NEW DESIGNS AND APPLICATIONS FOR INCREASED POWER RECOVERY AND IMPROVED RELIABILITY IN FCC EXPANDERS

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ABSTRACT

Fluid catalytic cracking (FCC) hot gas expanders were developed in the early 1960s and were improved in the early 1980s with updates in airfoil technology. Since then, units designed for pressure ratios of approximately 2.25 and inlet temperatures of 1350°F (732°C) are being operated at pressure ratios as high as 3.4 and 1400°F (760°C) through a single stage, despite the increased stress and flow path erosion this may cause the equipment. Advances in mechanical and aerodynamic design, materials, and an increase in the understanding of particle laden flows has led to the design of equipment capable of more capacity, higher efficiency, and less erosion. This paper discusses the results of redesigning several hot gas expander applications for increased flow, temperature rating, capacity, and improved reliability.

INTRODUCTION

The fluid catalytic cracking (FCC) unit of an oil refinery converts crude oil into usable products such as gasoline and heating oil. In this unit, catalyst is used to break down long carbon chains of the gas oil or crude. Passing large amounts of air through the fluidized bed regenerates the carbon-laden catalyst. Oxygen reacts with the carbon and is burned off, after which the catalyst particles are separated and returned to the process. The hot, pressurized flue gas is then cleaned and sent to a hot gas expander where the energy is removed. Typical gas conditions are 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). As the flue gas passes through the expander, the pressure and temperature are reduced, extracting energy, which is converted into mechanical work.

Over the years hot gas expanders have evolved through four major generations. Original production units were designed in the early 1960s when FCC units operated at lower temperatures and pressures. Typical operating conditions of a hot gas expander were an inlet temperature of 1200°F (648°C) and a pressure ratio of 1.7. Rate of heat/power recovery was 50 to 70 Btu/lb (114 to 160 kJ/kg). These unit designs were typically single-stage with overhung rotor. Only 13 or so units were placed into production from 1963 to 1976. Operating life of first-generation units was short due to high flowpath erosion. Improvements in separation technology and use of erosion resistant coatings extended the operating time between overhauls from six months to one to two years.

Second generation expanders were designed in the mid-1970s to the mid-1980s. Process temperatures and pressures were increased for improved production rates. With these changes, the flue gas to the expanders increased in temperature and pressure. This increase in gas available energy, in conjunction with the energy crisis, created a need for more efficient expanders. This age of efficiency generated multiple frame sizes from the various OEMs. Expanders were designed for optimized efficiency that resulted in multistage designs. Up to nine units were manufactured per year.

The efficiency era was followed by a period of low activity. Lower energy costs reduced the return on investment. From the mid-1980s to the early 1990s, expander population growth dropped to only a few new units a year. Once again, process improvements increased the operating pressures of the expanders. Expanders originally designed for a pressure ratio of 1.7 and operating temperature of 1200°F (648°C) were being pushed to pressure ratios of 3.4 at inlet temperatures up to 1350°F (732°C). This change in operation was often done with little or no change to the fundamental design of the expander. The higher power recovery and ultimately higher component stress led to many failures. With the higher energy levels, increased erosion was problematic and unit reliability was reduced.

Improvements in technology have provided the foundation for the next era of hot gas expander design. FCC unit operation and equipment reliability have improved and extended the time between shutdowns, forcing expander designs to be improved. Until this point, meantime between failure/overhauls for the expander industry was less than two years with unit turnarounds every four to six years. This forces an additional unit shutdown exclusively for expander overhauls resulting in increased maintenance costs as well as loss of production. Expander design, materials of construction, and continued development programs are extending expander runtime and reliability. Achieving consistent repeatable four to six year campaigns with an expander requires a sound design and understanding of the machine environment, and an appreciation for unit operation and quality manufacturing techniques.

UNDERSTANDING MACHINE OPERATION AND ENVIRONMENT

Understanding failures *(a failure in this paper is defined as any thing that has caused an unscheduled outage or creates an unsafe condition for the unit operation)* is the first step in designing reliable expanders. Operation of a hot gas expander with leaking flanges, seal rubs at startup, or even high-rotor vibrations may lead to more catastrophic failures. With a database of failures, categorized by components, redesigns of various parts can lead to the elimination of problematic areas that limit expander availability. Customer and industry specifications were developed to prevent reoccurrences of various types of failures.

Erosion

FCC expanders will always undergo some degree of flowpath erosion. Expanders are typically subjected to 50 to 100 ppm of catalyst particles every hour under normal conditions. Improvements in coating technology and improved blade metallurgy have extended the erosion life of the stator and rotor assemblies. Conversely, FCC units are increasing capacity by increasing operating pressures. The increase in inlet pressure and operating pressure ratio increases the flowpath velocities and erosion. Through laboratory testing, erosion has been found to be proportional to the velocity cubed. More significantly, the erosion varies with the impact angle of the particle to the base metal. Technology advances have allowed for the study of the aerodynamics and particle dynamics of the flue gas using computational fluid dynamics (CFD), which incorporates the lab erosion test results. Laboratory testing, the use of CFD, and, most importantly, correlation to field experience has led to new design criteria and even new flowpath airfoils.

Deposition

The catalyst fines have another characteristic, called deposition, which limits the expander operation. Deposition occurs when catalyst is mixed with water and other contaminants. A catalyst deposit will build up over time in areas of low flow, such as separated boundary layers. The most problematic area is the shroud above the rotor blades. This deposit can eliminate the blade tip clearance and cause a mechanical rub. A photograph taken with the unit online can be seen in Figure 1. Friction generates significant amounts of heat, sintering the catalyst deposit and potentially overheating the blade base material. Local metal temperatures have been estimated to be in excess of 2000°F (1100°C). In alloys such as Waspaloy®, the local microstructure of the material changes, resulting in increased grain size and reduced mechanical strength of the blade. A tip crack will often form and lead to a loss of a section of airfoil (Figure 2). Material upgrades to Inconel® 738 have eliminated this type of failure due to its increased mechanical strength at higher temperatures.

Corrosion

Flue gas is composed mostly of nitrogen, with some excess carbon dioxide, oxygen, and water (a by-product of combustion). In partial combustion FCC units, no excess oxygen is present and carbon monoxide is formed. In either case, trace amounts of sulfur create an environment for hot corrosion. Use of residual oil in the refining process has increased the sulfur levels of the flue gas and increased the corrosion potential.

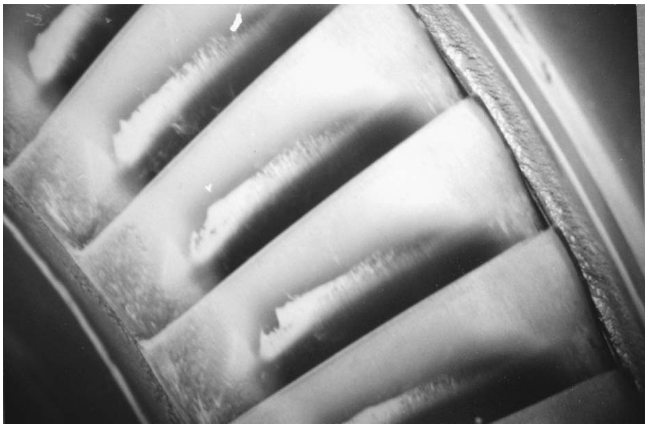

Figure 1. Online Photograph Showing Shroud Deposit Formation above Rotor Blades.

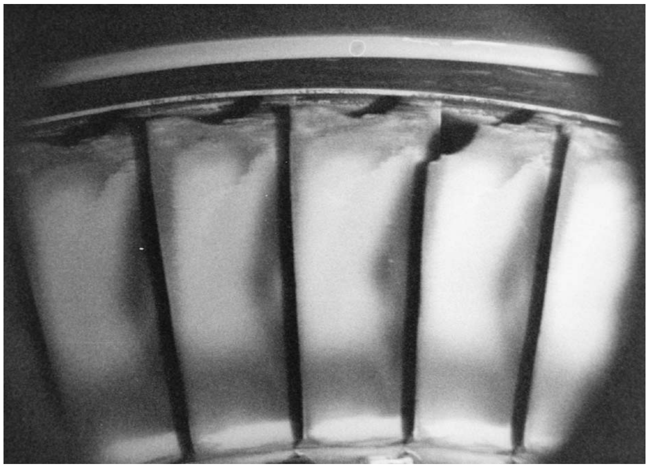

Figure 2. Online Photograph Illustrating Potential Damage Due to Blade Tip Rub with Catalyst Deposit.

Corrosion attack occurs mainly on the rotor blade to disc attachment area. Changes to the machine design have reduced the corrosion potential. Upgrades in cooling the blade attachment area of the disc have reduced the operating temperature and reduced the thermodynamic potential. Improvements in blade metallurgy have also reduced corrosion. Coatings have been applied as a sacrificial barrier; but due to the close tolerances required and high-contact stresses, coatings have not been effective in this area.

Shutdown corrosion has also limited the reliability of the outer casings. On a unit shutdown, steam is used to purge excess hydrocarbons from the piping. Where sulfur is present, sulfur-bearing acids can form that attack the heat-affected zones of welds. Since most casings are fabricated, they are especially vulnerable to this type of attack. Changes have been made to the post weld heat treat cycles of the stainless steel casing fabrications, and full solution anneal cycles with stabilization have been developed. Material upgrades have also been implemented to improve the corrosion resistance of the casings by using Inconel® 800H and Inconel® 600 instead of stainless steel.

The following case studies provide examples of problematic units. Using various methods, the root cause of the problems has been identified, and a brief description of the upgrades implemented are discussed.

CASE STUDIES

Pembroke, Wales—
Replacement Expander

The power recovery train (PRT) in Pembroke, Wales, consists of a hot gas expander, axial compressor, steam turbine, gear, and motor/generator. The original OEM commissioned the expander in 1982. Since commissioning, the expander was plagued with various problems that limited its reliability:

- Flange leakages were common, especially in the seal housing area where the shaft passes through the casing.
- The shaft seal would often rub on startup causing excessive clearances and leaks during normal operation.
- Flowpath erosion, especially on the rotor blades, led to potentially unsafe operation of the unit.
- The bullet portion of the nosecone collapsed on two separate instances. Although this did not affect machine performance, the potential for a catastrophic failure existed.
- The nosecone struts, which support the bullet, were found to be cracked at the leading edge weld at almost every service interval.
- Fasteners on the joints were failing due to stress corrosion cracking. This loss of clamping force led to flange leakages and erosion of the flange faces.
- The exhaust diffuser required weld repairs at each overhaul due to cracking in the weld and base material.

Typical time between overhauls was limited to a two year period.

In May 1995, a replacement unit was installed and commissioned. Each component of the replacement unit was redesigned to overcome the shortcomings of the previous unit, while maintaining the same machine footprint. The seal housing area was redesigned, eliminating the slip joint configuration on the vertical flange and changing it to a bolted joint. Inconel® packing was added to the vertical flanges of the seal housing and seal housing support, as well as all outer casing vertical joints. A comparison of the old and new designs can be seen in Figure 3. The horizontal joint was stiffened and keys were added for improved joint sealing. The new configuration eliminated the seal rubs during the startup cycle.

An aerodynamic analysis of the flowpath uncovered potential for improved erosion life. During this optimization, the expander was rerated for increased performance and capacity. The original OEM rating of the expander was 18,500 hp (13.8 MW) and the rerated unit would produce 30,200 hp (22.5 MW). Rotor blade material was upgraded from Waspaloy® to Inconel® 738, which provides increased strength at temperature, improved erosion resistance, and improved corrosion resistance. Cooling flow has been increased on the forward side of the disc and added to the aft disc cavity. These modifications allow for a uniform temperature profile through the disc in the blade attachment area. These advances in the cooling system design, along with the material upgrade, have eliminated the corrosion problem in the blade and disc attachment area.

A failure investigation revealed the nosecone bullet thickness needed to be increased to prevent future collapses. Additionally, an integral stator/shroud was designed to replace the cantilevered design stator. The new integral stator shroud provides a performance advantage by eliminating the clearance gap at the tip of the stators, but, more importantly, reduces the stress levels in the nosecone struts. The previous stator assembly design bolted to the bullet section of the nosecone. The weight of the stator assembly and the aerodynamic forces on the stator applied high loads to the bullet, which must be transmitted through the struts to the nosecone-mounting flange. The integral stator shroud bolts directly to the mounting flange, eliminating the forces on the bullet section of the nosecone. The lower stress levels have eliminated the cracking problem.

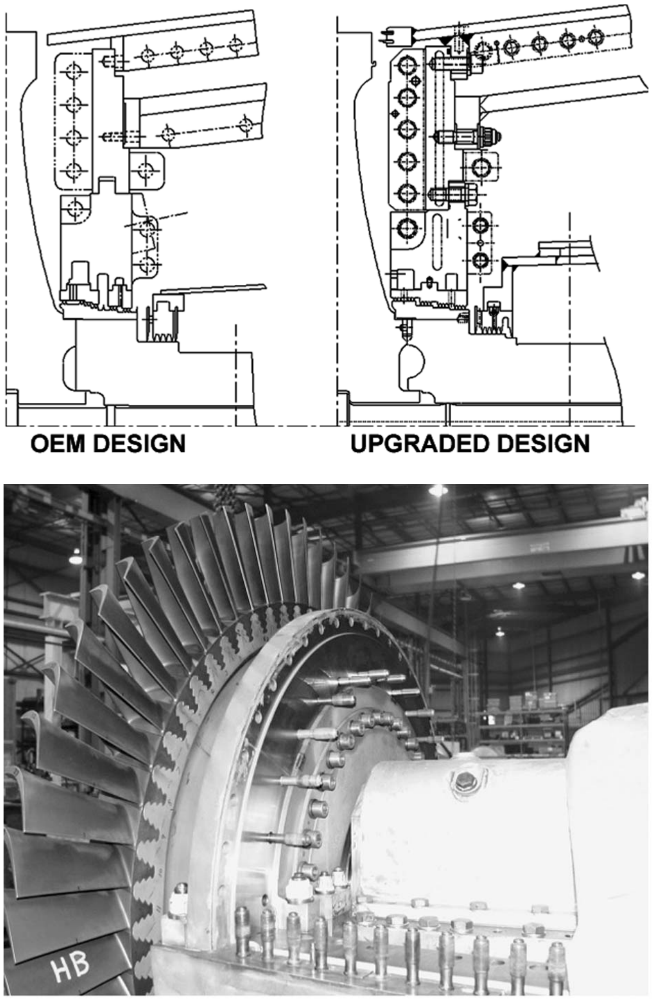

Figure 3. Cross Section of OEM and Upgraded Seal Housing Designs with Photograph of Installed Upgrade.

Casings were redesigned to incorporate thicker flanges for increased stiffness. Fastener size and quantity were increased, and a material change was implemented to reduce the potential for corrosion attack. The new Inconel® 718 (a nickel-based superalloy) fasteners provide increased strength over the previous OEMs use of A-286 (an iron-based superalloy). Fastener preload and joint clamping pressure were increased and flange leakages were eliminated. Analysis of the exhaust diffuser found the natural frequency of the component was near running speed. Diffuser designs now undergo structural analysis to determine the natural frequency, and stiffeners are added as required to "tune" the component.

The results of the upgraded replacement unit are excellent. Unit availability has increased from approximately 76 percent to over 98 percent, with no unscheduled shutdowns. The unit remained online for the full duration of the FCC unit overhaul cycle of 4.5 years. This represents an increase in run time of 125 percent, saving millions of dollars in lost production by eliminating a three week expander overhaul.

Corpus Christi, Texas—
Conversion to a Single-Stage Expander

The PRT in Corpus Christi, Texas, consists of a hot gas expander, motor/generator, axial compressor, and steam turbine. The original expander was a two-stage design by the OEM, commissioned in 1985. A machine cross-section can be seen in Figure 4. Several problems were experienced with the original unit:

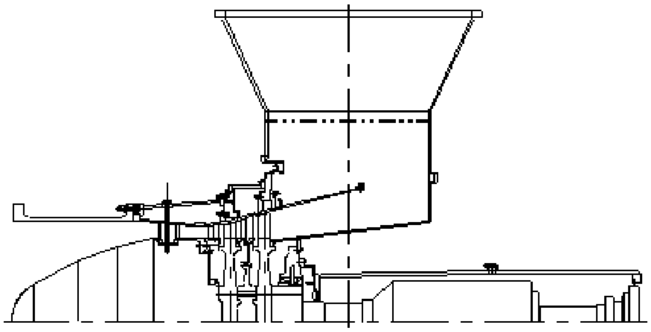

Figure 4. Cross Section of OEM Unit for Corpus Christi.

- The flowpath experienced catalyst deposition that caused blade wear and rotor vibrations.
- The intermediate casing had significant flange leakages and fastener failures during service.
- The interstage purge system was not adequate to maintain a positive purge of the disc seal area.
- The interstage seal area had experienced significant catalyst erosion on the second stage stator inner shroud, the seal diaphragm, honeycomb seals, and rotor disc seal.
- The second stage rotor blades experienced severe secondary erosion.

Unit operation was limited to two years between overhaul cycles (scheduled and unscheduled).

Two-stage designs offer higher efficiency than a single-stage machine operating at pressure ratios in excess of 3.4. However, the pressure ratio of the unit dropped to 3.0 since the original installation of the expander. In 1990, discussions began on the advantages and disadvantages of the two-stage design. A summary of the comparison can be seen in Table 1. The complexities of the design, along with poor aerodynamic design, were determined to be the main limiting factors to reliable operation. The unit was converted to a single-stage model and commissioned in November 1995.

Table 1. Comparison of Single and Multistage Expanders.

AREAS OF CONCERN	SINGLE STAGE	MULTIPLE STAGE
Reliability	Very Good	Poor
Efficiency		
Pressure Ratio:		
Low < 2.0	Good (84%)	Fair (80%)
Medium > 2.0 - < 2.5	Fair (79%)	Good (82%)
High > 2.5	Poor (76%)	Very Good (85%)
Operations		
Start up/shutdown	No significant differences	
Overtemperature	No significant differences	
Catalyst Carryover	Good	Poor
Deposition Resistance	Good	Very Poor
Erosion Resistance	Good	Poor
Loss of cooling	Good	More sensitive
Utility Usage (steam/air)	Low	High
Construction		
Complexity	Low	High
Costs		
Initial	Low	High
Maintenance	Low	High
Maintenance		
Overhaul Duration	Low	High
Required Inventory	Low	High
Assembly Difficulty	Low	High

The conversion process required a redesign of the intake casing assembly, hot section of the machine, to accommodate for the space created by eliminating a stage, as seen in Figure 5. This was an opportunity to eliminate the casing problems experienced with the intermediate casing, which spans the inlet to exhaust casings. A new design was developed, which manufactured the entire intake casing assembly with a single outer casing. This eliminated a set of flanges and the potential for leaks. The casing stiffness was also increased to accommodate increased piping loads that may occur during operation. The single piece casing utilizes heavier flanges for increase rigidity and improved sealing. Fasteners were upgraded in size, quantity, and material of construction as was described in the Pembroke case. The expander was inspected for the first time four years later when the FCC unit was shutdown for other repairs in 1999. Because of the expander's good condition, it remained in service until the FCC major turnaround in March 2001. The expander overhaul cycle was increased from two years to 5.4 years.

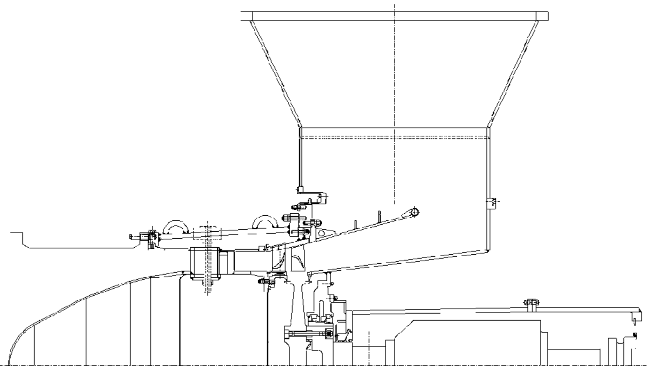

Figure 5. Cross Section of Single-Stage Conversion for Corpus Christi Unit.

Joliet, Illinois—
Redesigned Flowpath

The PRT in Joliet, Illinois, consists of a hot gas expander, axial compressor, motor/generator, and steam turbine. The original OEM commissioned the expander in 1986. Hot corrosion and flowpath erosion had limited the expander run time to less than two years. From its commissioning date in 1986 to 1995, the expander underwent six overhaul cycles, two of which were unplanned and caused by rotor blade failures. The mean time between overhauls was approximately 1.5 years.

The first rotor blade failure investigation determined the root cause to be sulfidation in the blade attachment area. The flue gas, feedstock, catalyst, and operating conditions of the expander were examined. The flue gas was found to have low levels of oxygen and significant levels of carbon monoxide, which can create a reducing environment. This environment, along with sulfur from the feedstock, allows for the formation of nickel sulfide. Sulfidation attack of the base metal occurs in the fillet radii of the blade attachment. An example of this type of attack can be seen in Figure 6. Each corrosion pit creates a stress riser and can accelerate fatigue crack initiation or propagation rates.

High rotor blade erosion due to poor flowpath design and third stage separator problems resulted in the second failure experienced at the Joliet site. As the rotor blade erodes, the loss in material causes a change in the blade natural frequencies. This shift in frequencies resulted in an interference with the number of nosecone struts (a known potential excitation). The result is a high-cycle fatigue failure of the airfoil. The design of the machine was evaluated using the latest technology in CFD and proprietary erosion prediction software as described in Carbonetto and Hoch (1999). Deficiencies in the flowpath design were highlighted, and, most importantly, an understanding of the design and effect on erosion was developed.

In 1994, the redesigned flowpath was optimized with CFD using the existing airfoil shapes and a new nosecone. These components were manufactured and commissioned in October 1995 into the

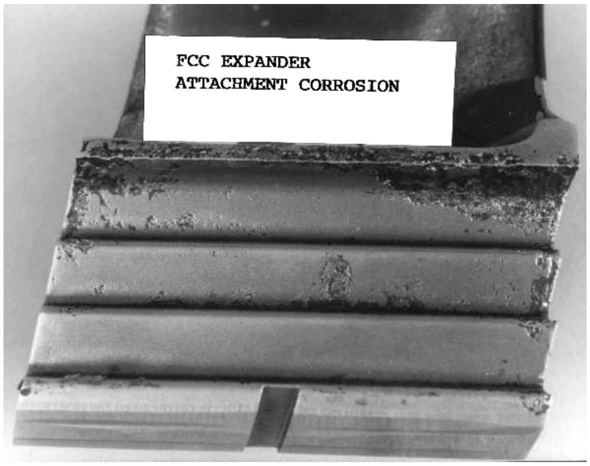

Figure 6. Blade Attachment Damage Due to Corrosion.

OEM machine. The new nosecone was not only more aerodynamically designed, but also included a change in the quantity of nosecone struts to prevent a potential interference with the rotor blade natural frequencies. Improvements in the cooling system were implemented to change the local environment around the blade attachment area, reducing the potential for sulfidation to occur. The third stage separator was overhauled as well to prevent excessive catalyst carryover to the expander. The expander provided service until its scheduled outage in September 1999, when the spare rotor was installed. The next scheduled outage is fall of 2003. The redesigned expander allowed for an increased time between overhauls from an average of 1.5 years to 3.9 years.

Torrance, California—
Replacement Expander

The PRT in Torrance, California, consists of a hot gas expander, motor/generator, axial compressor, and steam turbine. The original OEM commissioned the expander in 1983. The first inspection of the expander occurred in 1987. No visual damage was noted on the rotor blades or other flow path components and the expander was returned to service with no repairs. During a restart in 1989 after a process trip caused an unscheduled shutdown, a rotor blade tip rub occurred and caused high rotor vibrations. The unit was taken out of service and inspected. The inspection revealed severe rotor blade tip cracking, heavy stator erosion, nosecone strut weld cracking, exhaust casing, and diffuser cracking. After the OEM made the unit repairs, the unit was placed back in service in November 1989. During a scheduled FCC outage in June 1990, the rotor blades were found to be severely eroded and weld repairs of the exhaust casing and diffuser were again required. Repairs were made and the unit returned to service until November 1991, when a leak at the inner exhaust to seal housing support forced an unscheduled outage. Inspections revealed heavy deposits throughout the machine. Stator deposits were found to block nearly 30 percent of some stator passages. The expander was again taken offline in February 1992 to install a spare rotor and perform nosecone repairs. The next scheduled unit turnaround was performed in February 1993. Once again the expander had experienced excessive erosion. A new nosecone, stator assembly, shroud, and complete rotor, bearing, and seal assembly were installed. The rotor, bearing, and seal assembly were built from surplus components from an east coast refinery. The purchase of the second assembly was justified by the reduced overhaul cycle during unscheduled shutdowns. After 3.5 years, the expander was shutdown due to high rotor vibrations due to a rotor blade failure.

Visual inspection of the expander, following the shutdown, revealed a collapsed nosecone bullet and six missing nosecone baffle plate retainers. Due to their location in the machine and the observed damage to the stator/rotor, it was suspected that the retainers traveled through the gas path. Additionally, three or four stator vane passages were blocked with a wire mesh material that entered the gas path from a failed expansion joint in the upstream process piping.

Examination of the failed blade suggests that the initial cracking was a result of high-cycle fatigue initiating from a notch in the leading edge of the airfoil. The notch most likely resulted from impact with the baffle plate retainers. While the notch provided a site for initiation of the crack, the high level of forced excitation created by the blocked stator openings and the collapsed nose cone ultimately caused the blade to fail in a fatigue mode.

In March 1997, a replacement expander was commissioned. The new expander was built with the proven design principles and improvements developed for previous units (Figure 7). These improvements included:

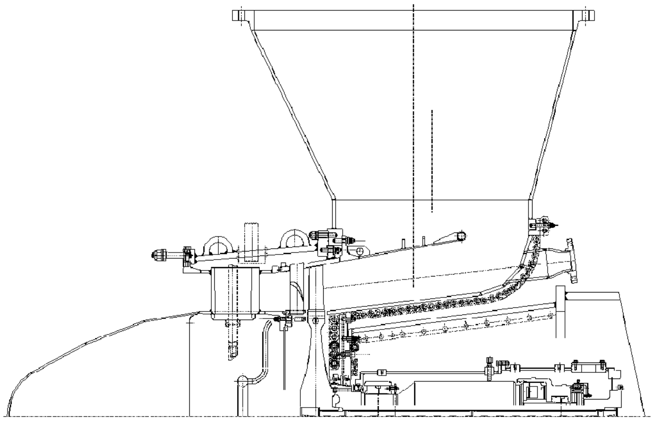

Figure 7. New Expander for Torrance Refinery.

- A single intake casing.
- Increased thickness on the nosecone bullet, aerodynamic strut designs, and elimination of the bolted retaining clips for the baffle plate.
- Integral stator/shroud was used for aerodynamic efficiency and also reduced nosecone strut stresses by 40 percent.
- With the one piece design, the integral stator/shroud bolts directly to the outer casing reducing the structural loads on the nosecone.
- Outer exhaust, diffuser, and inner exhaust casings have been upgraded. One notable improvement was making all butt welds of the fabrication full penetration welds.
- Thicker flanges with increased Inconel® 718 bolting were implemented to eliminate flange leakages and increase joint stiffness.
- The diffuser natural frequencies were evaluated and stiffeners were added to tune the component.
- The flowpath design was optimized to maximize the erosion life and power recovery.
- Upgraded rotor blade material was used for increased erosion resistance.
- The journal diameters on the shaft were increased for additional torque capability and improved rotordynamics.

During a nonmachinery-related shutdown in October 2000, an internal visual inspection of the expander was performed. Flowpath erosion was not evident and no repairs were made. The unit was returned to operation and is scheduled for an overhaul in Spring of 2003, extending its run time to six years from an average of 2.2 years.

Corpus Christi, Texas— New Expander Design for 1400°F (760°C) Operation

The PRT in Corpus Christi, Texas, consists of a hot gas expander, motor/generator, axial compressor, and steam turbine. The expander designed by the original OEM was commissioned in 1983. After a catastrophic failure of the rotor disc in 1988, the expander was rebuilt and upgraded. Even with the upgrades implemented, the process requirements for this residual oil unit have changed drastically, and large amounts of flue gas quench steam and water were needed to maintain the inlet temperature of the expander at the 1350°F (732°C) rating. A redesigned expander to handle the increase inlet temperature and increased flue gas flow was required.

A new expander was designed to operate at a continuous inlet temperature of 1400°F (760°F). The most significant changes occurred in the flowpath area. The flowpath was optimized using CFD to reduce the erosion potential and increase the capacity of the unit. This optimized flowpath would require new airfoil designs and, more significantly, a new rotor disc. The material lead times would extend the delivery of the unit beyond the next scheduled shutdown. Therefore, an alternative flowpath was designed using the existing disc and modified flowpath components.

A modification to the rotor blade tooling was performed to add an extended neck platform design. A comparison of the old and new rotor blade can be seen in Figure 8. This platform extension and the use of platform seals increase the effectiveness of the rotor blade to disc attachment cooling. The power recovery of this unit was increased from the OEM rating of 35,000 hp (26 MW) to 50,000 hp (37 MW). Increased operating stresses follow the increased power recovery. Therefore, maintaining metal temperatures below 1000°F (537°C) is critical to retain the mechanical strength of the disc and blades. A cross section of the new expander can be seen in Figure 9.

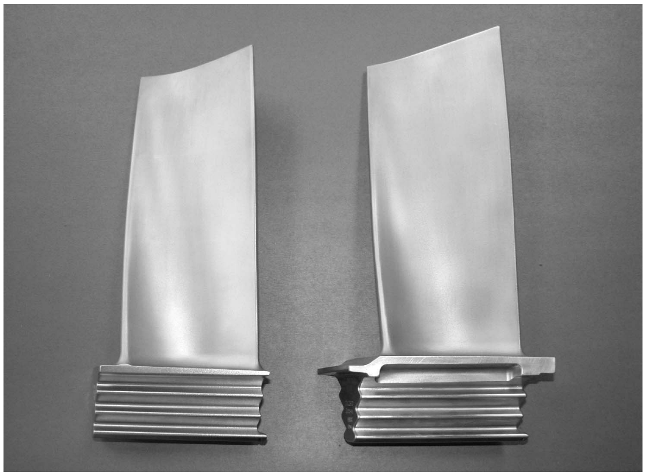

Figure 8. Comparison of Original Rotor Blade (Left) and Upgraded Design for Higher Operating Temperatures (Right).

The proven casing designs from the Corpus Christi model were scaled up for the increased size of the unit. A photograph of the complete unit during final assembly can be seen in Figure 10. The one piece inlet casing design, improved outer exhaust and inner exhaust casings, improved flanges, and increased fasteners were implemented. The unit was commissioned in February 1999 and is currently in operation.

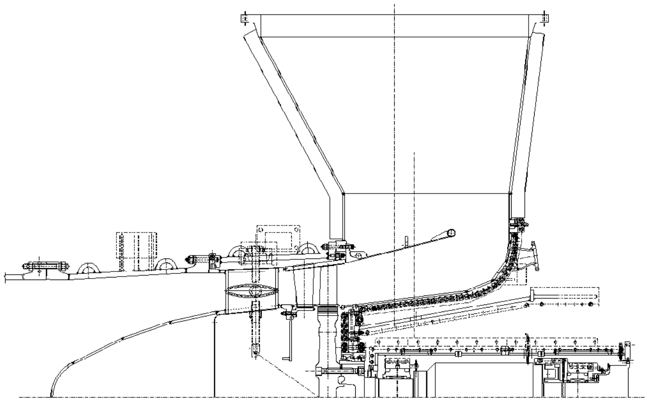

Figure 9. Cross Section of New Corpus Christi Expander.

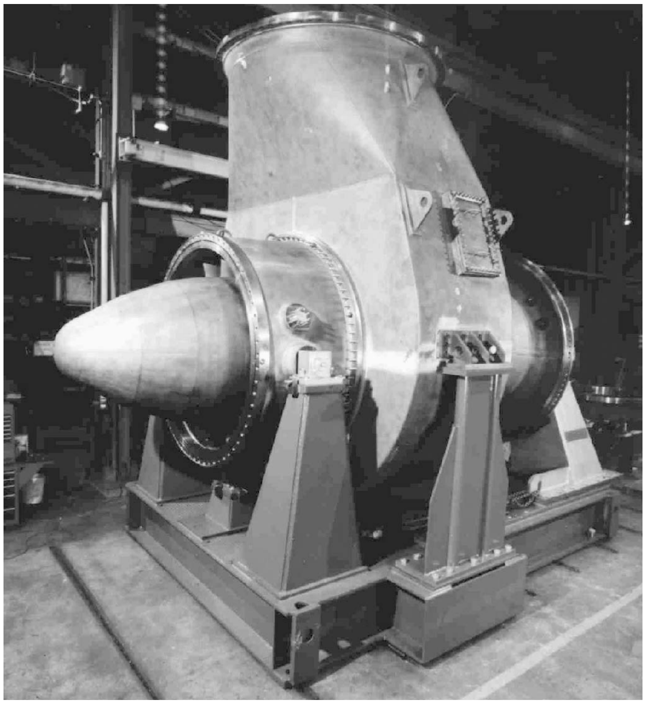

Figure 10. Photograph of New Expander During Assembly.

Yosu, Korea— Conversion to a Single-Stage Expander

The PRT in Yosu, Korea, consists of a hot gas expander, axial compressor, steam turbine, gear, and motor/generator. The two-stage expander designed by the original OEM was commissioned in December 1995. A machine cross-section can be seen in Figure 11. The unit experienced heavy flowpath erosion and catalyst deposition that caused blade wear and rotor vibrations, forcing an unscheduled shutdown in November 1996. By May of 1997, rotor vibrations had again increased and the unit was forced to shutdown due to excessive rotor blade erosion. The expander experienced a high vibration shutdown in August 1997 and again in October 1997. At that point the OEM redesigned the interstage seal and disc cooling systems and brought the unit back online in June 1999. During the heat-up cycle, the expander rotor vibration levels increased due to mechanical rubs and were taken offline. Since January 2000, the expander operated at partial load, producing only 30 percent of its rated power, due to increasing vibration levels with expander load. The decision was made to operate the expander at 30 percent load until the next scheduled outage in April 2001. Applying the design developed for the multistage unit in Corpus Christi, Texas, a single-stage conversion was performed and a new intake casing assembly was manufactured. A cross-section of the converted unit can be seen in Figure 12. The intake casing assembly uses the latest one piece intake casing design, integral stator/shroud, and improved nosecone design. The existing two-stage rotor was disassembled and reassembled as a single stage. New rotor blades of upgraded metallurgy, Inconel® 738, were installed for increased erosion resistance. The redesigned expander was commissioned in May 2001. At full capacity and power, the rotor vibrations are below 0.7 mils (18 m). At the time of this publication, the expander had almost a year of operation. Prior to the conversion to a single stage, the expander averaged less than 150 days between unscheduled shutdowns. The next scheduled shutdown is Spring of 2003.

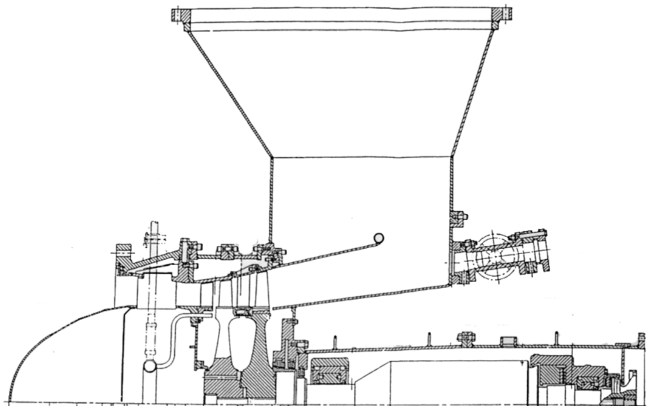

Figure 11. OEM Two-Stage Expander Design for Yosu.

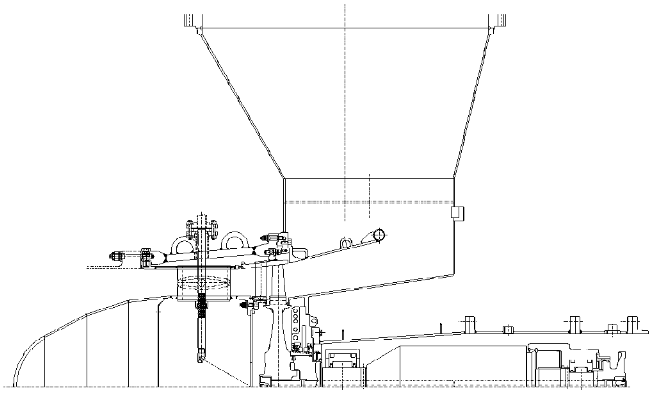

Figure 12. Single-Stage Conversion for Yosu.

DESIGNING FOR THE FUTURE

To date, most expander upgrades have focused on the outer casings. The more robust mechanical designs allow for higher operating temperatures, pressures, and increased power recovery. Optimizing power recovery as well as extending reliability for these new operating conditions represent the future of FCCU expander design. Redesigning the airfoils to optimize aerodynamics, reliability, and increase structural margins is required for the next generation of expander designs.

Recently, a refinery in Corpus Christi, Texas, requested improved reliability and efficiency, in conjunction with a 34 percent increase in flow capacity (from 1,250,000 lbm/hr to 1,675,000 lbm/hr) at roughly the same pressure ratio (~3.15). To reduce installation costs, the redesign needed to fit within the existing casing to minimize field modifications. Therefore, a new flowpath was required, including new airfoils, to meet the objectives. The resulting design will generate nearly 63,500 hp, a 27 percent increase over the existing 50,000 hp.

The following design modifications were made to the unit to satisfy the new requirements.

Flowpath Design

The flowpath design approach was based on applying the guidelines outlined in Carbonetto and Hoch (1999) to minimize erosion and maximize efficiency. The stator was designed with a 10 degree simple lean (Figure 13) to improve the spanwise work distribution (reaction). This approach more uniformly distributes the work on the rotor, which helps reduce erosion and improves aerodynamic performance. A more efficient constant solidity (chord/space) hub to shroud design approach was also used. The stator airfoil sections were designed to optimize the performance for transonic operation ($0.9 <$ Mach number < 1.2) to minimize the detrimental effect of trailing edge shocks. Designing for transonic operation involves minimizing the airfoil suction side curvature downstream of the throat and minimizing the trailing edge wedge angle (difference between suction and pressure side discharge blade angles). Airfoils designed in the 1960s and early 80s did not account for transonic operation due to the lower pressure ratios. At today's higher pressure ratios, the airfoils operate in the transonic region due to overexpansion downstream of the throat.

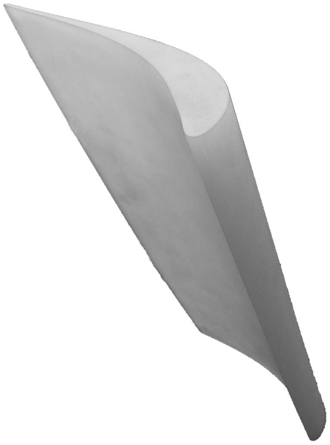

Figure 13. Prototype of Redesigned Stator.

The rotor was also designed for transonic operation as outlined above. Additionally, the leading edge incidence (difference between inlet blade angle and inlet flow angle) was optimized to minimize local flow accelerations. Figure 14 shows the final rotor blade geometry.

Figure 14. Prototype of Redesigned Rotor.

Additionally, stationary components were optimized for efficiency and erosion reduction, including the nosecone contour, nosecone strut profile, and exhaust diffuser contour.

The redesigned flowpath was analyzed using CFD to predict the resulting aerodynamic performance and erosion potential. The entire flowpath, including the nosecone, nosecone struts, stator, rotor, and diffuser were modeled. Results indicate that the predicted erosion has been reduced by greater than an order of magnitude on the stator and rotor. Figures 15 and 16 show the comparisons to the original designs for the stator and rotor, respectively. (Note that for both figures the maximum erosion on the color scale is one order of magnitude less for the redesigned airfoil [i.e., red represents an order of magnitude less erosion for the redesign than the current design]. If the erosion scale for the current design were used for the redesign, it would appear to have no erosion.) Based on the CFD analysis, the erosion life has been significantly improved while satisfying the objectives of maximizing power recovery and minimizing the cost impact.

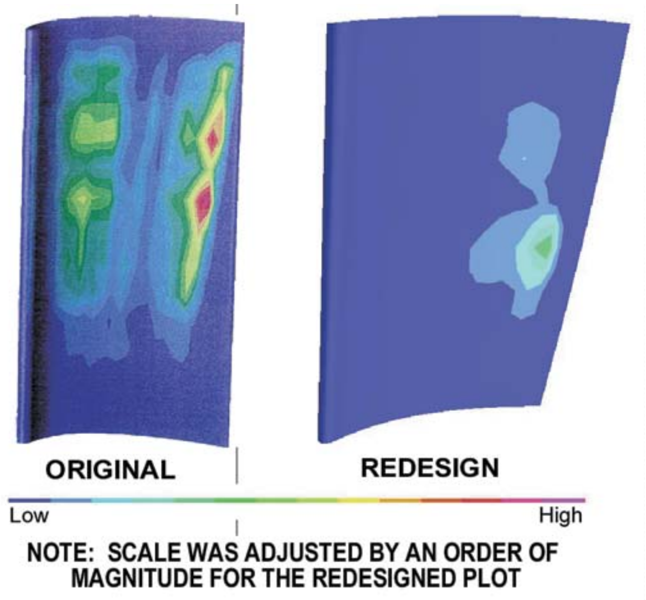

Figure 15. Predicted Erosion for Original and Redesigned Stator.

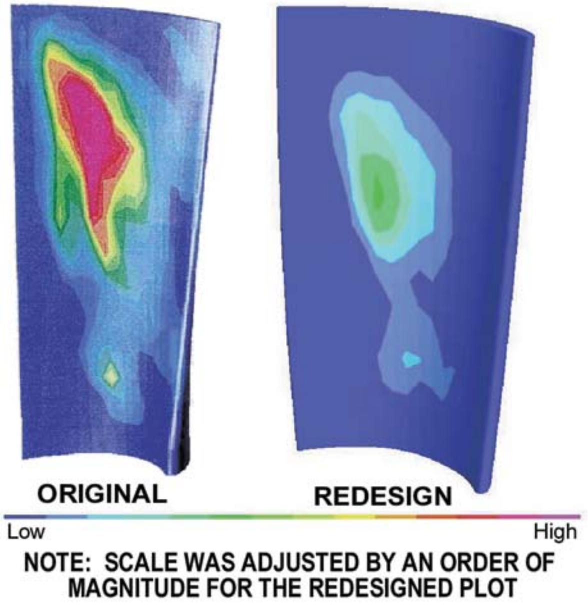

Figure 16. Predicted Erosion for Original and Redesigned Rotor.

Rotor Assembly Design

The 27 percent increase in power recovery necessitated a redesigned rotor assembly, including a new wider disc to reduce the blade attachment stresses. The extra available width was utilized to lengthen the rotor airfoil to reduce the aerodynamic and erosion loadings. The disc profile was optimized to maintain or reduce the operating stress levels relative to the existing design and utilized an improved attachment design to reduce blade attachment stresses.

The unit is currently in production with startup expected in Spring 2003.

CONCLUSION

Although failures are most often looked upon negatively due to the associated costs, they can be springboards for design improvements. Learning from the root cause investigation and updating the design principles and guidelines are critical to preventing future reoccurrences. One design lesson we can take from these case histories is that simple designs are more reliable, and one operating guideline that has emerged is that it is important to operate the unit within its design parameters. Extending expander reliability and improving performance requires an understanding of the operating environment, application of sound mechanical principles to the design, and the use of quality materials for the manufacture of the components. In addition to mechanical improvements, the next generation of hot gas expander designs will require renewed emphasis on airfoil designs to further reduce erosion and improve operating efficiency. Recent airfoil designs have proven that predicted erosion levels can be reduced by an order of magnitude while maintaining or improving aerodynamic performance. Although expander design has improved dramatically in the 40 years since they were first introduced, there are significant opportunities for still more improvement in reliability and performance.

REFERENCES

Carbonetto, B. and Hoch, G.L., 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. 1-7.