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# GAS TURBINE PACKAGING OPTIONS AND FEATURES

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## ABSTRACT

This tutorial provides an overview of typical packaging options for gas turbines in industrial applications. Applicable standards are discussed. The requirements for different systems, such as air filtration, and fuel systems are explained. Off shore requirements, especially on floating systems are highlighted.

## INTRODUCTION

Industrial and aeroderivative gas turbines are commonly employed in oil and gas applications where high power to weight ratio, low emissions, and high availability requirements are very advantageous compared to other drivers. Industrial gas turbines are frequently used as mechanical drivers for natural gas centrifugal compressors. Due to their operational flexibility, low maintenance requirements, and good speed match with the driven equipment, they are ideally suited for this service. As with any machinery, gas turbines require a significant number of on-skid and off-skid (also known as ancillary and auxiliary) equipment, such as lube oil systems, controls and instrumentation, fire-detection and suppression systems, fuel forwarding and filtration systems, starter and crank motors, and inlet/exhaust systems for their safe and efficient operation. Given a specific application, an optimal set of ancillary and auxiliary equipment options must be selected. This selection is not just based on the type of application and utilities available at the site, but the operator's requirements for operating profile, reliability, and/or availability, and the environmental conditions at the site must also be considered.

For many compression applications, gas turbines are located in unmanned stations with limited service access and are required to operate over wide ranges of loads and speeds while providing high availability and reliability. Air, fuel, and lube oil quality maintenance and monitoring are very important, but can be a challenge for these applications. The proper selection of ancillary/auxiliary equipment is critical to assure operation within the required operating parameters of output power, efficiency, reliability, availability, and emissions.

This paper will describe the standard ancillary/auxiliary equipment options for gas turbine driven compressor systems and their relative advantages and disadvantages in pipeline applications. Some discussion on API standards and how they relate to packaging options is also provided.

## OVERVIEW

The packaging of gas turbine driven compressors for oil and gas applications presents some very special challenges, and gas turbine manufacturers have developed specialized packaging options for these different types of services. Fundamentally, the package systems are designed to provide the gas turbine with its utility requirements (air, fuel, oil, and water), control the operation of the unit and process, and assure safety. The gas turbine, the gas compressor, and, if necessary, the gearbox are usually mounted on a skid, together with most of the systems described below. Thus, the primary gas turbine package systems are:

- Starting
- Lube oil
- Fuel
- Seal gas (if dry gas seals are utilized)
- Fire/gas detection and fire fighting
- Inlet and exhaust air
- Enclosure
- Control and instrumentation

Each of these package systems has a number of subsystems and components. Generally, package systems are classified into on-skid and off-skid systems. On-skid classification generally corresponds to all equipment inside the gas turbine enclosure, while off-skid or outside the package refers to equipment connecting to the gas turbine package, such as ancillaries and auxiliaries. The main turbo compressor's ancillary equipment, classified by this definition, is listed below:

*On-Skid – Inside the Package*

- Fuel system and spark igniter
  - Natural gas (control valves, filter)
  - Liquid (pumps, valves)
- Bearing lube oil system[1,2]
  - Tank (integral)
  - Filter (simple, duplex)
  - Pumps (main, pre/post, backup)
- Accessory gears[3]
- Fire/gas detection system
- Starter/helper drive
- Pneumatic, hydraulic, or variable speed AC starter motor
- Controls and instrumentation (on-skid, off-skid)
- Seal gas/seal oil system (compressors)

**Off-Skid – Outside the Package**

- Enclosure with lifting devices and fire protection system[4]
  - Enclosure ventilation
- Inlet system
  - Air-filter (self-cleaning, barrier, inertial, demister, screen)
  - Silencer
  - Inlet fogger/cooler
- Exhaust system
  - Silencer
  - Stack
- Lube oil cooler (water, air)
- Fuel filter/control valve skid
- Off skid control system
- Motor control center
- Switchgear, neutral ground resistor
- Yard valves (load, recycle, anti-surge)
- Turbine cleaning system (on-line, on-crank)
- Documentation

The different package components are described in more detail below. Also, because of the significance of filtration of the different utility streams (air, fuel, lube oil, and water) in a gas turbine package, this topic is discussed in additional detail below.

## API STANDARDS

The American Petroleum Institute (API) is the primary trade organization for the U.S. petroleum industry. API has over 400 member companies that cover all aspects of the oil and gas production. API 616 is the principal industry standard for gas turbines in oil and gas services and provides detailed requirements in Chapter 4 (mostly on-skid and core engine direct ancillaries) and Chapter 5 (off-skid) for gas turbine package systems. Other API standards that are relevant for gas turbines in pipeline service are API 614 (lube oil systems), 617 (centrifugal compressors), 670 (machinery protection), 671 (couplings), and 677 (gears). Similar standards have been developed by the International Standards Organization (ISO), but these are not as frequently used. API provides definitions and sets minimum functionality, materials, construction, testing, and machinery controls requirements. Consequently, API 616 has become a critical purchase contract document for gas turbines operators.

Oil and gas applications of gas turbines have requirements that are inherently different than those of the electric power industry, and customers require:

- High availability/reliability
- Ruggedness
- Low maintenance requirements and ease of maintenance

Because of these requirements, many operators insist on compliance with API codes and are willing to accept the associated increase in package costs. Within API, there are standards that address each engine and packaging systems; however, the focus of most API specifications is on packaging and ancillaries rather than on gas turbine core components. For example, API 616 covers the design of the gas turbine inlet, exhaust, enclosure, interface connections, instrumentation, base-skid, lube oil system, and fuel system in significant detail, whereas the core engine design specifications are generally broad and allow more manufacturing flexibility.

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[1] Some packages have two separate lube oil systems.
[2] Lube oil systems/lube oil tanks can also be separate skids.
[3] The accessory gear is used by the starter but can also drive the main lube oil pump and hydraulic pumps.
[4] Enclosures can be mounted on the skid, or they can be of the drop-over type.

API 617 covers the requirements for axial and centrifugal compressors, single-shaft and integrally geared process centrifugal compressors, and expander-compressor for use in the petroleum, chemical, and gas industry services that handle air or gas. As with all other API codes, the equipment vendor may offer alternative designs, if these designs improve the safety or performance of the equipment.

## STANDARD PACKAGE OPTIONS

The basic package options for a typical gas turbine driven compressor train are described below. Obviously, not all options and features that are provided by different manufacturers are included, and the focus here is simply a description of the most commonly utilized packaging equipment. For completeness sake, a brief description of the core engine (gas generator and power turbine) is also provided:

### *Gas Turbine Package Unit*

Most gas turbine units, as delivered by the manufacturer, consist of a completely integrated, fully operational package including driven equipment. They are equipped with all accessories and auxiliary systems necessary for normal operation when connected to suitable compressor station facilities.

A gas turbine driven compressor package set, thus, usually includes:

- Two-shaft industrial or aeroderivative gas turbine engine
- Engine air inlet and exhaust collectors
- Centrifugal gas compressor (driven equipment)
- Gear box
- Turbine/compressor control system
- Start system
- Fuel system
- Lubricating oil system
- Piping and manifolds (usually stainless steel)
- Seal system (dry gas seal system or seal oil system)
- Base gas turbine skid with integrated lube-oil tank and drip pans
- On-skid electrical wiring
- On-skid digital display

The gas turbine engine and compressor constitute the major elements of the package. These elements are installed on separate heavy-steel base frames in an in-line arrangement. The base frames are structural steel assemblies with beam sections and cross members welded together to form a rigid foundation. Once connected together, the total package may be suitable for three-point mounting, depending on the driven equipment configuration. Mechanical interface connection points for fuel, air, and water are conveniently located on the outer skid edge. Electrical connection points are made in on-skid junction boxes and terminal strips.

Typically, all package piping and manifolds are 316L stainless steel material. This applies to all package piping systems, including the start, fuel, lube oil, and wet/dry seal systems, as well as the supply, drain, and vent lines up to and including four inches in diameter. In addition, the associated flange assembly hardware is 316 stainless steel or equivalent. Piping sizes six inches in diameter or larger are usually carbon steel, and all tubing is 316L stainless steel with 316 stainless steel fittings.

The following items are usually not made from stainless steel, unless specifically requested by the purchaser:

- Valve bodies and system functional components
- Pipe support brackets
- Oil tank cover assemblies with connection piping and fittings welded in place
- Sliding lube oil drain couplings and plates
- Pipe flexible couplings
- Filter housings
- Lube oil tank

### *Electrical System*

Most North American applications require that the equipment meets National Electric Code (NEC) requirements. Details of these requirements can be found in the NEC National Fire Protection Association (NFPA) 70 code. In many parts of the world, Cenelec requirements, or local electric codes may apply.

On-skid electrical equipment is in accordance with NEC NFPA 70 requirements for electrical equipment installed in Class I, Group D, Division 2 hazardous locations. This means that all wire runs are made in copper-free aluminum conduit for physical protection and isolated from combustible atmospheres. When supplied, the turbine control console, variable frequency drives, and battery charger are non-explosion-proof and must be installed in a nonhazardous location.

### *Core Engine*

The core gas turbine engine is a self-contained, completely integrated prime mover of two-shaft, axial-flow, dry emissions control design. The gas producer and power turbines have separate shafts and are mechanically independent. Figure 1 shows a typical gas turbine core engine.

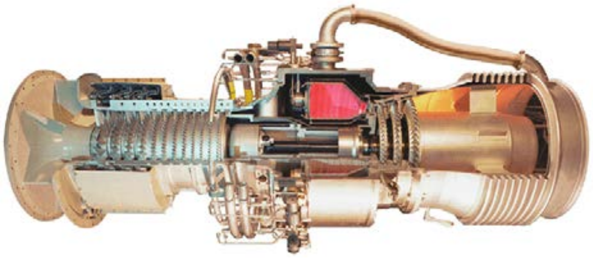


**Figure 1. Gas Turbine Core Engine**

The engine assembly consists of:

- Accessory drive assembly
- Air inlet collector
- Axial-flow compressor with variable geometry on the inlet guide vanes and first four rows of stators
- Combustor – Depending on the manufacturer, this is either an annular, can-annular, single-can, or multi-can design. Almost all new gas turbines installed in the North American and European markets utilize lean-premixed combustion for nitrous oxides emission control.
- Gas producer turbine assembly
- Power turbine assembly

- Turbine exhaust collector

The components of the gas turbine engine are maintained in accurate alignment by mating flanges with pilot surfaces and are bolted together to form a rigid assembly.

The gas turbine has four principal components: compressor, combustor, gas producer turbine, and power turbine. Air is drawn into the air inlet of the gas turbine and is compressed by the axial-flow compressor. The compressed air is directed into the combustion chamber in a steady flow. A portion of the air is premixed with fuel. This premixed fuel/air mixture is injected within the annular combustion chamber. During the turbine start cycle, this fuel/air mixture is ignited, and continuous burning is maintained as long as there is adequate flow of pressurized air and fuel. The hot pressurized gas from the combustion chamber expands through the two stages of the gas producer turbine to provide power to the axial compressor. Gases leaving the gas producer turbine then flow through the power turbine where the remaining energy of the gas stream is absorbed by the power turbine and is transferred to the output shaft. For lean premix combustion, the gas turbine requires approximately one-half of the total air it compresses. Lean premix combustion requires a higher air-to-fuel ratio than conventional stoichiometric combustion resulting in lower maximum flame temperature, which reduces pollutant formation. The excess air is used to further cool the combustion chamber and mixes with the combustion products to reduce the gas temperature at the inlet to the first turbine stage. The cooling air keeps metal temperatures in the combustion chamber and turbine section at design levels consistent with component service life objectives.

### *Driven Equipment Centrifugal Compressor*

Typical centrifugal compressor standard features include:

- Radial vibration monitoring, X and Y proximity probes
- Keyphasor probe
- Axial position monitoring
- Thrust bearing temperature monitoring
- Journal bearing temperature monitoring
- Rigid modular rotor construction
- Vertically split barrel-type construction
- Overcompensating balance piston
- Tilting-pad journal bearings
- Rotor trim balancing

#### *Compressor Centrifugal Impellers*

Impeller alloys can be selected to be in general conformance (chemical composition and hardness) with NACE (National Association Corrosion Engineers) standards for sour gas. Compressor impellers are made from investment castings or machined and are designed to conservative stress levels.

#### *Compressor Casings*

The pressure-containing outer casings of a compressor comprise of an assembly of three components: the suction and discharge end caps that contain the bearing and seal assemblies, and the center body, which holds the rotor and stator assembly. This is considered a vertically split “barrel” design. The end caps contain all the service ports for oil and gas. Alternatively, some manufacturers provide horizontally split compressor casings.

#### *Dry Gas Seal System*

The dry gas seal system is standard on most gas compressors and is composed of two closely interrelated systems: the buffer air system and the seal gas system. The buffer or separation air system maintains separation of the compressor bearing lube oil and the dry gas seals. The seal gas system maintains a barrier between the process gas in the compressor and the compressor dry gas seals. The seal gas is normally taken from the compressor discharge and is cleaned, sometimes cooled, heated, or dried (depending on the gas quality) before it is fed to the seal system. Since the dry gas seals both on the suction and on the discharge side of the compressor are exposed to compressor suction pressure, the pressure differential between discharge pressure and suction pressure pushes the seal gas through the filters in the seal gas system. When the compressor is started, and no pressure differential between suction and discharge side exists, additional gas boosters can boost the seal gas pressure. The standard package components that form part of the seal gas system are rated for pressures in accordance with the discharge pressure levels.

### *Gas Turbine Start System*

The start system provides torque to initiate rotation and assist the engine to self-sustaining speed. At self-sustaining speed, the start system disengages and the engine continues to accelerate under its power to loading speed. These are the most common gas turbine start system options:

#### *Pneumatic Starter*

The pneumatic start system can use either compressed air or natural gas as a power source. The engine start system incorporates a pneumatic motor to initiate engine rotation. Starting power to the engine is transmitted through an overrunning clutch and shaft.

The pneumatic start system includes the following primary components:

- Air or gas, rotary, positive-displacement, helical-lobe, lubricated screw-type expansion motor
- Pilot gas shutoff valve
- Pilot gas filter
- Inlet gas strainer

The supply gas may be delivered from a common source with the fuel system gas using an external manifold. If a separate source of compressed air or service gas is used, a quick-acting manual shutoff valve and a strainer must be installed at the gas inlet.

#### *Direct-Drive AC Motor Starter*

The direct-drive AC start system consists of a squirrel-cage 3-phase AC induction motor with a solid-state variable frequency drive (VFD). The start motor is specifically designed to provide high breakaway starting torque and acceleration from standstill to starter dropout speed. The motor is of explosion-proof/flame-proof construction and standard motor frame size. The motor has integral overtemperature protection thermostats that must be connected to the unit control system for hazardous area motor certification and protection. The motor usually includes a space heater suitable for 115/230-volt, single-phase power connection. Separate cable/conduit entries are provided for power connections, thermal protection wiring, and the space heater wiring. Starting power is transferred to the engine via the accessory drive gearbox and overrunning clutch and shaft assembly.

The VFD provides a pulse-width modulated variable frequency/variable voltage to the start motor. The VFD usually requires a supply of 3-phase AC power from 380 to 600 Vac ±5% and 50 to 60 Hz ±2 Hz. If supply voltage is greater than 600 ±5%, the use of a step-down power transformer is suggested. The VFD regulates the voltage and frequency to the start motor as required to initiate engine rotation, accelerate to purge speed, and then accelerate to ignition and starter dropout speed as commanded by the unit control system. The system should be capable of performing multiple start attempts per hour, as well as extended purge cycles for heat recovery unit applications and engine water or detergent wash cycles.

The VFD cabinet is usually shipped loose for installation off-skid in a nonhazardous location and provides for direct across-the-line starting control of the motor.

### *Power Wiring and Control System Wiring*

Off-skid wiring between starter motor, battery systems, instrumentation, and the control systems is usually not provided by the manufacturer and must be performed by an electrical contractor. The manufacturer provides drawings and specifications that detail these wiring requirements. It is beyond the scope of this paper to discuss the multitude of off-skid wire connections required. All on-skid wiring is usually completed by the manufacturer and tested prior to shipping.

### *Fuel Supply System*

The fuel system, in conjunction with the electrical control system, includes all necessary components to control ignition and fuel flow during all modes of operation. Gas, liquid, or dual-fuel options are usually available for the fuel supply system. For natural gas compression, most gas turbines are provided with gas-only fuel systems, but some applications make use of the capability to switch from gas to liquid fuel. This system can be made NACE compliant, if the fuel gas composition requires this. The natural gas fuel system includes:

- Supply pressure transmitter
- Pilot air operated primary fuel shutoff valve
- Pilot air operated secondary fuel shutoff valve
- Pilot air operated gas vent valve
- Pilot air valves
- Torch with associated shutoff valve and regulators
- Electrically activated fuel control valve
- Main fuel manifold
- Engine fuel injector assemblies
- Piping, manifolds, and tubing (usually 316 stainless steel)
- Inlet gas filter loose shipped for field installation

The gas fuel control valve is electrically operated and electronically controlled by means of an integral DC powered actuator that incorporates a brushless DC servo motor, a linear ball screw drive, a digital controller for precise motor control, and a resolver for position feedback. The valve is rated for operating pressure and temperatures that meet the specific application. It must also have a significant turndown ratio (greater than 200:1). Response time is usually less than 100 msec from 10 to 90 percent stroke. Fail-safe operation ensures bubble tight valve closing in case of loss of either the command signal or the control power. The valve body is fabricated either from aluminum or stainless steel.

## GAS FUELS

Gas fuels for gas turbines are combustible gases or mixtures of combustible and inert gases with a variety of compositions covering a wide range of heating values and densities. The combustible components can consist of methane and other low molecular weight hydrocarbons, hydrogen, and carbon monoxide. The major inert components are nitrogen, carbon dioxide, and water vapor. It is generally accepted that this type of fuel has to be completely gaseous at the entry to the fuel gas system and at all points downstream to the fuel nozzle (Kurz, 2004; Elliott, et al. 2004).

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 (Newbound, et al. 2003). Typically, the major sources of contaminants within these fuels are:

- Solids
- Water
- Heavy gases present as liquids
- Oils typical of compressor oils
- Hydrogen sulfide ($H_2S$)
- Hydrogen ($H_2$)
- Carbon monoxide (CO)
- Carbon dioxide ($CO_2$)
- Siloxanes

Other factors that will affect turbine or combustion system life and performance include lower heating value (LHV), specific gravity (SG), fuel temperature, and ambient temperature.

Some of these issues may co-exist and be interrelated. For instance, water, heavy gases present as liquids, and leakage of machinery lubricating oils may be a problem for turbine operators at the end of a distribution or branch line or at a low point in a fuel supply line.

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 startup 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)
- 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 the bottom section of the combustor when liquids gravitate towards 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 (Anderson 1980; Meher-Homji, et al. 1998; Newbound and Wagiealla 2003, and Newbound and Al-Showiman 2004).

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.

With a known gas composition, it is possible to predict dew point temperatures for water and hydrocarbons. However, the prediction methods for dew points may not always be accurate. In fact, it is known that different equations of state will yield different calculated dew points under otherwise identical conditions. Furthermore, the temperature in an unheated fuel line will drop, because the pressure drop due to valves and orifices in the fuel line causes a temperature drop in the gas (Figure 2). This effect is known as the Joule-Thompson effect. Most fuel gases (except hydrogen) will exhibit a reduction in temperature during an adiabatic throttling. Hydrogen, on the other hand, actually shows an increased temperature when the pressure drops, which is a potential explosion hazard.

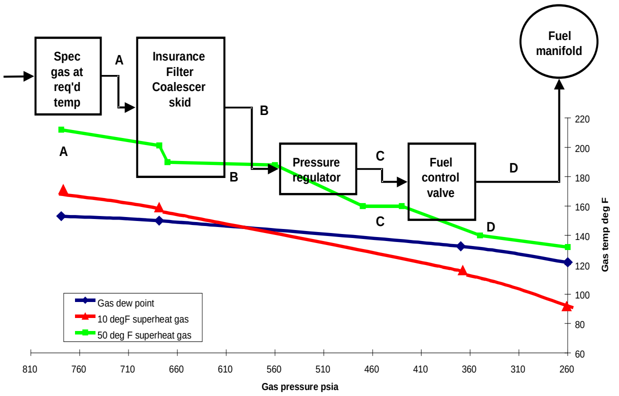


**Figure 2: Schematic of a Gas Fuel System Showing the Pressure Drop in Various Devices. If the Gas is not Superheated Sufficiently, its Temperature Will Eventually Fall Below the Dewpoint Temperature.**

Protection against heavy gases and water present as liquids can be achieved by heating the fuel downstream of knockout drums and coalescing filters (Figure 3). The idea is to have a saturated gas at the exit of the knockout drum and filters and then to raise the temperature to the necessary superheat to prevent subsequent liquid dropout. The system shown in Figure 3 is typical for fuel systems on oil or gas platforms, where the gas produced is usually wet. For dry gas of well-known composition, such as from gas plants or for pipeline applications, a less complex system may be appropriate (Figure 4).

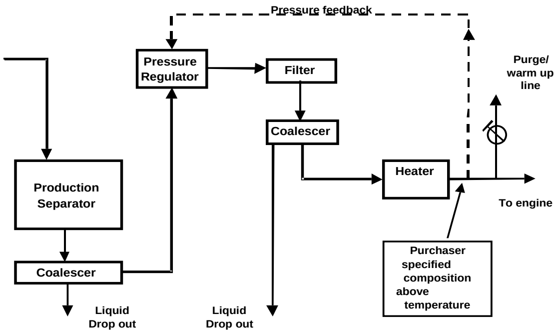


**Figure 3. Schematic of Typical Oil or Gas Platform Fuel Conditioning System**

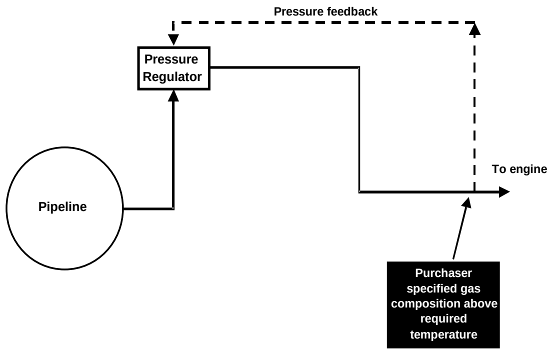


**Figure 4. Schematic of Gas Pipeline Fuel Delivery System with Gas at Greater than Minimum Superheat**

Figure 4 illustrates the necessity for a superheat of about 50°F (28 K) over the dew point to ensure that no liquid dropout appears in the fuel system components downstream of the heater. A superheating requirement of 50°F (28 K) is currently acknowledged as an industry standard. The heat input yielded by a specific gas fuel is determined by the gas composition (including the moisture content), its mass flow, and its heating value. Performance representations for gas turbines are usually based on the lower heating value of the fuel gas, because the exhaust temperatures are always high enough to keep the water vapor in the exhaust from condensing.

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. $C_{14}H_{30}$, even in parts-per-million amounts has a significant impact on the dew point of the gas mixture, as we will show 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.

Lower Heating Value, Specific Gravity, Fuel Temperature, and Ambient Temperature are important parameters since they influence the energy of the fuel flowing in the system. From the lower heating value (LHV) in Btu/scf [kJ/Nm$^3$] and the specific gravity (SG), the Wobbe Index (WI) of the gas can be calculated as:

$$WI = \frac{LHV}{\sqrt{SG}}$$

Because the fuel supply temperature, $T_f$, has an impact on the actual volumetric fuel flow, a temperature corrected Wobbe Index is often used, where the reference Temperature, $T_{ref}$, is usually 520°R or 288K:

$$WI = \frac{LHV}{\sqrt{SG}} \cdot \sqrt{\frac{T_{ref}}{T_f}}$$

If two different fuel gas compositions have the same Wobbe Index, the pressure drop in a given fuel system will be the same for both gases. The Wobbe Index is, thus, an indication of energy flow in the system at the same gas pressures and pressure drops.

A standard fuel system may, for example, be designed for a Wobbe Index of 1220 ±10% Btu/scf (48,031 ±10% kJ/Nm$^3$) based on the LHV of the fuel. Different gas compositions can yield the same Wobbe Index, but they will have widely different hydrocarbon dew points. Minimum engine flameout fuel flows will also vary, if the fuel contains high percentages of noncombustible gases. In addition, high fuel gas or ambient temperatures can cause problems, if the temperature capabilities of elastomeric seals, electrical devices or other system components are exceeded. Low fuel gas or ambient temperatures can cause water or heavy hydrocarbon condensation.

Protection against these factors includes analyzing the variations in the fuel composition, fuel temperature, and ambient temperature so that the required modifications to the fuel treatment system and turbine fuel system can be made. A turbine expected to operate with gaseous fuels exhibiting a wide Wobbe Index range will need to be configured differently than one that will only operate with a small variance in Wobbe Index. The fuel supply contract should include the allowable variations in composition and temperature. The probability of upset conditions needs to be evaluated, and fuel treatment systems and turbine fuel systems need to be designed for the upset conditions. Gas fuel supply and package lines may need to be heat traced to keep the gas fuel supply above the gas dew point during periods when the engine is not operating. Low point drains are also recommended, if liquids may be present in the gas fuel. This precludes burying the gas fuel supply lines underground when liquids may be present.

Gas turbines can be designed to operate on both liquid and gaseous fuels. Many systems allow the switch from gas fuel to liquid fuel and vice versa, under load. Liquid fuel contamination is an important concern, since even liquid fuel that meets the fuel specification can become contaminated during transport and storage. Fuel centrifuges and day tanks help to avoid liquid fuel problems.

### *Lube Oil System*

The package lube oil system consists of a complete system suitable for operation with purchaser-supplied lube oil but must conform to the manufacturer's fuel specifications. The lubrication system circulates oil under pressure to the various working parts of the drive train rotating elements. The system is supplied from the lube oil tank located in the driver steel base frame. Proper oil temperatures are maintained by a thermostatic control valve and an optional oil cooler. A typical lubrication system incorporates the following components:

- Oil tank
- Engine-driven, rotary screw type, primary pump
- Motor-driven auxiliary pumps, including AC pre/post and 120-VDC backup post-lube pump
- Duplex oil filters with replaceable elements
- Off-skid oil cooler
- Oil level, pressure, and temperature indication including engine oil drain temperature
- Pressure and temperature regulators
- Strainers
- Oil tank vent separator
- Oil tank vent flame trap

The filters are supplied with a transfer valve with differential pressure indication and alarm. The system includes all supply and drain piping and manifolds internal to the skid. The interconnect piping between the skid edge connection and the off-skid-mounted oil cooler is not supplied as part of this system. The lube oil filter canisters, tank, covers, and transfer valve are often fabricated from carbon steel and painted, or optionally, manufacturers offer these items in stainless steel. Also, an electric lube oil tank heater is often provided to ensure that lube oil temperature remains sufficiently warm for starting in cold ambient conditions. Because of its significance, lube oil filtration is discussed in more detail below.

### *Unit Control System*

The gas turbine package control system provides for automatic starting, acceleration to operating speed, sequencing control, engine and driven equipment monitoring during operation, and normal and malfunction shutdown. The unit control also acts as the primary machinery protection system. This is discussed in additional detail below in the section on machinery protection.

During operation, the control system, by means of automatic warning and shutdown devices, protects the turbine engine and driven equipment from possible damage resulting from hazards, such as turbine overspeed, high engine temperature or vibration, low lubricating oil pressure, and excessive oil temperature.

The control processor (controller) performs proportional control, startup, operation and shutdown sequencing, and protection functions, as well as detection and annunciation of abnormal operating conditions. Control for these functions comes from signals the controller receives from solid-state devices, control switches, speed, pressure and temperature transmitters, relays, solenoids, and vibration sensors. These components provide the controller with the data necessary to control and maintain desired process conditions, while maintaining engine speed and temperature at safe levels.

In the event of an abnormal condition or malfunction, the control system indicates the nature of the malfunction. When an alarm or shutdown is displayed, a sequence of appropriate operations begins in response to the detected condition. In the event of a control system failure, the backup relay system initiates a shutdown while operating the lubricating oil system and other subsystems, as required, to avoid engine and driven equipment damage during shutdown.

*Vibration and Temperature Monitoring*

Most standard control systems include vibration monitor and associated vibration sensing devices. The system is usually physically and functionally integrated with the control system. The vibration data values are displayed on the vibration monitor and on a dedicated control system vibration summary screen.

Most turbine engines incorporate the following standard vibration and temperature monitoring:

- X and Y proximity probes at each of the five engine bearings and one accessory drive gearbox velocity transducer
- Axial position probes at both the gas producer and power turbine rotors
- RTDs at both the gas producer and power turbine thrust bearings
- Gas producer and power turbine key phasors to provide vibration diagnostic capability with the use of externally applied diagnostic equipment
- RTDs at all turbine lube oil drain lines

The control system can either be mounted off-skid in a remote control room or on-skid directly on the package enclosure. These options are described below:

*On-skid Control System*

The control system components are mounted in one or more panels located on the package skid. These panels contain the key elements of the system, including the control processor, the I/O modules, the vibration monitoring system, and the display unit. The operator interface includes lighted switches for Start/Starting, Normal Stop/Stopping and Backup System Active/Reset and switches for Speed Increase/ Decrease, Off/Local/Aux, Horn Silence, Acknowledge, Reset and Emergency Stop. The Display System provides the following key features:

- *Operation Summary* – Overview of key operation parameters.
- *Temperature Summary* – Display of all monitored temperatures.
- *Vibration Summary* – Display of all vibration readings.
- *Alarm Summary* – Display of all malfunctions with date and time stamping.
- *First Out*– Display of unacknowledged malfunctions in high resolution sequence.
- *Event Log* – Display of date and time stamped sequence of events with sorting and filtering functions.
- *Historical Data* – Stores data surrounding specified events. Data can be played back using the Strip Chart feature.
- *Strip Chart* – Display of real-time data for selected analog signals in strip chart format. Configurable with legend, cursor and zoom features.
- *Program Constants* – Password protected display and modification of controls constant values.
- *Unit Valve Mimic* – Status indication and manual operation of unit valves (compressor sets).

*Off-skid Control System*

In this case, the control system is mounted in a free-standing console for installation in a nonhazardous area. The console contains the same key elements as described above for the on-skid system, but usually more graphic displays, monitoring, and control functionality is available.

*Data Storage and Display*

Data can be viewed in a strip chart format in real time, trended, analyzed on-line, or exported for off-line viewing. All logs are self-describing repositories containing site information, tag information, and the historical data itself. The data can be viewed on-line using the Historical Trend Display. The objective of historical data monitoring is to provide information of a type and in a format that allows informed decisions to be made in the areas of operation, maintenance, and optimization of the turbomachinery and associated equipment. The information is collected for on-line viewing and analysis, it or may be exported for storage and off-line analysis.

Typical data include:

- Driven equipment status
- Gas producer turbine speed
- Power turbine speed
- Turbine control temperature (e.g., T5, power turbine inlet)
- Lube oil header pressure
- Lube oil temperature
- Ambient temperature
- All alarms and shutdowns
- All panel light status

Supervisory control signals include:

- Start
- Stop
- Acknowledge/Reset
- Remote Speed/Load Set Point

*Engine and Compressor Performance Map Display*

The engine performance map displays real-time turbine performance corrected to standard conditions. This is a calculated performance based on package instrumentation readings. These maps are essentially for reference and are used to monitor trends in engine performance and operating point. The compressor map displays real-time compressor nominal head-versus-cfm performance map and shows the position of the actual operating point.

### *Compressor Surge Control*

Anti-surge control is provided to protect the compressor from surge. The system monitors the operating point of the compressor in relation to its surge line and, if conditions require, takes automatic corrective action by opening an anti-surge recycle valve. The system operates based on the position of the operating point and on the rate of change of position. Additional backup protection is provided through an integral surge detection system that will alarm and, if necessary, shut the equipment down, if multiple surge events are detected. The system usually also includes:

- On-screen, real-time graphic display and control parameter setting
- Suction flow differential pressure transmitter
- Suction and discharge pressure transmitters
- Discharge gas temperature RTD

Beyond the simple surge control functionality, most unit control systems can also be utilized for process control of yard valves and other process equipment.

### *Control and Accessory Power Supply*

The control and accessory battery system supplies power for the unit control system, electric fuel valves, engine bleed valve and variable guide vane actuators, and the backup post-lube oil pump. This system is always designed for indoor installation in a nonhazardous area.

### *Axial Compressor Cleaning Systems*

Most modern gas turbines are supplied with both on-line and off-line washing systems. The systems are independent of each other and include separate distribution manifolds with pressure atomizing spray nozzles in the engine air inlet collector and associated on-skid piping, filter, and solenoid operated shutoff valves to deliver water or approved cleaning fluid to the manifold. Both systems facilitate periodic cleaning of the turbine compressor and are designed for use in salt-laden or dusty atmospheres or where compressor contamination from hydrocarbon vapors is possible. The on-line cleaning system is operable between 90 and 100 percent gas producer speed with or without load, with the water/cleaning solution flow activated from the operator interface panel. This system is intended to supplement the on-crank system by increasing the time intervals between periodic on-crank water, detergent, or fluid cleaning, depending on site-specific contamination. The on-crank (off-line system) is operated with the gas turbine shutdown, and the rotor being cranked by the starting motor.

### *Air Inlet System*

The gas turbine's air inlet system typically consists of all components upstream of the engine inlet collector that are necessary to supply a clean, smooth flow of air to the turbine. The inlet air system components, silencers, ducting, and air inlet filter are designed to accommodate the required flow, as specified by the manufacturer. At this flow, the inlet pressure loss should be as low as practical consistent with requirements for cost, air filtration, and acoustical attenuation. Because of its significance, air inlet filtration is discussed in more detail below.

### *Exhaust System*

The turbine exhaust system typically consists of all components downstream of the engine exhaust flexible section that are necessary to ensure a smooth flow of exhaust from the turbine. The turbine exhaust system should be capable of handling the required gas flow as specified by the manufacturer. Pressure losses should be minimized as additional back pressure results in a decrease of available turbine horsepower. The system usually includes attaching hardware (bolts, nuts, washers, and gaskets) for the inlet flange of each component. The turbomachinery package includes attaching hardware for connection of the turbine engine exhaust flexible section to the first exhaust system component.

### *Gas Turbine and Driven Equipment Enclosure*

Although some compressors sets are sold without enclosures (i.e., only skid-mounted) and installed inside a compressor station building, most are delivered with a full sound and weather enclosure for outdoor installation. These all-steel enclosure housings are completely self-contained, weatherproof, insulated, and sound-attenuated enclosure assembled on the turbine package skid base. Figure 5 shows a pipeline compressor installation with a fully enclosed gas turbine and compressor.

**Figure 5. Fully Enclosed Gas Turbine Installation**

The enclosure sides and roof include panels and access doors supported on a heavy-duty frame. The side and roof panels are easily removed individually for complete access to the major components for inspection and maintenance and for component removal by forklift and overhead crane. The panels are treated with fiberglass material for noise attenuation and thermal insulation, and weather stripping is installed between all panels for sealing and sound attenuation. The enclosure is constructed to support adequate roof load (usually 50 lb/sqft) and to withstand a wind load of 120 mph (or more, if specified).

The following standard features are usually included in a basic enclosure:

- *Inlet and exhaust ventilation silencers:* The enclosure ventilation openings are equipped with vent silencers with weather louvers.
- *Single fan ventilation system:* Enclosure ventilation is provided by a single motor-driven fan. This motor is typically 3-phase AC, high efficiency, with Class F insulation. The fan is sized to provide the airflow required to ensure that the internal air temperature around the enclosed equipment remains within acceptable limits. Sometimes, for additional ventilation or certification requirements, a dual fan ventilation system may be required.
- *Pressurization system:* The enclosure is positive pressurized to prevent the ingress of external hazardous atmospheres through the enclosure seams. A differential pressure transmitter is provided for enclosure low pressure alarm and shutdown.
- *AC lighting:* 110-VAC or 220-VAC lights are provided to illuminate the enclosure interior, with on/off switches located at the interface panel.
- *Trolleys:* Internal movable trolley rails located over the turbine for turbine maintenance and removal are included.
- *Door Hardware:* All enclosure doors are equipped with a heavy duty stainless steel door locking mechanism, including handles, hinges, latching mechanism, internal lock override release, restraining device, and attaching hardware. The enclosure doors are equipped with door position switches to initiate an alarm whenever any of the enclosure doors are not securely closed.

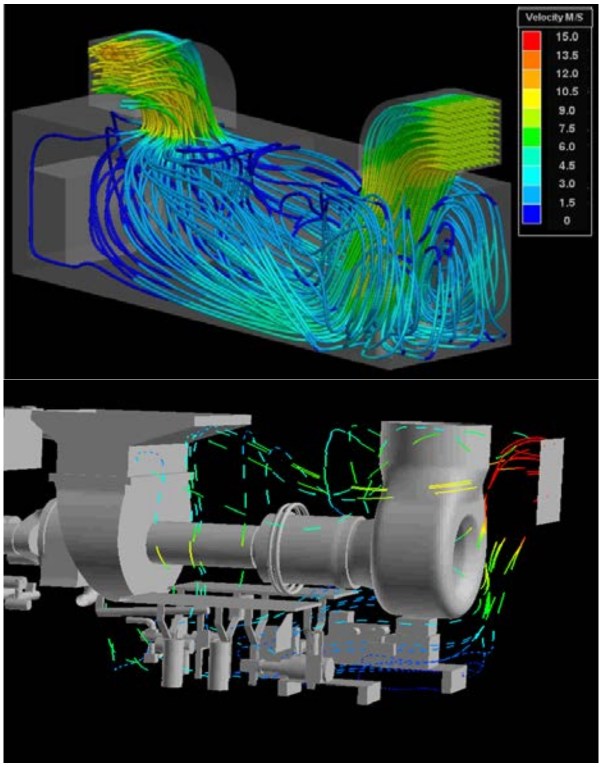


**Figure 6. Analysis of the Air Flow in a Gas Turbine Enclosure**

Computational Fluid Dynamic (CFD) tools are used in both on- and off-shore applications to validate design criteria. Previously, this data was only occasionally requested for off-shore applications. Now, however, it is becoming more of a requirement. We will focus on the application of this tool for the acoustic enclosures. The CFD tool is used to apply the surface temperature to the turbine, understand the temperature distribution within the enclosure, and determine the required flow distribution and proper size of the ventilation fans and motors. Understanding the flow distribution within the enclosure allows the optimization of the package design to minimize stagnant volumes where gas, if present, could be trapped, as well as position package components away from identified hot areas so the component temperature limits are not exceeded. Figure 6 shows the results of a CFD analysis in a sub-scaled test rig. The test rig is used to match the analysis with actual test data to validate the accuracy of the CFD tool. The colored streamlines represent airflow velocity throughout the enclosure with dark blue representing the lowest velocity flow and the light blue, green, and yellow representing progressively higher velocities. This CFD model represents a full size package with all of the major components. The dashed lines represent the flow direction. Again, the dark blue color being the lower velocity air; while green, yellow, and red represent increasing velocities.

Beyond the above described features, manufacturers often provide the following options for the enclosure:

### *Sound Attenuation*

The sound-attenuated enclosure is intended for use with suitable turbine air inlet and exhaust silencing systems in environments where low noise levels are a requirement. Ventilation openings are equipped with suitable silencers to achieve maximum sound attenuation. Sound levels at a specific site will depend on existing walls, barriers, equipment in close proximity, multiple units, and other installation considerations.

### *Enclosure Barrier Filter*

The enclosure ventilation inlet is equipped with a single-stage, disposable, barrier-type filter unit equipped with a delta-P alarm switch. The ventilation exhaust opening is equipped with back-draft dampers to prevent ingress of dust when the unit is not running.

### Fire and Gas Detection and Monitoring System

Usually, an automatic, electronically controlled fire and combustible gas detection and monitoring system is installed in the enclosure. A typical system description is provided below:

The primary fire detection system uses multi-spectrum infrared (MIR) detectors. The system includes an automatic optical integrity feature to provide a continuous check of the optical surfaces, detector sensitivity and electronic circuitry of the detector-controller system, and automatic fault identification with digital display of system status in numerical code. The secondary fire detection system consists of rate-compensated thermal detectors. The two detection methods act independently in detecting and reporting a fire.

The fire and gas system control panel provides system supervision (for open circuit, ground fault, or loss of integrity), initiates alarm, release of fire suppression agent, and visual display of system status. The suppression system agent release is activated automatically with release solenoids located on the fire suppression skid. The suppression system can also be activated by an electrical push button on the turbine enclosure or manually at the suppression skid. If a fire is detected, the detectors transmit an electrical signal to the fire and gas system control panel to activate the fire alarm and suppression system.

The enclosure is equipped with two gas detectors: one at the turbine enclosure ventilation air inlet and one at the ventilation exhaust to provide continuous monitoring for combustible gases at the enclosure ventilation inlet and outlet. The detectors are diffusion-based, point-type infrared devices that provide continuous monitoring of combustible hydrocarbon gas concentrations. The turbine start signal is interlocked with the fire and gas monitoring system to ensure the atmosphere is safe prior to initiating turbine engine start.

Most commonly, the enclosure is equipped with a $CO_2$ fire suppression system consisting of a primary total flooding distribution system and a secondary metered distribution system. In the United States, the system is designed in accordance with the U.S. National Fire Protection Association Code 12.

On detection of fire, the detectors transmit an electrical signal via the fire control panel to activate the fire suppression system release solenoids located on the fire suppression skid. On receipt of this signal, the solenoid actuated control heads activate the discharge valves on the primary and extended extinguishing cylinders, releasing the extinguishing agent into the enclosure. $CO_2$ pressure actuates the pressure trip operated dampers that close all vent openings. $CO_2$ release control heads are also provided with manual release levers.

Additionally, a weatherproof fire suppressant cylinder cabinet is sized to house the $CO_2$ extinguishant cylinders and is equipped with doors for servicing. The manual pull levers are routed, by cable, to break glass pull stations on the exterior wall of the cabinet. $CO_2$ cylinders are mounted on a weight scale with a preset alarm. Another frequently used fire suppression system uses water mist.

### *Equipment Handling System*

An equipment handling system is provided, consisting of external trolley beams and movable chain-fall hoists for removal of major equipment from the package. A trolley beam extension allows turbine removal through the side of the enclosure. One end of the beam extension attaches to the inside trolley rails; the other end is a floor-standing A-frame. The gas turbine or other heavy equipment is then removed through the enclosure side and placed on a truck bed or cart.

The above discussion provided typical package features found on most gas turbines in compression applications.

## MACHINERY PROTECTION

As turbocompressors are complex mechanical devices, they require electronic and mechanic controls as well as instrumentation. A compression station's most expensive assets are the gas turbine, centrifugal compressor, and/or turbo pump. This valuable equipment must be protected from station operational upsets and process excursions. For example, if the fuel constituents into the gas turbine combustion system vary significantly from the design point, liquids may form in the fuel system and combustor damage will likely result. Similarly, a rapid fluctuation in flow can take a compressor into surge, causing catastrophic damage. Clearly, a number of external events can lead to damage to the turbocompressor.

Thus, the gas turbine's unit control system principal design function is to protect the turbocompressor from these types of upsets. However, the unit control system relies on auxiliary measurements (flow, temperature, and pressure) for reaching set alarm points and/or shutdown levels. The unit's control system initiates auxiliary automatic valves (surge, loading, isolation, blowdown, etc.) action to avoid or mitigate a flow upset condition. An off-skid backup battery rack and a battery charger are employed to bring the unit to a safe shutdown upon a significant operational upset. Pressure relief valves are intended to avoid any equipment (and piping) overpressure situation.

If this auxiliary equipment (meters, chargers, batteries, and valves) is not regularly tested, maintained, and calibrated, the unit control system cannot protect the unit. Machinery protection also includes maintaining the air, oil, and fuel flow into the machine to prevent contamination of critical internal parts (bearings, seals, and fuel nozzles). This is accomplished with (self-cleaning) inlet air filters, duplex oil filters, and fuel gas treatment skids (scrubbers, separators, and filters).

The control system of a gas turbine driven compressor, at a minimum, must provide the following functions through the use of a Human Machine Interface (HMI):

- Machinery Monitoring and Protection
  - Equipment startup, shutdown and protective sequencing
  - Stable equipment operation
  - Alarm, shutdown logic
  - Backup (relay) shutdown

- Driven load regulation
  - Fuel/speed control
  - Process control
  - Surge control
  - Communication (SCADA) interface

## FILTRATION

There are usually only three or four utility fluids whose quality can affect a gas turbine's life and performance. These are the lube oil, the combustion fuel, the inlet air, or possible water used for washing or performance enhancement. Thus, on gas turbines, a number of streams must be filtered to protect the machine: air inlet flow, lube oil supply, and fuel gas supply.

### *Inlet Air Filters*

The selection of an inlet filtration system for a new or existing gas turbine installation is often underappreciated and handled as one of the low priority decisions in the overall equipment purchasing process. Considering that the inlet system only constitutes a small fraction of the total purchase price for a gas turbine package, this may appear appropriate.

However, the proper selection of the inlet filtration system can have a substantial impact on the overall life cycle cost of the gas turbine installation. While many operators only consider the filter replacement and sometimes the gas turbine's output power loss associated with the inlet pressure drop in their cost analysis, other factors that can also affect the overall operation and maintenance cost of a plant include downtime associated with off-line water-washing, reduced time-between-overhaul, and startup reliability. All of these can be directly attributed to the filter selection.

A normal mid-size (10 MW) gas turbine ingests about 100 million cubic feet (3 million cubic meters) of air per day. At that rate, even 100 ppb of foulant, such as dirt, oils, or minerals, contained in the airflow, will result in almost one pound of foulant entering the gas turbine per day. Axial compressor fouling due to blade dirt deposits, leading/trailing edge erosion, or surface corrosion, can reduce a gas turbine’s output power and efficiency by up to 20 percent.

**Figure 7. Gas Turbine Filter House**

It is important to realize that there is no universal gas turbine inlet filtration system that is optimal for all applications. Depending on the environmental conditions (arctic, offshore, marine, desert, tropical, urban, or industrial), the filter selection must be customized appropriately for the installation site. This is best done by evaluating the site's local air quality, wind conditions (through air sample testing), upset conditions (such as dust during harvest season in an agricultural area), and defining the desired gas turbine operating profile (including desired uninterrupted operating hours; for instance time between off-line water-wash, filter replacement, and time between overhauls).

Once the application and site conditions are understood, filter system design can begin. A broad range of filter system design considerations, such as number of stages, types of filter stages (barrier, inertial, coalescing, etc.), and inlet filter ducting layout, prevailing inlet orientation, downtime schedules, duty cycles, and more should be reviewed as options are developed. Other, more intrinsic filter properties, such as particulate removal efficiency, loading characteristics, water permeability, and face velocities (high versus low speed), must be considered and analyzed to determine an optimal filter selection. Of special consideration should also be the rain and snow/ice protection design of the inlet filter (usually weather louvers or vane separators or both and inlet heating, if necessary) in order to avoid wetting or icing of the filter surface and subsequent mineral and dirt penetration of the filter screen. Figure 7 shows a typical gas turbine inlet filter housing.

Gas turbines ingest a large amount of ambient air during operation. Because of this, the quality of the air entering the turbine is a significant factor in the performance and life of the gas turbine. A filtration system is used to control the quality of the air by removing harmful contaminants that are present. The selection of the filtration system can be a daunting task, because there are many factors to consider. The system should be selected based on the operational philosophy and goals for the turbine, the contaminants present in the ambient air, and the expected changes in the contaminants in the future due to temporary emission sources or seasonal changes. This tutorial outlines the primary considerations for selecting and installing a gas turbine inlet filtration system. First, the consequences that can occur due to improper inlet filtration are reviewed, then the different characteristics are discussed; after this, the components of a filtration system and considerations for the operating environment are outlined; and lastly, a procedure for quantitatively comparing inlet filtration system options is provided.

## CONSEQUENCES OF POOR INLET FILTRATION

When the quality of the air entering the gas turbine is not well controlled, there are several consequences which can occur. Some of the most common degradation mechanicals are reviewed below, including erosion, fouling, and corrosion. We emphasize the different mechanisms as they directly relate to air filtration.

### *Erosion*

Erosion occurs when solid or liquid particles approximately 10 microns and larger impact rotating or stationary surfaces in the gas turbine. The particles will impact the surface and remove tiny particles of metal, which eventually lead to changes in the geometry of the surface. This change in geometry causes deviations in the air flow path, roughening of smooth surfaces, alteration of clearances, and reduction of cross-sectional areas, possibly in high stressed regions. Erosion is a non-reversible process; therefore, the gas turbine components must be replaced in order to regain their original condition. However, particles of 10 microns and larger are easily removed by commercial filters

*Fouling*

Fouling of compressor blades is an important mechanism leading to performance deterioration in gas turbines over time. Fouling is caused by the adherence of particles to airfoils and annulus surfaces. Particles that cause fouling are typically smaller than 2 to 10 µm. Smoke, oil mists, carbon, and sea salts are common examples. Fouling can be controlled by an appropriate air filtration system, and often reversed to some degree by detergent washing of components. The adherence is impacted by oil or water mists. The result is a buildup of material that causes increased surface roughness and, to some degree, changes the shape of the airfoil (if the material build up forms thicker layers of deposits).Fouling occurs and, in turn, causes a decrease in the performance of the gas turbine.

Commercial filters can remove the majority of particles which cause fouling. But, there are several submicron particles, which are difficult to remove from the flow stream. The buildup of particles not removed by the inlet filtration system is removed with the use of compressor washing. This process recovers a larger portion of the compressor performance, but cannot bring the gas turbine back to its original condition (Wilcox and Kurz 2011)

*Corrosion*

When chemically reactive particles adhere to surfaces in the gas turbine, corrosion can occur. Corrosion that occurs in the compressor section is referred to as “cold corrosion” and is due to wet deposits of salts, acid, and aggressive gases, such as chlorine and sulfides. Corrosion in the combustor and turbine sections is called “hot corrosion.” Also, called high temperature corrosion, hot corrosion requires the interaction of the metal surface with another chemical substance at elevated temperatures. Hot corrosion is a form of accelerated oxidation that is produced by the chemical reaction between a component and molten salts deposited on its surface. Hot corrosion comprises a complex series of chemical reactions, making corrosion rates very difficult to predict. It is the accelerated oxidation of alloys caused by the deposit of salts (e.g., $Na_2SO_4$). Type 1, or high temperature hot corrosion, occurs at a temperature range of 730 to 950°C (1345 to 1740°F). Type 2, or low temperature hot corrosion, occurs at a temperature range of 550 to 730°C (1020 to 1345°F). Some of the more common forms of hot corrosion are sulfidation, nitridation, chlorination, carburization, vanadium, potassium, and lead hot corrosion.

Sulfidation Hot Corrosion requires the interaction of the metal surface with sodium sulfate or potassium sulfate, salts that can form in gas turbines from the reaction of sulfur oxides, water, and sodium chloride (table salt) or potassium chloride, respectively. It is usually divided into Type 1 and Type 2 hot corrosion, and Type 1 hot corrosion takes place above the melting temperature of sodium sulfate (884°C or 1,623°F), while Type 2 occurs below this temperature. Hot corrosion is caused by the diffusion of sulfur from the molten sodium sulfate into the metal substrate which prevents the formation of the protective oxidation film and results in rapid removal of surface metal. One should note that for hot corrosion to occur, both sulfur and salt (e.g., sodium chloride, potassium chloride, or chloride) have to be present in the very hot gas stream in and downstream of the combustor. Sulfur and salt can come from the inlet air, from the fuel, or water (if water is injected).

Corrosion is a non-reversible degradation mechanism. Therefore, corroded components must be replaced in order to regain the original gas turbine performance. Corrosion also initiates or advances other damage mechanisms in the gas turbine. For example, corrosion can intrude into cracks or other material defects and accelerates crack propagation

## FILTRATION CHARACTERISTICS

*Filtration Mechanisms*

Filters in the filtration system use many different mechanisms to remove particles from the air. The filter media, fiber size, packing density of the media, particle size, and electrostatic charge influence how the filter removes particles. Each filter typically has various different mechanisms working together to remove the particles. Four filtration mechanisms are shown in Figure 8.

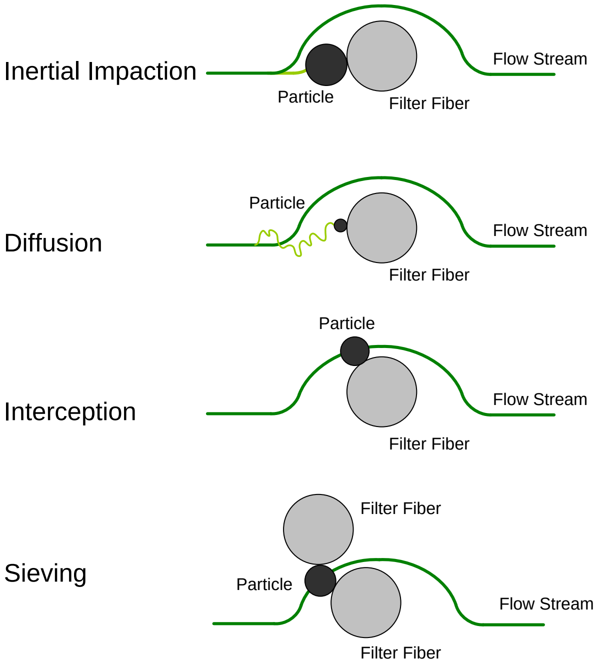


**Figure 8. Common Filtration Mechanism (Kurz and Brun, 2007)**

The first filtration mechanism is inertial impaction. This type of filtration is applicable to particles larger than 1 micron in diameter. The inertia of the large heavy particles in the flow stream causes the particles to continue on a straight path as the flow stream moves around a filter fiber. The particulate then impacts and is attached to the filter media and held in place, as shown in the top picture of Figure 8. This type of filtration mechanism is effective in high velocity filtration systems.

The next filtration mechanism, diffusion, is effective for very small particles, typically less than 0.5 micron in size. Effectiveness increases with lower flow velocities. Small particles interact with nearby particles and gas molecules. Especially in turbulent flow, the path of small particles fluctuates randomly about the main stream flow. As these particles diffuse in the flow stream, they collide with the fiber and are captured. The smaller a particle and the lower the flow rate through the filter media, the higher probability that the particle will be captured.

The next two filtration mechanisms are the most well-known; interception and sieving. Interception occurs with medium-sized particles that are not large enough to leave the flow path due to inertia or not small enough to diffuse. The particles will follow the flow stream where they will touch a fiber in the filter media and be trapped and held. Sieving is the situation where the space between the filter fibers is smaller than the particle itself, which causes the particle to be captured and contained.

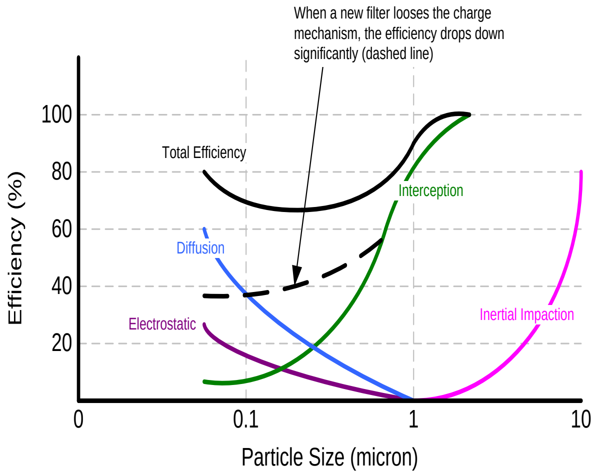


**Figure 9. Combination of Filtration Mechanisms to Obtain Filter Efficiency at Various Particle Sizes (Kurz and Brun, 2007)**

Another mechanism not shown in Figure 8 is electrostatic charge. This type of filtration is effective for particles in the 0.01 to 2 micron size range (Figure 9). The filter works through the attraction of particles to a charged filter. In gas turbine applications, this charge is applied to the filter before installation as a result of the manufacturing process. Filters always lose their electrostatic charge over time because the particles captured on their surface occupy charged sites, therefore, neutralizing their electrostatic charge. As the charge is lost, the filter efficiency for small particles will decrease. On the other hand, as the filter is loaded, the filtration efficiency increases, thus, counteracting the effect of the lost charge to some extent. This will offset some of the loss of filtration efficiency due to the lost charge. Figure 9 shows a comparison of a filter's total efficiency based on the various filtration mechanisms that are applied. The figure shows the difference between the filter's efficiency curve before and after the charge is lost. The performance of the filter should be based on the discharged condition.

*Filter Efficiency and Classification*

Filter efficiency is a broad term. In general, the filter efficiency is the ratio of the weight, volume, area, or number of particles entering the filter to the weight, volume, area, or number of the particles captured in the filter and ratings, respectively. A general efficiency calculation is shown in below equation, where $W$ is the variable for which efficiency is being calculated. The efficiency can be expressed in several ways: maximum, minimum, or average lifetime value. Many filters have poor performance against small particles at the beginning of their lives, but as the filter media becomes loaded with particles, it is able to catch smaller particles. In this case, the average efficiency would actually be higher than the initial efficiency. Some of the filters will never reach the quoted maximum efficiency before they are replaced.

$$\eta = \frac{W_{entering} - W_{leaving}}{W_{entering}} * 100\%$$

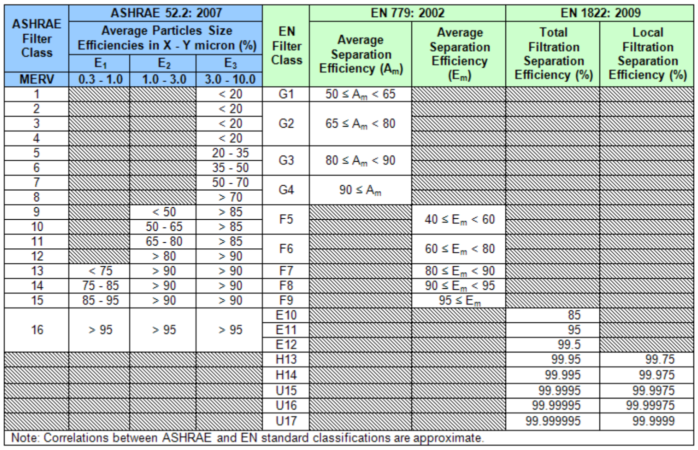
Filter efficiency is a trade-off against the pressure loss across the filter. Normally, the filtration system pressure loss will increase with an increase in filtration efficiency. As filters become more efficient, less dust penetrates through them. Also, the air flow path is more constricted with higher efficiency filters. This leads to higher pressure loss. Filter engineers must determine the acceptable pressure loss and efficiency for their application. Studies have shown that a higher pressure loss due to using a high efficiency filter has a lower effect on gas turbine power degradation than poor inlet air quality.

The efficiency of a filter cannot be stated as a general characteristic. The filter efficiencies vary with particle size, typically being lower for small particles and higher for large particles. They also vary with operational velocity. Filters designed for medium and low velocities will have a poor performance at higher velocities and vice versa. Therefore, a particle size range and flow velocity must be associated with the stated efficiency. For example, a filter may have 95 percent filtration efficiency for particles greater than 5 microns at a volumetric flow rate of 3,000 cfm, but the efficiency could be reduced to less than 70 percent for particles less than 5 microns or at a volumetric flow rate of 4,000 cfm.

Filters are rated for performance based on standards established in the United States of America and Europe. These filter ratings are based on the results of standard performance tests. In the United States, ASHRAE standard 52.2-2007 outlines the requirements for performance tests and the methodology to calculate the efficiencies. In this standard, the efficiencies are determined for various ranges of particles sizes. The filter is given a Minimum Efficiency Reporting Value (MERV) rating based on its performance on the particle size ranges (particle count efficiency) and the weight arrestance (weight efficiency). The weight arrestance is a comparison of the weight of the dust penetrating the filter to the dust feed into the flow stream. In this standard, a filter with a MERV of 10 will have 50 to 65 percent minimum efficiency for particles 1–3 microns in size and greater than 85 percent for particles 3–10 microns in size.

The European standards used to determine performance are EN 779:2002 and EN 1822:2009. The EN 779:2002 is used to rate coarse and fine efficiency filters. The EN 1822:2009 presents a methodology for determining the performance of high efficiency filters: Efficient Particulate Air filter (EPA), High Efficiency Particulate Air filter (HEPA), and Ultra Low Particle Air filter (ULPA). In EN 779:2002, the performance is found with average separation efficiency, which is an average of the removal efficiency of 0.3 micron particles at four test flow rates (particle count efficiency) for fine filters and with an average arrestance (weight efficiency) for coarse particle filters. This standard rates the filters with a letter and number designation: G1–G4 (coarse filters) and F5–F9 (fine filters). Filter performance is determined by the Most Penetrating Particle Size efficiency (MPPS) in EN 1822:2009. The MPPS is defined as the particle size, which has the minimum filtration efficiency or maximum penetration during the filter testing. The particle sizes tested range from 0.15 to 0.3 microns. The filter efficiency is calculated based on particle count. These filters are given a rating of E10–E12 for EPA type filters, H13–H14 for HEPA type filters, and U15–U17 for ULPA filters. Table 1 gives a general overview of the efficiencies for each filter rating and a comparison of the filter ratings between American and European standards.

**Table 1. Summary of Filter Classification for ASHRAE 52.2:2007, EN 779:2002, and EN 1822:2009**



| ASHRAE Filter Class | ASHRAE 52.2: 2007 | | | EN Filter Class | EN 779: 2002 | | EN 1822: 2009 | |
|---|---|---|---|---|---|---|---|---|
| | Average Particles Size Efficiencies in X - Y micron (%) | | | | Average Separation Efficiency ($A_m$) | Average Separation Efficiency ($E_m$) | Total Filtration Separation Efficiency (%) | Local Filtration Separation Efficiency (%) |
| | $E_1$ | $E_2$ | $E_3$ | | | | | |
| MERV | 0.3 - 1.0 | 1.0 - 3.0 | 3.0 - 10.0 | | | | | |
| 1 | | | < 20 | G1 | $50 \leq A_m < 65$ | | | |
| 2 | | | < 20 | G2 | $65 \leq A_m < 80$ | | | |
| 3 | | | < 20 | | | | | |
| 4 | | | < 20 | | | | | |
| 5 | | | 20 - 35 | G3 | $80 \leq A_m < 90$ | | | |
| 6 | | | 35 - 50 | | | | | |
| 7 | | | 50 - 70 | G4 | $90 \leq A_m$ | | | |
| 8 | | | > 70 | | | | | |
| 9 | | < 50 | > 85 | F5 | | $40 \leq E_m < 60$ | | |
| 10 | | 50 - 65 | > 85 | | | | | |
| 11 | | 65 - 80 | > 85 | F6 | | $60 \leq E_m < 80$ | | |
| 12 | | > 80 | > 90 | | | | | |
| 13 | < 75 | > 90 | > 90 | F7 | | $80 \leq E_m < 90$ | | |
| 14 | 75 - 85 | > 90 | > 90 | F8 | | $90 \leq E_m < 95$ | | |
| 15 | 85 - 95 | > 90 | > 90 | F9 | | $95 \leq E_m$ | | |
| 16 | > 95 | > 95 | > 95 | E10 | | | 85 | |
| | | | | E11 | | | 95 | |
| | | | | E12 | | | 99.5 | |
| | | | | H13 | | | 99.95 | 99.75 |
| | | | | H14 | | | 99.995 | 99.975 |
| | | | | U15 | | | 99.9995 | 99.9975 |
| | | | | U16 | | | 99.99995 | 99.99975 |
| | | | | U17 | | | 99.999995 | 99.9999 |

Note: Correlations between ASHRAE and EN standard classifications are approximate.

If an engine ingests 100 kg/year of contaminants, if there were no filtration system in a typical off-shore application, an F5[5] filter would reduce this to about 21 kg/year, an F6[1] filter to 6 kg/year, an F7/H10[1] filter system to 0.2 kg/year and an F7/F9/H10[1] system to as little as 0.05 kg/year.

This indicates two conclusions:

- While large particles have a significant impact on fouling degradation, a significant amount is due to the finer particles.
- The overall contaminant ingestion can be influenced by several orders of magnitude by using an appropriate air filtration system. Also, with filtration systems of this type, there are virtually no particles larger than a few microns entering the engine

### *Filter Pressure Loss*

As mentioned above, a higher pressure loss occurs with a more efficient filter due to air flow restrictions. Pressure loss has a direct impact on the gas turbine performance, as it causes a reduction in compressor inlet pressure. For the compressor to overcome the inlet system losses, the gas turbine will consume more fuel, and it also has a reduced power output. As the pressure loss increases, the power decreases and the heat rate increases linearly. A 50 Pa (0.2 in$H_2O$) reduction of pressure loss can result in a 0.1 percent improvement in power output. Typical pressure losses on inlet filtration systems can range from 2 to 6 in$H_2O$

The filter's performance needs to be assessed for the full pressure loss range over its life, not just when it is new. The pressure loss will increase over the lifetime of the filter. Therefore, one can expect a lower gas turbine performance over the life of the filter, or filters have to be changed or cleaned periodically in order to maintain a low pressure loss. The change of pressure loss over time is highly dependent upon the filter selection and the type and amount of contaminants experienced.

### *Filter Loading (Surface or Depth)*

During operation, as the filter collects particles, it is slowly loaded until it reaches a "full" state. This state is usually defined as the filter reaching a specified pressure loss or at the end of maintenance interval. Filters are loaded in two different ways: surface and depth loading.

Depth loading is the type of filtration where the particles are captured inside of the filter material. To regain the original pressure loss or condition, the filter must be replaced.

The other type of filter is a surface loaded filter. With this type of loading, the particles collect on the surface of the filter. Few of the particles may penetrate the fiber material, but not enough to call for a replacement of the filter. Surface loaded filters are most commonly used in, but not restricted to, self-cleaning systems, because the dust can easily be removed with pulses of air once the filter differential pressure reaches a certain level. Once the filter is cleaned, the pressure loss across the filter will be close to its original condition. The surface loaded filter's efficiency actually increases as the surface is loaded with dust, because a dust cake develops on the surface of the media, creating an additional filtration layer and also decreases the amount of available flow area in the filter media

### *Face Velocity*

Filtration systems are distinctively classified as high, medium, or low velocity systems. The velocity of the filtration system is defined as the actual volumetric air flow divided by the total filter face area. Low velocity systems have air flow at less than 500 fpm (feet per minute) (2.54 m/s) at the filter face. Medium velocities are in the range of 610 to 680 fpm (3.1 to 3.45 m/s). High velocity systems have air flows at the filter face in excess of 780 fpm (4 m/s).

#### *High Velocity Systems*

Historically, high velocity systems are used on marine vessels and off-shore platforms where space and weight are premiums. However, currently, low, medium, and high velocity systems are found on marine and off-shore applications. High velocity systems have the advantages of reduced size (cross-sectional area), weight, and initial cost. Filter efficiencies for

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[5] Per EN 779

small particles are significantly lower than those of lower velocity systems, and dust holding capacities are lower.

High velocity systems typically use vane separators upstream and, often, also downstream of the filter media to remove water from the air stream. For the vanes to work effectively, higher flow velocities are necessary.

Ultimately, this type of system requires more filter replacements when compared to the lower velocity system of similar performance.

*Low Velocity Systems*

Low velocity systems are the standard on land-based applications; however, high velocity systems are also used in some coastal applications. The low velocity systems are characterized by large inlet surface areas, large filter housings, and usually multiple stages of filters. The two- or three-stage filters provide an advantage over high velocity systems, because they have a high efficiency filter stage as the final stage to remove many small particles (especially salt) below 1 micron. Recently, developed filter media can also keep water from penetrating the media and, thus, entering the gas turbine. The lower velocity also provides a lower pressure loss or higher filtration efficiency. Using pre-filters to remove the majority of the particles, the life of the high efficiency filters is extended. Overall, low velocity systems can be more effective at reducing the mass of contaminants which enter a system, thus, extending the water wash intervals for the engine.

*Water and Salt Effects*

Many environments where gas turbines operate will have wet ambient conditions. This could be in a tropical environment where it rains a significant amount of time or a coastal location with ocean or lake mist. The difference between filter operation in wet and dry conditions can be significant. In some cases, the pressure loss across a filter can increase significantly, even with a little moisture. This is true for cellulose fiber filters, which swell when they are wet. These filters will also retain the moisture, which can lead to long periods of time when the pressure loss across the filter is elevated.

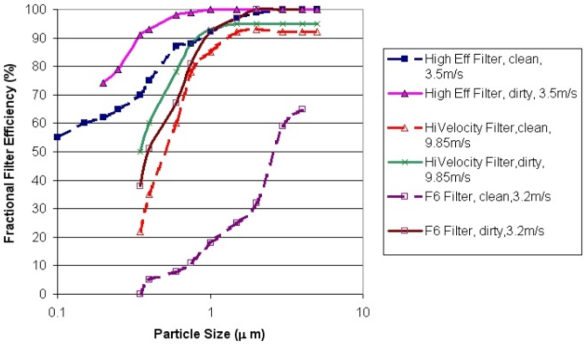

**Figure 10. Comparison of Fractional Efficiency for Filter Elements from Different Suppliers and Different Face Velocities in New and Dirty Conditions (Kurz and Brun, 2012)**

Salt can have a direct effect on the life of a gas turbine, if not removed properly. It is often carried into the engine dissolved in water spray. Salt can lead to fouling and corrosion. Gas turbine manufacturers usually recommend stringent criteria on the amount of salt that can be allowed to enter the gas turbine (less than 0.01 ppm). In coastal environments, the airborne salt can easily range from 0.05 to 0.5 ppm on a typical day. If the filtration system is not equipped to handle the salt, it can enter the compressor and the hot section of the gas turbine. Salt is present in the air either as salt dust or dissolved in seawater and contains sodium chloride, magnesium chloride, and calcium sulfate. Salt may also come from localized sources, such as a dry salt bed. The salt on compressor blades must be removed through water washing methods or direct scrubbing of the blades.

## COMPONENTS OF A FILTRATION SYSTEM

In order to protect the gas turbine from the variety of contaminants present in the ambient air, several filtration devices are used. Each of the devices used in modern filtration systems are discussed below (Wilcox et al, 2011).

*Weather Protection and Trash Screens*

Weather louvers, or hoods, and trash screens are the most simplistic of the filtration mechanisms, but they are important in order to reduce the amount of moisture and particles that enter the main filtration system. These are not classified as filters, but they are part of the filtration system and provide assistance in removal of large objects or particles carried in the flow stream.

Weather hoods are sheet metal coverings on the entrance of the filtration system (see Figure 11). The opening of the hood is pointed downward so the ambient air must turn upwards to flow into the inlet filtration system. The turning of the air is effective at minimizing rain and snow penetration. Weather hoods and louvers are used on the majority of inlet filtration systems, and they are essential for systems in areas with large amounts of rainfall or snow. Weather hoods, or another comparable weather protection system, are strongly recommended for all systems with high efficiency filter.

**Figure 11. Weather Hood on inlet Filtration System**

Next to the weather hood is a series of turning vanes called weather louvers that redirect the air so that it must turn. The weather louvers are also effective at minimizing water and snow penetration. Also next to the weather hood, or louver, is a trash or insect screen. Trash screens capture large pieces of paper, cardboard, bags, and other objects. The screens deflect birds, leaves, and insects. Screens that are installed specifically for preventing insects from entering the filtration system are referred to as insect screens. These screens will have a finer grid than trash screens. Weather hoods, louvers, trash screens, and insect screens are used on the majority of filtration systems due to their inexpensive cost and construction, and negligible pressure loss.

*Anti-Icing Protection*

Anti-icing protection is used in climates with freezing weather. Freezing climates with rain or snow can cause icing of inlet components that can result in physical damage to inlet ducts or to the gas turbine compressor. This ice can also affect the performance of the gas turbine. If ice forms on filter elements, then ice on those filters will be blocking the flow path, which will cause the velocity at the other filters to increase. This causes a decrease in filtration efficiency. Also, the filter elements with ice can be damaged. Figure 12 shows an example of ice formation on filters due to cooling tower drift. Heaters or compressor bleed air are often used in the inlet system in frigid environments to prevent the moisture in the air from freezing on the inlet bell mouth or filter elements.

**Figure 12. Cartridge Filters with Frost Buildup Due to Cooling Tower Drift**

*Inertial Separators*

Inertial separation takes advantage of the physical principles of momentum, gravity, centrifugal forces, and impingement, and the physical difference between phases to cause particles to be moved out of the gas stream in such a way that they can be carried off or drained. The higher momentum of the dust or water particles contained in the air stream causes them to travel forward, while the air can be diverted to side ports and exit by a different path than the dust. There are many types of inertial separators, but the ones commonly used with gas turbine inlet filtration are vane and cyclone separators

*Moisture Coalescers*

In environments with high concentration of liquid moisture in the air, coalescers are required in order to remove the liquid moisture. The coalescer works by catching the small water droplets in its fibers. As the particles are captured, they combine with other particles to make larger water droplets. Coalescers are designed to allow the droplets to either drain down the filter or be released back into the flow stream. If the larger drops are released, then they are captured downstream by a separator. Figure 13 shows an example of how the droplet size distribution changes across the coalescer that releases the droplets.

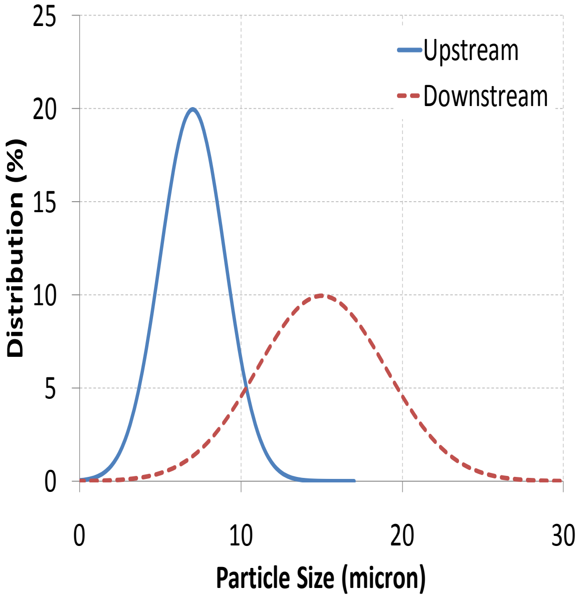

**Figure 13. Coalescer Droplet Formation Distribution (Wilcox et al, 2011)**

*Prefilters*

The air has a mixture of large and small particles. If a one-stage high efficiency filter is used, the buildup of large and small solid particles can quickly lead to increased pressure loss and filter loading. Prefilters are used to increase the life of the downstream high efficiency filter by capturing the larger solid particles. Therefore, the high efficiency filter only has to remove the smaller particles from the air stream, which increases the filter life. Prefilters normally capture solid particles greater than 10 microns, but some prefilters will also capture the solid particles in the 2–5 micron size range. These filters usually consist of a large diameter synthetic fiber in a disposable frame structure. Bag filters are also commonly used for prefilters. These offer a higher surface area, which reduces the pressure loss across the filter. In many installations, the prefilters can be exchanged without having to shut the engine down.

*High Efficiency Filters*

As discussed above, there are filters for removing larger solid particles that prevent erosion and FOD. Smaller particles, which lead to corrosion, fouling, and cooling passage plugging, are removed with high efficiency filters. These types of filters have average separations greater than 80 percent. Three common types of high efficiency filters are EPA, HEPA and ULPA. EPA and HEPA filters are defined as having a minimum efficiency of 85 percent and 99.95 percent, respectively, for all particles greater than or equal to 0.3 microns. ULPA filters have a minimum efficiency of 99.9995 percent for particles the same size or larger than 0.12 microns. Often, these names are used loosely with the discussion of high efficiency filtration. However, the majority of the high efficiency filters used in gas turbine inlet filtration does not meet these requirements.

The high efficiency filters used with gas turbines have pleated media, which increases the surface area. In order to achieve the high filtration efficiency, the flow through the filter fiber is highly restricted, which creates a high pressure loss, unless the face velocity is kept low. The pleats help reduce this pressure loss. Initial pressure loss on high efficiency filters can be up to 1 inH$_2$O with a final pressure loss in the range of 2.5 inH$_2$O for rectangular filters and 4 inH$_2$O for cartridge filters. The life of the filters is highly influenced by other forms of filtration upstream. If there are stages of filtration to remove larger solid articles and liquid moisture, then these filters will have a longer life. Minimal filtration before high efficiency filters will lead to more frequent replacement or cleaning. High efficiency filters are rated under various standards. The majority of filters used in gas turbines are not classified as EPA, HEPA, or ULPA. The filters used in gas turbines are rated with ASHRAE 52.2:2007 and EN 779:2002.

There are many different constructions of high efficiency type filters: rectangular, cylindrical/cartridge, and bag filters. The rectangular high efficiency filters are constructed by folding a continuous sheet of media into closely spaced pleats in a rectangular rigid frame. Rectangular filters are depth loaded; therefore, once they reach the maximum allowable pressure loss, they should be replaced. Two examples of rectangular high efficiency filters are shown in Figure 14. High efficiency filters can also be made from media that does not allow water to seep through the filter media.

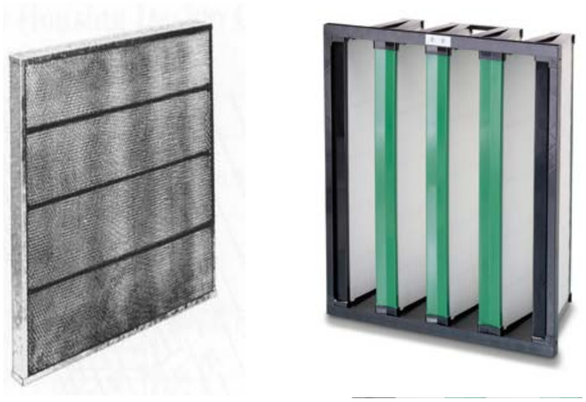

**Figure 14. Rectangular High Efficiency Filters**

Cartridge filters are also made up of closely spaced pleats, but they are in a circular fashion (Figure 15). Air flows radially into the cartridge. They are installed in a horizontal or vertical fashion (hanging downward). These types of filters can be depth or surface loaded. The surface loaded filters are commonly used with a self-cleaning system, but not all of them are designed for self-cleaning. Cartridge filters used in self-cleaning systems require a more robust structural design in order to protect the filter fiber media during the reverse air pulses. The more common structural support is a wire cage around the pleated media on the inside and outside of the filter. The filters shown in Figure 15 are not designed for a self-cleaning system since there are no structural supports on the outside of the filter. Self-cleaning filtration systems are discussed in the next section.

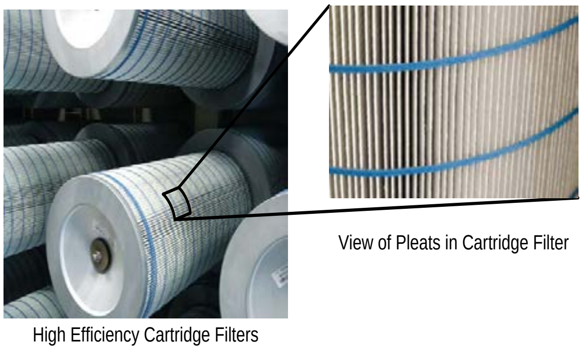

**Figure 15. High Efficiency Cartridge Filters**

### *Self-Cleaning Filters*

All of the filters with fiber type media previously discussed are required to be replaced once they reach the end of their usable life. In some environments, the amount of particles can be excessive to the point where the filters previously discussed would have to be replaced frequently to meet the filtration demand. A prime example of one of these environments is a desert with sand storms. In the 1970s, the self-cleaning filtration system was developed for the Middle East where gas turbines are subject to frequent stand storms. Since then, this system has been continually developed and utilized for gas turbine inlet air filtration.

The self-cleaning system operates primarily with surface loaded high efficiency cartridge filters. The surface loading allows for easy removal of the dust that has accumulated with reverse pulses of air (Figure 15). The pressure loss across each filter is continuously monitored. Once the pressure loss reaches a certain level, the filter is cleaned with air pulses. The pressure of the air pulses ranges from 80 to 100 psig. The reverse jet of compressed air (or pulse) occurs for a length of time between 100 and 200 ms. To avoid disturbing the flow and to limit the need for compressed air, the system typically only pulses 10 percent of the elements at a given time. With this type of cleaning (see Figure 16), the filter can be brought back to near the original condition

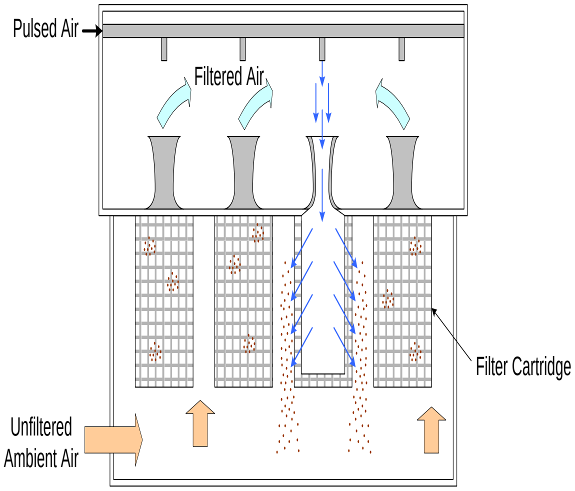

**Figure 16. Example of Operation of an Updraft Self-Cleaning Filters**

### *Staged Filtration*

Any gas turbine application typically needs more than one type of filter, and there are no “universal filters” that will serve all needs. Therefore, two-stage or three-stage filtration systems are used. In these designs, a prefilter, or weather louver, can be used first to remove erosive particles, rain, and snow. The second may be a low to medium performance filter selected for the type of finer-sized particles present or a coalescer to remove liquids. The third filter is usually a high-performance filter to remove smaller particles less than 2 microns in size from the air. Figure 17 shows a generalized view of a filtration arrangement. This arrangement is not correct for all cases due to the fact that the filter stages are highly influenced by the environment they are operating in.

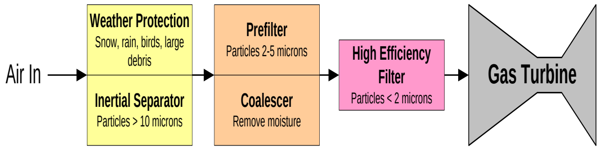

**Figure 17. Multi-Stage Filtration System**

### *Lube Oil Filtration*

Contamination, such as particles, water, and process fluids in lubricant streams can lead to increased maintenance costs and reduce equipment service life on lubrication systems, such as the turbine bearing lube and hydraulic control systems. Gas turbine manufacturers have very strict guidelines for lube oil quality, and failure to maintain the lube oil to these standards is often sufficient reason for manufacturers to disclaim their warranty obligations.

Most modern gas turbines employ duplex lube oil filters with a continuous flow transfer valve. The media inside these filters can range from paper cardboard to synthetic matrix fibers. Multi-layer filter cartridges with a high flow, high efficiency media are typically provided by the manufacturer when the units are shipped. Special care should be taken to follow the manufacturer’s recommendations when replacing the original filters with third-party filters. Differential pressure transducers to monitor the pressure drop across the filter media should also be mounted with electronic signals and alarms to the unit control system for trending purposes.

## FUEL GAS HEATING

Fuel gas heating is generally employed to ensure that the fuel that enters the gas turbine is in entirely the gaseous state. To ensure that the fuel gas does not develop liquid drop-out as a result of the ubiquitous pressure drop in the fuel system, it has to be superheated to (typically) 28°C (50°F) above its dew point. However, the natural gas’ dew point is a strong function of its hydrocarbon composition; the higher the percentage of heavy hydrocarbons in the fuel, the higher the dew point. Consequently, swings in the composition of the natural gas supplied from the producer fields can easily move the average dew point of the gas significantly. If the fuel constituents into the gas turbine combustion system vary significantly from the design point, liquids may form in the gas turbine’s fuel system and combustor damage will rapidly result.

To ensure that a gas turbine’s fuel is free from liquids, a fuel heating system can be employed. A fuel heating system should be directly interfaced with either the unit control system or the station control system to maintain the fuel gas temperature constant above the dew point and to be automatically activated during significant fuel quality swings. Also, electric heat tracing of the fuel supply lines, rather than natural gas burners, is a safer and more controllable means to maintain the fuel gas temperature.

## MOTOR CONTROL CENTER

Motor Control Centers (MCC) provide the best method for grouping motor control, associated control, and distribution equipment. They provide a convenient, centralized means of protecting and controlling all of a facility’s motor loads. Motor control centers can be outfitted with a large number of electrical devices including solid state reduced voltage starters, AC adjustable speed drives, meters, programmable logic controllers, control relays, TVSS devices, lighting panel boards, distribution panel boards, distribution transformers, power management control systems, equipment ground fault protection, and spectra RMS circuit breakers.

## PACKAGE UTILITY REQUIREMENTS

For a typical mid-size gas turbine driven compressor set (7 MW), a list of the package utility requirements are provided in Table 2. It is important to understand that these utilities must usually be provided by the operator.

**Table 2. Typical Set of Package Utility Requirements**

| Device | Requirement |
|---|---|
| Starter Motor Drive | AC |
| Pre/Post Lube Oil Pump | AC |
| Lube Oil Cooler Motor | AC |
| Enclosure Ventilation System | AC |
| Lube Oil Tank Immersion Heater | AC |
| Enclosure Lighting | AC |
| Battery Charger | AC |
| Space Heaters | AC |
| Back Up Lube Oil Pump | DC |
| Gas Fuel Control Valve | DC |
| Bleed Valve and Guide Vane Actuators | DC |
| Control System/Control Console | DC |
| Air Inlet Self Cleaning Filter | Compressed Air |

Clearly, this list of utility supply requirement varies significantly depending on the application, operation, and equipment utilized. Additionally, the unit will also require a fill of the lube oil tank (typically between 1,000–2,000 gallons depending on the unit and driven equipment design) and may require clean water for inlet fogging, compressor water-wash, or combustor injection.

*Off-shore Applications*

Gas turbines are preferred prime movers for power generation, as well as drivers for compressors and pumps for off-shore installations. Many off-shore projects, especially in deep waters, use Floating Production Storage and Offloading systems (FPSO) as the equipment platform (see Figure 18). This type of system, as well as semi-submersible platforms, SPAR's, and TLP's, exhibit significant deck movement as a result of wave and wind action, as well as possible deck deflections. This requires specific design considerations for the turbomachinery packages employed to achieve the highest possible availability and reliability. There are various types of structures used for oil and gas exploration and production, either bottom supported structures and vertically moored structures [Fixed Leg Platform (FLP), Compliant Tower (CT), Tension Leg Platform (TLP) and Mini Tension Leg Platform (Mini TLP)] and the Floating Production and Sub-Sea category consisting of Spar, Semi-Submersible (SS) and Floating Production Storage and Off-loading (FPSO).

Off-shore platforms and Floating Production Systems perform complex operations in a compact space. As a result, there is a high value placed on the installed size of off-shore equipment. In addition to the installed footprint, successful design for operation in off-shore applications must address a variety of load cases. A prime initiator of many of these load cases is the environment. Wind and its resulting effects are key contributors to sea conditions causing wide variations from the relatively calm condition to the very severe condition as evidenced, for example, in the Gulf of Mexico during hurricane Katrina. At one stage, a Category 5 hurricane, Katrina ultimately made landfall in Louisiana and Mississippi, at Category 4 strength.

**Figure 18. Gas Turbine Installation on an FPSO**

In addition to considering the effects of the environment, code compliance to assure safe, reliable equipment, also has a role to play. The framework of directives and standards, such as ATEX and CSA, are one piece of the puzzle. There are other international, national, and local rules and regulations that must also be satisfied. These other rules and regulations are represented by two groupings of authority. International Authority, represented by an International Class Society, may represent a country's government's interest and also have the capability to enforce the laws. Additionally, each country may have a local authority. In the United States, the USCG Code of Federal Regulations (CFR) serves this function. Each Class Society has individually developed rules for building and classification of vessels. Depending on the type of machinery, and its usage, several options are available.

These rules will play a significant role in verifying the motion criteria to be used in the design effort. There are two major classifications for off-shore machinery: the "Main & Auxiliary Classification" applies to equipment that is essential to propulsion, vessel safety, utilities for deck support equipment and direct operation of the vessel, while the "Emergency Service Classification" applies to equipment used as a separate source of power for emergency duty. The support of the steering gear and fire-fighting equipment are two such examples. Generator sets fall into both classifications; however, Solar supplies only Main & Auxiliary generators that can only be used for Oil and Gas process electrical power. For example, using the "DNV Rules for Classification of Ships," each of Solar's gas turbines used in Oil and Gas applications, are supported by a DNV Type Approval Certificate. Renewed every 4 years through a detailed design assessment and type testing, the Type Approval provides documentation that all of the applicable codes, regulations, and rules have been met. A secondary benefit to receiving a Class Society Type Approval is the acknowledgement by that Class Society that the manufacturer is committed to quality and has a proven Quality System.

When designing to meet code requirements, an internal process known as a Task Risk Assessment, or TRA, may be performed. The TRA identifies potential effects of the requirement, so appropriate action can be taken if required. With this overview of the types of vessels, the environment, and the need to satisfy applicable codes and standards, we can now move into a discussion of designing packages to meet these challenges.

**Figure 19. Degrees-of-Freedom for Dynamic Movement and Static Displacement**

*Package Requirements*

Each of the criteria plays an important role in off-shore design and, as such, cannot be addressed independently of one another. Unlike a land-based application, all six degrees-of-freedom are considered when designing the machinery for floating applications (Figure 19). It is critical to understand the applicable class requirement, the type of vessel, the expected deck deflection, and where the equipment will be located on the vessel.

This information is then translated into the design conditions of:

- Type of mounting method used to attach the package to the deck
- Acceleration for structural analysis
- Static and dynamic angles for fluid management

Wind and Wave action causes stresses and deflections in the Floating Production System, resulting in hogging, sagging and twisting of the vessel's hull. Apart from the external connections between the package and site interfaces, the machine's drive train alignment requires close attention.

Figure 20a helps illustrate how, if not properly addressed, the effect of the deck deflection can translate through the base-plate and compromise the machinery's alignment.

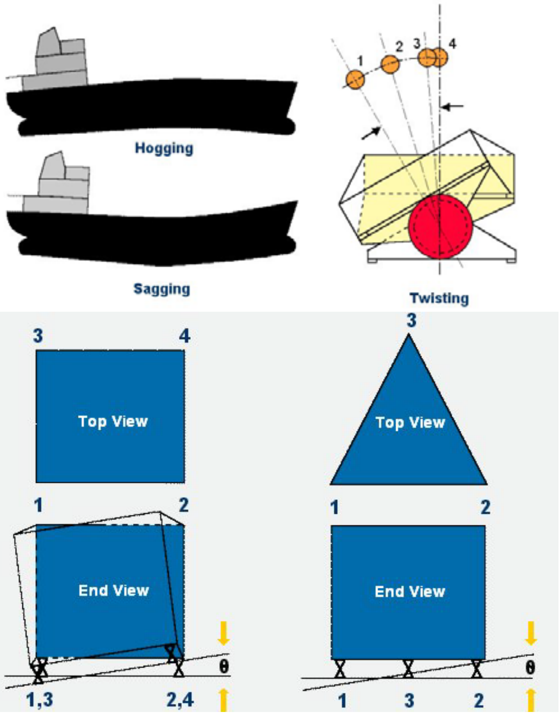

**Figure 20(a). Deck Deflections and (b) Their Impact on a Turbomachinery Package for 4-Point and 3-Point Mounts**

Not enough stiffness in the machinery's supporting structure, or improper attachment to the deck, can result in unwanted vibration levels. Illustrated in Figure 20b are two methods of attaching a turbine package to a vessel's deck. The four-point tie-down graphic on the left does not decouple the vessel's structural deflections from the package. Although acceptable under certain conditions, in this mounting arrangement, the package will see more of an effect from deck twist. On the other hand, the three-point tie-down graphic on the right allows the vessel's structural deflections to become decoupled from the package. With less effect from deck twist being transmitted to the package, this is generally considered to be the preferred arrangement for off -shore applications.

Understanding the benefit of three-point mounting is only one aspect. The success of three-point mounting the equipment is dependent on what is used to connect the package to the deck. There are two common mounting methods of transitioning from the turbine package to the deck. One method is using an Anti-Vibration Mount, commonly referred to as an AVM. The AVM is located between the package and the deck in sets of three. The AVMs are positioned to most effectively carry the package operational load requirements. The AVM affords a level of protection to the package and drive train alignment from deck movement, but less than that provided by a gimbal design. AVMs are used when there is a need to isolate the turbomachinery package from deck vibration, or, when installation near onboard living quarters mandates a level that cannot be achieved without them. AVM selection is project specific and depends on the package weight, center of gravity location, and application (i.e., moderate or severe duty).

The second method commonly used is the gimbal mount. The gimbal mount is also located between the package and the deck in sets of three. Like the AVM, the gimbal mounts are positioned on the package to most effectively carry the package operational load requirements. A gimbal is designed with a spherical bearing that allows the two mounting surfaces to move independent of one another. This, in effect, isolates the package and the drive train alignment from the deck's constant movement. The gimbal is chosen when the package will be exposed to excessive deck deflection, or the deck deflection data is not available. Although three-point mounting decouples the turbomachinery from the vessel's structural deflections, it does not alleviate the requirement to react to the dynamic forces applied to the components supported by the package structure. Structural requirements, transportation needs, and handling all play a role in the design of the base-plate resulting in three basic methods (Figure 21):

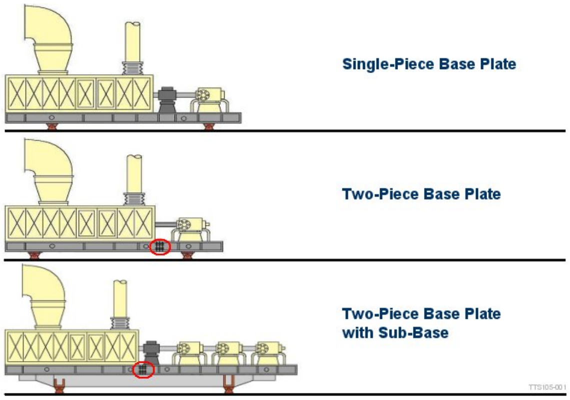

**Figure 21. Base-Plate Design**

- Single-piece minimizes the number of on-site connections, but depending on factory needs and/or transportability to site, this is not always a practical solution.
- Two-piece is an appropriate solution when transportability, manufacturing, and non-operational requirements take precedence. This allows the machine to be easily moved and

transported in smaller modules, and then assembled either dock-side for single lift or assembled on the deck.

- Two-piece with a sub-base is appropriate for large machines with long drive trains. More easily managed in the factory and during transport to site in smaller modules, these long base-plates alone do not provide enough structural rigidity for the severe environmental conditions of an FPS. As a result, a sub-base structure under the entire machine, designed to maintain the power train alignment, is required.

To develop and predict how the machinery will respond to the various load cases, finite element models are used to evaluate the base-plate designs. With the environmental loads applied to the model, deflection and stresses can be determined. Using this information, structural design of the base-plate can be compared with established design criteria to ensure it meets the application requirements. In addition to the base-plate analysis performed in the as-installed condition, analysis is also performed for the off-shore lift scenarios. In off-shore applications, the engine handling kits are designed with an integrated braking system for safety. A chain is welded along the underside of the beams, and a sprocket is incorporated into the hoist.

In the same way that the base-plates are analyzed using finite element analysis, the enclosure and ancillary structures are also evaluated using 3-D beam analysis.

Fluid management is another important aspect of ensuring successful operation of the equipment. A key data point here, is knowing the installed package orientation relative to the vessel centerline. Installation perpendicular to the vessel centerline is a structurally simpler design but is not as prevalent on FPSs. This is because perpendicular orientation provides a level of difficulty in designing for fluid management of the lube oil system. By far the most common and recommended installation option is parallel with the vessel's centerline. While this option presents difficulty in structural design, it is the simplest orientation when considering fluid management of the package lube oil system. CFD tools are also used to assist the engineer in efficiently addressing fluid management within the package. Regardless of the location of the equipment, accurately monitoring the nominal oil level is critical to successful operation. With the constant motion of the lube oil within the tank, monitoring the lube oil level within the tank must be handled differently than in a non-floating application. Installing the level indicator inside a stilling tube to dampen the effect of the oil movement can assist in accomplishing this vital operational feature. Due to the constant motion off-shore, if such a simple feature is not incorporated, even the most efficient placement of baffles within the oil tank can cause false low and/or high level alarms to be sounded.

As mentioned earlier, the severity of the dynamic or static inclinations experienced may exceed the baffle and gate valve capability, and/or cause the lube oil drain lines to no longer slope downwards. In these instances, a scavenge system is required. To ensure oil is drawn out of the turbine bearing cavity regardless of the inclination, the addition of a dedicated scavenge pump and drain line to return lube oil back to the tank may be the only turbine modification required. The package scavenge system ensures that all other lube oil drain lines return oil back to the oil tank efficiently. There are two scenarios that can drive the need for a package scavenge system. These are defined by not only the magnitude of movement but also the package length: Where the package length is such that even slight inclinations cause the lube oil drains to no longer slope downwards back to the tank, a second tank system is added to the driven base-plate. This is dedicated to ensure effective bearing drainage of the driven equipment. When the inclinations seen by the package are significant, a completely separate oil tank system located beneath the package may be required. Locating the tank system below the package provides the additional insurance that, regardless of inclination, the drains will always have a downward slope to the tank.

Other environmental considerations taken into account that are vital to the longevity of the machinery are: corrosion due to chemical reactions with oxygen, water and sulfur; erosion as a result of wind, sand and salt; electrolysis, resulting from contact of dissimilar materials. These elements are addressed with the type of attachments, consideration for galvanic bonding, material selection, and coatings.

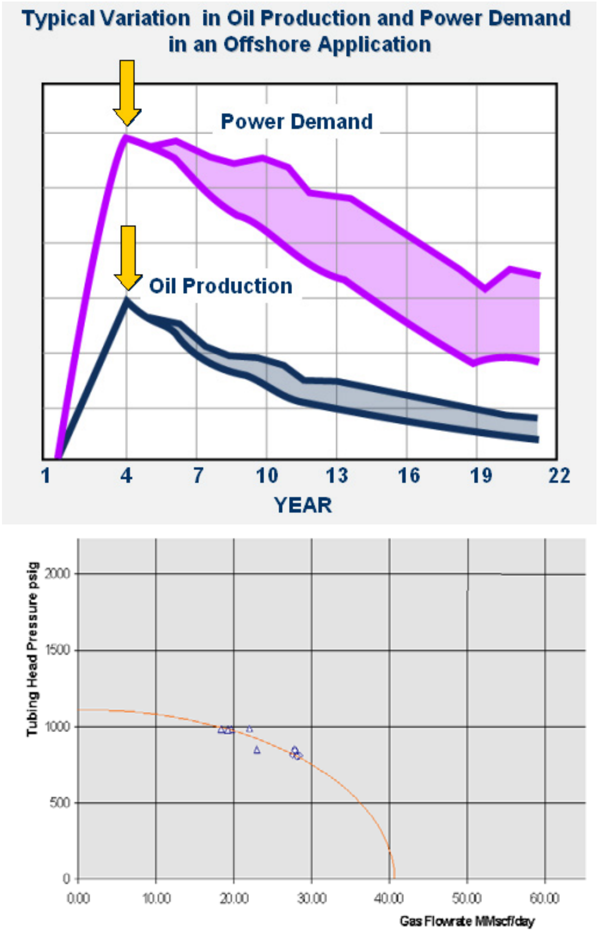

**Figure 22.(a)Variation in Oil Production and Power Demand in an Off-Shore Application**
**(b). Dependency of Compressor Suction Pressure on Well Yield. Typical Wellhead Performance, Showing the Well Yield as a Function of Pressure. The Lower the Compressor Can Draw the Tubing Pressure, the Higher the Flow.**

Off-shore applications also impose specific requirements on the turbomachinery (gas turbines or compressors) employed regarding flexibility, maintainability, and reliability in an environment characterized by ever-changing operating conditions on all time scales (Figure 22), a salt laden atmosphere, and opportunity fuels. Compressors need to lend themselves to easy restaging to adapt the driven equipment to changing operating conditions (Figure 23).

**Figure 23. Centrifugal Compressors for Re-Injection Duty at 240 bar (3,500 psi) Discharge Pressure**

Particular attention needs to be given to the dynamic behavior of the equipment during load changes, as well as during transients. An important aspect of surge avoidance lies in the design of the compressor module and, in particular, the piping upstream and downstream of the compressor. Most anti-surge systems are perfectly capable of avoiding surge during normal operating conditions. Good control systems, with properly sized recycle valves and appropriate control algorithms are capable of allowing compressor package to operate from design flows, down to full station recycle without upsetting the process. However, unplanned emergency shutdowns present a significant challenge, and surge avoidance in these cases depends to a large degree on the dynamic behavior of the station, including driving equipment inertia, valve dynamics, and the stored pressure energy in the pipe volume downstream of the compressor. Furthermore, the concepts used in the anti-surge system (valves, piping, coolers) also impact the startup of the installation, or of individual units of the installation (White and Kurz 2006).

Another topic is the decision to use gas turbines as the drivers for compressors, or electric motor drives. Results of studies (e.g., Kurz and Sheya 2005) point out that the decision of which scenario to use, an all-turbine approach versus an electrified approach, is a complex one; dependent on numerous factors including life-cycle costs, emissions, reliability, availability, flexibility and design simplicity. Installations, where the compressors are driven by electric motors, while the electric power is generated by gas turbine driven generators, will always require larger overall amounts of installed power than a solution where gas turbines drive the compressors, too. The all-electric solution requires a higher efficiency for the generator sets to break even to the all-turbine approach on system efficiency. This break-even point is mandated by the power ratio between the compression and electrical loads required.

Both the electrified approach and all gas turbine approach can meet the paramount requirement of flexibility for off-shore platforms. However, the electrified approach does add considerable additional scope of electrical equipment resulting in a more complex solution.

Availability is driven not only by the frequency of machinery failure, but more so by the time it requires to repair the problem. There are large differences between different manufacturers and different service arrangements.

Sparing of equipment improves equipment uptime. The loss of a certain percentage of power does not necessarily equate to an equal percentage of production flow reduction. The actual production impact due to turbomachinery downtime is application dependent.

## AIR INLET SYSTEMS

The off-shore environment imposes challenges on the treatment and conditioning of gas turbine combustion air, as well as the fuel, and water used. To help protect the internals of the turbine from the elements mentioned, a stainless steel turbine air inlet filter designed for off-shore applications is used. The design is specific to mitigating water, salt, and dust from entering the turbine. Off-shore filters have to be capable of removing water (as droplets or mist) and with it the salt that may be dissolved in it, from the air stream. They also have to be efficient, especially in dry environments, to remove small, dry dust, and salt particles.

The inlet air filtration system has to minimize the amount of solid particles and liquid, salt laden droplets entering the gas turbine. Besides the choice of filter concepts, an important consideration is the arrangement of the filter system on the deck. Considerations include avoidance of excessive sea water spray into the air inlet, but also ingestions of exhaust gases from other processes. Maintenance of the air filter system by appropriate cleaning or exchange of filter elements help to limit the pressure drop from the inlet system as well as the contamination of the turbine (Figure 24).

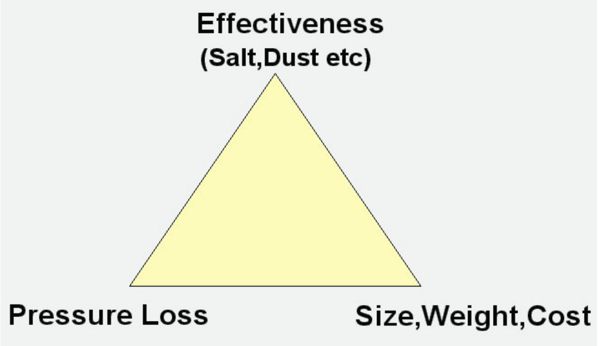

**Figure 24. Air Filtration Trade-Off**

## FUEL

Gaseous fuels can vary from poor quality wellhead gas to high quality consumer or “pipeline” gas (Kurz 2004). Typically, the major sources of contaminants within these fuels are: solids, water, heavy gases present as liquids, oils typical of compressor oils, hydrogen sulfide ($H_2S$), hydrogen ($H_2$), carbon monoxide (CO), and carbon dioxide ($CO_2$).Other factors that will affect turbine or combustion system life and performance include lower heating value (LHV), specific gravity (SG), fuel temperature, and ambient temperature. Some of these issues may co-exist and be interrelated. For instance, water, heavy gases present as liquids, and presence of $H_2S$or $CO_2$ may be a problem for turbine operators using associated gas as fuel gas. 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 startup 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
- 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 towards 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. With a known gas composition, it is possible to predict dew point temperatures for water and hydrocarbons. However, the prediction methods for dew points may not always be accurate. In fact, it is known that different equations of state will yield different calculated dew points under otherwise identical conditions. Furthermore, the temperature in an unheated fuel line will drop, because the pressure drop due to valves and orifices in the fuel line causes a temperature drop in the gas. This effect is known as the Joule-Thompson effect. Most fuel gases (except hydrogen) will exhibit a reduction in temperature during an adiabatic throttling. Hydrogen, on the other hand, actually shows an increased temperature when the pressure drops, which is a potential explosion hazard. Protection against heavy gases and water present as liquids can be achieved by heating the fuel downstream of knockout drums and coalescing filters (Figure 3). The idea is to have a saturated gas at the exit of the knockout drum and filters and then to raise the temperature to the necessary superheat to prevent subsequent liquid dropout. The system shown in Figure 3 is typical for fuel systems on oil or gas platforms, where the gas produced is usually wet.

Liquid fuels are often used during the startup phase, or as backup fuel. Proper storage and handling of this fuel is important. Transporting liquid fuel in open barges can cause contamination with salt water. Hydrogen sulfide, or any type of sulfur, can form salts in the presence of sodium or potassium that promote hot corrosion of the engine hot section components. Appropriate air filter selection, good placement of the air inlet, proper fuel handling, and fuel treatment, where necessary, can prevent these problems.

## SUMMARY

Industrial and aeroderivative gas turbines are commonly employed in applications where high power-to-weight ratio, low emissions, and high availability requirements prohibit the use of other mechanical drivers. Industrial gas turbines are frequently used as mechanical drivers for natural gas centrifugal compressors. Due to their operational flexibility, low maintenance requirements, and speed match with the driven equipment, they are ideally suited for this service. As any machinery, gas turbines require a significant number of on-skid and off-skid equipment – such as lube oil systems, controls and instrumentation, fire-detection and suppression systems, fuel forwarding and filtration systems, starter and crank motors, and inlet/exhaust systems for their safe and efficient operation. Given a specific application, an optimal set of ancillary and auxiliary equipment options must be selected. This selection is not just based on the type of application and utilities available at the site, but the operator's requirements for operating profile, reliability, and/or availability. The environmental conditions at the site must also be considered. This paper discussed packaging equipment selection options for a typical gas turbine driven compressor unit. API considerations were discussed. Because of their special significance, filtration, machinery protection, and utility requirements were also covered in additional detail.

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## REFERENCES

Anderson, A.W., 1980, *"Sawyers Turbomachinery Maintenance Handbook"*, Vol.1, Turbomachinery Intl Publications, Norwalk, CT.

Elliott, F. G., Kurz, R., Etheridge, C., and O'Connell, J .P., 2004, "Fuel System Suitability Considerations for Industrial Gas Turbines", TransASME Journal of Engineering for Gas Turbines and Power, Vol. 126, pp119-126.

Kurz, R., 2004, "Gas Fuel Considerations", Gas Machinery Conference

Kurz, R. and Brun, K., "Gas Turbine Tutorial – Maintenance and Operating Practices Effects on Degradation and Life," Proceedings of 36th Turbomachinery Symposium, 2007.

Kurz, R. and Brun, K., 2012, "Fouling Mechanisms in Axial Compressors", Trans ASME Journal of Engineering for Gas Turbines and Power, Vol. 134, 0323401.

Kurz, R. and Sheya, C., 2005, "Gas Turbines or Electric Drives in Offshore Applications", ASME GT2005-68003.

Meher-Homji, C. B. and Gabriles, G. A., 1998, “Gas Turbine Blade Failures-Causes, Avoidance and Troubleshooting”, Proc. 27th Texas A&M Turbomachinery Symposium

Newbound, T. D. and Wagiealla, W., 2003, “On-Line Hydrocarbon Dew Point Monitoring in Fuel Gas”, ASME GT2003-38868

Newbound, T. D. and Al-Showiman, K. S., 2004, “Tuning Your Fuel-Gas Delivery System”, ASME GT2004-53298.

Wilcox, M. and Kurz, R., 2011, “Successful Selection and Operation of Gas Turbine Inlet Filtration Systems”, Turbomachinery Symposium, Houston, TX.

White, R. C. and Kurz, R., 2006, “Surge Avoidance for Gas Compressor Systems”, Turbosymposium, Houston, TX.