Proceedings of the First Middle East Turbomachinery Symposium
February 13-16, 2011, Doha, Qatar

GAS TURBINES DURABILITY IN HARSH ENVIRONMENTS

Zaher Mutasim
Manager, Materials and Processes Engineering
Solar Turbines Incorporated
San Diego, California, USA

ABSTRACT

The performance and durability of industrial gas turbines are strongly dependent on the operating conditions and the environment in which they function at. Engine performance and durability must be equally considered when operating in environments that challenge engine component lives. This paper describes the various elements that contribute to engine durability when operating in offshore applications with high salt/Sulfur fuels, and a “Systems-Solution” approach to attaining excellent turbine power and efficiency by mitigating the risk of degradation mechanisms that the turbine materials are subjected to. The System Solution to be discussed involves the use of advanced materials in conjunction with appropriate air and fuel filtration systems. Advances in alloys and coatings as well as air and fuel filtration systems have been very strong in the last number of years, and as a result new solutions have emerged to support the new challenging demands and requirements of gas turbines.

INTRODUCTION

The design of industrial gas turbines and package systems has been optimized to provide reliable service over a wide range of operating conditions when running on pipeline quality natural gas or clean distillate fuels. The demand for greater power output and thermal efficiency has led to increased turbine rotor inlet temperature (TRIT) of industrial gas turbines. As a result, turbine hot section designs and materials have evolved over the past several decades to operate at higher temperatures. Under normal operating conditions with reasonably clean fuel and inlet air, reliable operation at high TRIT has been achieved and durability well demonstrated. However, when the high temperature environment is combined with contaminants in the fuel, special product design and operational precautions must be taken in order to avoid the risk of damage by hot corrosion.

Hot corrosion failures of turbine hot section components are the primary factor for compromising engine durability in harsh environment applications (Hendrix, 1998). Units operating in coastal, marine and offshore applications, where the gas/liquid fuel quality and the air filtration system are sub-optimal, are particularly prone to this form of degradation. Over the past several years there has been a growing trend towards applications with more challenging fuel and air qualities, and as a result more focus must be placed on risk mitigation solutions to assure reliable operation. . Gas and liquid fuel quality has also been a growing issue in markets, where availability of low sulfur fuels becomes a logistical and cost issue. Various technical solutions are now available to improve air filtration performance, enhance hot section components’ resistance to hot corrosion and to improve fuel quality, (Mutasim, 2008). Together, all these enhancements improve product durability for operation in harsh environments.

INGESTION OF CONTAMINANTS

A large variety of contaminants can enter a gas turbine engine through the air inlet system, water systems (from evaporative cooler carryover, compressor wash solutions, NOx control injection water, and dual fuel injector purging), and fuel (gaseous and liquid) as illustrated in Figure 1. A number of these contaminants, either as chemical elements or compounds, are potentially harmful to the engine. The following contaminants are known to be detrimental to gas turbine engines.

Sodium	Potassium	Vanadium	Sulfur
Lead	Chlorine	Fluorine	Magnesium
Calcium	Silicon	Nitrogen	Water
Sediments	Inert particulates		

The contaminants listed below are only present in unusual or accidental circumstances, but their presence above threshold concentrations requires special treatment and precautions.

Mercury	Cadmium	Bismuth	Arsenic
Indium	Antimony	Phosphorous	Boron
Gallium			

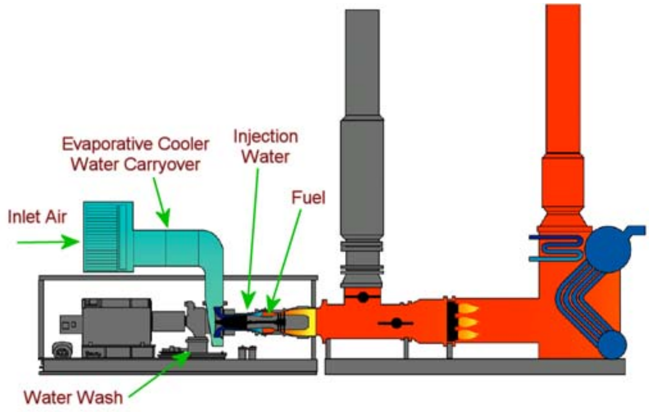

Figure 1. Sources of Contaminants

Inlet Air

Industrial gas turbines operate in all types of geographical and physical locations worldwide. Airborne contaminants often are site specific (McGuigan, 2004). For example, contaminants can include sea salt, dust and sand, factory discharge gases, exhaust fumes containing oil and fuel vapors, particulates such as chemicals, fertilizers, mineral ores, and any variety of industrial by-products. Airborne contaminants can vary daily and/or seasonally. They are subject to climatic conditions such as prevailing wind direction, wind speed, temperature, relative humidity and precipitation. Modern air filter systems are now available to handle even the most extreme environments. The key is proper selection, then on-going maintenance once in service. The most important consideration in selecting an air filter is the particulate size and composition of contaminants contained within the incoming air. The incoming air can contain contaminants from many sources, depending on the site's location (Shelton and Carleton, 1984). For instance, a site near an ocean is likely to have significant amounts of sea salt in the air, thus providing sodium and potassium. A site in the desert could have a variety of contaminants in the air depending on the local mineral content. These are naturally occurring contaminants. Incoming air can also contain contaminants from nearby facilities such as mines, refineries, chemical processing plants and farms, which use aerial application of fertilizers, etc. The possible contaminants are numerous and sometimes not predictable. In the case of fuel and water, the contaminants are more predictable and can be readily analyzed. Additionally, airborne particulate larger than 5 microns are known to cause erosion to compressor blades and vanes.

Water

Water is used in turbines for three primary purposes: 1) evaporative cooling to increase hot day power, 2) water washing of the compressor section, and 3) suppression of NOx emissions. Evaporative coolers are employed with gas turbine engines to reduce the inlet air temperature and thereby increase power output. They are most effective in hot, dry environments. As inlet air flows through the evaporative cooler media, the resulting water evaporation extracts heat from the air, thus cooling it. With these systems, there is potential for water carryover into the turbine. Although proper design (e.g., vane type mist eliminators), installation, operation, and maintenance can minimize the amount of water carryover, it is recognized that some amount of water will carry over from the evaporative cooler in the form of water droplets of varying size. The water carryover contains some water-soluble contaminants originally found in the inlet air and dissolved in the water during passage of the air through the evaporative cooler.

Water can also be introduced into the engine through the solutions used for compressor cleaning. The compressor deposits removed by these solutions travel through the engine and exit through the combustor housing drain (on-crank wash) or exhaust (on-line wash). Water can be injected into the combustor for NO_x emission control purposes. This water will travel through the turbine hot section gas path. Although water consumption is typically somewhat less than fuel consumption, the total volume of water introduced into the engine can be quite large. Finally, water is used in small amounts from time to time to purge liquid fuel passages in dual fuel injectors during fuel transfers and liquid fuel shutdown.

Water used for all these purposes, if not properly treated, can often introduce sodium, potassium, or other contaminants into the turbine leading to higher risks of corrosion.

Fuels

Gas turbine engines can operate on gaseous or liquid fuels. There are many types of fuels as shown below (Meier et al, 1986):

Gaseous

Gaseous fuels include natural gas, digester gas, landfill gas, associated gas, coal gas or syngas, and coke oven gas (COG). Natural gas is the most common fuel used for industrial gas turbines and is produced by decomposition of organic matter in the ground. It consists primarily of methane with small amounts of inert substances such as nitrogen and carbon dioxide, and heavier hydrocarbons such as ethane and propane. These heavier hydrocarbons are sometimes used as fuels by themselves or in mixtures. The contaminant of greatest concern that may be found in natural gas is hydrogen sulfide. If the gas is contaminated with water, it may also contain alkali metals.

Digester gas is produced in sewage treatment plants by conversion in anaerobic (i.e., in the absence of oxygen) conditions of biological waste matter to methane and carbon dioxide. The resulting digester gas can contain hydrogen sulfide, water, and solids of various compositions. Landfill gas is produced by decomposition of trash in landfills and contains a great variety of chemical elements and compounds, some unique to the particular landfill. Landfill gas typically consists of methane, carbon dioxide, and air. Decomposition of plastics in landfills can introduce many detrimental compounds. Major contaminants in landfill gas include methylene chloride, carbonyl sulfide, sulfur dioxide, chlorine, and, of greatest concern, siloxanes.

Associated gas is extracted with crude oil and found either dissolved in the oil or as a cap gas above the oil in the reservoir. The majority of associated gas is produced offshore and its composition depends on the type of reservoir from which it originated. Associated gas in certain reservoirs may contain hydrogen sulfide.

Coal derived gas or syngas is a fuel produced by gasification of coal. These gases consist primarily of carbon monoxide, carbon dioxide, and hydrogen. These gases may contain solid-particle contaminants containing alkali metals, ash and vanadium.

Coke oven gas is the gas released during conversion of coal into coke. Coke oven gas is composed mainly of hydrogen, methane, water, oxygen, carbon monoxide, nitrogen and carbon dioxide. Coke oven gas also contains contaminants such as tar, light oil vapors (aromatic hydrocarbons), naphthalene vapor, ammonia gas, hydrogen sulfide, hydrogen cyanide, calcium carbonate and trace metals.

Liquid

The four main types of liquid fuels are crudes, distillates, residuals and non-hydrocarbons. Distillates and residual fuels are obtained by the refining of crudes. Therefore, the contaminants found in distillates and residuals originate from the crude feedstock or mishandling during processing or transportation.

The contaminants in crude petroleum can be divided into oleophilic and oleophobic. Oleophilic contaminants include sulfur as hydrogen sulfide and various sulfur-hydrocarbon compounds, nitrogen, and organo-metallic compounds containing vanadium, calcium and other metals. Oleophobic contaminants include water containing dissolved salts, including those of alkali metals, and fine solid sediment.

Some of these contaminant species are removed in the distillation process and are retained in the residuum. Some of the sodium, potassium and calcium present in the crude, along with ash, sulfur, and sediment can be carried into the distillate at levels associated with the particular refining, filtration, and removal processes. If vanadium is found in a distillate fuel, it is usually the result of poor handling practices such as mixing with crude or a residual. Lead is not usually present in crude in significant quantities. Its presence in a gas turbine fuel is indicative of contamination with gasoline (the lead content in unleaded gasoline is still above allowable limits for gas turbine engines).

Residual fuels typically contain all the contaminants present in the crude, but at higher concentrations because the distillate volume has been removed.

In addition to petroleum-based fuels, there are non-hydrocarbon liquid fuels, the most popular of which are the alcohols, e.g., ethanol. In most cases, the processes used to generate these fuels produce relatively contaminant-free fuels.

The liquid fuel most frequently used in gas turbine applications is diesel. Different specifications for this fuel limit the amount of sulfur to certain levels. These limits are different in different countries and different parts of the world. In addition, diesel fuel may be subject to further contamination during transportation.

EFFECTS OF CONTAMINANTS

Contaminants can affect gas turbine engine components in three ways: fouling/deposition, erosion, and corrosion. Fouling/deposition and erosion are physical phenomena induced by the ingestion of chemically inert solid particulates. Corrosion includes a variety of chemical phenomena induced by the reaction of contaminants with turbine engine components. Of the contaminant effects, corrosion has the greatest impact on power output and durability for industrial gas turbines (Bornstein, 1996). The various forms of corrosion will be covered in a separate section.

Fouling/deposition in the compressor section is produced when solid particles travel through the inlet air cleaner and stick together on compressor component surfaces with the aid of binders. Hydrocarbon compounds like oil and fuel vapors are typical binders. The gradual deposition of matter on compressor components eventually results in measurable and significant loss of airflow and engine output. The degree of fouling/deposition is primarily a function of the total mass of particulate traveling through the inlet air filter, the particle size and shape, particle velocity and incident angle, the nature of other contaminants ingested through the inlet cleaner, and the surface roughness of the compressor components. Small solid particles, loosely defined as those less than 5 microns (µm) in size, are mainly responsible for compressor fouling/deposition. Inlet air cleaners can reduce the rate of fouling/deposition, but inevitably the compressor will need to be cleaned to restore engine output. Fouling/deposition can also affect combustion system and turbine section components. In these areas, fouling/deposition can be caused not only by airborne particles, but also by those introduced via fuel and injected water.

Larger particles, typically those greater than 5 µm in size, are generally responsible for erosion, i.e. material removal, of compressor components. The degree of erosion is dependent on particle size, shape, hardness, velocity, mass, and impingement angle, along with the hardness of the compressor components (Tabakoff, 1989). Fortunately for industrial gas turbines, erosion is controlled effectively with the use of inlet air filtration.

GAS TURBINE CORROSION MECHANISMS

Ingested contaminants can result in corrosion to the compressor, combustion, and turbine sections of gas turbine engines if proper product design and mitigation solutions are not applied. The types of corrosion experienced in these sections are as follows:

Compressor Section

In most applications, corrosion of compressor components is unlikely during engine operation because the compressor is dry. However, during shutdowns where cold surfaces condense water, chemical species such as hydrochloric acid and sulfur trioxide can be absorbed in the water producing an acidic, corrosive liquid. This liquid phase can result in aqueous corrosion of compressor components through a variety of mechanisms, e.g., generalized, pitting, and crevice corrosion, and stress corrosion cracking. In cases where hydrochloric acid and sulfur trioxide are present and the relative humidity is high, the high velocity of the air at the compressor inlet causes the temperature of the air to drop due to conversion of internal energy to kinetic energy. The temperature drop can result in the formation of a liquid phase in the forward stages of the compressor during operation.

The compressor coatings used in Solar's engines are effective at retarding corrosive attack. However, some compressor component surfaces that are inherently difficult to coat, e.g., variable stator vane actuating ports, have experienced corrosion. Corrosion in some instances has resulted in the binding of variable stator vanes and subsequent high cycle fatigue failure of compressor airfoils.

Combustion Section

Two main types of corrosion are known to affect components within the combustion section. Aqueous / acidic corrosion of fuel delivery system components such as fuel manifolds and fuel flow dividers (Figure 2), and fuel injector braze joints can occur in much the same way as the aqueous corrosion of compressor components, except that the contaminants can also be fuel borne. Corrosion to these components can result in fuel leaks and fires, and malfunction of fuel injectors.

Figure 2. Liquid Fuel Flow Divider Aqueous Corrosion

Sulfidation, which is the reaction between a metal and a sulfur/oxygen-containing atmosphere to form sulfides and/or oxides, can affect fuel injector tips (Figure 3). In essence, sulfidation attack is a form of accelerated oxidation resulting in rapid degradation of the substrate material due to loss of corrosion protection (John et al, 2004). Whereas during oxidation protective oxide scales can form, the metallic sulfides formed are not protective. This accounts for the rapid rate of degradation produced by sulfidation attack.

Figure 3. Fuel Injector Tip Sulfidation

Turbine Section

Hot corrosion is the most serious form of corrosion experienced by the turbine section components (Rapp, 1990). To better understand hot corrosion, it is useful to first discuss oxidation. Oxidation is the chemical reaction at high temperatures between a component and the oxygen in its surrounding gaseous environment. Oxidation of turbine section components is relatively easy to predict and measures can be taken to control it since it primarily involves relatively simple metal/oxygen reactions. The oxidation rate increases with temperature. Metal loss due to oxidation can be reduced by the formation of protective oxide scales. Chromium, aluminum, and silicon are the only chemical elements known to form protective oxide scales at the temperatures encountered in gas turbine engine hot sections. The presence of these elements in turbine engine alloys and coatings results in improved oxidation resistance.

Hot corrosion is a form of accelerated oxidation that is produced by the chemical reaction between a component and molten salts deposited on its surface (Stringer and Whittle, 1973). Hot corrosion comprises a complex series of chemical reactions, making corrosion rates very difficult to predict. Sodium sulfate is usually the primary component of the deposit and degradation becomes more severe with increasing concentration levels of contaminants such as sodium, potassium, vanadium, sulfur, chlorine, fluorine, and lead. The rate and mechanism of hot corrosion attack is influenced by temperature. There are two types of hot corrosion (Duret-Thual et al, 1988). Type I or high temperature hot corrosion, occurs at a temperature range of 730 to 950°C. Type II or low temperature hot corrosion occurs at a temperature range of 550 to 730°C. These types of hot corrosion attack feature distinct mechanisms and exhibit unique features. Both types can occur in the turbine section. Because of the varying service temperatures experienced by turbine section components, both corrosion types can occur on the same component. For example, Type I hot corrosion may occur on first and second stage turbine blade airfoils and tips (Figure 4), whereas Type II hot corrosion may occur under the platform of first and second stage turbine blades (Figure 5).

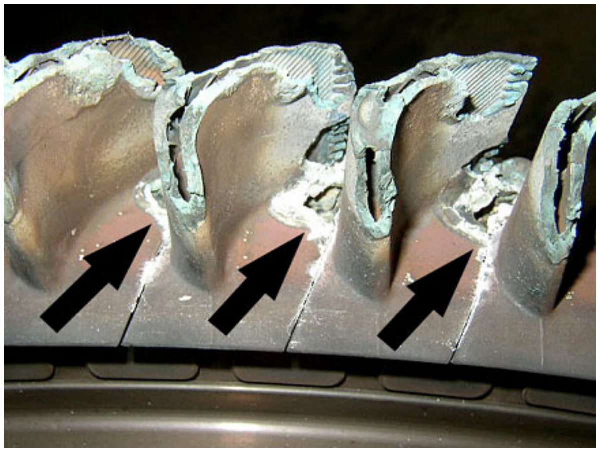

Figure 4. Type I Hot Corrosion Attack to Turbine Blade Airfoils and Tips

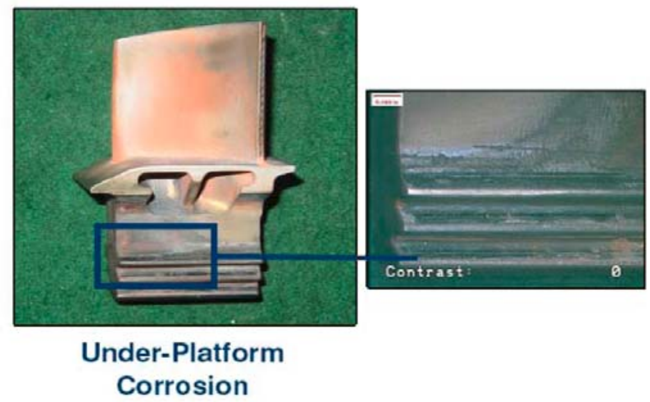

Figure 5. Type II Hot Corrosion Attack to Turbine Blade Shank

To achieve higher power density, gas turbines must run at higher firing temperatures. This can be achieved with advanced alloys that can withstand the higher operating temperatures. To achieve the alloy's desired high temperature mechanical properties, alloy compositions must be altered. For example, refractory elements are added to alloys to increase their mechanical strength, but at the expense of other elements such as chromium, which is essential for hot corrosion resistance. Figure 6 shows trade off curve between alloys high temperature strength and hot corrosion resistance

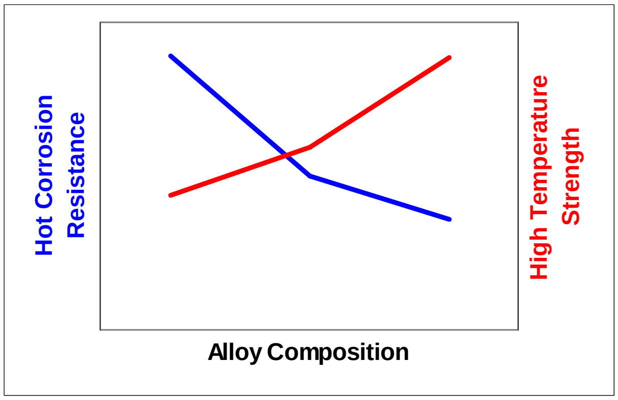

Figure 6. Corrosion Resistance vs Strength Trade-off Curve

PREVENTION AND MITIGATION

Solar Turbines has developed a process to mitigate hot corrosion degradation of turbine components through an integrated systems approach, comprised of inlet air filtration, fuel treatments and gas turbine component design / material solutions.

Air inlet Filtration

Environmental Categories

There are three categories of environments to consider in relation to hot corrosion: Marine, Offshore, and Coastal. Salt is present in all of these environments, and it is critical to stop it from entering the turbine where it can cause corrosion. A site environmental analysis survey should be performed at the earliest opportunity of the project planning process to understand the conditions that affect filtration selection. (Note: inland sites such as certain deserts, dried lakes, and certain industrial sites may contain significant concentrations of salt. These environments should be thoroughly evaluated, and should be treated as coastal when salt levels are determined to be significant.)

Marine: This classification includes marine applications where the inlet to the filtration system is located within 30 meters from the ocean surface. Applications include some FPSO's, gas turbines used for marine propulsion, semi-submersibles, etc., where the air-filter may be subjected to green water. Weather conditions can run from dry and sunny to rain, snow, sea mist and freezing fog. Temperatures range from about –25 to 45°C. In most installations, dust concentrations will be about 0.01 to 0.1 parts per million (ppm) of dry, non-erosive particulate of 0.01 to about 5 µm. In addition, installations in offshore Middle East areas will usually be subjected to heavy concentrations (approaching 500 ppm) of blowing sand with particulate as large as 500 µm. Because the smaller particulate contain salt particles, the effect on the gas turbine will be fouling and potentially hot corrosion.

Offshore: This classification includes offshore applications where the filtration system is more than 30 meters above the ocean surface. The environmental conditions are the same as the marine classification above, but the air filters will not be subjected to green water. Humidity has a large effect on sea salt particle sizes. Humidity lower than 50% (seen frequently in the Middle East) causes the salt particles to reduce in size below 1 µm.

Coastal: This classification includes any land-based application within 16 km of a coastline. Weather conditions can run from dry and sunny to rain, snow, sea mist and freezing fog. Blowing sand, industrial dusts, and unburned hydrocarbons are present in many coastal environments. Tropical conditions such as heavy rains, high humidity, and large quantities of insects can also occur. High velocity filters are not recommended for any coastal application due to their low dust holding capability. Medium velocity (for better protection against smaller particles in areas with humidity below 50%) or self-cleaning filters should be used, depending on the environment.

Inland: More than 16 km from the coast. Special considerations may occur if salt is present in the environment. Examples include dry salt beds such as deserts, sites located close to roadways where salt is frequently applied during wintertime, and sites located near processing plants using or producing salt.

Types of Air Filtration Systems

There are many types of inlet air filtration systems. Each is designed with specific features intended to provide protection against the elements of a particular environment. Because many environmental conditions will be found at more than one location, these air filters combine many of these features. Therefore, one type will often be suitable for more than one environment. Inlet air filters must be designed with many different factors in mind. Some of these are: the volume of air, types of filters, wind loading, snow loading, negative pressure inside the filter house, and restrictions of the dimensions imposed by space limitations.

Air Filter Design

Filters remove solid and liquid particles from the air by means of diffusion, interception, inertial impaction, sieving and gravity action. Filters discussed here do not remove gaseous contaminants from the air. Filters differ in their capability to remove very small particles. They also differ in their dust holding capability, and their static pressure drop. These parameters are highly dependent on the face velocity of the air into the filter. Filters are also classified by their ability to trap liquid water or allow it to pass through. This is of importance for applications in high humidity climates, or where water spray may be present. The latter type of filters may require separator vanes downstream of the filter.

Filters are usually combined as stages in series (one filter is placed behind the other) within the air filtration system. Filter manufacturers rate their filters at various flow velocities for efficiency, dust holding capacity, and static pressure drop. Standardized test dusts are used for laboratory testing. Most manufacturers perform their efficiency tests in their own laboratories in accordance with the ASHRAE Standard 52-1-1992 and 52-2-2002, or EN 779-2002, for pre-filters and high-efficiency filters. Manufacturers of HEPA filters will use EN1822. If efficiencies of filters provided by various manufacturers are to be compared, certified test results performed in independent laboratories must be used. The best comparisons between filters from several manufacturers will be made from tests conducted in the same laboratory, using the same test standard, with the same test dust, on filters purchased on the open market.

Regardless of the environment and location, gas turbines ingest large quantities of air ranging from a few cubic meters per second (m^3/s) for the smaller turbines to thousands of m^3/s for large units. Contaminants found in this air will enter the gas turbine unless they are filtered out. Unfortunately, the value of the effective filtration of turbine inlet air is often overlooked. Frequently, the least expensive air filter is used without regard for its suitability for the environment. In some environments, application of an inappropriate air cleaner will become quickly evident by consistently having a high-pressure drop and by requiring frequent filter maintenance, or in the need for frequent compressor water washing. In other environments, it will be much more subtle and it could be months, before the unsuitability of the air cleaner becomes evident in the form of turbine hot corrosion. The prudent selection of inlet air filtration components will greatly reduce the ingestion of contaminants which cause reduced gas turbine performance and even eventual gas turbine failure. These air cleaners transfer the maintenance from the gas turbine to the air cleaner. This is preferable to the more costly and serious consequences of exposing the gas turbine in operating harsh environments to inlet air without appropriate filtration.

Fuel quality and environmental conditions are the primary factors to consider when selecting an extreme condition filtration system. The major considerations are hydrogen sulfide or sulfur in the fuel and/or air, dust/smoke/UHC concentration levels in the air, and relative humidity. All these factors are important in Marine, Offshore, or Coastal environments.

Fuel Treatment

Gas and liquid fuels may contain corrosive constituents at varying concentrations depending on the fuel source. Of greatest concern are gaseous fuels associated with oil recovery that contain significant levels of water, H_2S, and CO_2. Turbine operators must ensure that the fuel supply will meet the specified gas turbine fuel requirements. This process should also include a thorough evaluation of all possible fuel sources and the required fuel treatment whenever the fuel gas supply quality does not meet the specified limits.

Gas Fuels

Water in the presence of H_2S or CO_2 will form acids that can attack supply lines and components and then the turbine and turbine package components. Protection against water requires a careful comparison of the gas turbine manufacturer's fuel specification with the gas supplier's contractual limits, the proper coalescing filter selection, and a supply line layout with automatic or manual drains to remove accumulations of free water. Fuel heating, or a reduction in the fuel gas pressure after the coalescing filter, may be required to provide enough superheat to prevent water dropout. Fuel line heat tracing may be required to prevent water dropout in static fuel lines during periods when the turbine is not operating. Coalescing filters should include automatic or manual drains with level controls or alarms. The coalescing filters should include a “knock out” section to trap slugs of liquid and should be designed and instrumented to prevent filter breakthrough or collapse. Multiple coalescing filters in series may be required to effectively remove water, since filters do not always operate as efficiently as advertised.

On dual fuel systems, injector-to-injector crosstalk in the dormant liquid circuit can occur resulting in water condensation that will combine with H_2S to form acid. Acidic corrosion of brazed joints in the liquid circuit of the injector and fuel divider block is the result. Therefore, if the gas fuel contains significant concentration of H_2S, a system using cooled PCD air to continually provide forward purge of the dormant passage preventing cross-talk should be part of the fuel system design.

Carbon Dioxide (CO_2) is an acidic gas that forms acids when combined with water. CO_2 is also very permeable and can cause explosive decompression problems in elastomers, including O-rings and diaphragms. High levels of CO_2 raise the combustor lean blowout limits and increase the probability of flameout and/or reduce the offload transient performance of the turbine without flameout. Protection against CO_2 in the gas requires removal of water from the gas, selection of appropriate seals, and adapting operating procedures for limitation.

Liquid Fuels

Typically, the major sources of contaminants within liquid fuels that can cause corrosion are water and contaminants.

Water in the fuel can cause problems if it contains contaminants such as sodium, potassium, calcium, and magnesium. Protection against water contamination requires installation of properly designed tanks with floors sloping to drains at the bottom and floating suction pipes (Figure 7), using day tanks for delivery of fuel to the gas turbine, a properly sized centrifuge for the removal of water, allowing for adequate settling time in the day tank and the use of commercial additives. Water must also be drawn from the bottom of the tanks on a regular basis to prevent excessive build up.

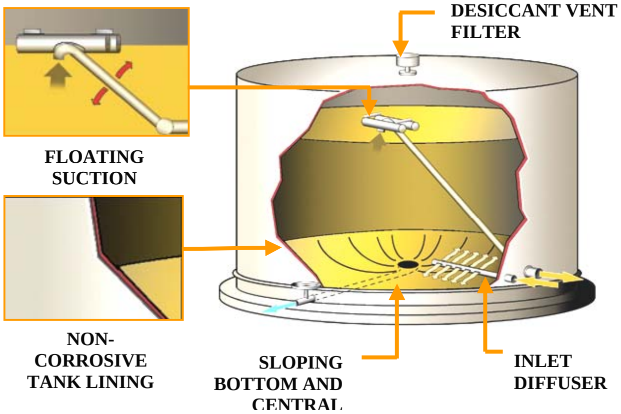

Figure 7. Liquid Fuel Storage Tank

Chemical contaminants in the fuel can by themselves, or through interaction with each other, adversely affect the engine system, particularly turbine hot section life.

Sulfur in the fuel burns or oxidizes to form sulfur dioxide. In the presence of even minute quantities of sodium and potassium in the combustor environment (excess oxygen and high temperature), sodium and potassium sulfates are readily formed. These salts have melting points in the operating range of the gas turbine and condense onto turbine airfoil surfaces and react with the base metal, resulting in severe hot corrosion degradation.

Vanadium can form low melting point compounds such as vanadium pentoxide, which melts at 690°C, and alkali metal vanadates, which melt at temperatures as low as 570°C. These compounds can cause severe corrosive attack on all of the high temperature alloys in the gas turbine hot section.

Sodium and potassium can combine with vanadium to form eutectic compounds, which melt at temperatures as low as 570°C, and can combine with sulfur in the fuel to yield sulfates with melting points in the operating range of the gas turbine. Accordingly, the sodium plus potassium level must be limited. Blending fuel with lower sodium and potassium bearing fuel reduces the concentration of sodium and potassium.

Contaminants such as mercury, cadmium, bismuth, arsenic, antimony, phosphorous, boron, gallium and indium are unlikely to be present except in unusual or accidental contamination of air, fuel or water supplies. If present, these contaminants can cause significant corrosion to the engine package and components.

Protective measures against chemical contaminants can be taken in various parts of the fuel delivery system. In the fuel supply to the site, the fuel should be inspected and tested to ensure that the chemical contaminant levels are below those detailed in the specification. Periodically, the fuel tank should be sampled and tested for chemical contaminants. If the levels are above the recommended values in the specification, then further action should be taken. This could include mixing the fuel in the fuel tank with low contaminant fuels, or cutting with other fuels in the supply, or introducing additives to react with the contaminants.

Gas Turbine Material Solutions

While recognizing that prevention, i.e., control of contaminants to concentrations below specified limits, is the preferred path towards trouble-free operation, other material and design solutions are taken to mitigate the effects of gas turbine engine hot corrosion.

The selection of materials, i.e. alloys and coatings, takes into account typical operating conditions and allows for some occasional system upsets. Corrosion resistance is one of the attributes considered when selecting materials. In situations where the corrosion resistance of alloys is deemed insufficient for the application, protective coatings are specified.

Stainless steels such as 410 and 17-4PH are commonly used for compressor stationary and rotating applications. Although these alloys have inherently good corrosion resistance, a protective coating is commonly used on compressor components made from these alloys to enhance their durability. Superalloys, such as 718 and 901, used in the compressor section do not require protective coatings.

Fuel injectors and fuel flow dividers are fabrications in which detail parts are joined by brazing or welding. Fuel injectors typically use 316L stainless steel and Inco 625 for most details and superalloys such as Haynes 188 and Hastelloy for details in, for example the injector tips, that are exposed to the highest service temperatures. These details are brazed using nickel braze filler metals. All these alloys and filler metals have adequate corrosion resistance for the vast majority of applications. In the most severe applications, protective coatings, more corrosion resistant alloys, e.g. superalloys such as 625 replacing 316L, HR-160, and braze filler metals such as gold alloys may be used.

Combustor liners are also fabrications, made of sheet metal alloys such as Hastelloy X, Haynes 230 or Haynes 214, and machinings from forgings, brazed together. The alloys used for these applications have adequate corrosion resistance and generally do not require protective coatings. When predicted metal temperatures exceed the strength and oxidation resistance of these alloys, thermal barrier coatings (TBCs) are utilized.

Turbine section airfoils, i.e. blades and nozzles, are the components most susceptible to hot corrosion attack. Superalloys first developed specifically for these applications, e.g. S-816, U500, Waspaloy, IN738, IN792 and MAR-M421, relied heavily on chromium for oxidation and corrosion resistance. However, as gas turbine engine operating temperatures increased, these chromium-rich alloys were found to be lacking in high temperature strength. To achieve increased strength, alloy designers replaced chromium with refractory metals such as tungsten, molybdenum, and tantalum, increased the aluminum content, and more recently added rhenium. These alloying element changes also achieved gains in oxidation resistance because of the additional aluminum employed, but resulted in much reduced hot corrosion resistance. Consequently, the successful utilization of these high strength alloys in industrial gas turbines is highly dependent on protective coatings such as diffusion aluminide coatings. Turbine section airfoil components are thus considered as systems in which the base alloy provides the mechanical and structural capabilities, and the coatings contribute the resistance to oxidation and hot corrosion attack. Coatings, such as silicon aluminides, or overlay MCrAlYs (M = Cobalt and/or Nickel) for under-the-platform regions of the turbine blades may be required for severe conditions (Type II hot corrosion regime) (Neff et al, 2004). High chromium weld materials, such as IN-738, may be applied onto turbine blade tips to enhance blade tip hot corrosion resistance (Type I hot corrosion regime). It should be recognized however, that even the most corrosion resistant systems developed and in production are not immune to hot corrosion attack. Therefore, control of contaminants ingested by industrial gas turbines to specification requirements remains of paramount importance.

Advanced multi-wall turbine blade cooling designs are being developed to significantly reduce the metal wall temperatures without sacrificing engine efficiency or performance. These advanced cooling designs will allow the use of chromium-rich alloys in high temperature engines by maintaining the wall temperatures at levels that provide the strength required for long durability.

DISCUSSION

Turbine Air Inlet Filtration System Life Cycle Cost

Many projects are driven by first cost considerations that do not take into account the other components of a lifecycle cost evaluation. This is at least partially due to the fact that parties in the procurement phase of the business are not always aware of the different operational and maintenance costs associated with the various turbine air inlet filtration systems available for different applications.

Also, the benefits of improved lifecycle cost, which is usually very apparent to the operators, may not form a part of the initial project requirements. Thus it is not always part of the evaluation process performed by Engineering Procurement Construction contractors, fabricators or other procurement organizations.

The type of air filtration becomes an important issue when operators and maintenance departments become part of the procurement process, and look for operating and maintenance cost reduction and improvements in production output. Working with the turbomachinery OEM and filter manufacturers, as well as attempting to define the site conditions as precisely as possible, allows optimization of the air inlet system for the customer’s operational goals. The results are operational and commercial benefits associated with improved lifecycle cost.

The risks are that many end user Operations and Maintenance Departments, OEMs, and filter manufacturers do not fully understand each other’s requirements. Therefore, they sometimes identify solutions, which do not maximize the life and minimize the cost of operating turbomachinery equipment in certain environments.

Through thorough evaluations of the application and open communications with end users, OEMs and filter manufacturers can optimize turbine performance, maximize operational uptime and minimize maintenance costs. Analyzing and reducing lifecycle costs can accomplish these objectives. In reality, lifecycle costs take a net present value (NPV) approach while balancing the considerations in Figure 8.

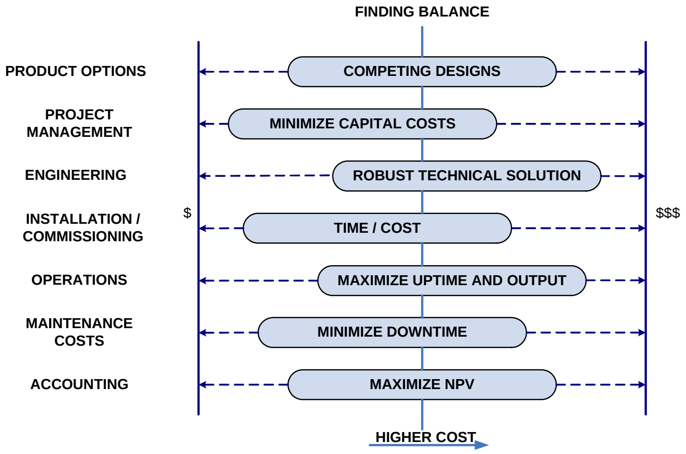

Figure 8. Lifecycle Cost Optimization Tool

For management, finding a lifecycle cost balance and making economical decisions by addressing commercial, logistic, technical, future operational and maintenance requirements can be a challenge, not to mention costly and time consuming. The benefits are far outreaching when one considers the benefits of optimized performance and minimized downtime.

If engine availability and/or performance are critical, then a detailed Life Cycle Cost analysis is highly recommended. A few general questions for this analysis include:

- What are the availability and reliability requirements?
- Is lost performance an issue? (As it relates to lost production and engine fouling)
- Will this product be installed in an extreme duty environment?
- Are there environmental conditions that could put this product at risk?
- Are there man made or influenced conditions that could put this product at risk?

Knowing, or at least determining, answers to these types of questions will help in the filtration system evaluation and selection process. If availability and reduction in lost performance is a requirement, then these lost opportunities should be a major consideration. Ultimately as businesses start using lifecycle cost tools for analysis purpose, the substantial impact of overall cost reductions will be realized. These benefits will dwarf any initial cost reductions being utilized today.

Fuel Monitoring and Handling

In many installations, the fuel quality and composition will change over time. Gas fuel compositions may change during upset process conditions, or due to changes in fuel supply (different wells). Initially specified fuel compositions may be based on assumptions that prove inaccurate once the units are installed. Liquid fuel may incur contamination during transport, or may be purchased from different sources with sources.

All of the above indicates the need to analyze the fuel used in gas turbines on a regular basis.

A further concern is the practice to test gas turbines in the fabrication yard using liquid fuels. These fuels may not receive the same scrutiny as the fuel used in the ultimate installation. It is important to analyze fuel samples prior to starting the unit.

Furthermore, The proper storage and handling of liquid fuel is key to obtaining reliable operation from the engine. This means installing the correct equipment, as well as requiring the proactive attention of the user/operator to ensure that fuels remain within specification

SUMMARY

The intent of this paper has been to inform and educate gas turbine procuring specialists, operators and owners on how to manage turbomachinery systems to maximize life and minimize operational downtime in environments that are potentially corrosive. When the environment and paths for corrosion are understood, the necessary steps for cleanup of these contaminants and prevention of damage can be planned. Taking these steps will help the gas turbine owner achieve satisfactory use and life of their equipment. For many applications the focus will be to determine paths for ingestion of sulfur, sodium, and potassium into the gas turbine and keeping the fuel clean and dry. Knowing these paths, the proper air filtration and fuel handling & treatment selections can be specified to keep contaminants at or below acceptable levels. The final point that must be made to close out this document is that, with care managing contaminants that can cause corrosion, gas turbines have proven to be reliable and robust prime movers that can be counted on to provide years of cost effective service.

NOMENCLATURE

COG = Coke Oven Gas
FPSO = Floating Platform Production, Storage and Operation
HEPA = High Efficiency Particulate Arrestance
NOx = Oxides of Nitrogen
OEM = Original Engine Manufacturer
PCD = Primary Cooling air Discharge
TBC = Thermal Barrier Coating
TRIT = Turbine Rotor Inlet Temperature
UHC = Unburned HydroCarbons

REFERENCES

Bornstein, N.S., 1996, “Reviewing Sulfidation Corrosion-Yesterday and Today,” *Journal of Metals, November*, pp. 37-40.

Duret-Thual, C., Morbioli, R., and Steinmetz, P., 1988, “A Guide to the Control of High Temperature Corrosion and Protection of Gas Turbine Materials,” Commission of the European Communities, PB88-107412.

Hendrix, D.E., 1998, “Hot Corrosion Failure of a 25 MW-Land Based Gas Turbine in a Marine Environment”, Corrosion 98. pp. 203/1-203/23.

John, R.C., Pelton, A.D., Young, A.L., Thompson, W.T., Wright, I.G., and Besmann T.M., 2004, “Assessing Corrosion in Oil Refining and Petrochemical Processing,” *Materials research, 7*, No. 1, pp. 163-173

McGuigan, P.T., 2004, “Salt in Marine Environment and the Creation of a Standard Input for Gas Turbine Air Intake Filtration Systems” ASME paper Number GT2004-53113, Gas Turbine Conference.

Meier, J.G., Hung, W.S.Y., and Sood, V.M., 1986, “Development and Application of Industrial Gas Turbine for Medium-BTU Gaseous Fuels,” Journal of Engineering for Gas Turbines and Power, *108*, pp.812-190.

Mutasim, Z.Z., 2008, “New Gas Turbine Materials-Improving Mechanical Strength and Resistance to Hostile Environments” International Turbomachinery*, 49*, No.5, pp. 38-42.

Neff, R.A., Katz, G.B., Nagaraj, B., and Tarvin, R., 2004, “Metallurgical Analysis of Rainbow Rotor Coatings: Analysis of Fleet Blades,” ASME Paper Number GT2004-53461, Gas Turbine Conference.

Rapp, R.A., 1990, “Hot Corrosion of Materials,” *Pure and Applied Chemistry*, *62*, No. 1, pp.113-122.

Shelton, L.V., and Carleton, R.S., 1984, “The Marine Environment and its Influence on Inlet System Design,” ASME Paper Number 84-GT-137, Gas Turbine Conference.

Stringer, J., and Whittle, D.P., 1973, “High Temperature Corrosion and Coating of Superalloys,” *Proceedings of the High Temperature Materials in Gas Turbines Symposium, Baden, Switzerland*. pp. 283-314.

Tabakoff, W., 1989, “Investigation of Coatings at High Temperature for Use in Turbomachinery,” *Surface and Coatings Technology, 39/40*, pp.97-115.

ACKNOWLEDGMENTS

The author would like to acknowledge Paul Bullara, Luke Cowell, and Colin Etheridge all from Solar Turbines Incorporated for their individual contributions to various sections of this paper.