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GAS TURBINE TUTORIAL—
MAINTENANCE AND OPERATING PRACTICES
EFFECTS ON DEGRADATION AND LIFE

by

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INTRODUCTION

Proper maintenance and operating practices can significantly affect the level of performance degradation and thus time between repairs or overhauls of a gas turbine. Proactive condition monitoring will allow the gas turbine operator to make intelligent service decisions based on the actual condition of the gas turbine rather than on fixed and calendar based maintenance intervals. Maintaining inlet air, fuel, and lube oil quality will further reduce gas turbine degradation and deterioration. This tutorial provides a discussion on how degradation develops and affects the performance of the gas turbine. Recommendations are provided on how the operator can limit this degradation and any deterioration of the gas turbines through proper maintenance practices. The effects of water-washing and best washing practices are discussed. Emphasis is on monitoring of gas turbines performance parameters to establish condition-based maintenance practices.

GAS TURBINES

Gas turbines are widely used in industrial applications. They usually are either single shaft or two shaft designs. Either design can use a standard, diffusion flame combustor, or a dry-low-emissions combustor. Most mechanical drive applications for gas turbines employ two-shaft gas turbines, while applications for power generation either employ single shaft or two shaft concepts.

A two-shaft gas turbine (Figure 1) consists of an air compressor, a combustor, a gas generator turbine, and a power turbine. (Some engines are configured as multispool engines. In this case, the gas generator has a low-pressure [LP] compressor driven by a low-pressure turbine and a high-pressure [HP] compressor driven by a high-pressure turbine. For this configuration, the shaft connecting the LP compressor and turbine rotates inside the shaft connecting the HP compressor and turbine. In general, all the operating characteristics described above also apply to these engines.) The air compressor generates air at a high pressure, which is fed into the combustor, where the fuel is burned. The combustion products and excess air leave the combustor at high pressure and high temperature. This gas is expanded in the gas generator turbine, which has the sole task of providing power to turn the air compressor. After leaving the gas generator turbine, the gas still has a high pressure and a high temperature. It is now further expanded in the power turbine. The power turbine is connected to the driven equipment (compressor, pump, or in some cases a generator). It must be noted at this point that the power turbine (together with the driven equipment) can and will run at a speed that is independent of the speed of the gas generator portion of the gas turbine (i.e., the air compressor and the gas generator turbine). The gas generator is controlled by the amount of fuel that is supplied to the combustor. Its operating constraints are the firing temperature (turbine inlet temperature [TIT]: temperature of the gas upstream of the first stage turbine nozzle; turbine rotor inlet temperature [TRIT]: temperature of the gas upstream of the first stage turbine rotor) and the maximum gas generator speed. If the fuel flow is increased, the firing temperature and the gas generator speed increase, until one of the operating limits is reached. (At the match temperature of the engine, both limits are reached at the same time. At ambient temperatures below the match temperature, the speed limit is reached first [in twin spool engines, this could be either the LP spool speed or the HP spool speed]. At ambient temperatures above the match temperature, the firing temperature becomes the limiting factor.) Often, variable geometry either for the stators of engine compressor or the power turbine nozzles is used to optimize the gas generator operating points for different loads or ambient conditions. The fuel to air ratio varies greatly between full load and idle, because the fuel flow at part load is reduced at a higher rate than the airflow. The fuel to air ratio is thus leaner at part load than at full load. Gas generator speed and firing temperature also impact the pressure in the combustor: The combustor pressure increases with gas generator speed and firing temperature.

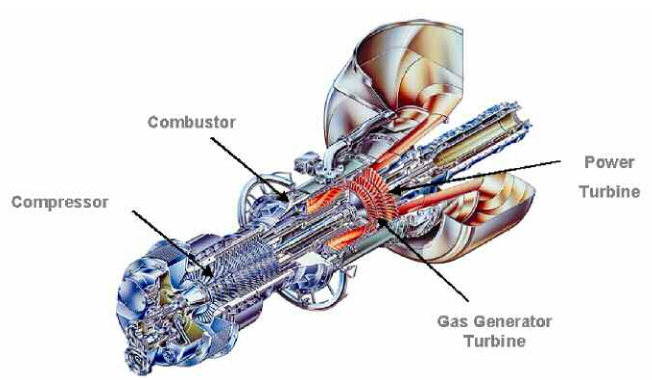

Figure 1. Typical Industrial Two-Shaft Gas Turbine.

Engines with emissions control systems (dry-low-NOx [DLN]) require that the fuel to air ratio is kept within a narrow window at all loads. Otherwise, the nitrous oxide (NOx), carbon monoxide (CO), and unburned hydrocarbon (UHC) emissions cannot be kept within the required limits. The engine thus has to employ an additional means of control. In two-shaft engines, this could mean the bleeding of combustion air, or the use of staged combustion. While the combustor exit temperature at part load drops significantly for engines with standard combustion, it stays high for DLN engines.

In a single shaft engine, the air compressor and the turbine section operate on the same shaft, thus at the same speed. For the purposes of this paper, the authors will consider only single shaft machines that are operated at constant speeds, as is common practice in power generation applications. Since the generator speed has to be kept constant in order to avoid frequency shifts, it will be controlled to run at constant mechanical speed. The gas generator is controlled by the amount of fuel that is supplied to the combustor. Its operating constraint is the firing temperature (TIT, TRIT). If the fuel flow is increased, the firing temperature increases until the operating limit is reached. The firing temperature also impacts the pressure in the combustor.

Due to the constant speed, the airflow through the engine will not vary greatly between full load and part load. This means that the fuel to air ratio drops significantly at part load and the combustor exit temperature drops significantly from full load to part load. Therefore, most single shaft engines with DLN combustors use variable stator vanes on the engine compressor to vary the airflow, and thus keep the fuel to air ratio relatively constant. For single shaft engines as described above the part load efficiencies of gas turbines with DLN combustion and conventional combustion are very similar.

GAS TURBINE DEGRADATION

Any prime mover exhibits the effects of wear and tear over time. The problem of predicting the effects of wear and tear on the performance of any engine is still a matter of discussion. Because the function of a gas turbine is the result of the fine-tuned cooperation of many different components, the emphasis of this paper is on the entire gas turbine as a system, rather than on isolated components. Treating the gas turbine as a system reveals the effects of degradation on the match of the components.

The function of a gas turbine (Figure 1) is the result of the fine-tuned cooperation of many different components: The gas generator consists of the air compressor that is driven by the gas generator turbine. The air compressor provides compressed air to the combustor where the fuel is burned. The hot, pressurized exhaust gases power the gas generator turbine, and subsequently the power turbine. In multispool gas turbines, the air compressor and the gas producer turbine may consist of several sections, while in a single shaft gas turbine, the power turbine sits on the same shaft as the gas generator.

In this system, the airflow (and thus the compressor operating point) is determined by the turbine flow capacities, while the compressor absorbed power has to be balanced by the power produced by the gas generator turbine. The compressor discharge pressure is dictated by the engine firing temperature, which in turn impacts the engine power.

Any of these parts can show wear and tear over the lifetime of the gas turbine, and thus can adversely affect the operation of the system. In particular the aerodynamic components, such as the engine compressor, the gas generator turbine, and the power turbine have to operate in an environment that will invariably degrade their performance. The understanding of the mechanisms that cause degradation, as well as the effects that the degradation of certain components can cause for the overall system are a matter of interest.

Several mechanisms cause the degradation of engines:

Fouling

Fouling is caused by the adherence of particles to airfoils and annulus surfaces. The adherence is caused by oil or water mists. The result is a build-up of material that causes increased surface roughness and to some degree changes the shape of the airfoil. Particles that cause fouling are typically smaller than 2 to 10 μm. Smoke, oil mists, carbon, and sea salts are common examples. Plugging of turbine blade cooling holes, caused by submicron particles, promotes damage from overheating. Air contamination can be significantly reduced by the use of efficient air filtration systems, especially those that reduce the quantity of smaller particles ingested. Therefore, it is essential that the air filtration system be optimized to remove small particles, while also being capable of protecting against larger contaminants. Some filter companies have developed media, using micro and nanofiber technologies, to capture more particles in the submicron to 2 μm size range, while still offering satisfactory filtration of larger particles and acceptable service life. Another issue may be the change in pressure drop and filtration efficiency if the filter medium is wet. Air filtration systems have to balance the conflicting requirements for particle removal, pressure loss, cost, and service life, for various types of contaminants.

The filtration system should be optimized for the specific site contamination and environmental conditions (Figure 2). A marine filtration system will be very different from a filtration system in a desert application. A marine filtration system will be designed to avoid the ingestion of salt laden water droplets, for example by use of combinations of vane separators and coalescing filters. The filtration system also has to protect the engine from dry dust particles, which may be coated by sea salt. Beyond the air filtration system, it is also prudent to optimize the package installation:

Ingestion of oil mist, or exhaust gases from the gas turbine, other engines, flares, or other contaminant producing processes during the prevailing main wind direction should be avoided. In offshore applications, the inlet should be arranged to minimize the impact of spray water for the prevailing wind direction. Some types of filtration media only achieve their best filtration efficiency after becoming dirty, so in areas without large dust loads, it may take significant time until the filter reaches the design efficiency especially for very small particles. Certain types of filtration media can avoid this problem. Particles below about 0.3 μm are usually capable of following the air even through the strong accelerations, decelerations, and centrifugal forces in the gas turbine flow path and are therefore not a significant problem for the compressor section, unless they coagulate to larger particles (Dring, et al., 1979; Kurz, 1991a).

Figure 2. Air Inlet System with Filter and Silencer for a Gas Turbine Installation.

Because of very high mass flows, even very low levels of ingested foreign material can produce a substantial input of contaminants through gas turbine engines. For example, 1 ppmw of impurities entering the engine results in over 1100 lbs of ingested material for a small 3.5 MW industrial engine over an 8000 hr operating period. Even after several stages of state-of-the-art filtration of ambient inlet air, deposits commonly form in gas turbine compressors due to ingested particulate so that compressor washing is periodically needed to restore efficiency by removing deposits.

Fouling can be reversed to a large degree by regular offline washing or a combination of online and offline water washing. Offline (or on-crank) washing (Figure 3) requires the gas turbine to be shut down. After a waiting period to let the engine cool down (or crank cooling it), large amounts of cleaning solution (about 120 liters [31.7 gallons] for a 10,000 hp gas turbine, plus another 120 liters [31.7 gallons] of water for rinsing) are flowed through the engine compressor while it is operated at crank speed.

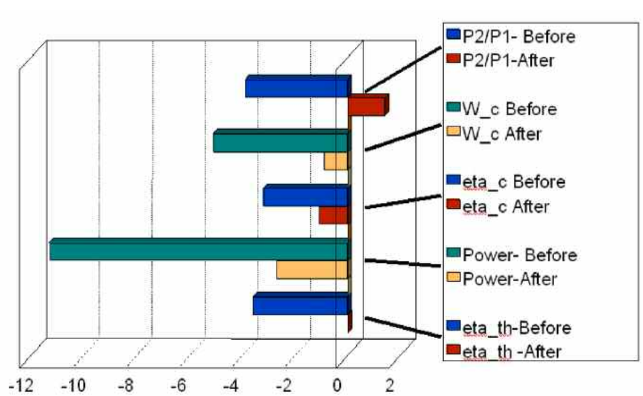

Figure 3. Performance Recovery (Compressor Pressure Ratio, Air Flow, Compressor Efficiency, Power, Thermal Efficiency) from on Crank Wash.

Because the engine has to be shut down for on-crank cleaning, online cleaning methods, where the engine stays online, are very attractive to operators. Here, a cleaning solution is sprayed into the running engine through spray nozzles in the engine inlet. The nozzles have to provide a spray pattern that covers the entire inlet area of the engine, with droplet sizes that are large enough to provide some cleaning action, but small enough to avoid blade erosion. The key limitations of online cleaning are twofold:

- Because the air temperature in the compressor increases from stage to stage, eventually the cleaning detergent will evaporate. Therefore, online cleaning will only clean the first few stages.
- Dirt particles dissolved in the cleaning detergent can be redeposited at the later stages of the compressor, or will be transported into the hot section of the turbine. The latter effect is in particular a problem in salt laden atmospheres, because sodium and potassium are key ingredients for hot section hot corrosion.

Online cleaning is, nevertheless, a valuable practice to extend the operating hours between on-crank cleaning events. The success of either type of cleaning is particularly dependent on a regular application. Severely fouled compressor blades may yield only limited performance recovery from cleaning. It has become good practice to schedule online and offline cleaning not calendar based, but performance based. Using condition monitoring systems, cleaning can be initiated whenever the engine shows a certain amount of power degradation, or reduction of compressor discharge pressure or airflow. Since all these parameters are varying significantly depending on load and ambient conditions, methods of data corrections to datum conditions have to employed. This will be discussed later in this paper.

Hot Corrosion

Hot corrosion is the loss or deterioration of material from flow path components caused by chemical reactions between the component and certain contaminants, such as salts, mineral acids, or reactive gases (Figure 4). The products of these chemical reactions may adhere to the aero components as scale. High temperature oxidation, on the other hand, is the chemical reaction between the component's metal atoms and oxygen from the surrounding hot gaseous environment. The protection through an oxide scale will in turn be reduced by any mechanical damage such as cracking or spalling, for example during thermal cycles.

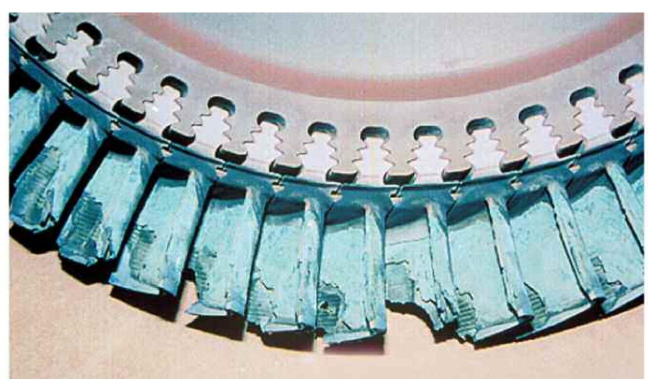

Figure 4. Hot Corrosion on a Turbine Rotor.

Corrosion

Corrosion is caused both by inlet air contaminants and by fuel and combustion derived contaminants. Fuel side corrosion is typically more noted and severe with heavy fuel oils and distillates than with natural gas because of impurities and additives in the liquid fuels that leave aggressive deposits after combustion. Corrosion is also accelerated by impurities present in the air due to the combustion of fuel in the engine. "Natural gas" is a generic term applied to a mixture of hydrocarbon gases, with methane as the predominant constituent. In most cases, pipeline natural gas contains at least some impurities. Quality specifications, which in the US are detailed in an interstate pipeline's tariff, are established to protect the pipeline and compression equipment against physical damage and performance degradation. When tolerances for impurities are exceeded, decisions must be made as to how much, if any, gas of substandard quality can be accepted, or if filtration solutions are required to gain or maintain acceptable cleanliness. For compressor stations operating on substandard field gas, gas cleanup is generally essential. Technology is available to accomplish this task.

Corrosion is often produced by salts such as sodium and potassium, but lead and vanadium are also common contributors. Since many oil and gas gas turbines are located near the sea, sea salt (sodium chloride) is often a potential offender. Cold engine parts are attacked by sodium chloride, whereas hot parts are subject to sodium sulfate (sulfidization) corrosion. Sodium sulfate is produced from the combination of sulfur in the fuel and sodium chloride in the air. As with erosion and fouling, corrosion can be controlled with filtration, however the filtration solution must be carefully thought out, especially in terms of filter media selection and droplet and moisture control. Manufacturers specify limits on the amount of contaminants in the fuel, combustion air, and the water used for various purposes (e.g., water or steam injection, evaporative cooling, fogging and overspraying, and detergent washing). Corrosion on engines that are not operated for extended periods is an issue that needs to be addressed by preservation methods.

It is important to recognize that corrosion processes are often self-propagating, and will continue even if the source is removed or abated.

The fusion of particles on hot surfaces leads to another source of problems. While dry, 2 to 10 μm size particles could pass through older engines, causing little or no damage, these particles can cause problems in new generation, hotter running engines. If the fusion temperature of the particles is lower than the turbine operating temperature, the particles will melt and stick to hot metal surfaces. This can cause severe problems since the resultant molten mass can block cooling passages, alter surface shape, and severely interfere with heat transfer, often leading to thermal fatigue. Affected surfaces are usually permanently disfigured and will eventually need replacement.

Consequently, gas turbine materials need to be protected from the service atmosphere by coating, and in some cases it is the coating integrity that limits the lifetime of the component. Manufacturers successfully use coatings in gas turbines to combat oxidation, corrosion, and erosion, and as thermal barriers. Some coated parts can be added during maintenance, if economically and technically warranted. The use of coated parts, however, does not mitigate the requirement for good filtration.

Erosion

Erosion is the abrasive removal of material from the flow path by hard or incompressible particles impinging on flow surfaces. These particles typically have to be larger than 10 μm in diameter to cause erosion by impact. Erosion is more a problem for aero engine applications, because state-of-the-art filtration systems used for industrial applications will typically eliminate the bulk of the larger particles. Erosion can also become a problem for driven compressors or pumps where the process gas or fluid carries solid materials.

Damage

Damage is often caused by large foreign objects striking the flow path components. These objects may enter the engine with the inlet air, or the gas compressor with the gas stream, or are the result of broken off pieces of the engine itself. Pieces of ice breaking off the inlet, or carbon build up breaking off from fuel nozzles can also cause damage.

Abrasion

Abrasion is caused when a rotating surface rubs on a stationary surface. Many engines use abradable surfaces, where a certain amount of rubbing is allowed during the run-in of the engine, in order to establish proper clearances. The material removal will typically increase seal or tip gaps.

While some of these effects can be reversed by cleaning or washing the engine, others require the adjustment, repair, or replacement of components (Diakunchak, 1991). It is thus common to distinguish between *recoverable* and *nonrecoverable* degradation. Any degradation mechanisms that can be reversed by online and offline water washing are considered recoverable degradation. Degradation mechanisms that require the replacement of parts are considered nonrecoverable, because they usually require an engine overhaul. There are some grey areas, because some degradation effects can be recovered by control system adjustments (that are however difficult to perform in the field due to limited capabilities to measure mass flow and performance). Another area where not all authors agree is regarding the performance recovery at overhaul. While many manufacturers offer overhauls to the same performance specifications as new engines, there are some cases where full performance recovery is deemed impossible.

It should be noted that the determination of the exact amount of performance degradation in the field is rather difficult. Test uncertainties are typically significant, especially if package instrumentation as opposed to a calibrated test facility is used. Even trending involves some uncertainties, because in all cases the engine performance has to be corrected from datum conditions to a reference condition.

DEGRADATION OF COMPONENTS

Airfoils

In order to judge the degradation of aerodynamic components, the authors will first evaluate the effect of fouling, erosion, deposits, corrosion, and other damage on the individual airfoil. Fouling, and to some extent erosion generate a blade surface with increased roughness. Any increased roughness can increase the friction losses. It also may cause early transition from laminar to turbulent boundary layers, which increases loss production. Erosion, deposits, or damages to the airfoil change the geometric shape of the airfoil. On a well-designed airfoil, optimized for the application, this will always reduce the performance of the airfoil.

Bammert, et al. (1965), Bammert and Sonnenschein (1967), Kind, et al. (1996), Kurz (1991a, 1991b, 1995), and Boelcs and Sari (1988) have reported investigations on the change of *turbine blade performance* due to alterations of the blade geometry due to erosion, corrosion, and fouling. The deterioration of the turbine blades is accompanied by changes in exit angles (thus reduced work) and increased losses. If the blade operates at or near transonic velocities, deposits or added roughness (with the associated growth in boundary layer thickness) will also reduce the possible flow through the blade row. Thicker boundary layers on the blades and sidewalls reduce the flow capacity, especially near choking conditions. On the other hand, if the trailing edge erodes, the throat width of the blade is increased, thus allowing more flow, but with less work extraction. Schmidt (1992) describes the effect of a deliberate reduction of the chord length in a power turbine nozzle that significantly reduced the work output of said turbine.

Erosion typically has the most significant effects on the blade leading edges. This can significantly affect the location and extent of the transition from laminar to turbulent boundary layers (Pinson and Wang, 1994). Because the heat transfer characteristics of a boundary layer depend, besides its thickness, on its state (i.e., laminar, turbulent, transitional, separated), leading edge erosion can influence the heat balance of the blade.

Milsch (1971) reports increases in profile losses from 2 percent at $k_s/s = 0.3 \times 10^{-3}$ to 10 percent at $k_s/s = 5 \times 10^{-3}$ for NACA65-(12)06 compressor cascades, as well as significantly reduced turning. This reduction in performance is caused by significantly increased boundary layer growth, premature transition to turbulent flow, and premature flow separation.

In general, all these influences will create higher losses and less turning. This means that the following row of airfoils will see different incidence angles, higher temperatures, lower (for compressors) or higher (for turbines) pressures and densities.

Clearances

Clearances between stationary and rotating parts (i.e., between stationary blades and the rotating hub or between rotating blades and the stationary casing) have a tendency to open up during the aging process of the equipment. This results in higher leakage flows. These leakage flows reduce the possible head capability and the efficiency of the components (Shabbir, et al., 1997; Khalid, et al., 1998; Frith, 1992). Because a significant amount of the loss production in an axial compressor occurs in the tip endwall region, an increase of the rotor tip clearance from 1 percent of blade chord to 3.5 percent of blade chord reduces the pressure ratio of the stage by up to 15 percent.

The loss production is due to intensive mixing of leakage flows with the main flow, thus producing losses and reducing the effective through-flow area (blockage). A simulation by Singh, et al. (1996), on various compressor stages suggests that the effects of tip clearance and added roughness after ingestion of sand lead to about the same magnitude of performance deterioration. However, the degradation mechanism by sand ingestion is more relevant for aero applications than for industrial applications.

Gas Turbine Compressor

Three major effects determine the performance deterioration of the gas turbine compressor:

- Increased tip clearances
- Changes in airfoil geometry
- Changes in airfoil surface quality

While the first two effects typically lead to nonrecoverable degradation, the latter effect can be at least partially reversed by washing the compressor (Stalder, 1998). Typically, a degraded compressor also will have a reduced surge or stall margin (Spakovszki, et al., 1999; Brun, et al., 2005). While the reduced surge margin may not directly affect the steady-state operation, it may reduce transient capabilities (e.g., block loads or dropped loads for generator sets), and could cause damages if other actions are taken that further reduce the surge margin. Examples are the use of overspraying (i.e., the spraying water in the engine inlet to reduce the engine inlet temperature, to the extent that some of the water does not completely evaporate before entering the compressor) for performance enhancement, or if fuels with a very high content of dilutants are used (Brun, et al., 2005).

Millsaps, et al. (2004), show in their simulation of a fouled (as a result of increased airfoil roughness) three stage axial compressor that the fouled first stage has a higher impact on the overall compressor performance (in terms of pressure ratio, efficiency, and mass flow) than a similarly fouled later stage.

Syverud, et al. (2005), and Syverud and Bakken (2005, 2006) performed tests on a gas turbine, where they deteriorated the compressor performance by spraying salt water in the engine inlet. The deposits cause increased surface roughness on the compressor airfoils. They found that the majority of deposits occur on the first stage, and become insignificant after about the fourth compressor stage. One interesting finding is that the deterioration shifts the equilibrium operating line to both a lower flow rate and a lower pressure ratio. The data show further that the degradation not only leads to reduced stage performance, but also to additional losses because individual stages no longer operate at their design flow coefficients.

In fact, the operating points of the deteriorated engine were consistently at lower flow coefficients than for the clean engine. This also leads to additional efficiency reductions due to the movement of the stage operating points away from the stage design point.

Syverud, et al. (2005), are able to show the direct impact of the blade surface roughness on added profile losses, and the increase of sidewall boundary layers due to the deposits on the deteriorated compressor performance. However, their data also show that the compressor condition cannot be separated form the turbine section of the engine, since the turbine flow capacity determines the operating point of the compressor.

Graf, et al. (1998), show data for an axial compressor, where increased clearances caused reduced surge margin and reduced efficiency. In this case, the clearance was increased from 2.9 percent (design value) to 4.3 percent. This lead to an increase in surge flow coefficient of about 20 percent, a reduction in design pressure coefficient of 12 percent and a loss of design point efficiency of 2.5 points. Notably, the loss in pressure coefficient became negligible closer to choke flow. Similar results are reported by Smith and Cumpsty (1984) where an increase of the clearance from 1 percent to 3.5 percent reduced the pressure coefficient by 9 percent.

Frith (1992) tested a helicopter gas turbine with compressor blades cropped to simulate increased clearances. A 3 percent crop on the axial compressor stages reduced airflow by 4.6 percent and pressure ratio by 3 percent. The compressor discharge temperature is reported to remain unchanged, which indicates a reduction in compressor efficiency by about 2.5 percent.

For a given speed of a degraded compressor, each subsequent stage will see lower Mach numbers (because of the higher temperature), and less pressure ratio (due to the reduced work), thus an increased axial velocity component. This means in particular that stage degradation has a cumulative effect, because each subsequent stage will operate further away from its design point. While in the new machine all stages were working at their optimum efficiency point at design surge margins, the degradation will force all stages after the first one to work at off-optimum surge margins and lower than design efficiency. This will not only lower the overall efficiency and the pressure ratio than can be achieved, but also the operating range. Further more, increased tip clearances will effectively reduce the flow capacity of the compressor. It should be noted that the reduced mass flow alone will not automatically lead to changes in the local axial flow velocities at midspan, because the reduced mass flow is largely due to increased blockage at the endwalls. Careful readjusting variable geometry where available could be used to counteract some of the mismatching effects of degradation.

Combustion System

The combustion system is not likely to be the direct cause for performance deterioration. The combustion efficiency will usually not decrease, except for severe cases of combustor distress. However, deterioration could potentially lead to a variation in the combustor exit temperature profile. The problems with a distorted exit temperature distribution are threefold:

1. Local temperature peaks can damage the turbine section

2. The altered temperature profile will increase secondary flow activity, thus reducing the turbine efficiency.

3. Because the control temperature is measured at discrete circumferential points the average of these measured temperatures is not the same as the true thermodynamic average temperature in this plane.

Therefore, in the factory test, the correlation between the measured average and the true thermodynamic average is established. If the temperature field is altered due to 1) or 2), this correlation is no longer correct. The engine could therefore be overfired (thus producing more power, but shortening the life) or underfired, thus additionally losing power. On a two-shaft engine that uses the power turbine inlet temperature as a means to indirectly control the firing temperature (i.e., the firing temperature is inferred from the power turbine inlet temperature), degradation of the gas producer turbine (i.e., reduction of gas power turbine efficiency) will lead to a reduction in firing temperature. This is actually one of the positive side effects of this control mode—the engine is not driven into a more damaging overfiring situation.

Since many engines bleed air from the compressor discharge directly into the exhaust, either for surge avoidance during startup or for emission control purposes, it should be mentioned that leaks in the bleed valves have a significant impact on the engine performance. Leaking valves can be relatively easily detected, and, since they are usually external to the engine, easily repaired.

Turbine Section

The turbine section of a gas turbine is subjected to an environment of very high temperatures. The gas properties are significantly different from the inlet air, as they contain the combustion products. A significant amount of problems in the turbine section arises from the type and quality of the fuel, or interactions between the fuel and contaminants in the combustion air. Gaseous fuels can vary from poor quality wellhead gas to high quality consumer or "pipeline" gas. In many systems, the gas composition and quality may be subject to variations. Typically, the major sources of contaminants within these fuels are: Solids, water, heavy hydrocarbons present as liquids, oils typical of compressor lube oils, hydrogen sulfide (H_2S), hydrogen (H_2) carbon monoxide (CO), carbon dioxide (CO_2), and siloxanes. Water in the gas may combine with other small molecules to produce a hydrate—a solid with an ice-like appearance. Hydrate production is influenced, in turn, by gas composition, gas temperature, gas pressure, and pressure drops in the gas fuel system. Liquid water in the presence of H_2S or CO_2 will form acids that can attack fuel supply lines and components. Free water can also cause turbine flameouts or operating instability if ingested in the combustor or fuel control components.

Heavy hydrocarbon gases present as liquids provide many times the heating value per unit volume than they would as a gas. Since turbine fuel systems meter the fuel based on the fuel being a gas, this creates a safety problem, especially during the engine start-up sequence when the supply line to the turbine still may be cold. Hydrocarbon liquids can cause:

- Turbine overfueling, which can cause an explosion or severe turbine damage due to high local temperatures.
- Fuel control stability problems, because the system gain will vary as liquid slugs or droplets move through the control system.
- Combustor hot streaks and subsequent engine hot section damage.
- Overfueling of the bottom section of the combustor when liquids gravitate toward the bottom of the manifold.
- Internal injector blockage over time, when trapped liquids pyrolyze in the hot gas passages.

Liquid carryover is a known cause for rapid degradation of the hot gas path components in a turbine. The condition of the combustor components also has a strong influence, and fuel nozzles that have accumulated pipeline contaminants that block internal passageways will probably be more likely to miss desired performance or emission targets. Thus, it follows that more maintenance attention may be necessary to assure that combustion components are in premium condition. This may require that fuel nozzles be inspected and cleaned at more regular intervals or that improved fuel filtration components be installed. A gas analysis alone may not be entirely sufficient for the detection of heavy hydrocarbons, because it may only include the gases, but not the liquids in the stream. Also, it is common practice to lump all hydrocarbons from Hexane and heavier into one number. While this is perfectly acceptable for the calculation of the lower heating value as long as the hexane and heavier hydrocarbons constitute a minute fraction of the gas, it will lead to a wrong estimate of the dew point. Tetradecane ($C_{14}H_{30}$), even in parts-per-million amounts has a significant impact on the dew point of the gas mixture, as will be shown later. Certainly a gas analysis has to be used in the project stage to allow for equipment sizing. Also, fuel systems usually limit the gas supply temperature due to temperature limits of its components. If the necessary superheat temperature exceeds the fuel system temperature limits, additional gas treatment may be necessary.

Industrial gas turbines can also burn liquid fuels. The source of liquid fuels is usually petroleum liquids, but liquid petroleum gas, natural gas liquids, and alcohols have also been used. Petroleum liquids originate from processed crude oil. They may be true distillates (diesel, kerosene) or ash-forming fuels. Natural gas liquids (NGL) are paraffin hydrocarbons other than methane found in natural gas, which can be extracted and subsequently handled as liquid fuels. They can also include liquid petroleum gas (LPG). LPG fuels are primarily mixtures of propane and butane.

The combustion of liquid fuels in gas turbines is dependent on effective fuel atomization to increase the specific surface area of the fuel, thus resulting in sufficient fuel-air mixing and evaporation rates. Ignition performance is affected by two factors: the fuel volatility, as indicated by the Reid vapor pressure or the ASTM evaporated temperature, and the total surface area of the fuel spray, which is directly related to the spray Sauter mean diameter (SMD), and hence the fuel viscosity.

One of the main differences in the combustion between liquid and gas fuel is the presence of free carbon particles (soot), which determine the degree of luminosity in the flame. The presence of carbon particles at high temperatures is highly significant and luminous radiation from the liquid fuel dominates, whereas the nonluminous radiation of gas fuels is less important. The amount of radiation impacts the combustor liner temperature, and the heavier the fuel, the greater the emissivity and the resulting wall temperatures become.

Further issues involve the storage and transport of the liquid fuel: Low viscosity fuel (such as LPG) requires special pumps to avoid problems due to poor lubrication of the pump. Foaming and formation of solids and waxes have to be avoided (Reid vapor pressure, cloud point). The fuel has to be warm enough to be still capable of flowing under gravity (pour point), but not too warm to exceed is flash point temperature (flash point). The fuel also has to be evaluated for its capability to corrode components of the fuel system (copper strip corrosion). The ash content has to be limited to avoid fuel system erosion. Excessive content of olefins and diolefins can cause fuel decomposition and plugging of fuel system components. If the carbon residue of the distillate is too high, carbon deposits may form in the combustion system. Solids in the fuel can cause clogging of the fuel system, in particular the very fine flow passages in injectors.

Lastly, certain contaminants that can cause corrosion of the hot section of the engine have to be limited. These contaminants include sodium, potassium, calcium, vanadium, lead, and sulfur, and in general the ash content. Sodium is often found in liquid fuels that are transported in barges, due to the contamination with salt water.

Trace metal contaminants of concern include: sodium, potassium, calcium, lead, vanadium, and magnesium. At elevated temperatures, vanadium, sodium, potassium, and lead are corrosive to the turbine buckets, particularly when present in amounts above specification limits. All of these materials, plus calcium, can also form hard deposits, which are difficult to remove with a normal turbine wash system. These deposits can cause plugging and reduced output.

Table 1 lists the trace metals of interest, their specified limits in the fuel supply, their effect on the turbine, the means of treatment to reduce harmful effects, and typical gas turbine permissible limits in fuel supplied to the turbine.

Table 1. Trace Metals Specifications and Effects.

Trace Metal	Limits in Raw Fuel	Effect on Turbine	Type of Treatment	TypicalLimits in Fuel to Turbine
Sodium Plus Potassium	150 ppm	High Temperature Corrosion	Fuel Washing	1 ppm
Calcium	10 ppm	Fouling Deposits	Fuel Washing to a Limited Extent	10 ppm
Lead	1 ppm	High Temperature Corrosion	None (Controlled by Fuel Spec)	1 ppm
Vanadium	**	High Temperature Corrosion	Inhibited by Magnesium	0.5 ppm
Magnesium	None	Inhibits Vanadium/ Forms Deposits	Used to Inhibit Vanadium	None

** Maximum vanadium levels may be dictated by local codes regarding stack particulate emissions and the user's acceptable costs to inhibit.

The quality of the gas available at each installation determines the gas filtration requirements, if any, needed for a given site. Keeping fuels free of contaminants such as water, compressor oils, and dirt are important to efficient operation and low maintenance. Coalescer technology for liquid/gas separation is available. Coalescer technology is also available for liquid/liquid separation and disposable filter elements can effectively control particulate in liquid fuel systems.

Another issue that may cause problems is the clogging of cooling passages due to insufficient filtration of the inlet air. Further, and this may be a problem if it is insufficiently addressed, the injection of water or steam in the combustor section will cause a change in the heat transfer capability of the exhaust gas, which can cause accelerated degradation of turbine blades and nozzles due to overheating.

Just as for the compressor section, the *turbine section* experiences the following issues as a result of degradation:

- Increased tip clearances
- Changes in airfoil geometry
- Changes in airfoil surface quality

Maintenance of tip clearances is in particular a problem in the turbine section, due to the extreme changes in temperatures between a cold engine and an engine accelerating to full load. In many designs the stationary components expand at a different rate than rotating components. Many new turbine designs use abradable seals to minimize these clearances. However, the most severe case, which is usually after a hot restart, will determine the minimum clearance for the engine. Clearance losses are approximately linear with the clearance (Traupel, 1988) and there is an indication that these losses increase with the increase of flow. In addition to a reduced efficiency, added clearances will also increase the axial flow blockage, and thus will cause reduced through-flow, and increased velocities in the main flow. Radtke and Dibelius (1980) report a reduction in efficiency of a multistage turbine by 0.6 percent when they increased the radial clearances from 0.5 percent of the blade height at the rotors and 0.4 percent of the blade height at the stators to 0.8 percent of the blade height at rotors and stators.

Corrosion tends to alter the flow path in two regards: It increases the surface roughness, but it may also remove material, in particular at the leading edges and the trailing edge of the airfoils. Especially the turbine nozzles, operating at or near choked conditions, are very sensitive to changes in flow area. Furthermore, changes in the flow capacity of the turbine section will subsequently alter the operating points for the engine compressor.

Increased surface roughness causes thicker boundary layers on the blades and sidewalls, and thus may reduce the flow capacity, especially near choking conditions. Boyle (1994) found for a two-stage turbine efficiency losses of 2.5 percent for a 10.2 μm surface roughness when compared to smooth blades. He also found that the most pronounced differences appear at the optimum operating point at the turbine, whereas the far off-optimum efficiency was almost the same for rough and smooth blades. It should be noted that the losses due to clearances were in the same order of magnitude as the profile losses.

However, if the degradation of the turbine section leads to material removal, especially in the nozzle area, the opposite effect is seen: The flow capacity increases for any given pressure ratio. Because the flow capacity of any nozzle is limited by the effective throat area, erosion of the trailing edge causes the throat area to increase and the exit flow angle to become more. This means a reduction of turning in the stator and the rotor, which will lead to reduced work extraction for this stage and to an increased flow capacity. Since the turbine nozzles constitute a flow restriction, any change in the flow capacity of the turbine section will also impact the operating points that the engine compressor will see.

EFFECT OF DEGRADATION ON THE GAS TURBINE

Degradation of engine components has a compounded effect on engine performance, because the change in component performance characteristics leads to a mismatch of these components on the engine level. The impact of individual component degradation is also influenced by the control system and the control modes of the engine. Single shaft engines, operating at constant speed, will show different degradation behavior than two-shaft engines. The impact of degradation on two-shaft engines depends on the control mode they are in, i.e., whether the gas generator speed or the firing temperature are the limiting factors. Additionally, the method and location of measuring the firing temperature will determine the behavior of the engine in degraded conditions.

In the following comparisons, it should be noted that the authors separate effects that normally occur together: Compressor degradation will impact pressure ratio, efficiency, and flow capacity, albeit to various degrees, depending on the type of degradation.

First, the authors will review the case of an engine with *reduced compressor efficiency* due to fouling.

Compressor degradation, in the overall engine environment will yield different results for single and two-shaft engines. Due to the fixed speed of the single shaft machine, in combination with a usually choked turbine nozzle, loss of compressor efficiency will mostly affect compressor pressure ratio, but only to a very limited degree the flow through the machine (Figures 5 and 6). A two-shaft engine with a compressor with reduced efficiency will exhibit significant changes in flow and pressure ratio. The reduction in flow is observed by numerous authors (Syverud, et al., 2005; Millsaps, et al., 2004) Figure 7 reflects the same findings as Spakovszky, et al. (1999) (Figure 8): The pressure ratio-flow relationship of the gas turbine compressor remains unchanged (because it is determined by the turbine section), but the engine will have to run faster, and the compressor will consume more power for any point on the pressure-flow line once it deteriorates.

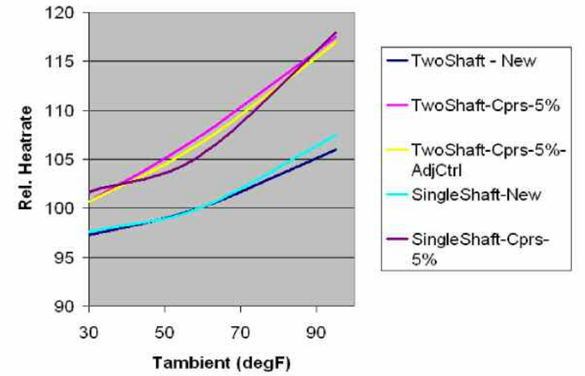

Figure 5. Impact of Loss of Compressor Efficiency Due to Degradation on Gas Turbine Heat Rate.

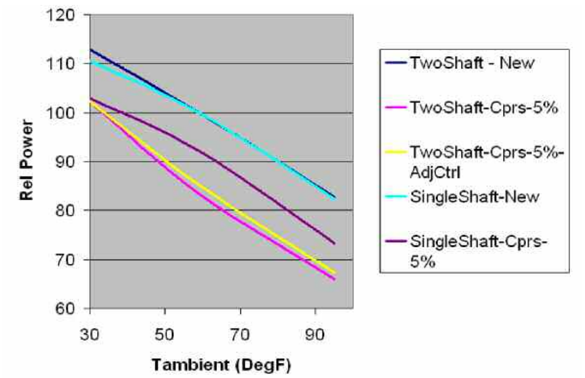

Figure 6. Impact of Loss of Compressor Efficiency Due to Degradation on Gas Turbine Power Output.

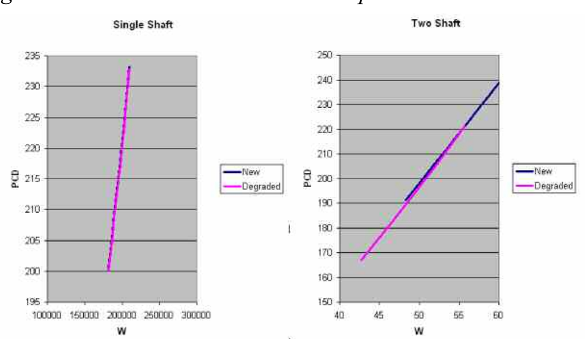

Figure 7. Gas Generator Compressor Operating Line for a New and Clean, and a Degraded Engine Compressor. (Single Shaft Left, Two Shaft Right.)

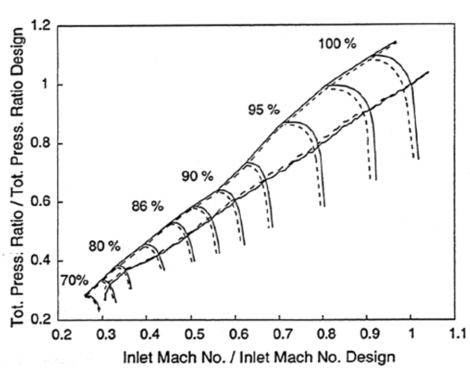

Figure 8. Comparison of a New and Clean (Solid Line) with a Degraded (Broken Line) Engine Compressor Map, and the Respective Operating Points of the Compressor. (Courtesy of Spakovszky, et al., 1999, ASME)

It seems that the power output of a single shaft engine is less susceptible to the effects of degradation, while the heat rate of single and two-shaft engines is affected at about the same rate. Both Tarabrin, et al. (1998), and Meher-Homji and Bromley (2004) also find that twin spool and three spool engines seem to be particularly susceptible to performance deterioration. For all types, the relative degradation in power is far more pronounced than the degradation in heat rate for a two-shaft engine.

Next, the authors consider the impact of *reduced compressor flow capacity*, which can be the result of fouling, or increased clearances.

Again, the finding is that the same level of compressor flow blockage leads to more power degradation in a two-shaft engine than in a single shaft engine. It is interesting that neither for single shaft, nor for two-shaft engines there is a significant impact on heat rate at higher ambient temperatures. Only for temperatures below 50°F, the heat rate starts to increase slightly at about the same rate of single shaft and two-shaft machines.

For two-shaft engines, the effects of degradation depend also on the control mode the engine is in. If the engine is operating at ambient temperatures below the match temperature, it will be in speed topping mode, i.e., the gas generator output is limited by the gas generator speed. If the engine is operating at ambient temperatures above the match temperature, it will be in turbine inlet temperature topping mode, i.e., the gas generator output is limited by the firing temperature (so will any single shaft engine).

Tarabrin, et al. (1998), point out the effect of degradation is typically more severe for two-shaft engines than for single shaft engines. However, since compressor degradation on the two-shaft engine leads to a drop in gas generator speed at high ambient temperatures, then, if variable geometry is available (in the Tarabrin, et al. [1998] example adjustable PT nozzles, in the example cited by Kurz and Brun [2001] adjustable compressor inlet guide vanes (IGVs) and stators), this drop in speed can be avoided by readjusting the settings, and the effects of compressor degradation are closer between single and two-shaft engines.

Another point worth mentioning is the part load behavior. An operating point at part load (i.e., below maximum firing temperature and below maximum NGP) can still be maintained with a degraded engine, albeit at a higher firing temperature and a higher gas generator speed than for the new condition. The relative loss in efficiency is significantly lower than for an engine at full load for the same amount of degradation.

Compressor deterioration by itself will usually cause higher power losses than losses in heat rate, because higher compressor exit temperature (due to lower efficiency) at a fixed firing temperature will reduce the possible fuel flow. MacLeod, et al. (1991), who investigated the effect of component deterioration on overall engine performance on a single shaft turboprop engine, found that an increase in GP nozzle through-flow area of 6 percent due to erosion, cracking, bowing, and corrosion caused an increase in heat rate by 3.55 percent but virtually no loss in power.

Rather severe degradation of the gas generator turbine nozzle occurs when material is removed due to erosion or corrosion. In this case, the pressure ratio over the turbine and its efficiency will drop. In a two-shaft engine, this will lead to a reduction in gas generator speed. The effect on the overall engine performance depends on the speed characteristic of the compressor, but if it is assumed that the compressor efficiency does not change with speed, then a significant reduction in engine output and efficiency is seen, in particular at higher ambient temperatures. For some compressor designs, the design operating point is at slightly higher speeds than the optimum efficiency point of the compressor. In this case, the increase in compressor efficiency at reduced speeds can to some extent counteract the loss of engine efficiency (Kurz and Brun, 2001).

For a single shaft engine, operating at constant gas generator speed, an increase in gas generator flow capacity will lead to a drop in compressor discharge pressure (that is, the compressor gains in surge margin), while the engine flow stays the same. This is accompanied by a loss in power and efficiency.

Yet another effect is introduced by the fact that in most engines the turbine inlet temperature is not measured directly. Rather, the power turbine inlet temperature (PTIT) or (on single shaft engines) the exhaust gas temperature (EGT) are measured, and TIT is calculated. The measured PTIT or EGT is not the thermodynamic average temperature, but the arithmetic average of several point measurements. Degradation of engines can lead to a shift in the true ratio between TIT and PTIT, thus causing the engine to over or underfire. This shift can be due to several reasons:

- Change in flame patterns, with resulting change in temperature patterns
- Change in gas generator turbine efficiency or flow capacity

The second cause in the list has in fact a pronounced effect, mainly on the engine output, but only a small effect on engine efficiency. It should be noted that these losses can be recovered by readjusting the control system. It can be shown that a reduction of gas generator turbine efficiency or an increase in flow capacity will lead to a underfiring of the engine under these conditions. This is actually one of the positive side effects of this control mode—the engine is not driven into a more damaging overfiring situation.

Degradation also affects the optimum power turbine speed, albeit not very much. If a lower engine compressor ratio or deterioration at the gas generator turbine itself leads to a lower gas generator turbine pressure ratio, then the actual flow through the power turbine will increase slightly, thus increasing the optimum speed. However, the effect on the engine output at fixed power turbine speed is rather small (less then 0.1 percent) for modern power turbines with relatively wide operating range.

Figure 9 shows the result of a variety of measures to reverse the effects of degradation. In the example, the engine was returned to the factory after several thousand hours of operation. The initial run of the engine, without any adjustments whatsoever and at the IGV and T_5 topping temperature from the original factory test, showed the TIT was 40°F (22°C) below design T_3 and the gas generator speed was 3 percent below design speed. After adjusting the guide vanes to get back to the desired design T_3 and gas generator speed, the engine improved power and reduced heat rate. Then, the engine was detergent washed and continued to improve performance. Next the individual stages of compressor variable vanes were adjusted to the factory settings improving power. After all of the adjustments the engine, compared to the factory testing when the engine was new, had lost 2.5 percent in power and 1.2 percent in heat rate. These results show that a significant amount of apparent degradation can be reversed by washing and adjustments.

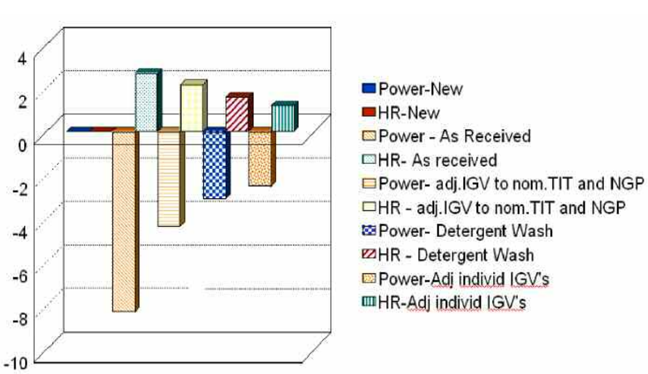

Figure 9. Performance Recovery from Sequentially Applied Methods: Adjustment of IGVs, Detergent Wash, Individual Adjustment of IGVs. (Courtesy of Kurz and Brun, 2001, ASME)

In another example, an industrial gas turbine was operated 3500 hours without a detergent wash. The environment was laden with jet engine exhaust and salt laden air. Borescope inspections had shown deposits on the compressor and turbine. A detergent wash was recommended. Control system data were recorded at full load before and after detergent washing and are displayed in Figure 9. The data were taken with the ambient temperature below the design match temperature.

The improvement in compressor pressure ratio, compressor efficiency, power, and heat rate are as expected, because the washing was reported to be very black and dirty. The engine was also underfired, because one of the effects of degradation is the reduction in the T_3/T_5 ratio. These improvements explain the very substantial 9.7 percent increase in output power. After washing, and given the test uncertainties, this engine appears to be performing essentially the same as when new. The model predicts exactly this behavior: if one uses a 2.1 percent loss in compressor efficiency, a 5 percent reduction in airflow and pressure ratio, and a 0.5 percent reduction in gas generator turbine efficiency, one sees a reduction in power of 8.6 percent, the efficiency drops by 3.5 percent, while the engine speed stays almost the same, and T_3 drops due to a reduction in T_3/T_5 ratio (Figure 10).

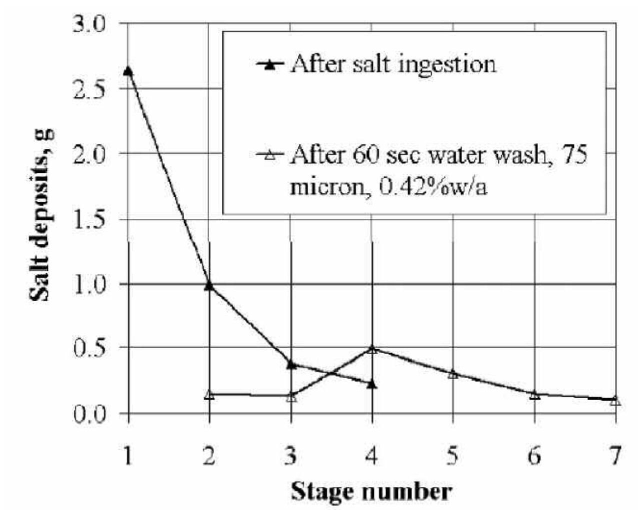

Figure 10. Salt Deposits on the Compressor Blades, Before and After Online Washing. (Courtesy of Syverud and Bakken, 2005, ASME)

Interestingly, while Tarabrin, et al. (1998), indicate that smaller engines may be more susceptible to degradation, the study of Aker and Saravanamuttoo (1988) reaches exactly the opposite conclusion. It is suspected that the intricate interactions that define the amount of degradation as a function of a certain level of ingested material, or of a certain amount of material removal are very engine specific, and do not lend themselves to simplified rules of thumb.

RECOVERABLE AND NONRECOVERABLE DEGRADATION

The distinction between recoverable and nonrecoverable degradation is somewhat misleading. The majority of degradation is recoverable, however the effort is very different depending on the type of degradation. The recovery effort may be as small as water or detergent online washing, or detergent on-crank washing. The degradation recovery by any means of washing is usually referred to as recoverable degradation. However, a significant amount of degradation can be recovered by engine adjustments (such as resetting variable geometry). Last, but not least, various degrees of component replacement in overhaul can bring the system performance back to as-new conditions.

There are few publications indicating the rate of degradation on gas turbines. It seems that, in many instances, the initial degradation on a new engine is seen as more rapid than the degradation after several thousand hours of operation. One cause for this might lie in different performance test practices of different manufacturers. If the engine, as a part of the factory test process, is subjected to a hot restart (i.e., the engine is shut down, and almost immediately restarted. This will normally cause the largest possible clearances. Therefore, during later operation of the engine, clearances will not open up further) prior to the performance test, the performance data will already reflect the clearances that will likely not deteriorate during the later engine operation. In this case, the early sharp drop in degradation may be reduced. Another design feature that can slow degradation is the effort to thermally match stationary and rotating parts of the engine. This means that the thermal growth of components is matched such that the running clearance remains constant during thermal cycles (i.e., change of load or start and stop).

Data gathered by Veer, et al. (2004), indicate that both recoverable ("fouling") and nonrecoverable degradation follow a logarithmic pattern, i.e., a large rate of initial degradation that is reduced gradually. The nonrecoverable degradation of the power output in their data indicated a loss of power of 3.5 percent in the first 5000 hours, followed by only an additional 0.5 percent over the next 5000 hours. However, this is not universally confirmed for other applications.

Obviously, the dominant degradation mechanisms for aircraft engines and industrial engines are different. Aircraft engines are operated without the benefit of an inlet air filtration system, and, therefore, erosion is one of the key contributors. Industrial engines, assuming an appropriate air filtration system is installed, are probably more subject to fouling caused by smaller particles (and possibly lube oil).

PROTECTION AGAINST DEGRADATION

While engine degradation cannot entirely be avoided, certain precautions can clearly slow the effects down. These precautions include the careful selection and maintenance of the air filtration equipment, and the careful treatment of fuel, steam, or water that are injected into the combustion process. It also includes obeying manufacturers' recommendations regarding shutdown and restarting procedures. For the driven equipment surge avoidance, process gas free of solids and liquids, and operation within the design limits need to be mentioned. With regard to steam injection, it must be noted that the requirements for contaminant limits for a gas turbine are, due to the higher process temperatures, more stringent than for a steam turbine.

The site location and environment conditions, which dictate airborne contaminants, their size, concentration, and composition, need to be considered in the selection of air filtration. Atmospheric conditions, such as humidity, smog, precipitation, mist, fog, dust, oil fumes, industrial exhausts, will primarily affect the engine compressor. Fuel quality will impact the hot section. The cleanliness of the process gas, entrained particles, or liquids will affect the driven equipment performance. Given all these variables, the rate of degradation is impossible to predict with reasonable accuracy.

While the rate of deterioration is slowed by frequent online washing, thorough on-crank washing can yield a more significant recovery. Online washing will usually only clean the first few stages of the compressor, because the increase in air temperature during compression will evaporate the washing detergent. The online washing process therefore can transport contaminants from the front stages of the compressor to rear stages or the turbine section. No matter how good the washing, the rear stages of the compressor will not get cleaned. If the compressor blades can be accessed with moderate effort (for example, when the compressor casing is horizontally split), hand cleaning of the blades can be very effective.

WATER WASHING

Syverud and Bakken (2005) performed investigations on the effectiveness of ingestive online cleaning on the performance recovery of a gas turbine compressor that had been deteriorated due to salt water ingestion. Online water washing has the advantage that engine shutdown can be avoided. They found that some of the salt will redeposit on the aft stages, but state that if the water flow is high enough, most redeposition can be avoided. They recommend that a high water flow rate produces the least redeposition in the aft stages. It should be noted however that the compressor they wrote about has only a pressure ratio of 6.5, which is significantly less than what is found in modern industrial gas turbines. In higher pressure ratio machines, redeposition of dirt in the later stages is almost unavoidable, because the air temperature in the compressor increases with pressure. Further findings include (Syverud, et al., 2005; Tarabrin, et al., 1998) that the vast majority of initial deposits (50 to 60 percent) occur on the first stage, with another 20 to 25 percent on the second compressor stage (Figure 10).

Online washing reduces fouling in the compressor only if the cleaning is performed in very frequent intervals. The duration can be very short because most of the cleaning occurs within the first 20 seconds after turning on the spray. An even spray pattern is critically important. Online cleaning will only extend offline cleaning intervals and does not eliminate the need to perform offline compressor cleaning. Redeposition of the fouling in downstream stages of the compressor cannot be avoided, but an increased water-to-air ratio reduces the level of redeposit. However, too much water (and large liquid droplet sizes) will lead to surface erosion and possible aerodynamically induced high cycle fatigue if operated for extended periods. Also, although some manufacturers claim that specialized liquids will improve the cleaning efficiency and reduce fouling redeposition, test results show that the type of liquid being used does not significantly affect either one. Clean, deionized water works as well as any liquid but will not introduce other undesirable deposits.

INLET SYSTEM

Industrial gas turbines usually employ an air inlet system that includes some sort of filtration system, a silencer, and ductwork (Figure 2). The inlet system of the gas turbine needs to be mentioned for two reasons:

- It is one of the key devices that protects the engine from the deteriorating effects of airborne contaminants.

- The pressure loss created by the inlet system increases over time, therefore reducing gas turbine power and efficiency (Figure 11). It should be noted that the exhaust system can similarly increase the pressure loss over time, especially if waste heat recovery is employed.

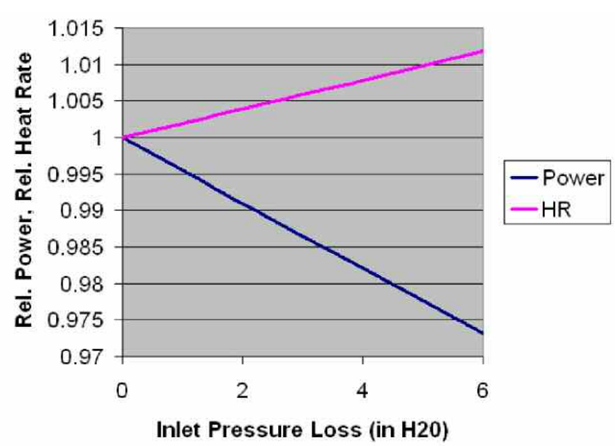

Figure 11. Impact of Inlet System Pressure Losses on Power and Heat Rate of a Typical Two-Shaft Gas Turbine.

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Previous conventional thinking was that a well designed air filtration system for a given application would perform well in almost any environment with equal results. This thinking has been proved to be faulty and economically costly. Many companies offer a wide range of filter houses, filtration systems, and air filter elements for gas turbine engines to help them perform successfully in specific operating environments. Modular construction means custom and standard designs are available in self-cleaning, reverse-pulse, barrier, upflow, crossflow, and downflow models. These units are generally engineered for fast and easy onsite erection, initially and for retrofit, and can be configured to meet many application requirements, including multistage filters with extremely low-pressure drop. As mentioned earlier, there is a tradeoff between cost, size, pressure drop, and filtration efficiency that has to be balanced.

In terms of gas turbine filter cartridges for pulse filter houses, the trend has been moving steadily toward improved "self-cleaning" pulse filter systems that can easily be pneumatically cleaned by compressed air. Manufacturers have been focusing on new media blends (impregnated to be moisture resistant) and spunbond synthetics. These synthetics, which were designed to replace older less efficient cellulose fiber type media, often provide better release of dust particles.

Different sources of contaminants produce particles of vastly different sizes: Diesel soot smoke, and smog are typically smaller than 1μm (and can be as small as 0.01μm), while coal dust can range from 1 μm to 10 μm. Dust in industrialized areas has diameters between 2 and over 10 μm (Bammert, et al., 1965).

Pulse filter housing construction has also advanced. Most filters are available with corrosion-resistant materials, including zinc coatings and stainless steel metals. Pulse filter manufacturers also have added strength supports to their filters and upgraded adhesives that seal better and prevent bypass into the air stream.

Offshore applications (or applications close to shore) are particularly challenging due to airborne salt. Airborne salt concentrations vary widely, as shown in Figure 12. Airborne salts can simultaneously exist as aerosols, sprays, or crystals. Of importance is that aerosols typically range in size from 2 microns to 20 microns, while spray generates much larger droplet sizes in the range of 150 to 300 microns. Sea salt crystals are typically below 2 microns in size, and absorb moisture under the relative humidity conditions found in typical offshore applications (Meher-Homji and Bromley, 2004). Additionally, there are other contaminants present on offshore platforms, such as carbon or sulphur from flares, drilling cements, and other dusts. Poorly positioned flare stacks, or sudden changes in wind direction can cause problems. Filter systems that combine vanes (for moisture removal) with coalescing filters (to coalesce small droplets and to remove dust particles) can be very effective in this environment.

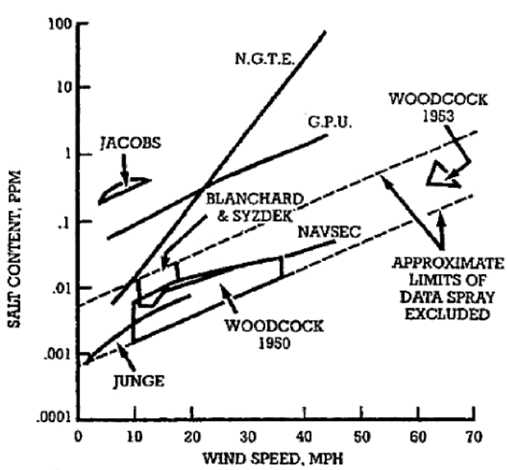

Figure 12. Salt Content in the Air in PPM as a Function of Wind Speed. (Courtesy of Cleaver,1988, BHRA)

The economic impact of faulty filtration is often under appreciated. Poor filtration can lead to degraded power output, accelerated damage to components leading to premature servicing and expensive parts refurbishment or replacement, and unscheduled downtime. Properly conditioned inlet air is critical for keeping gas turbines and other rotating machinery operating at peak performance. Since gas turbines are installed in all types of environments, the air filtration system for a particular application must be designed for specific environmental conditions. High quality air is required to prevent fouling, erosion, corrosion, and particle fusing, regardless of site conditions. The air filtration system must provide low flow resistance (low-pressure drop), long service life, and ease of maintenance. It is important to compare filtration systems not only on the basis of filtration efficiency, but also on the basis of the pressure drop necessary to achieve a certain filtration efficiency at a given airflow. Also, the efficiency of the filter in a new and clean condition (where the pressure drop might be low, but the filtration efficiency may not yet be at its peak) and in a dirty condition (where the pressure drop will increase, but possibly also the filtration efficiency, especially for very small particles) need to be evaluated.

CONDITION MONITORING AND DATA CORRECTION

Determining the degradation of a gas turbine in operation requires a certain level of instrumentation and a methodology to compare data taken under various ambient and operating conditions. The most accurate way of correcting the operation of gas turbines to datum conditions is by using manufacturer software that models the gas turbine or manufacturer-supplied performance curves. This is especially important if part-load operating points are used to monitor the engine efficiency. The general correction procedure is as follows:

1. The control system can calculate full load power and heat rate for the recorded, prevailing ambient conditions and a defined power turbine speed based on the package sensor data. It can also record compressor discharge pressure, and possibly inlet system pressure losses.

2. Use the maps or the performance program to calculate the performance of a "reference" engine (usually "nominal") under the conditions above.

3. Calculate the percent difference between the test results for power and heat rate in (1) and the reference results in (2) above.

The same procedure will also apply to part-load conditions. The idea is now to monitor the percent difference from the reference ("nominal") performance. This allows detection performance changes in the engine. Good practice is to exclude data taken under transient conditions. Engine compressor discharge pressure is a good indicator for compressor fouling, and thus for compressor cleaning decisions. Some parties suggest using inlet air flow measurements for this purpose (usually based on a drop in static pressure when the air is accelerated in the engine bellmouth). The authors find the compressor discharge pressure measurement simpler and more reliable. While driven generators are an excellent means of measuring engine power output, a driven compressor will yield data with significant test uncertainties, unless the driven compressor instrumentation is significantly upgraded (and regularly calibrated). Power measurements using torquemeters are an alternative, but tend to be rather expensive. If the gas turbine drives a pump, measurements of absorbed pump power are virtually impossible. Reliable fuel flow metering is state-of-the-art for most modern packages (Coriolis flow meters, turbine flow meters, or flow orifice metering runs are accurate and reliable).

The reason for the described method is that gas turbine performance is very sensitive to ambient conditions (pressure and temperature) and power turbine speed and, in addition, the heat rate of the gas turbine is sensitive to part load. The results can be quite different for the different loads, particularly for gas turbines that bleed air at part-load operations (such as for emissions control). Therefore, the information about the power produced is useless for condition monitoring if it is not corrected for the prevailing operating conditions.

Other parameters, such as alarms, vibrations, bearing temperatures, oil temperatures, etc., need to be recorded as well, as they can give valuable correlations in the search for causes of performance degradation, in particular if the degradation is unexplained and rapid.

CONCLUSIONS

The paper covered in detail degradation mechanisms and the impact of component degradation on overall gas turbine performance. Proper design and selection of inlet systems and fuel treatment systems, together with proper maintenance and operating practices can significantly affect the level of performance degradation and thus time between repairs or overhauls of a gas turbine. The authors have avoided presenting figures about the speed of degradation, because it is subject to a variety of operational and design factors that typically cannot be controlled entirely.

Proactive condition monitoring will allow the gas turbine operator to make intelligent service decisions based on the actual condition of the gas turbine rather than on fixed and calendar based maintenance intervals. Recommendations are provided on how the operator can limit this degradation and any deterioration of the gas turbines through proper maintenance practices. The effects of detergent washing and best washing practices are discussed.

Maintenance and overhaul decisions are ultimately based on economic and safety considerations. Understanding performance degradation, as well as factors that influence degradation, can help in these decisions.

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