ONLINE TECHNIQUES TO MITIGATE THE RISKS THAT LIMIT EXPANDER RELIABILITY

by
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ABSTRACT

Expander reliability has been limited by flow path erosion, corrosion, and deposition. Through root cause determination of the failures and laboratory testing, advances in machine designs and online monitoring and cleaning techniques have been developed. This paper explains the root causes of erosion, corrosion, and deposition and includes recommended online monitoring and cleaning methods.

INTRODUCTION

The fluidized catalytic cracking (FCC) process converts gas oil to usable products with the aid of a catalyst in the reactor (Figure 1). The catalyst attaches itself to a carbon atom that breaks down the long carbon molecules into useful products. Catalyst can be reused by removing the carbon atom. The catalyst is separated from the hydrocarbon products. The separated catalyst is moved to a vessel known as the regenerator, where large amounts of oxygen are introduced to the catalyst bed. In the regenerator, the oxygen reacts with the carbon and the carbon is burnt off the catalyst; heat is generated and catalyst is separated from the flue gas. The regenerated catalyst is returned to the reactor. Flue gas, typically 25 to 50 psia (1.7 to 3.4 bara) and 1250 to 1400°F (675 to 760°C) with flow rates as high as 1,700,000 lb/hr (775,000 kg/hr), has additional catalyst removed by passing it through the third stage separator. The flue gas then passes through an expander. A cross-section of a state-of-the-art single stage expander can be seen in Figure 2. Figure 3 shows an example of a typical two stage expander. In the expander, the pressure and temperature are reduced, energy is extracted and converted into mechanical work. Even though the flue gas has been processed through multiple stages of separation, a fair amount of catalyst will remain in the flue gas and pass through the expander.

The use of power recovery expander installations peaked during the late 1970s and early 1980s due to the energy crisis and cost of electricity. The number of new expander installations has been reduced from the late 1980s to today, due to the limited reliability and availability of expanders in service. Advances in technology (Carbonetto and Hoch, 2002) have improved expander reliability and availability. Today's increases in energy costs and awareness of "green" energy are again increasing the interest for expanders.

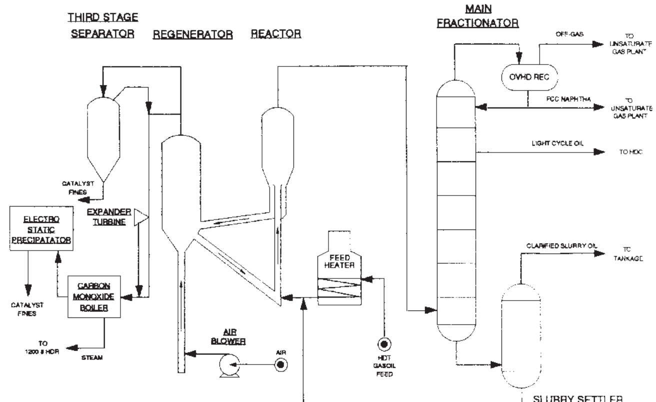

Figure 1. Typical FCC Process with Power Recovery System.

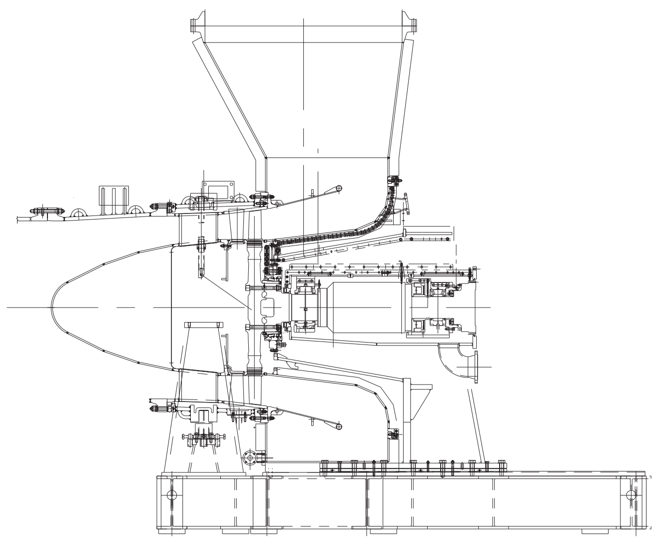

Figure 2. Cross-Section of State-of-the-Art Single Stage Expander.

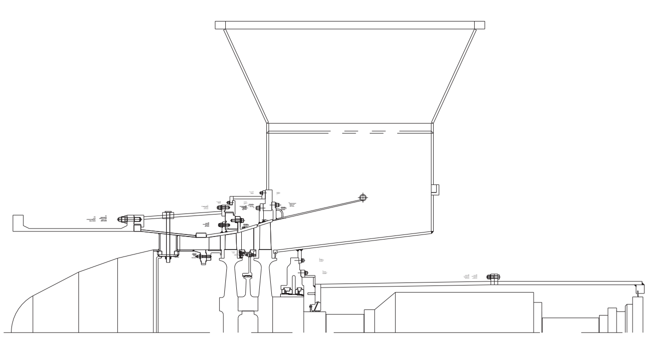

Figure 3. Cross-Section of Two Stage Expander.

Current expander users are looking to maximize power recovery and reliability, while other users of FCC units are looking to retrofit an expander into their process. Reliable expander operation can be ensured through an understanding of the major root causes of unscheduled shutdowns and various online monitoring and preventive maintenance procedures.

Since the initial development in the late 1950s, expanders have experienced many types of failures. The expander environment is dirty, corrosive, and erosive. The severe operating environment causes most failures, while some are attributed to design errors. Catalyst particles (a carrier of contaminants that may lead to corrosion and/or a fouling element in the form of deposition) in the flue gas may act as an abrasive media and cause erosion. From the database of failures recorded, the most common root cause mechanisms of unscheduled shutdowns are: operation, deposition, erosion, and corrosion. Operation problems are related to the controls and operators of the FCC unit and are not addressed within this paper; but, the online monitoring and preventive maintenance to reduce the impact on expander reliability are discussed.

DEPOSITION

Fine catalyst particles, typically less than 1 micron in size, have a tendency to collect in areas of flow separation and form deposits. These deposits may be seen throughout the FCC unit wherever a pressure drop is taken. Some areas where deposits may form are: downstream of a valve, downstream of a critical flow orifice of a third stage separator (TSS), and within the expander flow path.

The deposits within the expander affect the operation in various ways. A catalyst deposit may form on the shroud of the rotor blades. The tip clearance is reduced and a tip rub may occur. Figure 4 illustrates an expander operating under normal conditions. The reduction in tip clearance can be seen in Figure 5. During the tip rub, heat generated due to friction may increase the blade metal temperature in excess of 2000°F (1100°C). The localized heat can cause damage to the base material of the rotor blade. For example in Waspaloy®, these temperatures will cause grain growth and a reduction in mechanical strength and often leads to blade tip cracking and partial airfoil losses (Figure 6). The use of higher temperature alloys, such as Inconel® 738, is less affected by the temperatures experienced during a blade tip rub. No changes in microstructure have been seen with the use of Inconel® 738, reducing the potential for blade tip cracking and partial airfoil loss.

Figure 4. Online Photograph Showing Normal Operation.

Stator assembly fouling can also occur in areas of flow separation or downstream of shocks in supersonic flows. Multistage expander designs (Figure 3) are more susceptible to this type of deposition; but, deposition is a problem in single stage units as well. Deposits, which form at the hub or tip region of the passage, alter the machine performance. Figure 7 illustrates the deposit

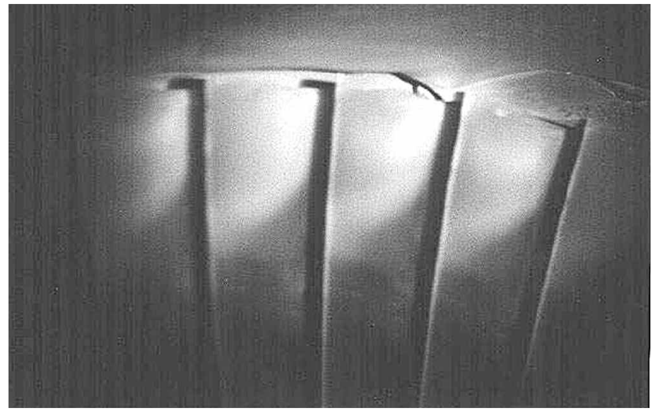

Figure 5. Online Photograph Showing Shroud Deposit.

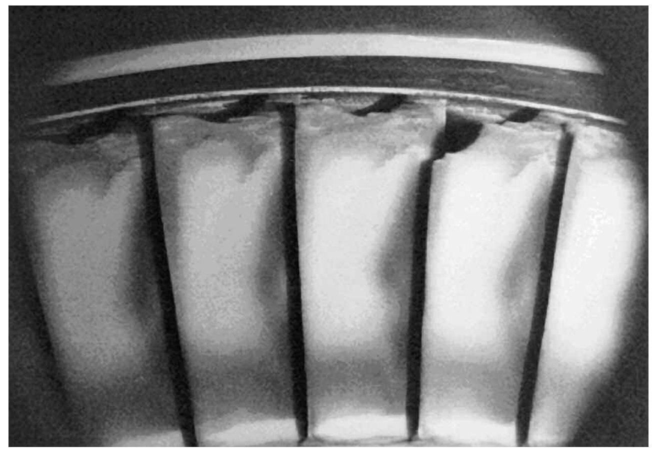

Figure 6. Partial Loss of Airfoil Due to Tip Rub on Catalyst Deposit.

Figure 7. Stator Assembly Deposition, Decreasing Capacity and Performance.

formation in the stator assembly of a two-stage unit. The depositmay "grow" toward the rotor blade and result in a mechanical rub with the rotor blade, as seen in Figure 8. Note the blade height was originally 4.2 inches (107 mm).

The rotor assembly is also subjected to catalyst build up during operation. Rotor disc deposits can form on the faces of the disc. This region of expander is subject to turbulent and complex flows. On the forward side, cooling steam is introduced in this cavity. On the aft side, sealing steam or air discharges into the cavity. Due to

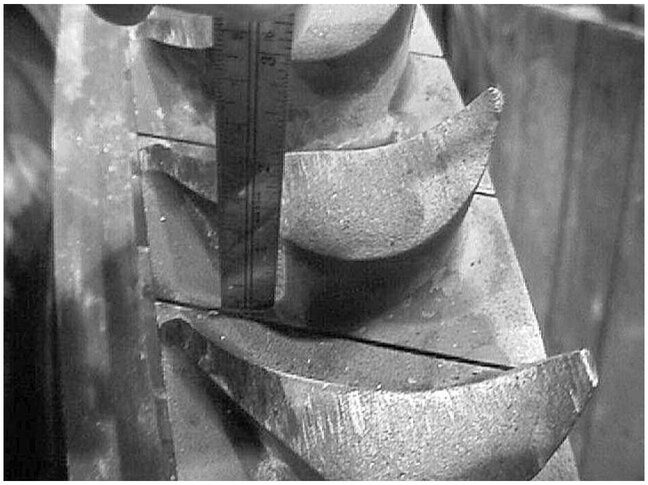

Figure 8. Severe Stator Deposition Resulting in Rotor Damage.

a phenomenon known as disc pumping, catalyst laden flue gas is drawn into the area on the original designs (Figure 9). The catalyst separates from the flue gas and will tend to deposit under the rim of the disc, as seen in Figure 10. Deposits can also form in the rotor blade passages for the same aerodynamic reasons as listed under the stator assembly. Examples of the deposit can be seen in Figures 11 and 12. The deposit also affects performance, but more often an increase in machine vibration levels can be seen. The deposit can be significant in size and weigh up to 5 oz (140 g) per blade. An increase in rotor vibration is often noted when a partial loss of deposit is noted. Total deposit would equal 5 oz (140 g) times 62 blades (typical), or 310 oz at a 26 inch radius. The total deposit will introduce an unbalance for a typical single stage expander of > 50 times the unbalance tolerance of 4 W/N.

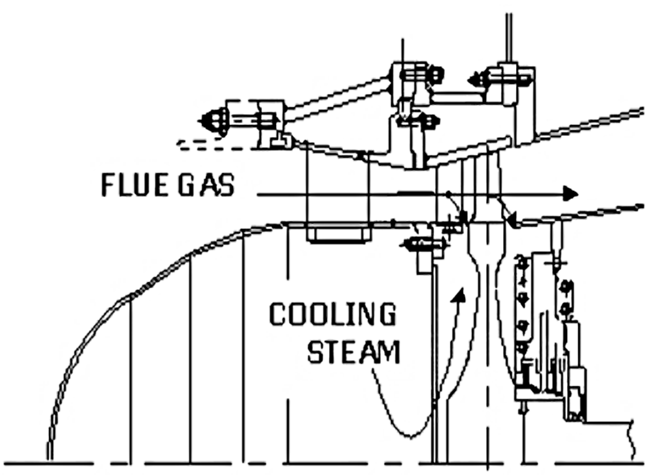

Figure 9. Original Expander Design.

Samples from various refineries were analyzed to understand the mechanism of catalyst deposition. Catalyst deposits from the rotor blade and shroud were examined to determine their chemical analysis and then viewed under a scanning electron microscope (SEM). All deposits show signs of layering (Figure 13). The lighter colored layers had evidence of iron oxides. Neither process piping, crude oil, nor the catalyst contain iron. Operating data review suggests the layers could be correlated to an intermittent steam quench, supplied through a carbon steel pipe (high in iron).

Further review under the SEM revealed different morphology for each sample. Deposits start as a conglomeration of submicron sized catalyst particles, mostly spherical in shape or fractions of a sphere. Fresh catalyst is spherical in shape, correlating well to the

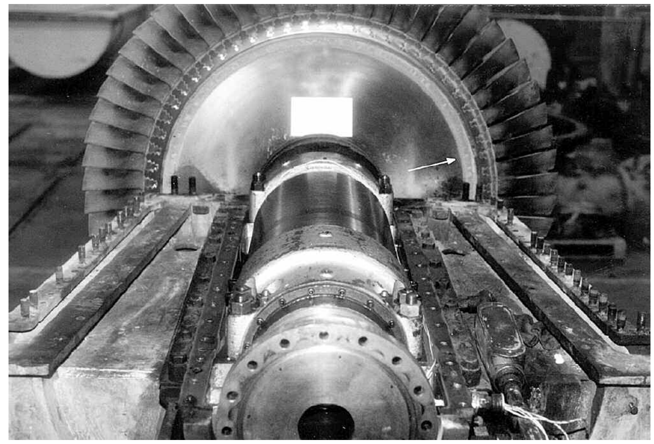

Figure 10. Deposit on Disc Face.

Figure 11. Online Photograph Showing Deposit Formation at Base of Rotor Blade.

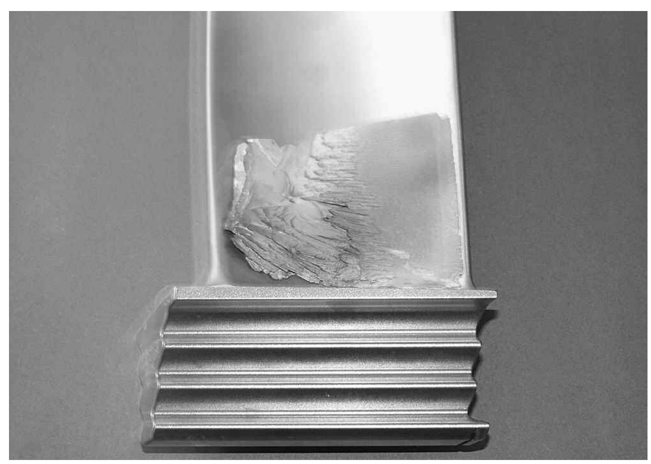

Figure 12. Rotor Blade Deposit Found During Shutdown.

findings. Shroud deposits exposed to elevated temperatures have an amorphous structure. This is known as sintered catalyst. Figure 14 illustrates the difference in morphology between a deposit and sintered catalyst. Sintered catalyst becomes very hard like a ceramic, where as a newly formed deposit will be brittle in nature. SEM analysis was taken further to determine the “glue” that causes the catalyst particles to initially stick together. The major element found in the binder is sulfur; but other salts could also act as a binder.

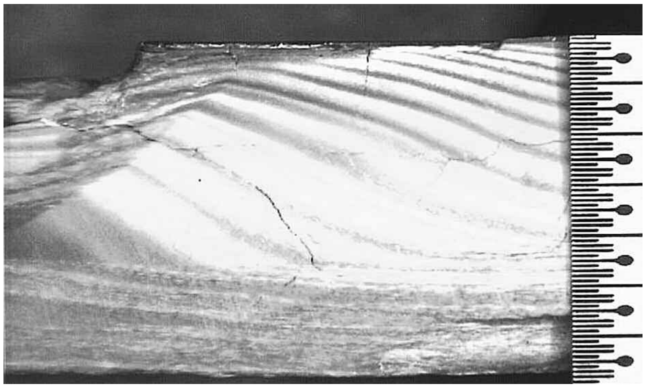

Figure 13. Layering Within Catalyst Deposit.

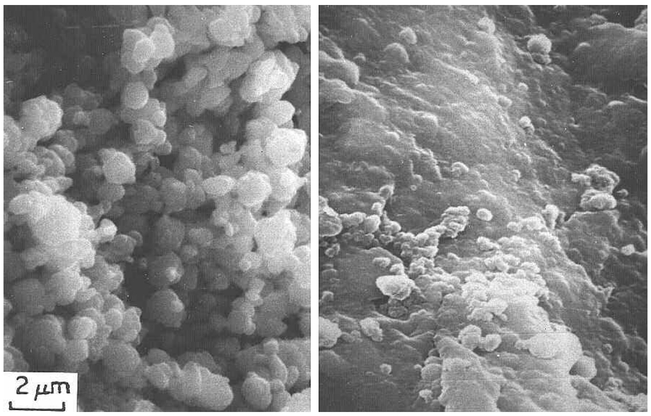

Figure 14. Deposit Structure (Left) Versus Sintered Catalyst (Right).

EROSION

The same catalyst, which has a tendency to form a deposit, can cause erosion. Caution must be used when reviewing erosion damage, since some erosion can be caused by steam. Erosion can be classified as primary or secondary. Primary erosion is caused by larger (> 5 microns) catalyst particles impacting the surface and removing material. Typical primary erosion on a rotor blade can be seen in Figure 15. Some rotor blades experience secondary erosion at the hub of the airfoil. Secondary erosion occurs when smaller catalyst particles, and sometimes steam, get caught in areas of the flow path where low axial velocities exist. A region of flow recirculation develops, and the entrained catalyst and/or wet steam will start to erode the base material. Due to the complex aerodynamics, multistage expanders are more susceptible to secondary erosion than single stage expanders.

Solutions to erosion problems can only be found when the entire FCC unit is reviewed. Although the expander design can be a significant contributor to erosion, the effectiveness of upstream equipment such as the TSS and/or the regenerator cyclones impact erosion significantly. The expander design can be improved to decrease erosion. Aerodynamic tools such as computational fluid dynamics (CFD) have enabled designers to fully understand the particle dynamics, as well as the aerodynamics. After understanding the root cause, aerodynamic changes can be made to significantly improve the erosion life of the flow path components, such as the rotor blades, by using the tools and techniques described in Carbonetto and Hoch (1999). Material and coating selections also have a significant impact on erosion. Figure 16 illustrates the effect of base material and coating selection on the erosion rate of the material at various particle impingement angles. As seen in the graph, coatings provide up to 10 times more erosion resistance than the base materials. Base material selection is still critical because the coatings are limited in thickness, typically 0.006 to 0.008 inch (0.15 to 0.20 mm).

Figure 15. Rotor Blade Primary Erosion.

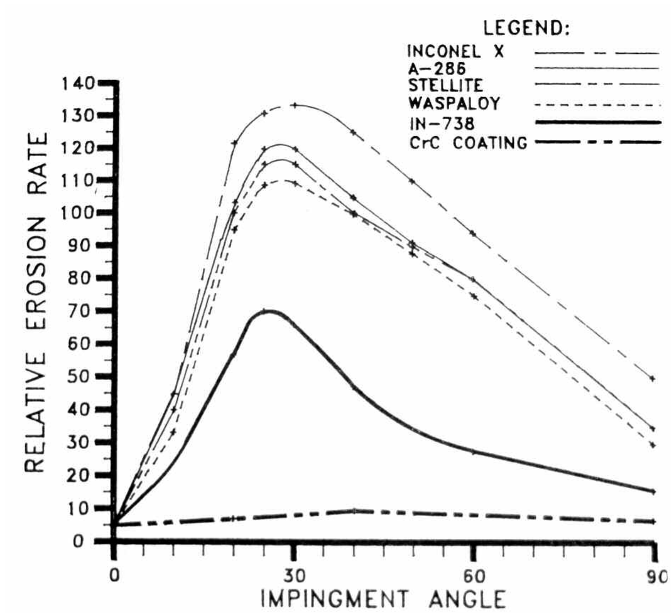

Figure 16. Effect of Base Material and Coating Selection on Erosion Rate at Various Angles of Impact.

HOT CORROSION

ASM Handbook (1987) defines hot corrosion as an accelerated corrosion of metal surfaces that results from the combined effect of oxidation and reaction with sulfur compounds and other contaminants, such as chlorides, to form a molten salt on a metal surface that fluxes, destroys, or disrupts the normal protective oxide. Hot corrosion is categorized as either Type I or Type II. Type I corrosion occurs at temperatures of 1550 to 1750°F (850 to 950°C), well above FCC temperatures and is not a problem in FCC expander applications. Type II corrosion occurs at 1200 to 1400°F (650 to 750°C), within the typical operating temperatures of FCC expanders. Sulfur oxides in the flue gas break down the protective oxide layers and react with the base materials. During this reaction, eutectic salts are formed. The eutectic salts and other heavy metals present accelerate the hot corrosion. The end result is characterized by pitting (Figure 17). Hot corrosion attack of the rotor blades and disc has limited the reliability of the expander. Over a dozen failures and unscheduled outages can be attributed to hot corrosion.

Figure 17. Hot Corrosion Damage of Expander Blade Root.

The potential for hot corrosion can be predicted through the use of phase stability diagrams (Figure 18). The phase stability diagram is a plot of the partial pressure of oxygen versus the partial pressure of sulfur at a given temperature and base material composition. Shown in Figure 18 is the nickel/chromium reaction for Waspaloy®. Depending on the ratio of oxygen to sulfur, protective oxides or corrosive sulfides can form. Identified on the chart is the typical incomplete combustion flue gas. Nickel sulfide (NiS), a potential corrosive, can be produced in this operating environment. A typical complete combustion process would shift the point to the right, into the chromium oxide and nickel oxide region. These oxides protect the base material and reduce the potential for hot corrosion attack or pitting.

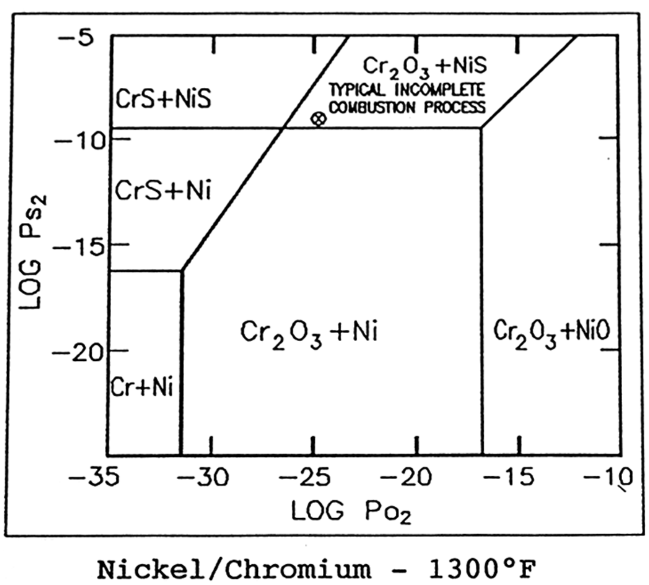

Figure 18. Nickel/Chromium Phase Stability Diagram.

Corrosion products on the rotor components are often overlooked during a normal overhaul, since they are not highlighted by typical nondestructive testing methods, such as liquid penetrant inspection. The corrosion products appear as a black deposit that is very tenacious and nearly impossible to remove (Figure 19). As seen in the phase stability diagram, Figure 18, the sulfur will tend to draw chromium and nickel from the base material to form a sulfide. Concern lies in the strength of the base material below the black deposit. Locally, the base material may be depleted of chromium and/or nickel. Advance inspection techniques, including eddy current, and structural reviews of these components are required to determine the component's suitability for service.

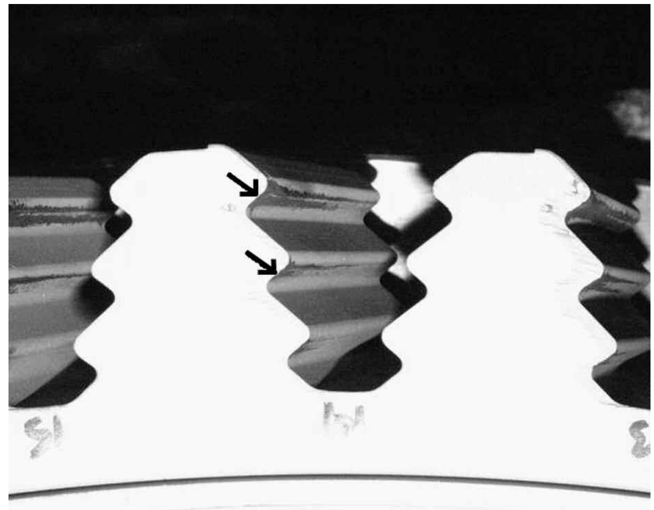

Figure 19. Corrosion Product on Disc.

Ideally, the best methodology to reduce the potential for corrosion is to remove the contaminants from the process or change the local environment, select the most corrosion resistant material for the application, and lastly use coatings to improve the corrosion resistance of the base material. Improved cooling and sealing arrangements have been designed and implemented in the hot gas expander application, which lowers the operating temperature of the base metal where the corrosion reaction cannot take place, and minimizes the amount of flue gas in the critical disc to blade attachment region. Changing the local environment has proven to be effective in reducing the corrosion potential. Using more corrosion resistant materials such as Inconel® 738 for the rotor blades will also reduce the potential for corrosion attack. A coating on the blade root form does improve the corrosion resistance of materials such as Waspaloy®. The blade base material upgrade to Inconel® 738 has shown superior performance in laboratory tests and field experience. Corrosion testing was performed on the commonly used materials for blades and discs. Based on the depth of corrosion penetration, which varied from negligible to 0.020 inch (0.5 mm) in depth, Inconel® 738 offered the maximum resistance, followed by A-286, Waspaloy®, and lastly Inconel® X-750.

ONLINE MONITORING TECHNIQUES

Isokinetic Testing

Catalyst will always be a part of the flue gas stream entering the expander. Knowing and understanding the amount and the particle size distribution are key to ensuring reliable operation of the expander. Online particle sampling techniques and services are available. A sample of catalyst laden flue gas is typically removed from two points in the FCC unit, before and after the third stage separator. The sample is taken with a probe at multiple points through the cross section of the piping. Typically, eight to 10 points are taken isokinetically to ensure a representative sample is taken. The total sample from all points collected is gathered and should be 3 grams (minimum). In order to obtain an isokinetic sample, the flue gas removed must be at the same velocity or energy as the point within the pipe. Deviations in velocity will create errors. During the testing, the flue gas flow rate is measured. The catalyst sample is filtered and analyzed to determine the concentration of catalyst in the flue gas stream, as well as the particle size distribution.

Ideally, the particles entering the expander would be 2 to 5 microns in size and at a concentration less than 100 ppm. Larger particles will tend to cause erosion within the flow path. Smaller particles may have the potential to deposit and foul the expander. By testing the inlet and outlet of the third stage separator, the overall separation performance can be evaluated. Even with third stage separators of the latest technology, faulty upstream regenerator cyclones will overload the separator, and the efficiency will be greatly reduced.

To determine the effectiveness of the separation system, the particle size distribution from both the inlet and outlet of the third stage separator are plotted on a performance chart (Figure 20). The x axis is the weight percentage of the sample for a given particle size. The y axis is the corresponding particle size. Reference lines are shown to qualify the test results to industry experience. The gray band to the left is the typical regenerator cyclone performance, third stage separator inlet sample. If the results are above and to the left of this band, the regenerator cyclones may be damaged. Similarly for the third stage separator outlet sample, expander inlet, the gray band to the bottom right of the chart is typical separator performance. Results above and to the left of this area highlight a potential problem with the third stage separator or a blocked underflow line (if equipped). A blocked underflow line can be detected by a reduction in line temperature. Often test results correlating to the defective third stage separator will result in excessive erosion in the expander flow path.

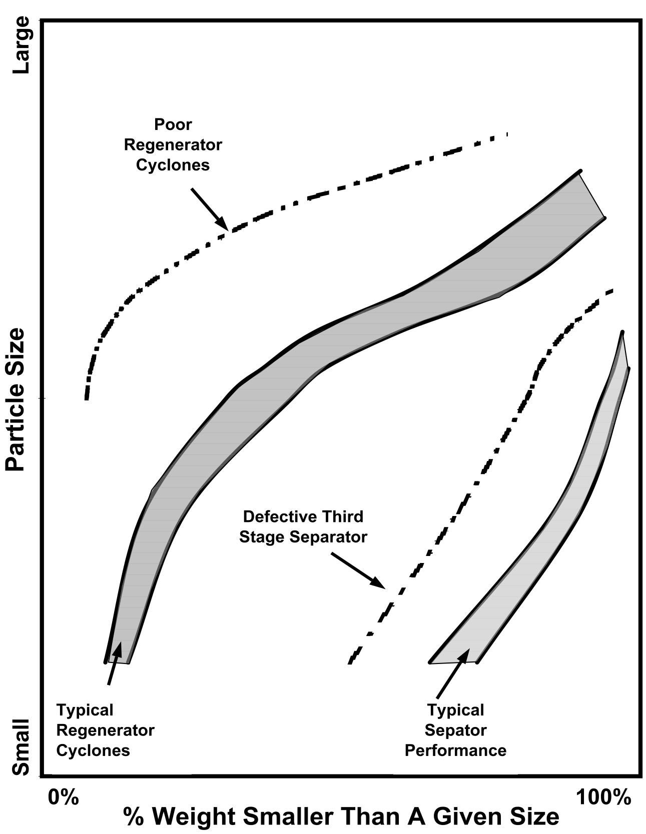

Figure 20. FCC Separator Performance.

Condition Monitoring Through the Viewports

FCC expanders are equipped with two viewports on the exhaust casing for condition monitoring during operation. The two viewports are aligned to a single point, approximately at the midspan of the blade. Figure 21 shows the typical arrangement of the viewports. The viewports are isolated from the flue gas with high temperature valves and borosilicate sight glasses. The isolation valves allow the user to remove the sight glasses for maintenance and cleaning while the unit is online. Two viewports are required. One is used for a light source, such as a high speed strobe. The second permits line of sight for visual inspection, photography, or videography of the blades' suction side (backside).

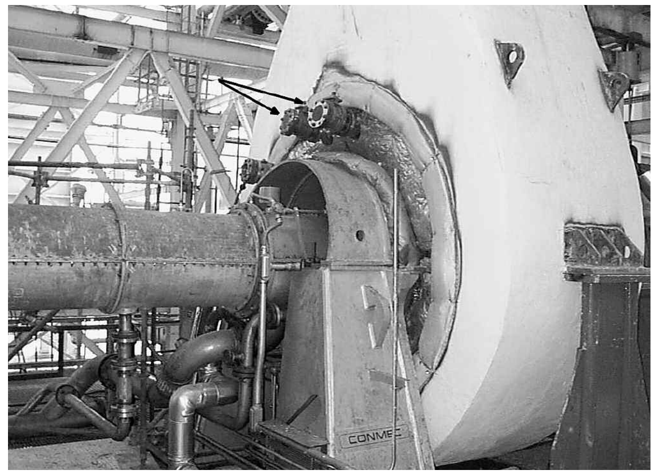

Figure 21. Typical Arrangement of Viewports.

The equipment required to capture an image of the blades consists of: personal safety equipment, 35mm single lens reflex camera with 135mm lens or equivalent digital camera, high speed and intensity strobe, patch cords to link the camera to the strobe, bright spotlight, and high temperature felt gaskets. The strobe is a specialized component due to the high intensity and short duration flash required. A flash intensity of 44×10^6 candela and a flash duration less than 8 milliseconds is needed to obtain a bright and clear image. Press the camera lens tight onto the sight glass surface. The camera is focused through the use of the spotlight or the strobe synchronized to the blade speed. A visual inspection of all blades is recommended and is performed by adjusting the synchronization of the strobe before photographs are taken. Once the camera is focused, the strobe is switched to single flash mode triggered by an external source (camera). Felt gaskets are used to block all stray light from entering the viewports around the camera lens and strobe. The camera shutter speed is typically set to 1/30th of a second. When the camera shutter is opened, the strobe is triggered and fires. Since there is no other light source within the machine during normal operation, the short intense flash captures the image of the blades, not the shutter speed (Figure 22). Many expanders now have numbers, marked with high temperature paint, on the backside of the blades for ease of identification (refer to Figure 3). Analysis of the colors and shadows in the photographs can be interpreted to determine the condition of the machine.

Alternatively or in conjunction with the still photographs, videography can be performed. A high quality 8mm camcorder with manual focus is sufficient. Protective cases for both 35mm cameras and camcorders are available to keep the camera clear of dust particles. The video camera is used in the same fashion as a visual inspection would be performed. The strobe is synchronized to the blade speed and adjusted to allow each blade to be inspected and recorded.

Condition Monitoring Through Supervisory Instrumentation

Most FCC expanders are an overhung rotor design. The rotor/bearing housing support pedestal must be robust to accommodate the overhung weight of the disc. A typical cross-section can be seen in Figure 23 and photograph in Figure 24. Typically the

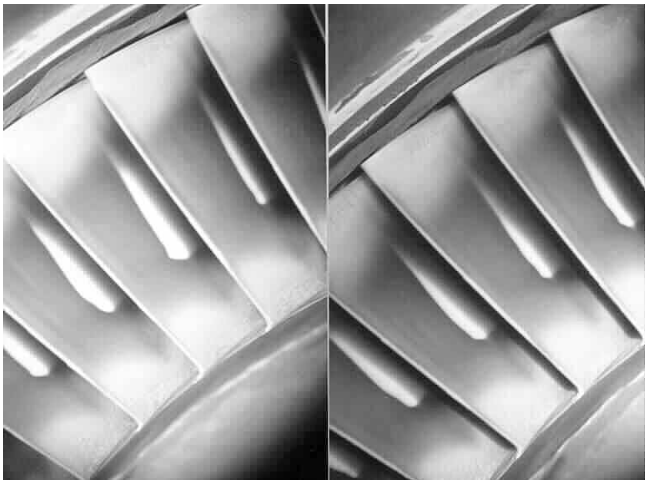

Figure 22. Sample of Online Blade Photograph.

overhung bearing (the bearing nearest the rotor disc) supports 80 to 90 percent of the rotor weight. Interesting vibration characteristics can be seen in this design.

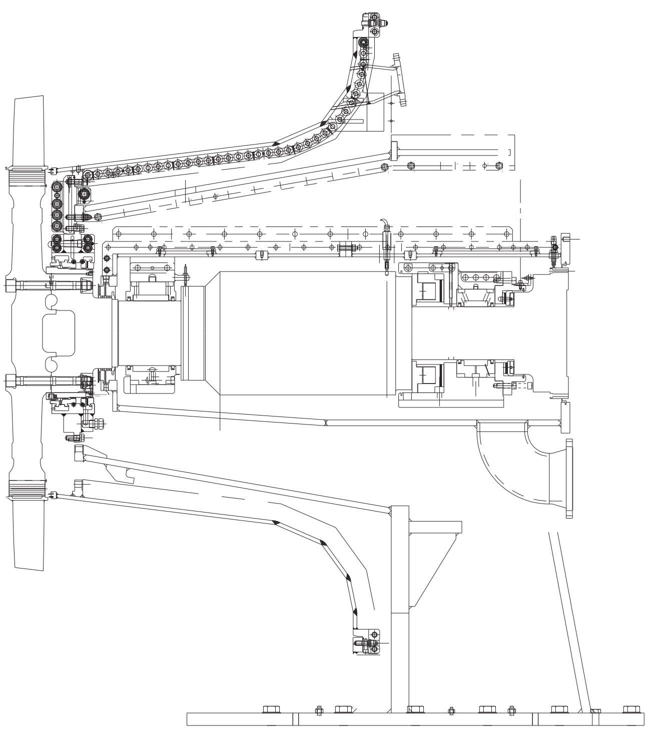

Figure 23. Cross-section of Expander Including Support Pedestal.

As a preventive maintenance measure, monitoring of the following instrumentation is recommended:

- Disc end vibration probes (x and y)
- Disc end accelerometer (attached to the bearing cap)
- Disc end bearing temperature detectors
- Coupling end vibration probes (x and y)
- Coupling end accelerometer (attached to the bearing cap)
- Coupling end bearing temperature detectors
- Axial position probes
- Active thrust bearing temperature detectors
- Inactive thrust bearing temperature detectors

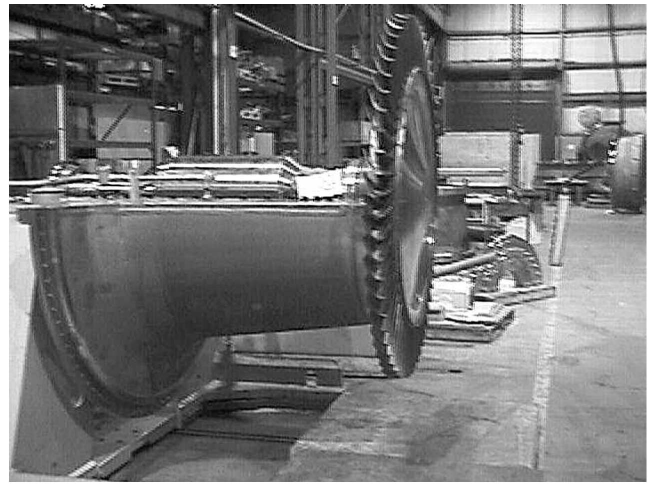

Figure 24. Photograph of Rotor, Bearing, and Seal Assembly.

During normal operation, catalyst will deposit on the flow path components. Changes in the supervisory instrumentation can be noted. As the deposit forms on the rotor blades or disc, an increase in vibration levels may be seen due to unbalance. If the deposit is forming on the shroud above the rotor blades, changes in the aerodynamic forces influence the rotor vibration. When the shroud deposit becomes excessive and contacts the blades, the vibration levels will quickly climb, often increasing 500 to 800 percent. Due to the conical shape of most shrouds, the shroud deposit will often push the rotor and increase the thrust load, resulting in an increase in active bearing temperature and a change in axial position of the rotor.

Accelerometers are recommended due to the flexibility of the support pedestal. Field experience has shown the accelerometers respond before the traditional vibration probes. Further analytical studies performed verified the shaft to bearing housing movement detected by the proximity probes can be small, while the entire assembly movement is relatively large due to the pedestal flexibility. Monitoring the changes in the vibration probe gap and shaft orbit is also suggested.

Condition Monitoring Through Performance Trending

Monitoring expander performance is important to qualify the amount of flow path deposition or fouling. Expander performance is difficult to accurately quantify. One method is to use torque meters (instrumented couplings). Torque meters have not been widely proven in this application. The alternative to measuring the power is to calculate it. Pressure and temperature instrumentation should be installed in close proximity to the inlet and discharge flanges using ASME PTC-10 (1997) as a guideline. The available energy drop and overall efficiency of the expander can easily be calculated. But continuous flow measurement devices are not readily available for the hot flue gas entering the expander. Therefore, the total power generated is difficult to accurately calculate.

The thermodynamic equations to determine the expander performance are listed in Equations (1) through (4). As previously stated, determining the flow is difficult. If a mass balance of the system is not available, the mass flow through the expander can be estimated by the flow function (FF). Typically the expander is designed for choked flow. The flow function in Equation (5) characterizes the capacity of the machine. Based on the original design data, the flow at the current operating conditions can be determined [See Equations (6) and (7)].

$$GHP = m\frac{k}{k-1}RT_1\left(1-\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right) \tag{1}$$

$$\eta_{poly} = \frac{In\left(\frac{T_2}{T_1}\right)}{In\left(\frac{P_2}{P_1}\right)}\left(\frac{k}{k-1}\right) \quad (2)$$

$$\eta_{ad} = \frac{1-\left(\frac{P_2}{P_1}\right)^{\eta_{poly}\left(\frac{k-1}{k}\right)}}{1-\left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right)}} \quad (3)$$

$$SHP = \eta_{ad} GHP - bearing\ losses \quad (4)$$

$$FF = \frac{m\sqrt{T_1}}{P_1} \quad (5)$$

Original Design

$$P_1 = 50\ psia$$
$$T_1 = 1340°F$$
$$m = 354\ lb/\text{sec}$$
$$FF = \frac{m\sqrt{T_1}}{P_1} \quad (6)$$
$$FF = \frac{354\sqrt{(1340+460)}}{50}$$
$$FF = 300$$

Current Operation

$$P_1 = 30\ psia$$
$$T_1 = 1275°F$$
$$m = ???\ lb/\text{sec}$$
$$FF = 300$$
$$m = \frac{FF * P_1}{\sqrt{T_1}} \quad (7)$$
$$m = \frac{300*30}{\sqrt{(1275+460)}}$$
$$m = 216\ lb/\text{sec}$$

Flow path deposition will decrease the capacity of the machine, as well as the performance. Trending the performance of the expander can help to schedule online cleaning cycles. For FCC units operating on expander inlet valve control (minimum to no flow bypassing the expander), the expander power recovery can be estimated from the compressor flow rate. Alternatively, the flow can be estimated by calculating the flow capability of the inlet valve. The pressure drop across the valve, angle of opening, and the flow coefficient curve for the valve are needed for this type of calculation. Trending this estimated performance and correlating online blade photographs can develop a recommended cleaning cycle.

ONLINE CLEANING TECHNIQUES

Two major online techniques currently applied in the FCC expander application are:

- Abrasive cleaning
- Thermal cleaning

Injecting an abrasive media into the inlet line of the expander performs abrasive cleaning. A pipe tap or port 3 to 4 inches in diameter is recommended. The tap should be located four to six pipe diameters from the inlet flange. A sealed hopper, isolated from the process with double block and bleed valves, is needed to pressurize the media and force it into the inlet. Nitrogen is typically used to pressurize the system. Depending on the size of the expander, the quantity of abrasive will change. Normally, 50 lb (23 kg) of media is used for every 250,000 lb/hr (100,000 kg/hr) of flue gas flow. Walnut shells or rice are the most common media used. Do *not* use spent catalyst, steel shot, sand, or other aggressive media. Using the view ports, visually monitor the abrasive media passing through the unit. Walnut shells, for example, should appear as glowing embers. If black smoke is observed, a change to the media size, injection rate, or inject location is required. Key points for success: clean frequently to prevent the catalyst from sintering, adjust media size and quantity by observing through the viewports, and inject the media quickly into the inlet.

Thermal cleaning requires the expander inlet temperature be reduced 400 to 600°F (220 to 335°C) below normal operating levels and maintained for a duration of 2 hours minimum. This technique requires a reduction in FCC feed rates to reduce the flue gas temperatures. The use of large amounts of water and/or steam is not recommended due to the potential for localized cooling of the casing components. Localized cooling will generate large thermal stresses and often results in distortion and possibly flange leakages. The advantage to thermal cleaning is its effectiveness in removing sintered catalyst deposits from the shroud, rotor blades, and disc. This method is effective because the coefficient of thermal expansion for catalyst is greatly different from the metals used in the expander construction. The difference in thermal growths allows for the deposits to spall from the metal surfaces during the reheat cycle. Abrasive cleaning on a weekly schedule has been effective in reducing the quantity of thermal cleaning cycles required. An increase in vibration levels may be noted during the cleaning procedure. The change and peak vibration levels should be monitored and recorded. It is common to have wandering or unsteady vibration levels for a period after the cleaning has been performed. Depending on the installation, the vibration levels may take 8 to 12 hours to stabilize.

CONCLUSIONS

Understanding the root causes of expander reliability and availability failures is critical. Erosion, corrosion, and deposition are the top three causes of expander failures and reduced reliability. Corrosion is not detectable through online monitoring and must be evaluated during routine overhaul of the components. Using Inconel® 738 for a rotor blade material and improving the cooling system design can minimize the corrosion potential. Online techniques to monitor erosion and deposition have been developed. When implemented, the techniques are an excellent tool to establish the type and frequency of online cleaning required. The use of online cleaning techniques can reduce the potential for an unscheduled outage through the reduction of vibration excursions.

NOMENCLATURE

FF = Flow function
GHP = Gas power (hp)
k = Average ratio of specific heat (dimensionless)
m = Mass flow (lb_m/sec)
P = Pressure (psia)
R = Gas constant (ft lb_f/lb_m °R)
SHP = Shaft power (hp)
T = Temperature (°R)

Greek

η_{ad} = Adiabatic efficiency
η_{poly} = Polytropic efficiency

Subscripts

1 = Inlet
2 = Discharge

REFERENCES

ASM Handbook, 1987, “Corrosion,” 13.

ASME PTC-10, 1997, “Performance Test Code on Compressors and Exhausters,” American Society of Mechanical Engineers, New York, New York.

Carbonetto, B. and Hoch, G., 1999, “Advances in Erosion Prediction of Axial Flow Expanders,” *Proceedings of the Twenty-Eighth Turbomachinery Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, pp. 1-8.

Carbonetto, B. and Hoch, G., 2002, “New Designs and Applications for Increased Power Recovery and Improved Reliability in FCC Expanders,” *Proceedings of the Thirty-First Turbomachinery Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, pp. 9-16.