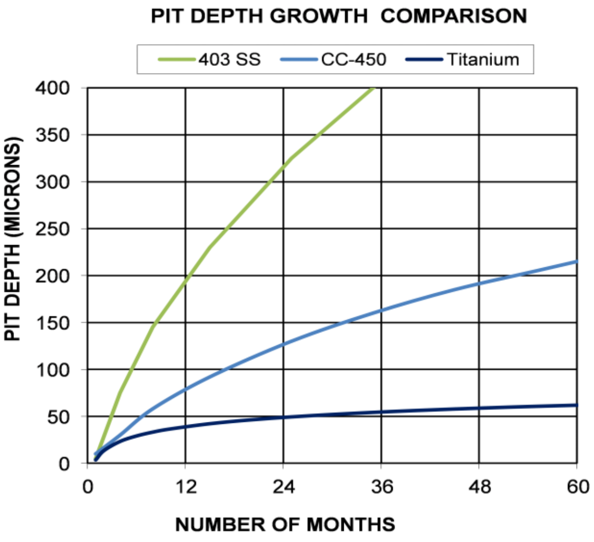

**Figure #14 – Pit Depth Growth vs. Time**

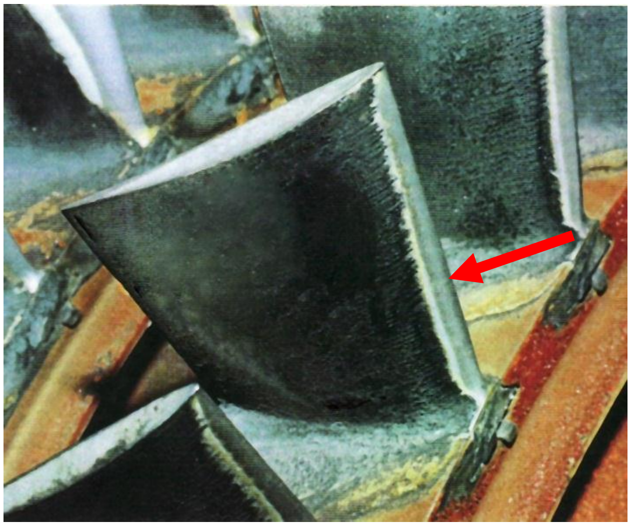

**Figure # 15 – Location of Erosive Wear**

**Figure#16 - Disk Coating Delamination** -18 months

## COMPRESSOR INLET FILTRATION:

Compressor erosion and flow path fouling has always been a concern in the operation of many industrial axial flow compressors. Flow path erosion and/or fouling causes both a reduction in flow capacity and efficiency. Reductions in flow capacity are often in the 3 to 5% range and have been seen to be more than 10% in some installations. Similar losses in efficiency have been noted. In addition to the performance losses, many compressor experience surge problems since the erosion or fouling changes the performance characteristics of the compressor. Fouling tends to cause surge to occur at a lower discharge pressure and effectively moves the compressor performance map to the left and downward (See Figure #17). The degree of erosion and fouling experienced by a compressor is dependent upon a large variety of items/issues including the type, size and concentration of the contaminants being ingested and the compressor aerodynamics. The local compressor operating environment is obviously most influential.

Inlet air filtration is obviously one of the most effective actions that can be taken to reduce the amount of flow path deterioration. Inertial and mechanical filters are commonly used. Typical industrial axial flow compressor inlet filter systems are a multistage design that should incorporate the following design features:

- Online replaceable filter elements.
- Designed to have a clean inlet pressure drop of less than 2 in. ($H_2O$) (50 mm) and a maximum pressure drop from fouling of less than 4 in. ($H_2O$) (100 mm).
- 1st Stage - Weather hood and screen to prevent the ingestion of rain, ice, snow, insects, birds, and other foreign materials.
- 2nd Stage – Pre-filter to remove larger particulate and increase the life of the final stage of filtration.
- 3rd Stage – Barrier Filter that removes more than 99% of 5 micron or larger particles.
- Air tight construction.
- Corrosion resistant (stainless steel) housings, internal supports and fasteners.
- Blow in provisions to prevent excessive pressure drop should the filter become clogged.
- Online monitoring of filter differential pressure.
- Provisions to allow online cleaning of the compressor.
- Designed to accommodate compressor surging.
- Anti-icing provisions if required.

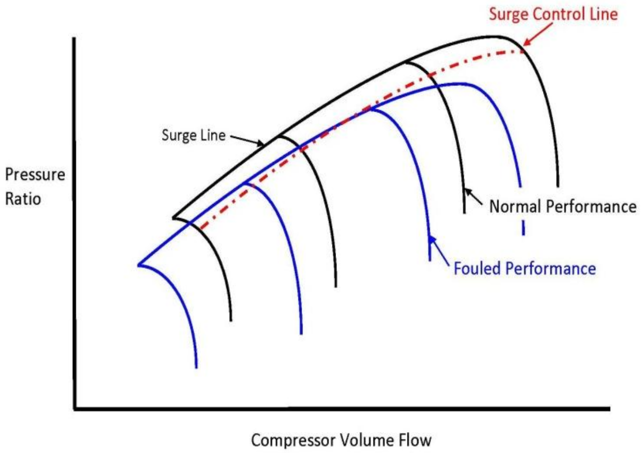

**Figure #17 – Effect of Flow Path Fouling on Compressor Performance**

As part of the subject compressor corrosion evaluations, the effectiveness of the inlet filtration systems was also evaluated at several installations. Almost one half of the compressors evaluated did not have inlet filters. These installations used inlet bells that partially removed large water droplets from the rain and prevented the injection of large objects only (bird screens). As would be expected, the compressor installations without inlet filters definitely experienced significantly more inlet duct corrosion and fouling, compressor blade/vane base material corrosion and erosion, flow path deposition and its resulting performance deterioration. The rate and amount of flow path erosion and fouling was typically more than three times higher than that of compressors operating with an inlet filtration system. While the benefits of an inlet filter system are quite evident, it should be pointed out that the filter systems have a significant initial cost, an ongoing maintenance cost, do require periodic maintenance and the additional inlet system losses result in a slight reduced compressor capacity.

The inlet filter evaluations included sectioning filter elements at given intervals to determine the effectiveness

**Figure #18 – Filter Element Captured Material** – 3X of the current filters. Trapped particle size analysis and chemical compositions of the captured material were made. One of the primary goals of the analyses was to determine the time intervals between filter element change outs. Filter element evaluations typically included examining the filter pads after 60, 90, 120 and 180 days of compressor operation.

The filter pad analysis work included macro and microscopic examination of the materials captured in the filter pads (See Figure #18). As expected, the material separated in the filter elements typically included ambient air particulates such as air borne dust, catalyst, sea salts and minerals, gaseous deposits (sulfates), and Iron and Zinc corrosion products.

Interestingly, high concentrations of chlorides and sulfates were found to be migrating through the filter elements over time. Aqueous chemical solubility of the chlorides and sulfates during periods of high rain and/or humidity was identified as the cause of the migration. Extremely high concentrations of chlorine and sulfur were found to be migrating through the filter pads after approximately 90 to 120 days of operation. Over time, the corrosive salt concentrations were actually found to be higher on the discharge side of the pads versus the inlet.

The following conclusions can be made after numerous filter pad analyses were made at multiple installations:

- Corrosion elements such as chlorides, sulfur and fluorine migrate through the filter pads over time.
- High efficiency filter elements do a good job in stopping the entrance of insoluble particulates of catalysts, metal, corrosion products and minerals.
- The filter elements do not prevent the ingestion of gaseous or water soluble compounds and particles.
- Filter analysis was found to be very helpful in determining the optimum filter change out period. The change out period varied between different compressor installations.

## COMPRESSOR FLOW PATH CLEANING:

One of the most effect actions that can be taken to reduce compressor flow path corrosion is to keep compressor flow path clean of deposits. Figures #19 and 20 show a fouled compressor flow path after only a few months of operation and a clean flow path after several years of operation. An added benefit of compressor online cleaning is the maintenance of high compressor performance. Several compressor installations have been able to maintain both the compressor capacity and efficiency within 2.5% of the initial startup values, four to five years after the unit start up.

**Figure #19 – Typical Inlet Stage Flow Path Deposits**

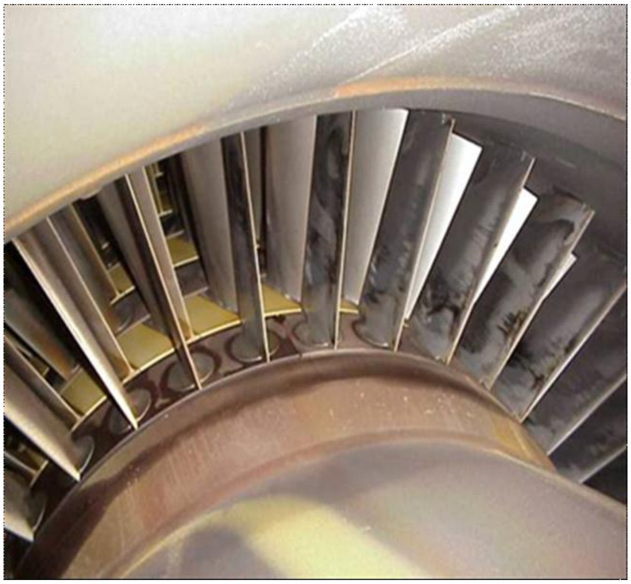

**Figure #20 – Cleaned Flow Path from Online Washing**

Online cleaning of the compressor flow path is most effective if it is conducted on a routine basis and as a preventative to the buildup of deposits. Online cleaning should be started at the beginning of the operating campaign before the deposits have had a chance to adhere to the flow path surfaces. Many commercial online cleaning solutions include surfactants that inhibit the adhesion of the deposits to the flow path. Accumulated deposits are very tenacious adhered to the blade surfaces and the most difficult to remove. Often, the removal of accumulated deposits can only be accomplished by slow speed or crank washing, abrasive cleaning or in the extreme, mechanical polishing.

## ONLINE CLEANING METHODS:

*Water or Detergent Washes* – One of the most common practices for cleaning in-service compressors is to inject a liquid into the inlet of the compressor. The cleaning solution helps to dissolve many of the soluble flow path deposits and washes them off of the blades. Additional cleaning action is also achieved via the liquid droplet impaction. Figure #21 shows the injection of a cleaning solution into the inlet of a compressor. A variety of cleaning solutions have been used that vary from treated water to commercially available detergent or solvent based mixtures. The wash solution is generally injected via a number of nozzles (typically 6 to 10) strategically located in the compressor inlet casing. Critical to the process is the nozzle sizing and location to assure effective cleaning and the full coverage of the flow path.

Experience has shown that water/detergent washing is effective in cleaning the inlet (1 thru 5) stages of the compressor. Since the inlet stages of the compressor determine its capacity, it is understandable why online cleaning helps to maintain the compressor's capacity. The migration of the cleaning solution to the outside of the flow path and the vaporization of the cleaning solution in the later stages prevents effective middle and discharge stage cleaning. Some compressors have experienced the removal of deposits in the inlet end of the compressor and a re-deposition of the removed material in the latter stages.

The effectiveness of the online cleaning is very site specific, but generally depended upon the type of wash media, the quantity of the media, the wash media droplet sizes, the duration of the cleaning and the frequency of cleaning. Flow rates of 4 to 10 gallons (16 to 38 l) per 100,000 SCFM are typical cleaning flow rates.

Field experience has shown that online water/detergent washing should be conducted at least once or twice a week throughout the compressor's operating campaign. Online cleaning is conducted at the compressor's full operating speed and load.

Water or Detergent Slow Speed/Crank Washes – Slow Speed or Crank washes are similar to the online full speed water/detergent washes of the compressor. Slow speed washes are generally done at greatly reduced operating speeds such as 500 RPM. Crank washes are generally conducted with the compressor on turning gear 5 to 50 RPM). At the lower speeds, significantly (2 to 4X) increased quantities of cleaning solution are injected into the compressor. The increased solution flow, the low flow path air velocities and the reduction in centrification of the solution make the cleaning of all compressor stages more likely. The solution is generally allowed to soak for a period of time to assist in dissolving built up deposits.

**Figure #21 – Online Liquid Cleaning of Comp.** Blading

**Figure #22 – Typical Online Liquid Cleaning Skid**

Casing drains are opened after the soak period to remove and prevent the accumulation of the cleaning solution in the bottom of the compressor.

Most online cleaning is done via dedicated cleaning skids (See Figure #22) that mount the pump, regulators, controls and cleaning solution. The controls can be used to vary the cleaning parameters and make the operations totally automatic if desired.

Online Abrasive Cleaning – Another effective online cleaning process for the cleaning of the compressor flow path is abrasive cleaning. This is sometimes referred to a walnut shelling. Cleaning is accomplished by injecting abrasive media into the compressor inlet. Generally, very fine organic materials such as nut shells or rice are commonly used. The abrasive material will remove more of the tenaciously attached deposits and get further through the compressor than the liquid cleaners.

While abrasive cleaning is very effective, one downside of abrasive cleaning is that excessive quantities or the use of too large of an abrasive can cause erosion of the flow path components. Blade and vane corrosion coatings are most susceptible to the erosive effects of the cleaning media.

<u>Shut Down Cleaning</u> – At ambient temperatures, it has been found that many of the compressor flow path deposits are hygroscopic (attract and hold water molecules). During periods of compressor shut down or even when removed and stored in the fouled condition, the later stage dry deposits will hydrate and form the aggressive acids previously discussed in this paper. The same type of corrosion damage see in the inlet stages can begin to quickly occur in the later stages of the compressor, where in-service corrosion did not occur. With this in mind, compressors that are shut down for extended periods of time (weeks) should be kept dry via external blowers and heaters. In addition, removed rotors should immediately be cleaned within days of decommissioning. A light abrasive cleaning onsite is highly recommended.

## SUMMARY/CONCLUSIONS:

This paper summarized the results of comprehensive corrosion studies carried out in seven industrial axial flow compressor installations. The following conclusions can be made basis the studies:

1. The local environment around a compressor installation can cause very corrosive environments in the compressor. Salts and sulfur in the air are the primary cause for the formation of corrosive deposits.

2. While general surface corrosion often occurs on the flow path components, the most damage to the compressor blading is the result of local pitting corrosion.

3. The inlet stages (1 through 5) of the compressors are the most susceptible to in-service corrosion due to the presence of liquids in these stages.

4. Severe corrosive environments are those with significant levels Sulfur and Chlorides. High salt levels and Fluorides make the environment even more corrosive.

5. The flow path corrosion is the result of deposits on the blades, that when wetted, cause local conditions on the surface of the blades to be highly acidic.

6. The corrosion characteristics of the different flow path materials in use are very different.

7. Upgrades of the compressor flow path metallurgy are available to minimize the potential for corrosion:

   a. Bare 403 Stainless Steel should not be used for flow path components in the first five stages of the compressor.

   b. Duplex stainless steel significantly improves the corrosion resistance of the compressor flow path. Although, under the most severe operating conditions, the duplex alloys will also experience dangerous corrosion pitting. The duplex alloys should not be coated due to coating compatibility issues.

   c. Aluminide coatings can be very effective in reducing corrosion on Alloy Steels and 400 Series Stainless Steel. These coatings do deteriorate with time and should be limited to single operating campaigns of less than 6 years.

   d. Titanium Alloys were found to provide excellent corrosion resistance for even the most severe operating environments.

8. Corrosion coupons were found to be a good tool for monitoring the corrosion potential inside the compressor over time. Corrosion coupons can be used to predict operating time and turnaround intervals.

9. Keeping the flow path clean of deposits significantly reduces the amount of corrosion experienced.

   a. Inlet filtration significantly reduces the amount of contaminants entering the compressor.

   b. Online cleaning is effective in reducing flow path deposition in the inlet end of the compressor. It has little effect in cleaning the middle or latter stages.

   c. Slow speed/crank liquid cleaning is effective in reducing flow path deposition throughout the compressor.

   d. Online Abrasive cleaning is also effective in reducing flow path deposition. The abrasive cleaning material can clean more stages than the liquid cleaning practices.

e. Abrasive cleaning can cause compressor flow path erosion. Particularly to the Aluminide type corrosion coatings.

10. Compressor rotors should be immediately cleaned of flow path deposits during unit turnarounds to prevent shut down corrosion in all stages.

11. In order to prevent shut down corrosion in all stages, compressor internals should be dried during unit shut downs.

12. A comprehensive corrosion control program should include:

    a. Minimize the source of corrosive material such as Sulfur, Salts and Fluorine.

    b. The use of a compressor inlet filter.

    c. Periodic inlet filter pad replacement.

    d. Online Water/Detergent washing of the compressor at least weekly.

    e. Crank washing of the compressor at any unit shut down.

    f. Abrasively clean the flow path monthly.

    g. Keep the compressor dry during shut down periods.

    h. Clean the rotor as soon as possible during each major unit overhaul to prevent shut down corrosion.

    i. Upgrade the flow path metallurgy or coatings as appropriate.

## REFERENCES:

Angello, L., 2005, Axial compressor Performance Maintenance Guide Update, EPRI Technical Guide 1008325

Chow, R., McMordie, B., Wiegan, R. Coatings Limit Compressor Fouling, 1995, Turbomachinery International

Gresh, M.T., Sassos, M. and Watson,A., 1992, Axial Air Compressor – Maintaining Peak Efficiency, Proceeding of the Twenty-First Turbomachinery Symposium

Kalyanaraman, Kalyan, Water Washing – Is it Good For Your Gas Turbine, July/August 2009, Turbomachinery International

Linden, D., 2001, Corrosion control in Industrial Axial Flow Compressors, , Proceeding of the Thirtieth Turbomachinery Symposium

Meher-Homji, C., Bromley, A.,2004, Gas Turbine Axial Compressor Fouling and Washing, Proceedings of the Thirty Third Turbomachinery Symposium

Meher-Homji, C., Focke,A. and Wooddridge, M.B., 1990, Fouling of Axial Flow Compressor – Causes, Effects, Detection and Control, Proceeding of the Eighteen Turbomachinery Symposium

Mosser, M., and Brooks, P., 2008, Gas Turbines: Field application of compressor coatings saves dollars, Sermatech International Inc.

Syverud,E., Brekke,O. and Bakken, L., 2005, Axial Compressor Deterioration Caused by Saltwater Ingestion, @ASME Paper # GT2005-68701, GT 2005 Proceedings

Watson, D., Carter, D., Alleyne, C.D., 1995, Cleaning Turbomachinery without Disassembly, Online and Offline, Proceedings of the Twenty Fourth Turbomachinery Symposium

Wert, D. and DiSabella, R., 2006, Strong Corrosion-Resistant Stainless Steel, Advanced Materials & Processes