



**SELECTION AND USE OF  
CHEMICAL CLEANERS FOR THE INGESTIVE CLEANING  
OF INDUSTRIAL GAS TURBINE ENGINES**

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## I INTRODUCTION AND OVERVIEW

During the course of a single running year, a gas turbine engine might ingest several billion pounds of air containing airborne contaminants. These contaminants include soils, fibers, insects, herbicides, insecticides, soot, corrosive chemicals, pollutants, etc. Most contaminants pass through the compressor and are combusted. However, some contaminants combine with moisture and internally emitted lubricants and then adhere to the airfoil surfaces, which disturb the airflow and creates friction. The accumulation of these contaminants can have a profound effect on the efficiency of the engine; they reduce the compressibility of the ingested air mass which in turn lowers the pressure ratios and increases operating temperatures. Periodic removal of accumulated contaminants from airfoils of axial flow compressors is required for

sustained operating efficiency. This paper discusses commercially available cleaning fluids (solvents and surfactants), the mechanisms of removal for each, and the cost consequences associated with each. Also discussed are the considerations for the design and use of fluid delivery equipment as well as the determination of dosages and cleaning frequency. Finally, it offers some considerations for evaluating the cost effectiveness of on line ingestive cleaning.

## II. EFFECTS OF FOULING

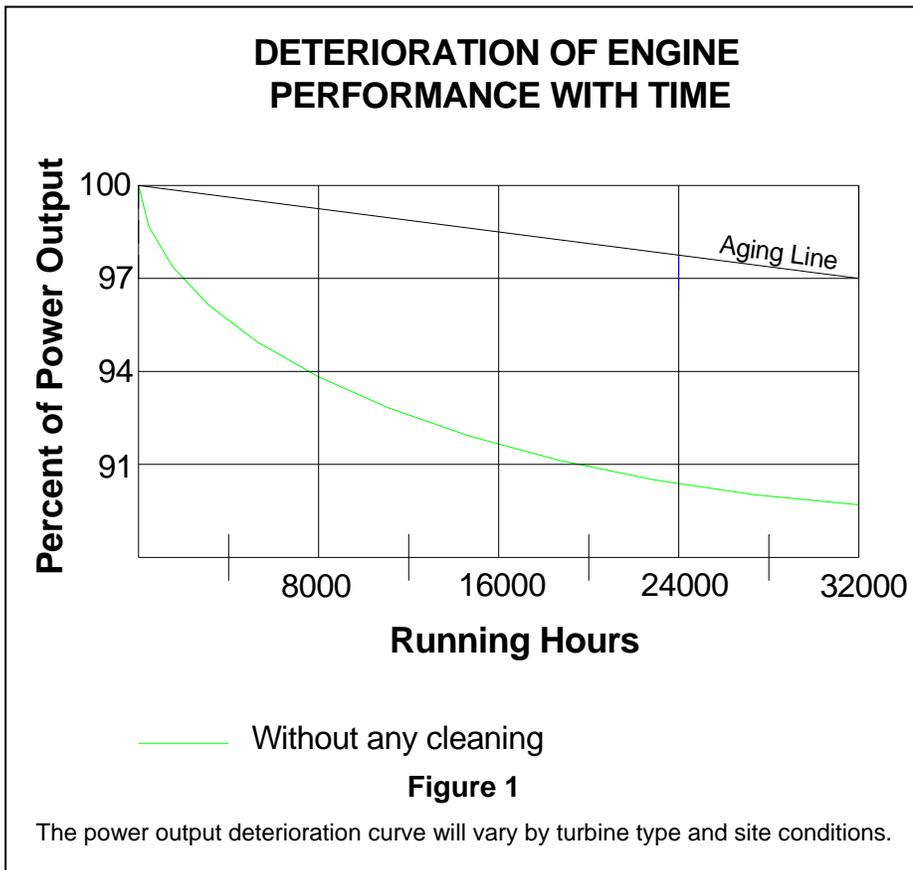
On average, about two-thirds of the fuel energy used by a typical gas turbine engine is consumed by the compressor. Therefore, a single percentage point lost in compressor efficiency will result in about double the loss in thermal efficiency. Under typical running conditions, about 70% of the efficiency loss can be attributed to fouling. The effects of fouling on engine performance are

most pronounced in the initial 2000-3000 running hours after an engine has been put into service in a "new and clean" condition. Once contaminants have plated and varnished on the hot airfoil surfaces, the rate of efficiency deterioration decreases and performance tends to stabilize. See Figure 1 for reduction in power output over time. Recovery from the degraded condition is not possible without removing the foulants.

A badly fouled compressor will show reduced compressor discharge pressure (CDP), elevated compressor discharge and exhaust gas temperatures, which reduce power output and increased heat. In addition, the increased temperatures hastens the aging process and can necessitate unscheduled shutdowns when the thermal limits have been reached or when vibration problems associated with fouling are encountered. These elevated temperatures may also increase the level of NO<sub>x</sub> and CO<sub>x</sub> emissions.

### The Mechanism of Fouling

Contaminants can be either organic or inorganic. Even the best-maintained engines experience lubricant leaks and vapors. In addition, moisture from the ingested air is condensed and precipitates in the forward stages of the compressor. Ingested contaminants then adhere to the moist, oily airfoil surfaces where, if not removed, they will plate and varnish in the elevated temperatures. Because the type and volume of ingested contaminants vary seasonally or even with the time of day, the rate of deposition is not uniform. The resultant fouling is a rough layered matrix of foulants on the compressor's forward blading. In the aft stages of the compressor, where sustained temperatures in excess of 450° F, foulants are "baked" to a dried, solid state and migrate through the compressor and are combusted in



the hot section. Unremoved contaminants in the forward stages typically undergo physical state changes that can render the plated contaminants very difficult to remove. Since the combustion air is gathered in the forward stages of an axial flow compressor, the effects of turbulence and friction from fouling on compressor efficiency are profound. For this reason, removal of foulants from the forward stages of the compressor is the most important consideration in cleaning. However, liquid cleaners must be in a wet state to attack contaminants, on-line ingestive cleaning can only be effective if the correct chemical type is selected.

### III TYPES OF CLEANERS

There are essentially two methods of cleaning: mechanical and chemical. Similarly, there are two methods of ingestive cleaning: on-line and off-line.

### Mechanical Cleaners

To some extent, all ingestive cleaning agents rely on mechanical removal of contaminants. Fouling is simply loosened by the impact of the cleaning media and loosened contaminants migrate through the compressor with the airflow and are combusted in the hot section as previously discussed. Abrasive cleaning agents rely solely on mechanical removal. Since newer gas turbines utilize extensive cooling ducting, variable pitch blading, internal air extraction and other features to increase their thermal efficiency, abrasive cleaning compounds have fallen into relative disuse. Although abrasive compounds are effective in the removal of foulants, they can clog the cooling air ducts in hot section components. They can also impede the operation of variable pitch

blading, the bearings and the air

extraction equipment. If used too aggressively, these abrasive compounds can also alter and deform blading shapes and surfaces.

### Chemical Cleaners

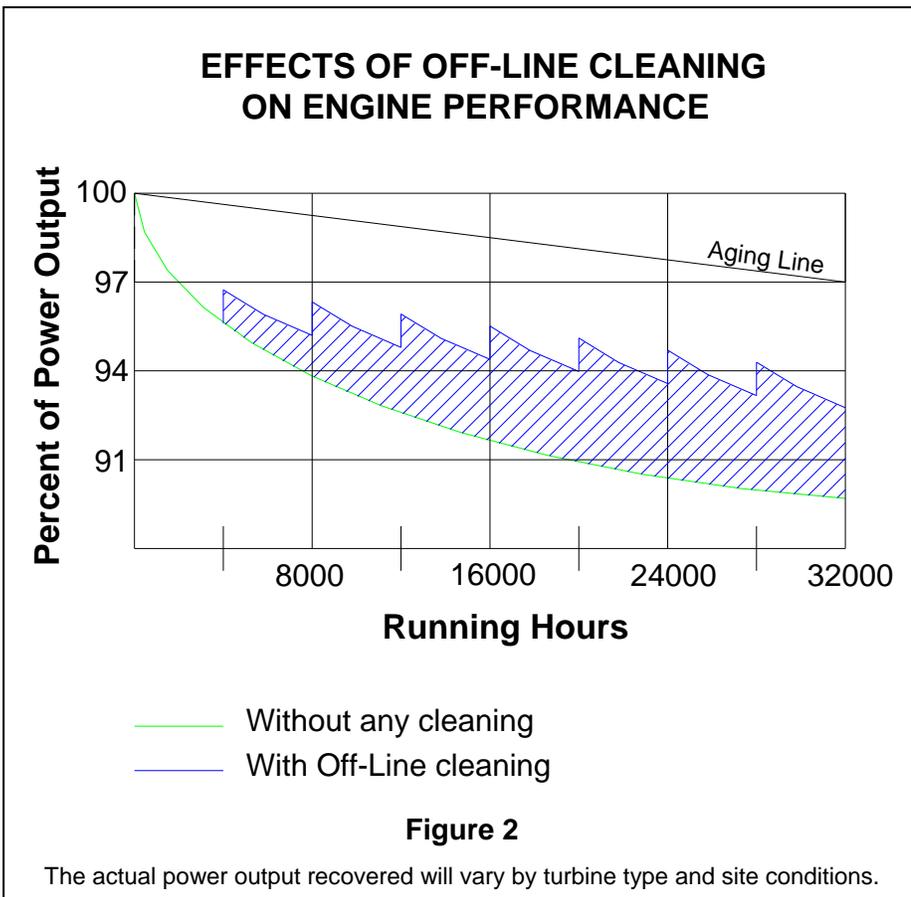
In nature, a substance can only be dissolved by a like substance, therefore chemical cleaning relies on the interaction of "fat loving" lipophiles and "water loving" hydrophiles. Lipophilic substances are hydrophobic and hydrophilic substances are lipophobic. Based on this, lipophilic substances, such as oil, grease, fats, etc., are readily dissolved in lipophilic solvents but not in water. These lipophilic substances can be emulsified or dispersed in water if a compound is added to the water that changes the water's chemical and physical properties.

Lipophilic compounds can be incorporated in an aqueous media by a process called emulsification. By the addition of a surface active agent (detergent) to aqueous media, lipophilic substances can be emulsified into a stable dispersion. All aqueous cleaners, even the most chemically complex detergents, rely on this principle.

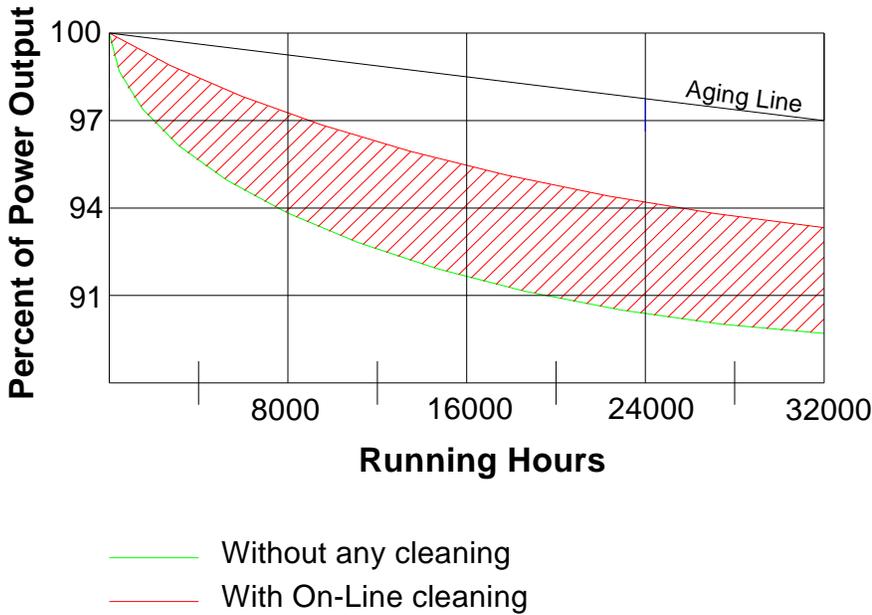
### IV. CLEANING METHODS

#### Crank Washing.

The most effective and commonly used cleaning method is crank washing (also known as off-line washing), wherein the compressor section is flooded with a chemical cleaning agent while rotating the blading, and then allowed to soak. After soaking, the compressor is rinsed thoroughly using deionized/demineralized water. The shaded area in Figure 2 shows the power output typically recovered from crank washing. Hence, economics show the need for regular crank washing to ensure optimum performance. Although very effective in restoring



## EFFECTS OF ON-LINE CLEANING ON ENGINE PERFORMANCE



**Figure 3**

The actual power output recovered will vary by turbine type and site conditions.

can be maximized. The shaded area in Figure 4 shows that most of the power lost due to fouling can be recovered.

### Abrasive Compounds

Nut shells, rice and aluminum oxide to name a few, are effective in removing contaminants and dramatic power recovery may be experienced. However, abrasive compounds can impede the movement of variable blades and vanes, clog bleed and cooling air ducting systems. In the case of inorganic compounds, they can pass uncombusted into the turbine to erode hot section components. The obvious advantages of ingestive cleaning with abrasive compounds are cost, ease of use, and handling and storage. Most OEMs discourage the use of abrasive cleaning on their newer models. The OEMs that do approve abrasive compounds impose limitations on particle size, stone content, and residual ash.

compressor efficiency, crank washing requires costly outages, resulting in lost revenue. Equally important are the mechanical effects of starting and stopping, which accelerate the engine's aging.

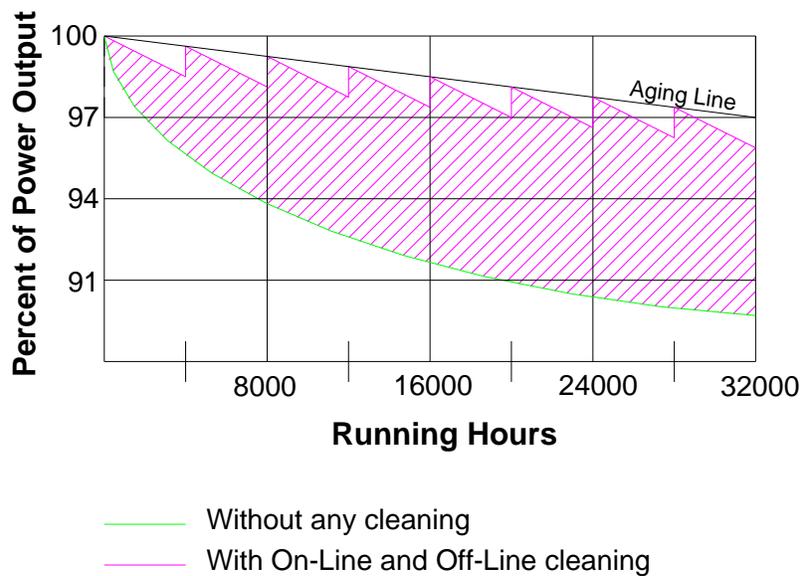
### On-line Cleaning

On-line cleaning is accomplished through the injection of an abrasive materials, water or chemical cleaning agents into the running engine. This type of cleaning, if performed regularly, can extend the time between crank washes. The shaded area in Figure 3 shows the power output recovered from On-line cleaning. Each On-line cleaning media has advantages and disadvantages.

### Combining On-Line and Off-Line Cleaning

When Off-line cleaning is combined with regular On-Line cleaning, the total amount of power recovered

## COMBINED EFFECTS OF ON-LINE AND OFF-LINE CLEANING ON ENGINE PERFORMANCE



**Figure 4**

The actual power output recovered will vary by turbine type and site conditions.

## Water

Under no circumstances should potable or untreated water be used for the ingestive cleaning of an engine. The presence of chlorine, fluorides, heavy and earth alkali metals can cause severe damage to the hot section components. Only deionized/demineralized water (DI/DM) having very low levels of solids should be used. Most OEMs have published water content specifications, which should be followed. The advantages of cleaning with DI/DM water are lower cost, ease of handling and storage and its availability. In operating activities, which generate DI/DM water of sufficient quantity and purity, the cost is generally not a factor. If DI/DM water must be purchased, the cost may approach \$1-\$3 per gallon. The main disadvantages of using DI/DM water are the promotion of corrosion, erosion, and poor cleaning effectiveness.

## Corrosion

Because DI/DM water has very low levels of electrical resistance (usually less than 3 megohms), it becomes an excellent electrolyte for the establishment of galvanic cells between mismatched metal substrates. The effects are especially pronounced in crevices such as those found in blade roots and variable stator vane bushings. Over time, this corrosion can induce blade rock; seizure of moveable components, and even cause catastrophic failure of stressed blading.

## Erosion

DI/DM water has a surface tension of about 73 dynes @ 70°F, about 30-50% higher than that of surfactant based detergents. Surface tension is basically the fluid's ability to hold its shape. Therefore, the higher surface tensions make DI/DM water more

erosive when impinging on airfoil surfaces. Since fluid delivery equipment is normally designed to accommodate the properties of their recommended chemical. The cleaning effectiveness of water will vary from delivery system to delivery system. Water alone is generally not as effective as a cleaning chemical specifically designed for that task. Frequent on-line cleaning using water and delivery equipment that does not provide full and uniform coverage of the inlet area, can result in selective erosion of early stage blading.

Water has been called the "universal solvent", however, as an ingestive cleaning agent for gas turbines, it is extremely inefficient. Since water is lipophobic, it is not capable of combining chemically with hydrocarbons, which are the most frequently deposited compounds on airfoil surfaces. Water, unless heated to a temperature over approximately 150°F, will not remove hydrocarbon-based contaminants. The application of water at elevated temperatures can improve its cleaning effectiveness, but heating will also hasten its evaporation within the compressor casing and therefore reduce the depth of droplet migration. Standard tests such as described in MIL-C-87504 show the cleaning effectiveness of water to be about 15-20%. This compares unfavorably with chemical cleaners, which generally attain cleaning effectiveness of 80-100%. Water can act as a dispersant for soils and salts, but limited to the extent that those contaminants are embedded in a mechanically bonded matrix of hydrocarbons, making water less effective. Water relies heavily on its abrasion capabilities to clean. However, to function effectively as an abrasive media, water must be applied in large quantities at high pressures. Therefore, a water-washing program capable of providing effective cleaning may have an adverse

effect in the form of accelerated corrosion and erosion.

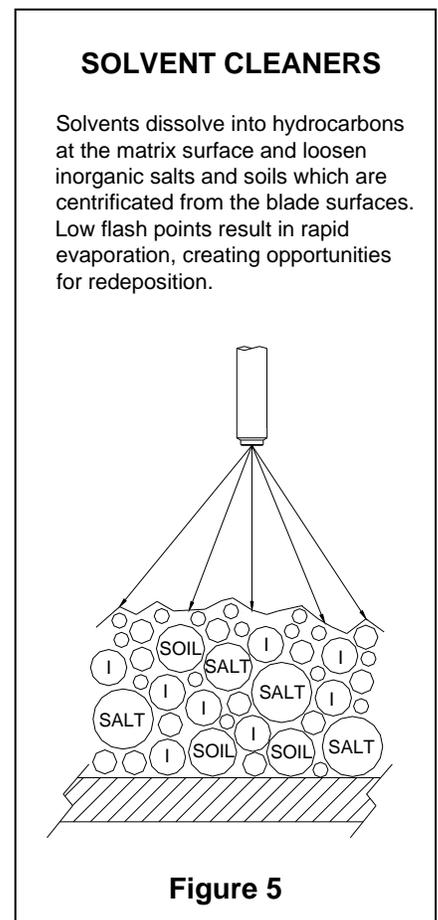
## V CHEMICAL CLEANERS

Chemical cleaners for compressors fall into two categories: petroleum-distillates (solvents) and detergents.

### Solvent-Based Cleaners

Petroleum distillates (petro-distillates), commonly referred to as solvents, are strongly lipophilic, and rely on the dissolution of organic contaminants as the principal mechanism of removal. As the cleaning solution impinges on the contaminated surfaces, it is dissolved into the organic contaminants, loosening and softening the embedded particulate as shown in Figure 5.

The loose and softened compounds are then centrifugated from the



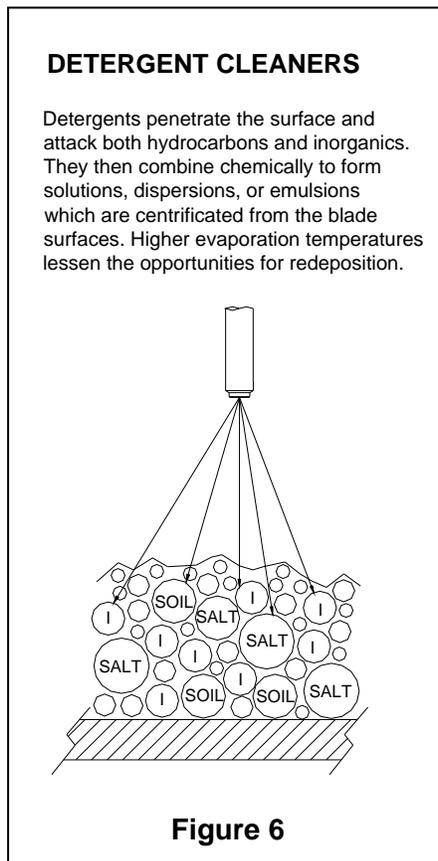
blading to migrate through the compressor. Hence, solvent-based cleaners are most frequently used for crank washing. Since solvent-based cleaners have low flash points, the cleaner "flashes" in the elevated temperatures of the casing when used for on-line cleaning. The dissolved contaminants become more adherent (or sticky) and readily accumulate on the already fouled surfaces of succeeding stages. This uneven deposition may cause vibration problems as well as accelerated deterioration of engine performance. There have even been instances of combustion within the compressor casing, causing over-tempering, over speeding and engine trips. This tendency of solvent-based cleaners to redeposit contaminants from the early to intermediate blading stages, makes them of questionable efficacy for on-line cleaning, and therefore, not frequently used for that purpose.

Solvent-based cleaners are also intrinsically toxic and usually contain high levels of benzenoids, chlorinated hydrocarbons (which typically exceed OEM limitations). Furthermore, solvents routinely require secondary storage and special handling for disposal.

### Surfactant-Based Cleaners.

Surfactant-Based Cleaners are detergents that clean by lowering the surface tension of the aqueous carrier. As the wet fluid impinges on a contaminated surface, the solution of water and surfactants readily penetrates the porous foulant matrix and dissolves into or combines chemically with the surface contaminants as shown in Figure 6.

The results depend on the type of detergent used, either an anionic, nonionic, or cationic material. The liquefied foulants are then centrifugated from the blading and migrate through the compressor and burned in the hot section. Surfactants, unlike solvents, have



high evaporative temperatures, which permit the wet fluid to migrate well into the compressor. Some surfactant-based products will stay in a wet state at temperatures exceeding 400° F and in the pressure environment typically experienced in an axial flow compressor. Another feature of surfactant-based cleaners, is their wetting ability. Most surface-active products have a low surface tension (less than 35 dynes @70° F.). This allows surfactants to have larger droplet sizes that produce a larger wet area than is achievable with the smaller drop sizes for solvent cleaners. This makes surfactant detergents far less erosive than water while providing significantly better wetting. One of the main considerations in the use of a surfactant detergent for on-line cleaning is the purity of the mix water. If mixing the cleaner from concentrate, the mix water should be deionized/demineralized water so that the active ingredients in the

cleaner will not combine with solids in the mix water and degrade the cleaning ability of the fluid. Operators should also ensure that the conductance of the mix water is less than 3 megohms. The manufacturer's water specifications and mix ratios should be closely followed when a concentrate product is used.

### Classes of Surfactants

Detergents used for compressor cleaning, generally rely on three classes of surfactants: linear alkyl sulfonates (LAS), ethoxylated alcohols (EA), and ethoxylated tertiary amines. All surfactants have low levels of heavy metals and chlorine to meet OEM specifications for on-line cleaners. These cleaners are non-flammable, and biodegradable. However, LAS surfactants contain alkali metals such as sodium and potassium, calcium, and magnesium and typically have high pH's in the range from 9.0 to 11.5 (before mixing with water). These strong base substances, when used frequently, will readily attack aluminum alloys and aluminides such as those used in ceramic-metallic coatings, VSB bushings, etc. whereas EA and tertiary amine-based products usually neutral or slightly basic.

### Linear Alkyl Sulfonates (LAS)

LAS surfactants comprise large molecules of at least 10 hydrocarbons (aromatic and aliphatic alcohols) bound with a hydrophilic group, such as a sulfonate group, in an aqueous carrier and a solublizer/wetting agent. The most commonly used solublizers are glycol ethers (2-butoxy-ethanol, dipropylene glycol, monobutyl ether, etc.). These compounds can be toxic and combustible. LAS-based detergents clean by the process of dispersion. The lipophilic portion of the LAS dissolves into the hydrocarbon-based foulants, loosening the matrix

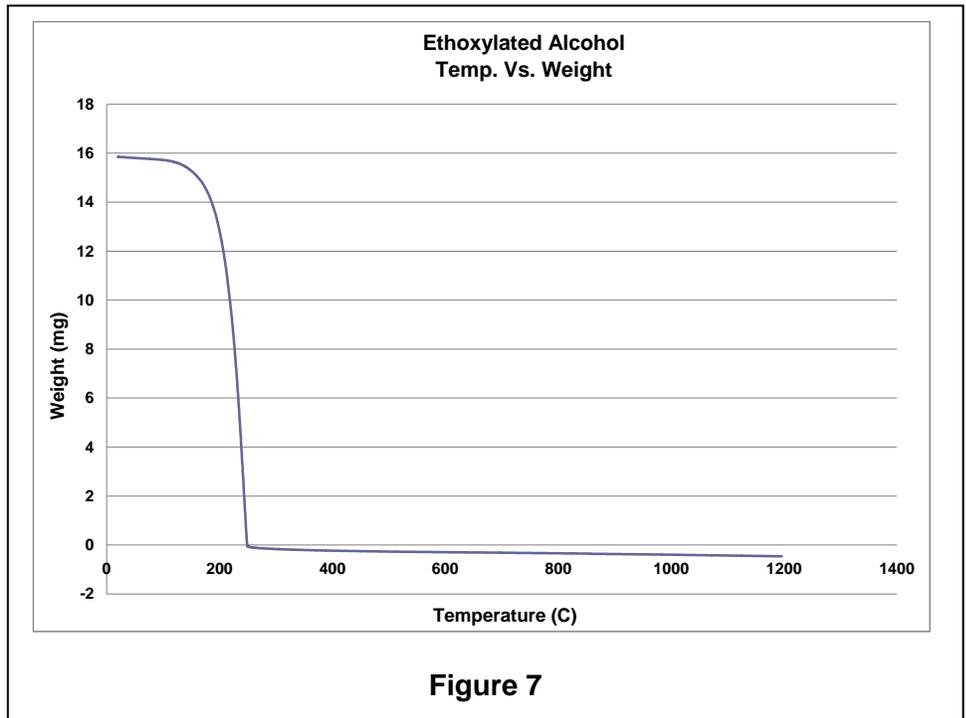
of contaminants such that they may be removed from the airfoil surfaces by centrifugation. LAS detergents must be handled, stored and used in accordance with regulations consistent with their compounds.

**Ethoxylated Alcohols (EOA)**

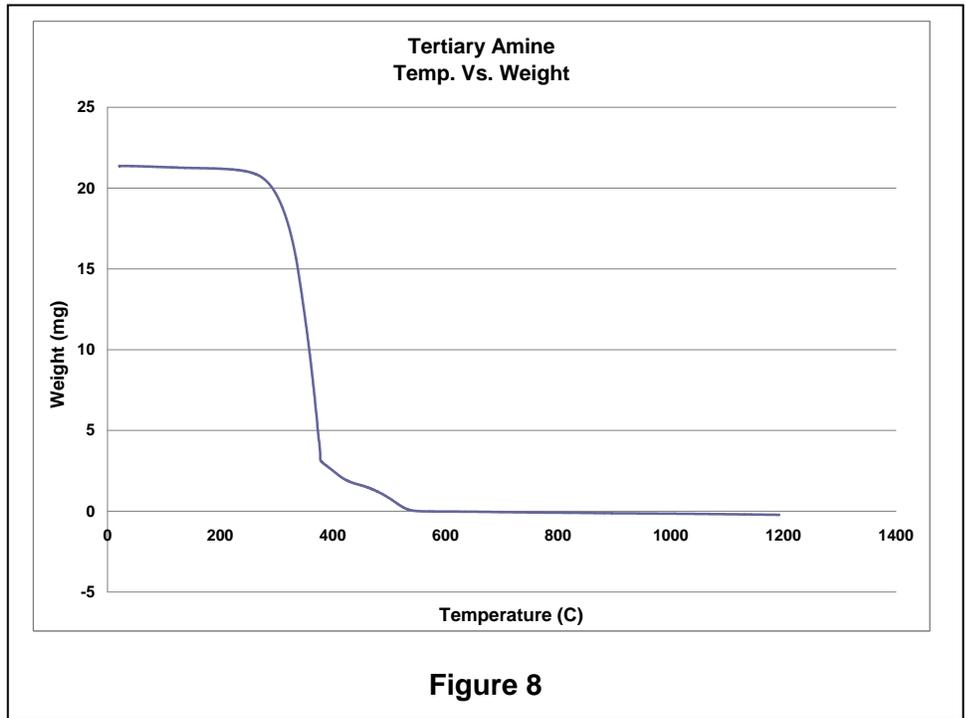
EOA surfactants are commonly selected based upon the anticipated temperature during cleaning. EOA based cleaners do not remove carbon based fouling as efficiently as Tertiary Amines. EOA tend to have lower boiling and flash points, as shown in Figure 7, which tend to increase the potential redeposition of contaminants removed in early stages to successive stages. In some cases these compounds may contain a VOC content, handling precautions can be a concern and local EPA restrictions should be considered prior to use.

**Ethoxylated Tertiary Amine Surfactants**

This class of surfactant is a combination of cationic and non-ionizing amines bound with three atoms of nitrogen into a more compact molecule. The mechanism of cleaning is cationic. Since tertiary amine surfactants are both lipophilic and hydrophilic, they readily combine with both organic and inorganic foulants to form an aqueous emulsion or dispersion, which is then removed from blading by centrifugation. Generally, tertiary amine-based detergents persist longer in a wet state at higher temperatures due to their higher boiling points as shown in Figure 8. Their low surface tension and smaller molecules promote penetration into the fouling matrix. The required duration of impingement on contaminated surfaces is somewhat longer than that of LAS-based detergents. For this reason, not only are lower injection flow rates possible, they are also desirable. Also, biodegradable, amine-based



**Figure 7**



**Figure 8**

detergents permit the disposal of spent containers as well as uncontaminated product without excessive regulatory constraints.

**VI. FLUID DELIVERY SYSTEMS**

**On-Line Fluid Delivery Systems**

On-line cleaning of gas turbine engines requires the installation of a fluid delivery system. Consisting of,

at a minimum, a fluid reservoir, a manifold nozzle ring, fluid supply piping and a means of transmitting the fluid from the reservoir to the nozzles at sufficient pressure to produce the needed droplet size and spray characteristics. Figure 9 illustrates a typical On-line skid plumbing diagram.

### Off-Line Fluid Delivery Systems

Fluid delivery systems for off-line cleaning are generally designed to meet OEM flow requirements. This usually means higher flow rates and less concern with full and uniform coverage of the inlet area. However, the reduced rotational speeds

attained while motoring the rotor, make nozzle placement and pressure requirements the critical design parameters. Excessive flow, coupled with low airflow, can mean wasting a large amount of cleaning fluid. More importantly, it reduces the cleaning effectiveness. In general, nozzle design should provide a flow rate consistent with OEM requirements with optimum wetting coverage of the inlet area. Typical flow rates are 0.8% – 1.0% of mass air flow. Nozzle placement should be such that the maximum amount of the cleaning fluid is ingested. Heaters for the detergent and rinse water are also useful; they increase the cleaning efficiency while reducing the risk of thermal shock. Although it is preferred to mount permanent off-line wash nozzles outside the plenum, should it be necessary to mount them inside the plenum, all fittings and components should be secured with weldments or safety wire. Off-line wash cleaning equipment should be capable of provide fluid pressures of 100-150 psi at the nozzles. Only very low foaming cleaning products should be used. Figure 10 shows a typical Off-line skid plumbing diagram. It is worth noting that although Off-line skids are generally higher in cost than On-line skids due to their higher flowrates, they may also be used for On-line cleaning. This is possible since On-line cleaning flowrates are about a third of Off-line flowrates.

### Manifold Nozzle Assembly

Typically, the manifold nozzle assembly consists of spray nozzles mounted such a way so that the nozzle discharge is in the engine air inlet to provide full and uniform coverage of the blading. Each nozzle is connected together by flexible hoses or rigid tubing. The manifold may be closed or it may consist of two or more interconnected sections. It can also be mounted forward or aft of the inlet housing as dictated by the

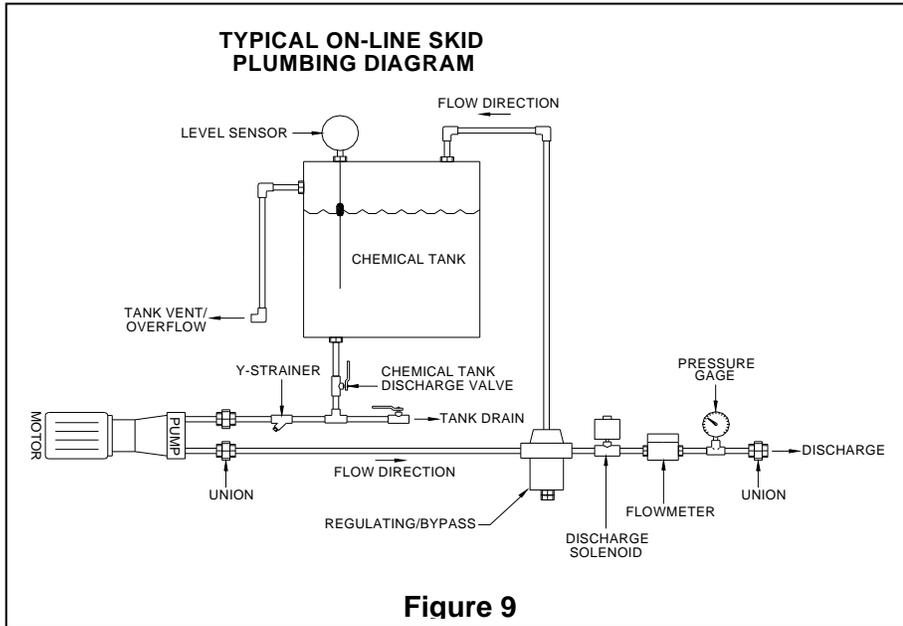


Figure 9

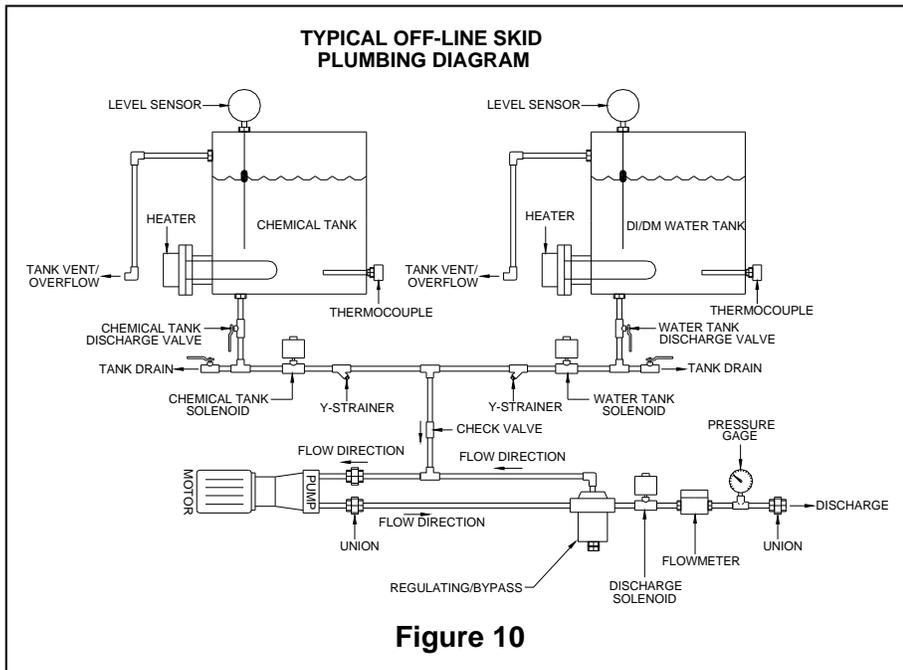


Figure 10

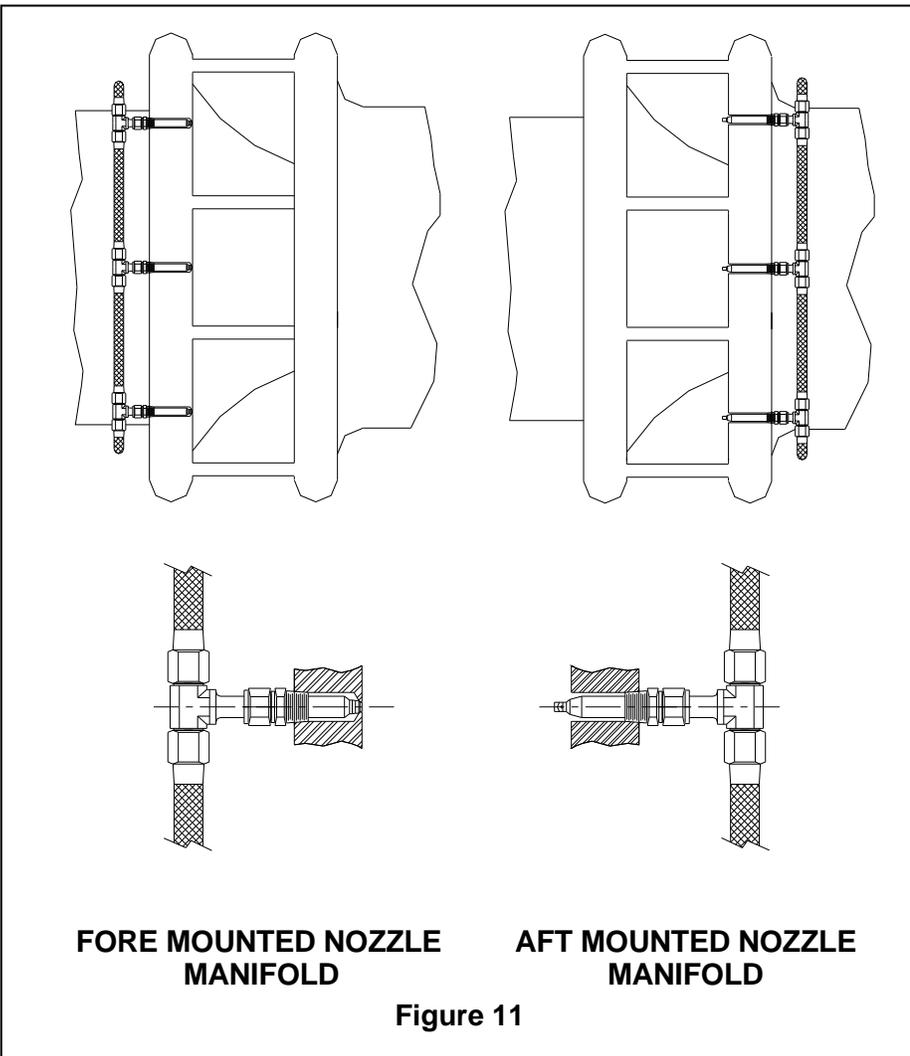


Figure 11

configuration of the plenum. Figure 11 illustrates the fore mounted and aft mounted configurations. The spray of fore mounted nozzles should have a full cone pattern and be oriented directly toward the first stage blading. This configuration provides the most effective cleaning. Aft mounted nozzles usually employ a flat spray pattern oriented toward the unit's center-line. The materials utilized in the fabrication of a nozzle manifold should be corrosion resistant and capable of withstanding pressures exceeding up to 200 psi.

### Mounting

The method for mounting a nozzle manifold will vary with the engine type and model. Devices such as

Swagelok™ assemblies are commonly used. In most instances, it is necessary to drill holes through the engine inlet, inlet ducting or the plenum wall to facilitate the mounting of the nozzles. Other methods are available for mounting on FOD screens or air inlet ducting. Most nozzle manifolds are, in fact, mounted by the end user since the installation can be completed in the field.

### Nozzle Selection

When selecting a spray nozzle, several factors must be considered; notably, fluid flow rate, spray type, spray angle, droplet size, available motive pressure, etc.

### Flow Rate.

In general, the required fluid flow rate is defined by the engine's mass air flow. Mass air flow and power output are directly proportional, thus it is possible to use the power output as the parameter to calculate the cleaning fluid flow rate. In general, the flow rate for on-line injection of cleaning fluid into a running engine should not exceed 0.2% - 0.3% of designed mass flow. In practice, the recommendations of OEMs and fluid manufacturer vary. The fluid flow rate is a function of the nozzle capacity, pressure, surface tension, viscosity, and evaporative properties of the cleaning fluid, etc. Each nozzle type and size has a fixed capacity at a specific pressure. To clean effectively, the selected nozzle must be capable of delivering a sufficient volume of fluid to provide full and uniform coverage of the contaminated surfaces for a period of time sufficient enough to permit the cleaning fluid to remove the foulants. Delivery systems producing lower than optimum flow rates will produce less than optimum removal. Delivery systems using higher than optimal flow rates will result in the use of excess cleaning materials without an increase in cleaning effectiveness. Flow rate selection also has to be considered for the planning of field plumbing and selecting the appropriate propellant.

### Spray Type and Angle.

In the operation of an axial flow compressor, air cascades over the airfoil surfaces along the axis of the rotor. In the earlier stages, the air velocities are greater and the pressures are lower than in successive stages. Since flow within the compressor is laminar, there is little radial migration of the mass within the compressor casing. Therefore, if air enters the compressor at, for example, the one o'clock position, it will be discharged

from the compressor at the same approximate radial position (one o'clock). For this reason, the fan type and angle must afford full and uniform coverage of the inlet area. In designing a nozzle manifold, it is desirable to have the spray pattern overlap at the compressor inlet area. The number of nozzles is then determined by the spray angle produced. There are two basic spray patterns: the full cone (typically used in fore-mounted applications) and the flat fan (typically used in aft mounted applications). The discharge of a full cone nozzle is normally oriented directly into the compressor casing from a position forward of the inlet area. The required spray angle is determined by the distance from nozzle orifice to the first stage blading and the dimensions of the inlet area. Flat fan nozzles (or directional nozzles) are mounted aft of the inlet area, and produce a flat spray pattern. The spray is deflected at an angle toward the center-line of the rotor. Typical spay angle of flat fan nozzles are from 90° to 135°. These angles may vary with the physical properties of the cleaning fluid. Nozzle selection must also account for air velocity within the inlet plenum. Since the airflow will cause the fan angle to narrow, the chosen nozzle must produce a fan, which is proportionally wider than would be needed in static conditions.

### Compatibility of Equipment with Cleaners

Since the physical properties of cleaning fluids differ, the injection equipment designed for the application of one cleaner may not be completely suitable for use with another. Most commercially available detergent-based cleaners are suitable for any equipment designed for fluids having the general properties of water. Equipment designed for applying solvent-based products is seldom appropriate for applying detergent-based products. Similarly, equipment designed for detergent-based products cannot effectively apply solvent-based products.

### Droplet Size.

The size of the droplet produced by the nozzle is an extremely important factor in cleaning effectiveness; it affects both the rate of evaporation and the size of the wetting area. If the produced droplet is too small, it will evaporate more quickly and will not wet an area of sufficient size. If the droplet size is too large, it will not readily migrate into the compressor, leaving succeeding stages uncleaned. Irrespective of cleaning effectiveness, the droplet size along with surface tension is the principal factors in determining how erosive a fluid is. Assuming equal volumes of fluid, large

droplets tend to be more erosive than smaller. The size of a droplet produced is a function of the following: 1) the nozzle type (full cone or flat fan), 2) the diameter of the nozzle orifice, 3) the viscosity of the fluid, 4) the surface tension, and 5) the propellant pressure. In general, the droplet size varies directly with nozzle orifice diameter and inversely with propellant pressure. Therefore, the larger the nozzle orifice diameter, the larger the droplet size, and the higher the pressure the smaller the droplet size. Figure 12 summarizes the effects of fluid properties on spray characteristics. Most detergent cleaning fluids have roughly the same viscosity as water. Solvents generally have lower viscosity than water. At a given pressure, nozzles designed to produce a given droplet size when using a detergent cleaner will produce smaller droplets when a solvent cleaner is used due to the lower viscosity. The smaller droplets will reduce the ability of the droplet to migrate to successive stages and create conditions, which promote re-deposition of contaminants on intermediate stages of blading. Care should be taken to ensure that the selected cleaner possesses the appropriate properties for the production of the required spray characteristics. Generally, droplet size should be about 150 microns for On-line cleaning and about 500 microns for Off-line cleaning. These sizes will vary depending on the flowrate, inlet configuration, etc.

### Propellant Pressure

Each nozzle has spray characteristics that will produce a specific flow rate, drop size, and spray angle for a specific pressure. This makes pressure a key element to the production of the required spray pattern. If the fluid pressure is too low, ingestive spray patterns can be deformed in the airflow and droplet sizes enlarged. This can affect migration and wetting while increasing erosion. If the pressure is

**THE EFFECTS OF FLUID PROPERTIES ON SPRAY CHARACTERISTICS**

Nozzle Characteristic	Increase in Operating Pressure	Increase in Viscosity	Increase in Surface Tension
Pattern Quality	Improves	Deteriorates	Negligible
Droplet Size	Decreases	Increases	Increases
Spray Angle	Increases then Decreases	Decreases	Decreases

© Spraying Systems Co.

**Figure 12**

too high, droplet sizes will be reduced, hastening evaporation, while increasing flow rates and promoting waste. There are two principal methods of generating fluid pressure: pressure vessels and or pumps. Selection of the best means of providing fluid pressure would be determined by the end user, taking into consideration 1) engine service, 2) site conditions, 3) level of acceptable maintenance burden, and 4) available resources (air, power, etc.).

### **Pneumatic Systems**

The simplest form of delivery system is the drum pump. Requiring only the availability of a minimum of about 100 psi of air, pneumatic drum pumps can deliver cleaning fluid or water at lower flow rates and pressures suitable for some on-line cleaning applications at minimum cost. Drum pumps do however have their drawbacks. The pressure is pulsed (varying droplet size) and they impose a relatively high labor content. Using drums, cleaning fluid must be mixed and moved to the cleaning site, the pump affixed to the drum and manifold wash ring, and air connected and regulated before the cleaning cycle can be started. Use of drum pump systems is a cost effective alternative for operators of relatively small engines

### **Pressure Vessels**

Pressure vessels are cost effective at sites that allow the installation of a wash skid in close proximity to the engine. Concentrated cleaning fluid, instead of more expensive ready-to-use products, can be mixed with DI/DM water in the vessel and stored. This permits some maintenance savings by allowing multiple wash cycles with one filling. The principal disadvantages of pressure vessels are the necessity of having good quality factory air at sufficient pressures and lower flowrates. Pressure vessels for the cleaning of gas turbine engines

should be fabricated of good quality stainless steel. This prevents nozzle clogging from the corrosion released into the lines. They must also meet ASME Code standards, be fitted with fluid inlet and discharge valves, air pressure regulator(s) and pressure gages, drain valves, pressure relief valve, liquid level indicator, vent/overflow valve, and flowmeter/totalizer, at a minimum. Stationary vessels are most suitable for cleaning of a single engine, but smaller tanks can be mounted on a wheeled cart or truck for portability and make them useful for servicing multiple units. Automatic fill, mixing, and timed discharge features can also be added.

### **Electric Pump Delivery Systems**

Electric pump delivery systems utilize atmospheric tank(s) and a motor driven pump to deliver cleaning fluid. The system consists of a liquid tote plumbed to a pump and motor, a Start/Stop switch, a motor starter/contacter, relief valve, drain valve, discharge valve and pressure gage. It can also be as complex as a fully automated system where the cleaning cycle is initiated by an integral programmable logic controller (PLC), provide on-demand mixing of chemical concentrate with water, use signals from the engine control system as permissives to run, etc. The desired level of automation is at the discretion of the end user and depends upon other factors like the service and site conditions, the desired reduction in maintenance burden, the number of units to be serviced, etc.

## ECONOMIC ANALYSIS

A Frame 6 operating on natural gas at ISO conditions will have an output of 42,100 kW. The associated heat rate will be approximately 10,642 BTU/kW-hr. Typically, the heat rate will deteriorate 2 - 4% due to fouling over the first 2000 hours of operation.

### SAVINGS CALCULATION

#### Assumptions:

1. A recovery of
2. LHV of fuel in BTU/cubic ft. for natural gas.
3. Purchase price per thousand cubic ft. for natural gas.
4. Load Factor (LF): .
5. Gas turbine heat rate
6. Total output in kW
7. Total Dosage in Gallons
8. Usage - number of engine cleaning washes per week
9. Chemical cost (per gallon)

3%
1010 BTU/ft <sup>3</sup>
\$3.98 / 1,000 ft <sup>3</sup>
50%
10,642 BTU/Kw Hr
42,100 Kw
60 gallons
1
\$3.95

$$\Delta \text{ BTU/hr} = \text{Recovery \%} \times \text{Heat Rate (BTU/KW-hr.)} \times \text{Output (kW)}$$

$$\Delta \text{ BTU/hr} = 13440846 = \text{BTU/hr}$$

$$\text{Yearly Fuel Reduction (ft}^3\text{/yr)} = \Delta \text{ BTU/hr.} \times 1/\text{LHV (ft}^3\text{/BTU)} \times \text{LF(\%)} \times \text{hrs./day} \times \text{days/yr.}$$

$$\text{Yearly Fuel Reduction} = 58288025.23 \text{ ft}^3\text{/yr}$$

$$\begin{aligned} \text{Fuel Dollar Savings} &= \text{Yearly Fuel Reduction (ft}^3\text{/yr)} \times \text{Cost of Fuel (\$/1,000 ft}^3\text{)} \\ &= \$231,986.34 \end{aligned}$$

$$\text{Cleaner Cost} = \$12,324.00$$

$$\text{Net Annual Savings} = \$219,662.34 \text{ per year}$$

## Service and Site Conditions

Gas turbine units in power generation or mechanical drive services are typically in non-hazardous areas and do not impose special operating requirements such as explosion proof motors and enclosures, special spark or ignition shielding, etc. In hazardous area Classification I & II, Division I & II, Group A-D, special operating equipment is required that increase the system cost. Other considerations include the distance from skid to the unit to be serviced, elevational changes, etc. These items increase fluid pressure loss and the equipment and plumbing lines may have to be upsized to ensure that adequate pressure is provided at the spray nozzles

## VII. ASSESSING THE COSTS OF FOULING

The effects of regular cleaning at sites where airborne contaminants are heavy, or have long continuous running periods, can result in substantial savings. There are three types of cost savings associated with regular cleaning. The first type of savings is *avoided cost savings*. An avoided cost is just that, the savings from avoiding a cost that would have otherwise been required. For example, typical gas turbines may be scheduled for an overhaul after five years of service without regular cleaning. However, if that same gas turbine is cleaned regularly, the scheduled overhaul may not be required until seven years of service. Hence, the end user "avoided" the cost of the overhaul for two years and the time necessary between overhauls has been extended. The second type of cost savings are *direct cost savings*. Direct costs savings include operating materials such as fuel, lubricants, maintenance labor, as well as other items required for the operation of the gas turbine. The easiest direct cost to quantify is fuel savings. Regular cleanings allow

the gas turbine to run more efficiently; simply put, the more efficient a gas turbine runs, the less fuel that is required for the same level of output. The third type of savings is *indirect savings*. Indirect savings are the savings achieved indirectly from the effects of regular cleaning. A good example is the increased component life as operating temperatures decrease. Since regular cleanings allow the gas turbine to run more efficiently, higher output levels are achieved. These higher output levels can be easily quantified into revenue gains by multiplying the increase in output by the kWhr selling price. Certain types of equipment deterioration, such as aging, are unavoidable. Other factors, such as corrosion and fouling can be minimized through the use of performance enhancing measures such as coatings and rigorous cleaning programs. These performance enhancing measures have their own costs. The use of these measures can only be determined by calculating the direct and indirect costs of operations and then comparing those same costs with the enhancement measures in place. The economic analysis discussed here will be limited to the effectiveness of a gas turbine cleaning program. The most direct and simplest measure of compressor condition is Pressure Ratio (PR). As fouling accumulates, creating thermal and turbulence effects, the compressor discharge pressure (CDP) drops, reducing the ratio of compressor inlet pressure (PCI) to PCD. The decrease in Pressure Ratio can be expressed as a percentage of the OEM designed PR.

The following is an illustration of a typical economic analysis based on a GE Frame 6 operating on natural gas, and has a rated output of 42,100 kW at ISO conditions. The associated heat rate will be approximately 10,642 BTU/kW-hr. It is worth noting that the heat rate will typically deteriorate about 2% - 4%

over the first 2,000 hours of operation.

## VIII. CONCLUSION

Fouling resulting from the deposition of airborne contaminants on the aerodynamic surfaces of an axial flow compressor is the leading cause of performance losses in gas turbine operations. The practice of regular ingestive cleaning – on-line and off-line – can greatly reduce the rate of degradation. In establishing an effective cleaning program, the operator must account for the need to equip the engine with a fluid delivery system which accounts for the many engineering and environmental variables which can spell the difference between a successful program and a waste of time. Finally, the economic benefits of a solid compressor-cleaning program become apparent when the cost effectiveness is analyzed.