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9

Performance Deterioration in Industrial Gas Turbines

IHOR S. DIAKUNCHAK
Gas and Steam Turbine Engineering
Power Generation Technology Division
Westinghouse Canada Inc.
Hamilton, Ontario, Canada

ABSTRACT

This paper describes the most important factors affecting the industrial gas turbine engine performance deterioration with service time and provides some approximate data on the prediction of the rate of deterioration. Recommendations are made on how to detect and monitor the performance deterioration. Preventative measures, which can be taken to avoid or retard the performance deterioration, are described in some detail.

INTRODUCTION

Why does performance degradation of gas turbine engines occur with operating time?

Even under normal engine operating conditions, with a good inlet filtration system, and using a clean fuel the engine flow path components will become fouled, eroded, corroded, covered with rust scale, damaged, etc. (Upton, 1974, DeGreef et al, 1978, Bammert and Woelk, 1980, Bammert and Stobe, 1970, Haub and Hauhe, 1990). The result will be dereterioration in engine performance, which will get progressively worse with increasing operating time.

Types of engine performance deterioration may be listed under the following main headings:

1. Performance deterioration recoverable with cleaning/washing.
2. Performance deterioration non-recoverable with cleaning/washing.
3. Permanent performance deterioration, which is not recoverable after an overhaul and the refurbishment of all clearances, replacement of damaged parts, etc.

Recoverable Deterioration

Normal operation of an engine, even if it is equipped with a good filter, results in the accumulation of dirt, dust, pollen, etc. particles on the compressor airfoils and gas path surfaces, as well as blockage of the inlet filters (Thames et al, 1989, Saravanamuttoo and Lakshminarasimha, 1985). These particles, in addition to soot particles produced in the combustor, can also accumulate on the flow path surfaces of the turbine. Oil leaks into the compressor inlet or presence of oily hydrocarbons or other sticky chemicals in the atmosphere exacerbate the situation. The oil or "oily" substances in the incoming air act as glue to fix the dirt particles to compressor airfoil and shroud surfaces. In the back end of the compressor, where the temperatures are high enough, these "oils" bake on to the surfaces to produce a fairly thick coating. In the case of a compressor in a gas turbine installed in a paper mill, the paper fibres plus some "oily" substance present in the atmosphere resulted in a fairly thick, rough, baked on coating on most of the compressor flow path surfaces. When crude oil is burned in the gas turbine engine, the hot end is subjected to additional harmful deposits, including salt deposits originating in the inlet air or from fuel additives.

The "fouling" of the flow path surfaces, described above, results in varying degrees of performance deterioration in the different components of the gas turbine engine, and hence in a decrease in the overall engine performance. Compressor fouling results in a reduction of inlet mass flow and compressor efficiency. Hot end fouling results mostly in the reduction in the overall turbine efficiency and in a reduction in engine firing temperature.

The following methods are used in cleaning the flow path components of gas turbine engines, without the necessity of engine disassembly:

1. On line dry cleaning of compressors with new catalyst, rice husks, pecan shells, or some other dry abrasive material.
2. On line (at base load or part power) wash of compressor with water, water mixed with detergent, or some other suitable fluid, which is preferably non-toxic, non-flammable, and biodegradable.
3. Soak wash (with the engine not running) with a suitable fluid. This method is probably the most efficient for cleaning the compressor, and especially the hot end components, which were coated with deposits as a result of running on crude oil fuel, without opening up the engine.

The use of appropriate filters will attenuate the rate of fouling, but will not eliminate it. Smooth airfoil surfaces, or those coated with coatings, which reduce surface roughness, will be less susceptible to fouling and will give better response to cleaning or washing.

Icing up of the filter, the inlet cylinder, the inlet guide vanes and the front part of compressor can have a significant effect on engine performance and operation. The resulting performance deterioration may be even more severe and more sudden than that due to "normal" compressor fouling. The icing phenomenon is temporary, and, assuming it does not result in compressor damage, will not affect the rate of performance deterioration with time.

Non-Recoverable with Cleaning/Washing

Even with regular cleaning/washing some surface deposits will remain and will detract from the performance of the affected component. Any flow path damage, surface erosion/corrosion, tip and seal clearance increase, cylinder distortion, etc. will not be affected by cleaning/washing and the resulting performance deterioration will remain and perhaps get worse with time.

Permanent Performance Deterioration

During an engine overhaul the flow path components are thoroughly cleaned, damaged parts are replaced or damaged areas "blended out", tip and seal clearances are restored to "as new" condition, any obvious leakage paths are sealed up, the pertinent airfoils recoated, etc. These actions ensure that the engine is restored as closely as possible to the "as new and clean" condition. After the completion of a major overhaul the engine performance would theoretically be expected to be as per the initial

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performance acceptance test. However, it is usually the case that the engine performance is not restored to the "as new" condition because of cylinder distortion (and hence eccentricity in clearances and increased leakage paths), increased surface roughness of flow path components (due to erosion or rust scale deposits on compressor discs and annulus surfaces), distortion in platforms causing loss of aerodynamic performance and increased leakage, airfoil untwist, etc. Fortunately, under normal circumstances the unrecoverable performance deterioration is small.

FACTORS AFFECTING PERFORMANCE DETERIORATION

Contaminants

Air borne contaminants are listed below:

1. Hard Particles (causing erosion and fouling): dust, dirt, sand, rust, ash, carbon particles.
2. Soft Particles (causing fouling): oil, unburnt hydrocarbons, soot, air borne industrial chemicals, fertilizers, herbicides, insecticides, pollen, plant spores, air borne insects, air borne salts.

About 80% of particulate contaminants are below 2μm in diameter. If an evaporative cooler is used, then water borne contaminants, such as dirt and salts, may be introduced. These may result in fouling and corrosion. Contaminants affecting the hot end include some of those listed above, plus fuel borne contaminants, those produced as a result of the combustion process, contaminants in water or steam injected for NO_x control, and any particles, such as rust scale, etc., introduced through the cooling air system piping.

Fouling

Fouling is defined as degradation of flow capacity and efficiency caused by adherence of particular contaminants to the gas turbine engine airfoil and annulus surfaces. The result of fouling is build up of material which changes the shape of the airfoil, changes the airfoil inlet angle, increases surface roughness, and reduces the airfoil throat opening. The end result is reduced component performance.

Fouling, which can normally be eliminated by cleaning, can occur in both the compressor and the turbine. Compressor fouling is more common and has the more serious effect on engine performance. Typically about 70 to 85% of all gas turbine engine performance loss accumulated during operation is attributable to compressor fouling. The contaminants that cause compressor fouling enter the compressor with the inlet air. Those that cause turbine fouling enter the turbine with the inlet air, cooling air, fuel, fuel additives, and water/steam used for NO_x control.

All compressors are susceptible to fouling and the degree of fouling, the rate of fouling, and the effect on performance depend on the following: compressor design, compressor airfoil loading, airfoil incidences, airfoil surface smoothness/coating, type and condition of the air borne contaminants, the site environment, and the climatic conditions (high humidity increases the rate of fouling) (Seddigh, Saravanamuttoo, 1990). Compressor fouling not only reduces the inlet flow and compressor efficiency, but also reduces the compressor surge margin (Mezheritsky and Sudarev, 1990) and may result in compressor surge. Turbine fouling will depend on the ability of the contaminants to reach the turbine and to adhere to the gas path surfaces. Operation of a gas turbine engine on residual fuel oil, heavy oil, or crude oil will have a corrosive effect on the hot end gas path components. The corrosion plus deposits on the flow path surfaces will result in engine performance deterioration.

Types of Filters

The function of gas turbine inlet filters is to remove particles, such as dirt, dust, soot, etc., from the compressor inlet flow and prevent compressor fouling, erosion and corrosion. The three main types of filters are listed below:

1. Inertial Filter - This is the simplest and least expensive type of filter and it functions by centrifuging out particles from the inlet flow. The accumulated dirt is then removed (continuous 5 to 10% bleed). The velocity in the filter has to be fairly high to make it work. This filter is effective in removing particles above 20μm diameter. Thus, this type of filter is good in preventing erosion due to the presence of large dust or dirt particles in the inlet air. But it is not very effective in removing particles less than 20μm in diameter, and hence it is not very efficient in preventing compressor fouling. Compressor fouling is generally caused by particles with diameter of 5μm or less. The pressure loss in the inertial filter is about 1 in. (25 mm) H_2O, and it does not increase with service.
2. Self-Cleaning Pulse Filter - The system utilizes high efficiency media filter cartridges, which are sequentially cleaned during normal turbine operation by pulses of pressurized air. The compressed air jets set up vibration waves in the cartridges and shake off the dirt, which collects on the bottom. The inlet air enters the cylindrical cartridges from the sides and then flows radially outward through a venturi. The "pulse" air blows radially downward into the cartridges. As the contaminants build up on the outside surfaces of the cartridges, the pressure drop across the cartridges will increase. When the pressure drop reaches a pre-set limit [usually 1 to 1.5 in. (25 to 37.5 mm) H_2O above the initial "operating" pressure drop of about 1 in. (25 mm) H_2O] the automatic "pulse" cleaning sequence is activated. The air "pulse" is controlled by a timer/sequencer, which operates air valves attached to a high pressure air supply. This is a good filter to use when moisture is present in the air and where icing is likely to occur (the "pulse" knocks off the ice particles as they are formed). The efficiency of this filter can be quite high.
3. High Efficiency Filter - This filter uses glass fibre filter pads, which must be replaced when the loss becomes excessive. The engine must be stopped for filter pad replacement. There are special filters available which prevent salt migration downstream. The pressure loss with clean filter pads is about 1 in. (25 mm) H_20. This type of filter has the highest efficiency.

The choice of the most effective inlet filtration system depends on the site conditions, and may include a combination of the above filter types. It should be pointed out that the cost of even the most expensive inlet filtration system will be recovered as a result of improved engine performance.

Coatings

There are two main reasons for coating of compressor airfoils with a suitable coating which results in reduced surface roughness on compressor airfoils. The first reason is improved performance and the second is corrosion protection.

On a new engine, due to reduced airfoil surface roughness, the coating of compressor airfoils will result in an improvement in compressor performance and hence in output power and heat rate.This is only a part of the performance benefit resulting from the coating. In environments which have dust particles, etc. rough blades will foul very quickly. The result is a serious loss of performance over a period of several days. By washing the compressor only some of the performance loss is regained. Over a long period of time, even with repeated washing, the engine performance will have deteriorated by several per cent. With coated blades the fouling rate is greatly reduced, the intervals between washes is increased (to at least double of the interval with uncoated airfoils), the airfoils are easier to clean, and there is no significant reduction in the "clean" engine performance after many washes (i.e. there is no decrease in performance after a wash from one wash to the next). Thus over a long operating period the average performance with coated compressor airfoils may be 1 to 3% better than with uncoated airfoils.

Coating compressor airfoils with a coating such as Sermetel 5380 DP will result in reduced airfoil surface roughness, in increased protection from corrosion and perhaps in some protection from erosion.

Cleaning

The objective of cleaning is to restore the gas turbine engine flow path surfaces as closely as possible to their initial new condition. In installations where fouling is considered to be a serious problem, the cleaning operation should be started soon after engine commissioning and continued at regular intervals. If initially the engine is allowed to get massively fouled, subsequent dry cleaning or even on line washing may produce only limited results.

Compressor Cleaning

The following methods are employed to restore the compressor airfoil and annulus surfaces to the "clean" condition for an engine which is fully assembled:

1. Manual Cleaning - Hand cleaning of the inlet duct, inlet guide vanes, and perhaps the first stage compressor blades may be carried out by accessing these components from the inlet, when the engine is shut down. This hand cleaning can be quite effective, since the airfoil throat areas of the front stages have the most influence on the compressor inlet flow.
2. "Dry" Cleaning - The compressor is cleaned on line by injecting dry abrasive media, such as new catalyst, crushed pecan nut shells, etc. By the scouring action of the abrasive particles the deposits attached to the compressor surfaces are dislodged and blown downstream. There is a danger that the use of dry abrasive materials may result in erosion of

airfoil surface coatings and blockage of turbine airfoil cooling holes. Dry abrasive cleaning is usually not recommended for coated compressor airfoils. Figure 1 shows the effect of progressive fouling on the mass flow of an industrial gas turbine, as well as the results of on line dry cleaning and hand cleaning of the front components of the compressor.

3. Washing - Water or water mixed with detergents is injected into the compressor inlet when the engine is on line. The water used in this operation must be clean and free from such impurities as sulphates, carbonates and chlorides, which will be deposited as scale in the rear compressor stages where the air temperature is above the boiling point. The contaminants adhering to the compressor surfaces are "washed" away or dissolved and removed. Although sometimes the contaminants removed from the front stages may be deposited on the downstream stages, this is a very effective cleaning method. Even more effective method is to soak wash when the engine is shut down.

The selection of the most effective compressor cleaning method (whether dry cleaning or water/detergent washing or both) depends on the type and condition of the contamination. Dry cleaning is usually most efficient if the compressor is fouled by dry hard deposits. Contamination by oil or salt deposits is best taken care of by washing. Experimentation and good record keeping may be required to arrive at the optimum cleaning procedure.

Hot End Cleaning

Removing of deposits from the hot end components is more difficult to accomplish. This is done by injecting water through the existing atomizing air system when the engine is cold, with the rotor being rotated at about the ignition speed by the starting device. The injection is followed by shut down and a soak period. This cycle is repeated and finally followed by a spin to dry the engine (DeGreef et al, 1978). The effectiveness of the water washing depends primarily on the duration of the soaking.

Corrosion, Erosion, Damage

Corrosion is the loss of material from flow path components caused by the chemical reaction between these components and contaminants which enter the gas turbine with the inlet air, fuel, or injected water/steam. Salts, mineral acids and reactive gases such as chlorine and sulphur oxides, in combination with water, can cause wet corrosion, especially of the compressor airfoils. Coating of compressor airfoils will protect them against wet corrosion and prevent the resulting performance deterioration. Elements such as sodium, vanadium and lead, in metallic or compound form, can lead to high temperature corrosion of turbine airfoils. The result is a loss in both the service life of turbine components and in engine performance. Even in gas turbines running on clean gas fuel there will be hot end component surface oxidation, which will result in the formation of a rough scale and hence performance deterioration.

Erosion is the abrasive removal of material from the flow path components by hard particles suspended in the air or gas stream. Particles causing erosion are usually 20µm or more in diameter. The erosion of airfoil surfaces results in increased surface roughness, changes in the inlet metal angle (hence change in airfoil incidence), change in airfoil profile, change in airfoil throat opening, and increase in blade tip and seal clearances. The results of the above changes are increased losses and therefore a decrease in performance. Occasionally erosion results in reduced airfoil trailing edge thicknesses. This may be beneficial to performance, but is unacceptable from mechanical integrity considerations.

Damage is often caused by large foreign objects striking the flow path components of the gas turbine engine. These objects enter the engine with the inlet air or are the result of pieces of the engine itself breaking off and being carried downstream. Pieces of ice breaking off from the inlet of the compressor, or large pieces of carbon breaking off from fuel nozzles can also result in damage to internal components. The resulting damage can lead at worst to a catastrophic engine failure or at best to non-recoverable (with cleaning) engine performance deterioration.

Engine Operation and Maintenance Practices

The manner in which the engine is operated will have an effect on the performance deterioration rate. The starting cycle results in the most severe hot end thermal gradients experienced during normal engine operation. At ignition the combustor exit temperature exceeds that during normal operation for a short time until the control system regulates the fuel and air flows to lower it. Therefore, the oxidation and corrosion experienced by the hot end components is most severe during this time and will add to the engine performance degradation. During the starting cycle the rotor assembly passes through its critical speeds. The resultant increase in vibration, if the rotor is not balanced perfectly, will cause blade tip and seal rubs. Also on start-up, the transient differential expansion rates between the large mass stationary components and the lighter mass rotor assembly may result in blade tip and seal rubs. The increased clearances will result in increased leakage and hence in performance deterioration. Operation at peak rating will have similar results, as described above, with the exception of rubs due to running through criticals, and will cause performance deterioration. Frequent emergency trips from base load will also have a negative effect on engine performance. Therefore, an engine which is subjected to many starting and emergency trip cycles and/or is operated for considerable periods of time at peak rating will experience a more severe performance degradation than an engine which is operated at or below base load.

Maintenance practices of a gas turbine engine have a considerable impact on the rate of engine performance deterioration. The control system must be properly maintaned to ensure correct fuel scheduling during starting and normal operation, in order to prevent excessive temperature gradients. The fuel system and the water/steam injection systems must be maintained properly to prevent contaminants from getting into the engine. Proper maintenance of the combustion system is required to ensure low circumferential and radial temperature gradients. It is very important that the engine be operated within the specified safe operating envelope. Regular inspection of the inlet filter system and regular compressor cleaning should be instituted. Following the correct engine maintenance practices will result in reduced rate of performance deterioration.

PERFORMANCE DETERIORATION

Inlet

Fouling of high efficiency filters occurs progressively with time. The blockage of the filter pads results in increased inlet loss and hence in engine performance deterioration. This performance loss is recovered completely when new filter pads are installed. The performance deterioration for an industrial gas turbine engine with increasing inlet loss is shown in Figure 2. For a 6 in. (150 mm) H_2O inlet loss increase the engine output power decreases by about 2.6% and the heat rate increases by about 1%.

Compressor

Some information available from open literature indicates that fouling causing a 5% reduction in inlet flow will also reduce the compressor efficiency by about 2.5% (Saravanamuttoo and Lakshminarasimha, 1985). The resulting decrease in engine power will be about 10%. Usually the fouling trend is assumed to have a linear characteristic with time. Experimental tests on the compressor of a small turboprop gas turbine engine indicated that the prime effect of fouling is on the inlet air flow rather than on compressor efficiency, and that the reduction in flow varies with operating speed (being higher at design speed).

Site test data obtained on a large industrial gas turbine indicated that compressor fouling resulted in a 5% reduction in inlet mass flow and 1.8% reduction in compressor efficiency. This amount of fouling would reduce the engine output power by about 7% and increase the heat rate by about 2.5%.

Bleed valve leakage, flange and horizontal joint leakage, and the improper positioning of the inlet guide vanes will have a deleterious effect on the compressor performance. The compressor control bleed valves have a tendency to bind in the open position or to leak during full load operation. The latter is the more likely occurrence, which will get progressively worse with time and result in a performance penalty. The improper stagger of the inlet guide vanes will also result in a decrease in compressor performance.

The performance deterioration due to "nicks", tip and seal rubs, erosion, damage, etc., may be significant in some cases, but usually it is considerably less than that due to compressor fouling. It should be pointed out that compressor fouling and other compressor performance deterioration causes have no effect on engine firing temperature.

Hot End

Under "hot end" are included: combustion system, turbine, and exhaust diffuser. The combustion system is not likely to be the direct cause of performance deterioration with time. Irrespective of the fuel used (whether natural gas, distillate oil, or even crude oil) and even if the fuel nozzles are coated with carbon deposits, the combustion efficiency will not decrease. However, carbon deposits breaking off from the nozzles and soot produced as a result of incomplete fuel burning will result in performance deterioration. Also, changes in the combustor outlet Pattern Factor may result in a temporary or a permanent deformation of downstream components, which in turn will result in performance deterioration. Hot end cylinder warping, which will increase with time, may result in flange and horizontal joint leakage, and hence in performance deterioration.

Fouling of the turbine airfoils and annulus, surface erosion, "nicks" and deformation, blade tip and seal land rubs, and increased leakage and cooling flows will result in performance deterioration. Experiments carried out on a multi-stage axial turbine showed that both reduction in airfoil profile thickness (as caused by erosion) and increase in airfoil profile thickness (resulting from surface deposits) result in a significant performance reduction (Bammert and Stobbe, 1970). Any changes in the exhaust diffuser performance can be included in the overall turbine efficiency changes. A decrease of 1% in the overall turbine efficiency in an engine such as the CW251B12 will result in about 2.5% decrease in output power and a similar increase in heat rate. In addition, because of a decrease in the turbine temperature drop, the engine will be underfired by about 12°F (6.7°C) (note that the engine is controlled to a specified exhaust temperature). This will result in a further 1.2% decrease in output power and about .2% increase in heat rate. Thus the cumulative result of a 1% decrease in turbine efficiency with time is about 3.7% decrease in output power and about 2.8% increase in heat rate.

Gearbox, Generator, Auxiliaries, Exhaust System

The components included under this heading will also suffer performance deterioration with time and as a result will affect the overall engine performance. It is more difficult to detect the performance losses in these components or to predict their rate of increase with time. The exception is the exhaust system loss. The increase in exhaust loss can be measured and steps can be taken to remedy the situation if the loss becomes excessive. Figure 2 shows the effect of exhaust loss increase on the CW251B12 engine performance. It should be noted that an increase in exhaust loss will result in a reduction in the firing temperature and hence a further reduction in engine performance. Thus a 6 in. (150 mm) H_2O increase in exhaust loss will result in about 4.2°F (2.3°C) decrease in the firing temperature. Hence the total engine performance deterioration will be a 1.4% decrease in power and 1.1% increase in heat rate.

Overall Plant

The overall plant performance deterioration is the result of the combined effect of all of the performance shortfalls of the individual components described previously. Past experience with gas turbines has shown that after 3000 operating hours the output power loss can be as high as 20% under unfavorable conditions and as low as 2% under the most favorable conditions (Scheper et al, 1978). For instance, a 2 in. (50 mm) H_2O increase in inlet loss, a 5% decrease in inlet mass flow, a 1.8% decrease in compressor efficiency, and a .5% decrease in turbine efficiency, will result in a 10% decrease in output power and a 4.2% increase in heat rate.

The control system can also affect the perceived performance deterioration. If the control system is not properly adjusted, the engine may be operated below the desired base load setting. This will lead to decreased output power and higher heat rate.

METHODS OF DETECTION OF FOULING/PERFORMANCE DETERIORATION

Detection of the extent of compressor fouling or engine performance deterioration is necessary before the appropriate actions can be taken to restore the performance shortfall. A side benefit of monitoring the compressor fouling or engine performance is the early detection of potential engine mechanical problems, and their resolution before the occurrence of a catastrophic engine failure.

Economic considerations may enter into the determination of compressor cleaning frequency. On line washing usually requires running the engine at part load, while soak washing necessitates shutting down the engine for a considerable period of time. In both cases there is a loss in power, and hence in revenue. Therefore, washing more frequently than required is a wasteful procedure. However, if compressor washing is delayed too long, the resulting performance deterioration will also cause a loss in revenue. Thus it is important to be able to detect compressor fouling and to institute an optimum compressor washing frequency. The optimum will depend on the particular situation at each installation. As a general recommendation, the compressor should be cleaned/washed when the estimated mass flow decrease reaches the 2 to 3% level.

Compressor Fouling

Compressor fouling, and hence engine performance deterioration, can be detected using the following methods:

1. Change in Combustion Shell Pressure - The combustion shell pressure is one of the parameters used by the control system to maintain the engine at base load. Therefore, it is a readily available and accurate measurement. When the compressor is fouled the inlet mass flow is reduced, and as a result the engine matches at a lower pressure ratio. Therefore, the amount of compressor fouling can be deduced at any time by comparing the actual site combustor shell pressure to the expected pressure if the compressor were clean. One complication is that the combustor shell pressure varies with barometric pressure, inlet loss, compressor inlet temperature, and output power (assuming operation not at base load). If the assumption is made that the engine is operated at base load and that the inlet loss and barometric pressure variations are small, then the expected or "clean" combustor shell pressure variation with inlet temperature is a unique line (a typical curve is shown on Figure 3 for an engine at sea level on natural gas fuel). To check for fouling at any time, the site measured combustor shell pressure can then be plotted on this curve. If the point is below the line, then the compressor is assumed to be fouled. Each percentage point that the actual pressure is below the line corresponds to one per cent reduction in inlet flow.

2. Measurement of Inlet Cylinder Depression - The measurement of the inlet cylinder depression with the aid of a manometer gives an indication of inlet flow. The compressor inlet cylinder acts like an accelerating flow nozzle, since there is a continuous reduction in area from the inlet flange to the inlet guide vane inlet plane. Therefore, there will be a large difference in the static pressures measured at the inlet flange and the inlet guide vane inlet plane. As in a nozzle, the ratio of the static pressure difference measured at the two planes divided by the pressure at inlet is independent of the pressure loss upstream of the measurement plane for a given volume flow. A change in the inlet cylinder pressure ratio will result only from obstructions within the compressor itself, and hence can be used to detect compressor fouling.

   Assuming that a proper inlet cylinder flow calibration curve is not available, a plot of the static pressure ratio versus the non-dimensional compressor speed ($N/\sqrt{\theta}$, where θ is as defined on Figure 4) is produced when the compressor is "new and clean". In order to get a large enough variation of inlet speed, the data may have to be recorded over a length of time, in which there is a significant ambient temperature variation. The inlet cylinder static pressure ratio obtained at any time in the future is then plotted on this graph. If the new points fall below the "clean" curve, then the compressor is fouled. The reduction in compressor inlet flow is proportional to the square root of the reduction in the inlet cylinder static pressure ratio.

3. Inlet Scroll Calibration Curve - The compressor inlet scroll calibration curve is obtained during a shop test of the engine when accurate measurements are made of the inlet flow and the static pressures at the compressor inlet flange and just upstream of the inlet guide vanes. Figure 5 shows a typical inlet scroll calibration curve, which is the non-dimensional inlet mass flow plotted versus the inlet cylinder static pressure ratio. Occasionally there is an inconsistency between shop and site inlet flow measurements, even when the compressor is "new and clean", i. e. there is a difference in the inlet flow, for the same $N/\sqrt{\theta}$, between shop and site. This may be explained by the differences in the inlet ducting, pressure tap, and pressure line installations between shop and site. To be on the safe side, a new "clean" curve should be obtained from the site data as follows: As soon as possible after engine commissioning, when the compressor is clean, data points should be obtained over a wide ambient temperature range. With the compressor pressure ratio and non-dimensional speed determined from site data obtain the expected non-dimensional inlet mass flow from the compressor map (see Figure 6, derived from shop tests) at the different ambient temperature base load operating conditions. Then plot the non-dimensional inlet mass flow versus the site measured inlet cylinder pressure ratio. A smooth curve should be drawn through these points parallel to the original shop inlet scroll calibration curve. Then, as the engine operating hours increase, with the site measured inlet cylinder pressure ratio the inlet mass flow is read from the calibration curve (preferably the one established at site). This mass flow is then compared to the "clean" compressor mass flow from Figure 6 to determine the amount of compressor fouling that has occurred.

With the aid of the shop test derived compressor map it is also possible to determine the amount of compressor efficiency decrease that has taken place with operating time. A graph showing the base load compressor efficiency variation versus non-dimensional speed can be used for this purpose (see Figure 7). The compressor efficiency may be estimated approximately from the overall pressure ratio (combustion shell pressure divided by the ambient pressure, or preferably the compressor inlet pressure) and the compressor temperature rise from inlet to the combustor shell. The compressor efficiency estimated in this manner will be lower than the actual one because of the probable inclusion of inlet duct loss, inaccurate compressor exit pressure, and temperature pick-up across the combustor outlet transition ducts. However, as with the compressor inlet mass flow, efficiency data can be collected when the compressor is "new and clean" and can subsequently be used for comparison when compressor fouling has occurred.

Engine Performance

The extent of compressor fouling and the other deleterious effects that occur in an engine with increasing operating time can be determined by periodically monitoring the engine output power and comparing it to the expected value, or to the value when the engine was "new and clean". This type of monitoring is more complicated than just detecting compressor fouling. The simplicity or complication may range from the measurement of just a few key performance parameters to a full blown on line health monitoring system. To detect the power shortfall some or most of the following parameters must be measured: output power, auxiliary power, power factor, speed, inlet temperature, relative humidity, barometric pressure, exhaust temperature, combustor shell pressure, inlet loss, exhaust loss, water/steam injection rate, and instrumentation bleed air, if any. With the above information and with the aid of the correction curves for the deviation of site conditions from the standard or guarantee power the site output power is corrected to standard conditions and compared to the "clean" engine power. The amount of the power shortfall from the expected value will indicate the extent of compressor fouling or other problems causing performance deterioration.

A further complication could be introduced by measuring fuel flow, fuel temperature, fuel Lower Heating Value, etc., so as to be able to determine the engine heat rate and compare it to the "clean" value. For this exercise similar correction curves, as described above, will have to be used.

COST OF FOULING/PERFORMANCE DETERIORATION

There is a significant cost to the gas turbine engine operator associated with fouling and the resulting performance deterioration. To make an approximate estimate of the cost the following assumptions are made:

1. Simple Cycle CW251B12 Econopac Engine, on natural gas fuel, no injection.
2. Net Output Power = 46,500 KW

   Net Heat Rate = 10,550 BTU/KW.HR.

   The above are average yearly values.
3. Engine on base load operation for 8,000 hours per year.
4. Cost of electricity is $.04/KW.HR.
5. Cost of natural gas fuel is $2/MBTU
6. Improper cleaning, maintenance, etc. will result in an average yearly decrease in power of 3% and increase in heat rate of 1%.

The resulting yearly power shortfall = .03 x 46500 x 8000 = 11.2 x 10^6 KW.HR.

The cost of the power shortfall = 11.2 x 10^6 x .04 = $446,400.

The resulting yearly excess fuel flow = .01 x 10550 x

(1-.03) x 46500 x 8000 = 38.07 x 10^9 BTU.

The cost of the excess fuel = 2 x 38.07 x $10^9/10^6$ = $76,140.

The total yearly cost of the assumed average performance deterioration is $522,500.

Over the three year operating period between major overhauls the total cost will be about 1.5 million dollars.

In the case of a combined cycle application there will be an additional cost due to reduced steam production in the waste heat boiler. Although compressor fouling results in an increase in exhaust temperature (at the same ambient temperature), the reduced exhaust flow has a greater negative effect. Thus the net effect is reduced steam production as a result of compressor fouling.

PREDICTION OF PERFORMANCE DETERIORATION WITH TIME

There are several reasons why the prediction of performance deterioration with time is required. At the negotiation stage the prospective customer may request this information so as to be able to carry out a long term economic benefit analysis on the engine. A user of the engine may wish to know what is a reasonable performance deterioration after a specified number of service hours and what constitutes excessive fouling or performace deterioration rate which may require urgent remedial action. The vendor may be required to guarantee engine performance over a specified number of operating hours and will require a realistic prediction of the performance deterioration rate.

The exact degree of performance deterioration occurring with service time is impossible to predict accurately due to the large number of previously described variables. The amount of actual field test performance data that has been published on gas turbine engine performance deterioration with time is very limited. Some approximate published data (DeGreef et al, 1978) and some in-house test results are available.

At one installation site test data indicated that up to 8% power loss occurred over a two week period. Most of this power shortfall could be recovered by cleaning the compressor with new catalyst. At another installation, after incorporation of coated compressor airfoils, the fouling rate was reduced considerably and on line washing of the compressor recovered all of the power shortfall. At a third installation, after six months of continuous operation without compressor cleaning, the engine experienced a 4.3% loss in power. A series of on line, at reduced load, water washes recovered all but .5% of the power shortfall. It should be pointed out that this engine had a good inlet filtration system and coated compressor stator airfoils.

In order to even make an attempt at the prediction of performance deterioration some ground rules or assumptions must be made. In the prediction of the likely engine performance deterioration with time the following assumptions were made:

1. Types of fuel used: (a) Natural Gas, (b) Distillate Oil, and (c) Heavy or Crude Oil.
2. Clean environment.
3. The engine will start its service life at time zero in the "new and clean" condition with zero performance shortfall.
4. Continuous base load operation for three years (24,000 hours or equivalent service hours) before a major overhaul. During the overhaul the engine is refurbished to almost "as new" condition, i.e. tip and seal clearances restored, damaged parts removed, "nicks" blended out, flow path surfaces cleaned, etc.
5. Good filtration system used, clean operating environment (no oil leaks, no corrosive chemicals, no sand), no major foreign object damage, coated compressor airfoils.
6. Proper operating and maintenance procedures.
7. Effective and regular cleaning/washing of the compressor over the operating period.

Based on the above assumptions, the previously described engine component performance deteriorations, and some actual field test data, the overall engine performance deterioration with time can be estimated very approximately. The assumed shape of the typical performance deterioration versus service hours curve is shown on Figure 8. This curve shows results of frequent compressor cleaning and also the non-recoverable, with cleaning, performance deterioration line. It should be pointed out that the non-recoverable with cleaning performance deterioration will apply equally to power and heat rate. This can be explained by the fact that once the effect of compressor fouling (which has a more significant influence on air flow and hence power, than on compressor efficiency and heat rate) has been removed then the degradation of power and heat rate will be approximately similar.

In predicting performance deterioration with time the following scenario is assumed: that the engine has been manufactured correctly and does not have any hidden problems waiting to happen, is well maintained, is properly operated, does not experience overtemperaturing during starts, is not subjected to an excessive number of trips from full load, and is cleaned regularly (when the power loss reaches 2 to 3%) over the entire operating period. Although this scenario may be described as optimistic, it is not impossible to achieve in practice if all of the recommendations listed below are adhered to. In this case, after the three years of operation the permanent performance deterioration (after cleaning) is 1.25% on natural gas fuel, 1.75% on distillate oil fuel, and 3% on crude or residual oil fuel. Note that the performance deterioration percentages apply to both output power and heat rate, as was explained previously. After a major overhaul and complete refurbishing of the flow path parts, the permanent performance shortfall will be almost eliminated. The remaining unrecovered performance shortfall will be .25% for both natural gas and distillate oil fuels, and .5% for crude or residual oil fuel. The residual performance decrement is higher for crude/residual oil fuel because of the more severe deleterious effect of these fuels on the hot end, compared to natural gas or distillate oil. Figure 9 shows the typical performance deterioration (non recoverable with frequent cleaning) with operating time for the three cases. After the overhaul the engine performance deterioration will experience a similar rate as when it was new, that is the shape of the curve will be the same as in the first 24,000 operating hours, but its starting point will be the residual performance decrement.

RECOMMENDATIONS

Based on the considerations described in this report the following recommendations are made to obtain minimum engine performance deterioration rate and to achieve optimum engine performance over its entire service life:

1. To retard the rate of compressor fouling the engine site installation should incorporate the optimum inlet filtration system for the particular site environmental conditions.
2. Smooth and/or coated compressor, and if possible turbine, airfoils should be used.
3. Clean fuels and injected steam/water should be used.
4. The official site performance acceptance test should be carried out immediately after engine commissioning and initial synchronization in order to obtain reliable "bench mark" engine performance and health monitoring type of information when the engine is in the "new and clean" condition.
5. Engine performance deterioration and compressor fouling should be monitored regularly and recorded.
6. Appropriate and regular compressor, and if necessary turbine, cleaning procedure should be used.
7. Good operating and maintenance procedures should be employed.
8. The control system should be carefully monitored and adjusted as required to eliminate possibility of overtemperaturing on starts, operation above base load firing temperature for prolonged periods, and spurious engine trips.
9. Any required remedial actions as regards engine performance or mechanical integrity should be executed promptly.
10. During a major overhaul the engine should be restored as closely as possible to its original "new and clean" condition.

CONCLUSIONS

1. The most important factors affecting industrial gas turbine engine performance deterioration with time were discussed.
2. Methods of monitoring and preventing performance deterioration were outlined.
3. Estimates of the cost of performance deterioration were presented.
4. Approximate engine performance deterioration rates with operating time were proposed.
5. Recommendations were made on how to keep industrial gas turbine engine performance deterioration to a minimum.

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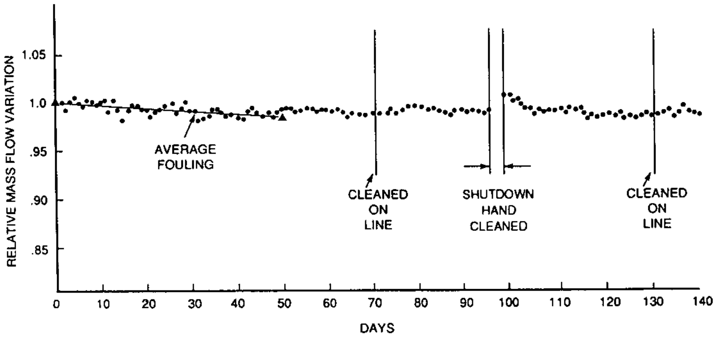

FIGURE 1 – RELATIVE MASS FLOW VARIATION WITH TIME

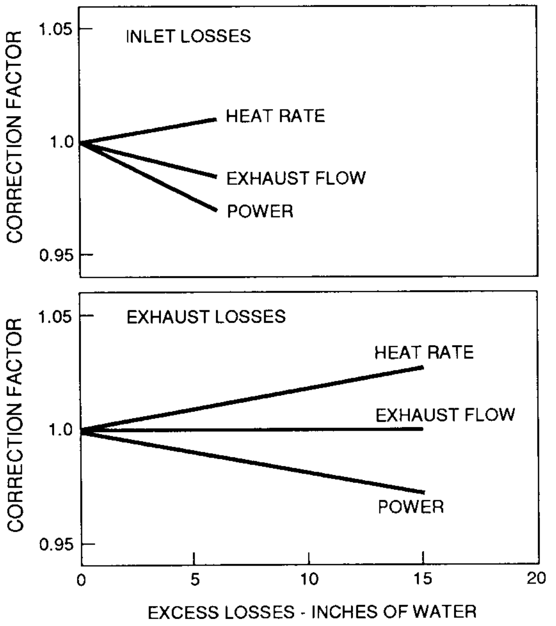

FIGURE 2 – CORRECTION FACTOR CURVES FOR INLET AND EXHAUST DUCT LOSSES

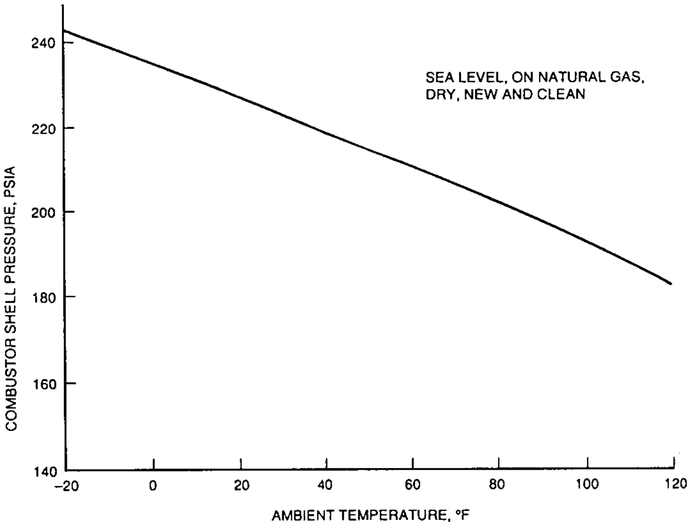

FIGURE 3 – COMBUSTOR SHELL PRESSURE vs AMBIENT TEMPERATURE

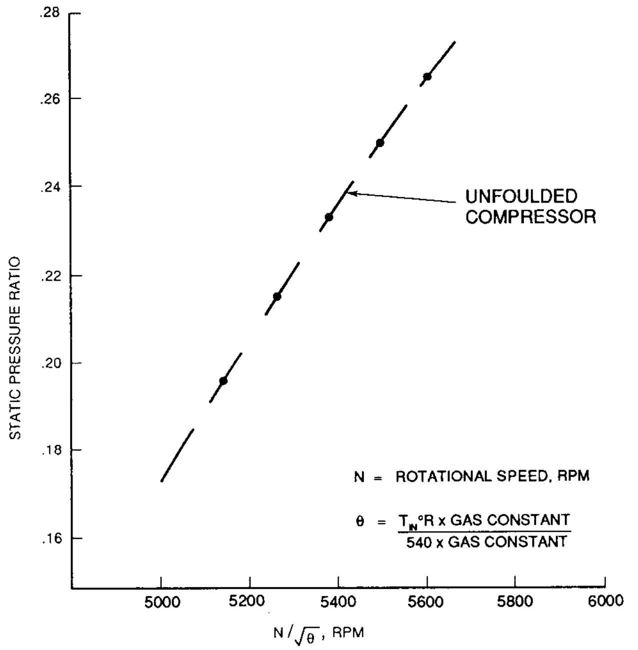

FIGURE 4 – INLET CYLINDER STATIC PRESSURE RATIO vs NON-DIMENSIONAL SPEED

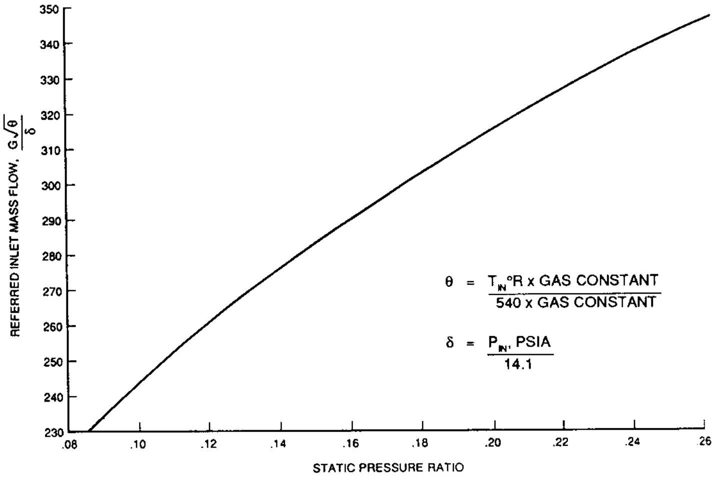

FIGURE 5 – TYPICAL INLET SCROLL CALIBRATION CURVE

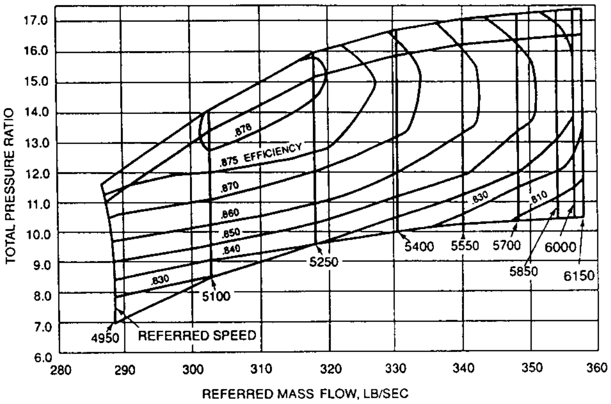

FIGURE 6 – COMPRESSOR MAP

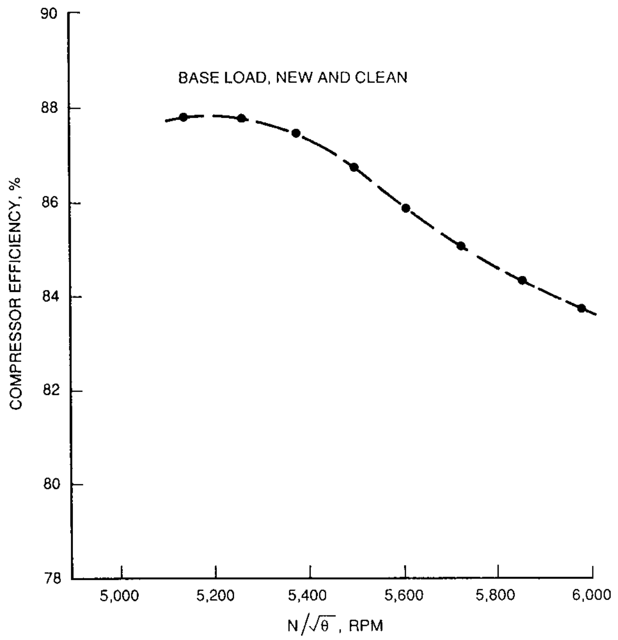

FIGURE 7 – COMPRESSOR EFFICIENCY vs REFERRED SPEED

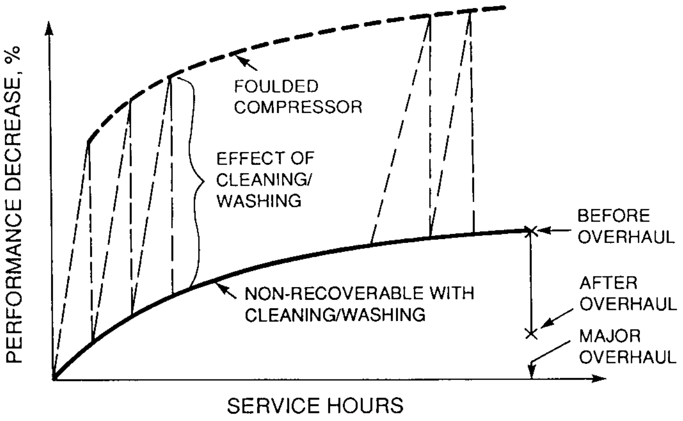

FIGURE 8 – TYPICAL PERFORMANCE DETERIORATION

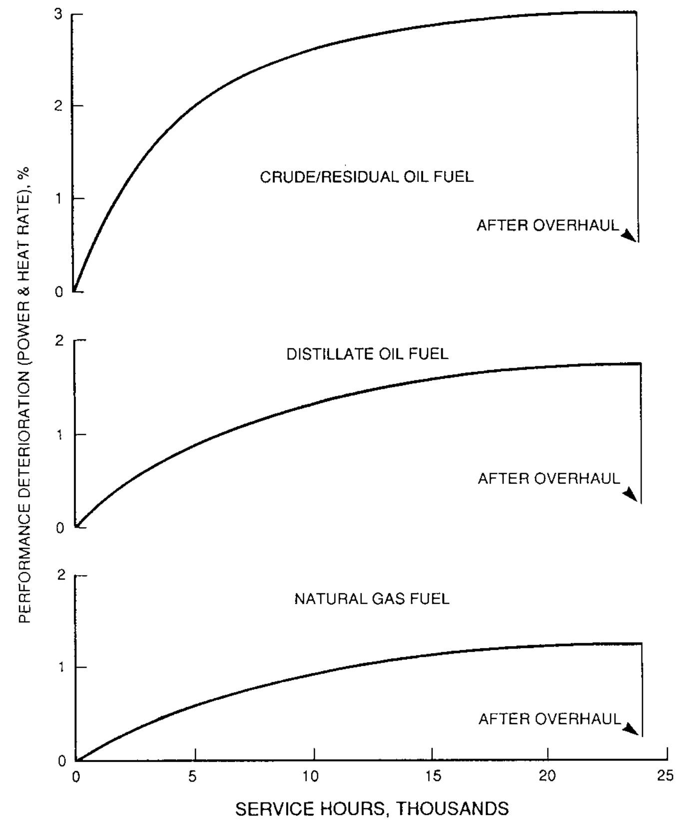

FIGURE 9 – PERFORMANCE DETERIORATION WITH SERVICE HOURS, NON-RECOVERABLE WITH PROPER CLEANING