Gas Turbines in the Modern Power Industry
Technical Report
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Introduction

Electricity is widely used within industrial, commercial and domestic properties throughout the world and is essential to modern day life.

It may be generated by a number of different means ranging from simple renewable supplies, such as solar and wind power, to the harnessing of energy within fossil fuels and radioactive materials.

Traditionally, the vast majority of the world’s electricity supply has been produced by raising steam through burning of fossil fuels such as coal, oil and gas and using this steam to drive a turbine generator to produce electricity.

This method currently accounts for roughly half of the world’s electricity supply with the remainder provided by nuclear, renewable and other fossil fuel-fired supplies, such as diesel engine and gas turbine based power plants.

Recent deregulation and privatisation of electricity generation industries throughout the world has also led to a new breed of generator, ranging from private independent power producers, to larger integrated energy suppliers.

This is a vast change from the previous government-owned utilities and since there is now increased competition, such companies are more focused on equipment life cycle costs, lead times, life time revenues and equipment availability, as well as production activities.

Many of the ‘new’ generators have looked to the gas turbine as a source of electrical power since it offers many advantages over the traditional fossil fuel fired power plant, namely relatively low equipment cost and lead time, high fuel to energy efficiency and low emissions. As a result, such equipment has been and continues to be developed by the manufacturers to meet customer demand for larger, more efficient machines.
Advanced technologies have been developed or introduced from the aircraft industry to allow such demands to be met. Though it is clear that there are distinct advantages to using a gas turbine based plant, such equipment is not without its problems. All of the leading equipment manufacturers have suffered from various failures as technological boundaries are pushed to meet new demands and these have led the insurance industry to be wary of recently developed and ‘improved’ machines.

Despite all the benefits provided by the use of gas turbines and the increasing normalisation of this leading edge technology achieved through numerous technical developments, the machinery breakdown exposure and ensuing business interruption impact are still causing significant concerns to both electricity generators and underwriters.

This technical report has been prepared to assist manufacturers, generators, risk managers, brokers and underwriters alike to understand the current critical underwriting issues relating to the use of gas turbines, so to facilitate the future insurance placement of this widely-used advanced technology.

This report provides a brief introduction to the gas turbine and its development, an overview of some of the critical problems associated with the use of these machines, and related insurance issues.
What is a Gas Turbine?

In its simplest sense, a gas turbine is a machine that is designed to convert the energy within a fuel into some form of usable power.

Gas turbines may be used for a variety of applications and these fall within two basic categories:

• for the provision of thrust – as is the case with a gas turbine aircraft engine
• for rotation of a shaft to drive machinery such as a pump, compressor, generator etc.

All gas turbines comprise three major sections: an air compressor, a combustion chamber and a turbine, as shown in the diagram below.

Compressor

Air is drawn into the compressor via guide vanes and flows in the direction of the shaft axis through several rows of stationary vanes (stators) and rotating blades (rotor buckets). Each vane/blade set is known as a compressor stage and serves to progressively increase air pressure as it passes from stage to stage.

Combustion Chamber

Within the combustion chamber the compressed air is mixed with vaporised fuel and the mixture is burned. This creates products of combustion that are at a higher temperature than the compressed air and is used to do more work than the energy used in compressing the air.

Turbine

The hot, high pressure products of combustion are passed to the turbine where they are allowed to expand through several rows of alternate stationary vanes and rotating blades. Each vane/blade set is known as a turbine stage, and as the mixture accelerates past each stage, the kinetic energy within the expanding gas is converted into rotational energy using the rotor blades.
Fuels
Several different types of fuel may be used to fire gas turbines. Natural gas is the most commonly used fuel though there are facilities that use other gases such as synthesis gas (syngas), a combination of carbon monoxide and hydrogen formed by gasification of residues, or other solid organic materials or liquids such as light fuel oil.

Some gas turbine installations that are designed to burn syngas feature an integrated fuel gasification system. These generally use turbine exhaust gases to raise steam which may then be used within the fuel gasification plant, and are generally found within refineries or other facilities with large amounts of organic waste materials.

It should be noted that turbines are specifically designed for the fuels they are to burn and as such a gas turbine that is designed to fire natural gas will not operate effectively with a syngas fuel stream and vice-versa. This is primarily due to differences in the calorific values of the fuels, meaning that different quantities of each fuel would be required to achieve the same output.

Gas turbines designed to burn more than one fuel are normally optimised for the main fuel, with a trade-off in performance on the reserve fuel supply. This allows for optimum reliability in critical applications with questionable or problematic fuel supplies and many designs allow for on-load change-over of the fuel supply.

Cleanliness of the fuel supply is of utmost importance as impurities within the fuel supply can lead to chemical and physical degradation of internal surfaces. As such, purification and filtration systems are provided within fuel supply systems. Quality control is also vital, as even trace quantities of certain elements can cause long-term problems e.g. corrosion associated with sulphur.

Turbine Power Output
In the case of a gas turbine that is used for the provision of thrust, most of the energy within the hot gases exhausted from the turbine is routed through a jet pipe or propelling nozzle to introduce forward movement. Auxiliary power systems may be driven via geared connections to the main machine shaft or by a mechanically separate power turbine depending upon the design of the machine.

Gas turbines that are arranged to drive a load generally have two parts to the turbine section, which are known as the compressor turbine and the power turbine, though these may be grouped together as a single turbine section. The compressor turbine is arranged to have sufficient power to drive the air compressor, and the power turbine is arranged to drive the generator.

These may be mounted on the same shaft as in a single shaft machine, or on mechanically separate shafts as in a dual shaft machine. Certain machines, particularly those derived from aero engines, feature several shafts to allow performance optimisation of turbine and compressor sections.
The origins of today’s gas turbines may be traced as far back as 1791 when the first patent was granted to a turbine design by John Barber, though it is unlikely that his design was ever manufactured. The next major development was not until 1872 when Stolze obtained a patent for a complete gas turbine.

In 1939, the first sizeable gas turbine power plant was built by Brown Boveri to provide emergency power at Neuchatel underground power station in Switzerland. This was a 4MW machine with a fuel-to-electricity efficiency in the region of 16%.

At about that time there was much technological activity throughout the world, though this was mainly to do with machines for jet propulsion and flight. It was not until after the war that gas turbines really began to be used as prime movers for rotating machinery, such as pumps, compressors and generators.

The 40s, 50s and 60s saw gas turbines used for a variety of applications, from simple pumping operations and vehicle propulsion, to power generation. However, the low fuel to electrical output efficiency associated with power generation applications led the machine to be used for peak shaving or emergency use only, and thus limited its development in this field.

By the 70s, simple cycle machines in the 5–25MW range with efficiencies in the region of 25–30% were commonplace, and along with the wider availability of natural gas led to gas turbines being scaled up in size to 50–100MW to produce base load electrical power.
To meet these requirements, the manufacturers have been responding by on-going development, using advanced technologies associated with increased air flow rates, higher firing temperatures, increased efficiency, higher output and reduced emissions.

Many of these technologies have been developed by, and have been obtained through, agreements with aero-engine manufacturers and include:

- use of advanced blade coatings
- improved methods of applying blade coatings
- advanced blade metallurgy
- enhanced blade cooling methods
- improved combustion systems
- advanced blade profiles.

In many cases, the reliability of these new technologies has not yet been proven, and many manufacturers are being forced as a result of commercial pressures to complete development and long term testing during commercial operation. This has led to a limited amount of fully proven plant available in the market, especially in the larger machine sizes.

To keep up with the demands of the equipment operators, development of advanced technology gas turbine based power plant is an ongoing process. Manufacturers are continually releasing new or modified machines to meet customer demand and maintain market share. This is expected to continue into the next decade.

However, some problems that were of a minor nature on the smaller machines became major issues on the larger equipment, and it was not until the 1980s that manufacturers began to solve these through the use of new technologies, such as computer aided design, advanced materials and stricter quality control procedures.

At about the same time, many of the world’s boiler manufacturers were working in conjunction with the turbine manufacturers to develop boilers to recover waste heat from the turbine exhaust gases. This heat could then be used to raise steam that might then be used to drive a steam turbine generator, further increasing fuel-to-energy efficiency to over 50%. This made a highly efficient power generation plant when compared to conventional coal fired stations with energy efficiencies of 35–38%.

With a gas turbine based power plant becoming a viable alternative to provide base load electricity, power generation companies began placing orders for such equipment, based principally on their benefits (see later) over conventional fuel-fired power plants. As a result, the late 1980s and 1990s saw a rapid development of these machines, driven by both the desire for manufacturers to lead the field, and demands imposed by commercial pressures on the generators operating in newly deregulated electricity markets.

These developments and commercial pressures have caused the following trends in the industry:

- to reduce their fleet size and generating costs, the generators have been demanding ever increasing machine sizes with units in excess of 250MW
- higher efficiencies/combined cycle efficiencies in the region of 60% are now the norm
- reduced capital costs
- reduced maintenance requirements.
Gas turbine based power generation systems may be as simple as a single gas turbine driving an electrical generator, through to a number of gas turbines discharging their hot exhaust gases into heat recovery boilers, where steam is generated to drive turbine generators.

In the simplest arrangement, the machine is operating in what is known as the 'simple cycle mode', whilst in the more complex arrangement it is known as the 'combined cycle mode.'
A brief description of each is provided below.

**Simple Cycle**

When a gas turbine is arranged to operate in simple cycle mode, air is drawn in from the atmosphere, compressed, heated by combustion with a fuel and expanded through the turbine. The mechanical power generated as a result of rotation of the turbine is used to drive an electrical generator and the hot gases are exhausted to the atmosphere.

**Combined Cycle**

Within the combined cycle arrangement the gas turbine is still the heart of the power generation system. Power is produced in much the same manner as in the simple cycle mode, but the hot exhaust gases are routed to a heat recovery boiler where they are used to raise pressurised steam. This steam is then passed to a conventional steam turbine-generator where the energy is converted into electrical power.

The connection between the turbine and the driven machine may be through direct coupling of the drive/driven machine shafts, or through a speed adjustment gearbox. Since the electrical generator speed is normally kept constant, the direct coupling is usually used for the larger power generation machines in order to optimise the mechanical efficiency.

There are several different arrangements of combined cycle plants, ranging from single unit stations, to multiple units arranged to feed a common steam turbine-generator. The steam and gas turbines may be either mounted on the same shaft to drive a common generator, or be completely separate machines with individual generators in different areas of the plant.

With a fuel-to-electricity efficiency as high as 60% in some cases, the combined cycle arrangement is the most commonly used gas turbine based power plant in recent years. A variation of the arrangement known as the combined heat and power plant is also widely used in the industry, where a user requires large quantities of electricity, plus steam for heating or process use. This offers a further improvement in overall thermal efficiency with a subsequent saving on plant fuel costs.

The simple cycle arrangement is often used for small installations, or in areas where there is a large demand for power and fuel prices are low. However, owing to its low fuel to electricity efficiency (30–35%), its use is not common in the industry.

Improvements to this efficiency can be made through recovering some of the heat in the gas exhaust and using it to preheat fuel or inlet air. Developments have led to other uses for the hot exhaust gas streams and the ‘combined cycle’ arrangement.
Modern gas turbine based power plants have many advantages over the available alternatives.

**Equipment Cost**
The basic cost of a gas turbine-based power plant is significantly less than similar sized alternatives, such as conventional coal or oil fired facilities. As an example, the cost per installed kilowatt (kW) for a gas turbine based plant is in the region of $200 to $350 compared with $750 to $1,000 for a conventional coal-fired plant.

**Lead Time**
The time from placement of order to final commissioning of a gas turbine based power plant can be significantly shorter than similar sized alternatives. As an example, construction of a simple cycle gas turbine based plant can take as little as 12 months, compared with three to five years for a conventional coal-fired plant.

**Efficiency**
Gas turbine based power plants can be extremely efficient depending on the design and arrangement of the equipment. Fuel to electricity efficiencies of 55–60% are achievable compared with a norm of 35–38% for conventional coal-fired plant.

**Environmental Impact**
Gas turbine based plant has much less impact on the environment than similar sized alternatives. Emissions of harmful gases and particulates are significantly lower than conventional coal-fired plants, and their physical size is also small since there is no need for large civil works, extensive fuel stock piles, ash dumps etc.
Gas Turbine Based Power Plant

Though modern gas turbine based power plants have many advantages over alternative generation methods, they are not without their problems.

All of the manufacturers have suffered technical difficulties with their advanced technology machines and though all have, and still are, addressing these issues, such difficulties have led to significant project delays, equipment downtime and plant modifications in the operational phase.

Some have not manifested themselves until much later in the initial operating period. As a result, there is much unease with the newer machines, since the industry does not know with any certainty whether the future will be problem-free, or beset with further failures. Only long term operating experience has proved the true characteristics of these machines.

Technical difficulties are not the only issues to affect gas turbines. Experience has also shown that these machines, as with any large rotating equipment, have suffered from various other upsets. These include poor quality assurance of materials or component parts, failures in start up and operating procedures, poor maintenance practices and failures resulting from air and fuel contamination.

Typical technical or design-based difficulties that have been encountered by some or all of the leading manufacturers include:

**Mechanical Problems**

As machines have increased in size and efficiency, there have been many difficulties with their mechanical integrity as a result of the increased workload imposed on components. Manufacturers have moved towards the installation of fewer rotor bearing points, putting additional demands on rotors and components, which in turn have been subject to stress cracking, distortion and rubbing. Such issues have led to failures and significant downtime whilst repairs take place.
In all cases that have appeared so far, redesign and modifications have addressed such deficiencies, but this has still led to extensive downtime, additional inspection frequencies and hence loss of capacity.

As an example, a significant failure occurred at a power plant in the USA in 1995 as a result of a turbine blading design fault. Blading within the gas turbine became detached leading to significant imbalance and subsequent destruction of the machine.

Surrounding auxiliary equipment was also damaged leading to a total property loss of $42 million and downtime costing $11 million. Another loss in the USA in 2000 occurred at a plant resulting from a crack in the compressor frame. The crack led to failure of the casing and subsequent disintegration of the machine.

**Thermal Problems**

The use of increased firing temperatures has led to use of advanced metallurgy, thermal barriers and advanced cooling techniques. Manufacturers have encountered problems with all three of these techniques, ranging from failure of thermal barriers and their attachment systems, to insufficient blade cooling leading to thermal distress. Again, redesign and modifications have addressed such problems in many machines.

There have been many cases of thermal barriers failing throughout the world and perhaps the most serious of these occurred in Chile in 1998. Here a thermal barrier tile became detached and passed with the products of combustion to the turbine. The tile became lodged within the inlet guide vane assembly upsetting flow patterns and on eventual release passed through the turbine section causing total destruction of the rotor. Repair costs were in the region of $2.3 million and the plant suffered a significant downtime.

**Burner Humming**

In a drive to reduce emissions, all of the modern gas turbine machines feature Dry Low NOx or Dry Low Emission-type burners. These represent a new generation of burners that have been developed by the equipment manufacturers to move away from the expensive traditional emission control measures of steam and water injection.

Some of the leading manufacturers have encountered problems with a phenomenon known as combustion chamber, or burner humming. This is a vibration induced noise that is brought about by flame instabilities within the burner area of the combustion chamber.

Though burner humming is not generally a short term threat to the operation of the machine, it could lead to long term damage as a result of excessive vibrations. Though modifications have been introduced, the problem has yet to be completely eradicated in some units and is still the subject of extensive research.

At various power plants within the USA, Canada and South America, there have been incidents of damage as a result of cracking within burner transition sections, believed to be attributed to vibrations caused by burner humming. Such cracks have led to detachment of parts of the transition sections, which have then become entrained within the products of combustion and passed through the turbine section causing extensive damage. Repairs have cost from $100,000 to in excess of $1 million depending upon the scale of the damage, availability of spare parts and equipment downtime.
Combustion Flashbacks
Combustion flashbacks occur when the burner flame front moves back from its intended location towards the burner front. The repositioned flame then impinges on components not designed to accommodate high temperatures, causing them to melt and become detached. The molten metal can then pass through the turbine, causing extensive damage. Though this has been a problem in the past, redesign of affected components has led to resolution of the issue.

Quality Assurance Issues
Quality assurance of component parts and materials is extremely important as gas turbines operate at high speed with high operating temperatures and pressures, and low tolerances between blades and veins. Failure of a relatively minor component within the machine can cause extensive damage.

As an example, one manufacturer suffered a problem with failure of rotor disc tie bolts leading to significant blading and rotor damage to a number of machines. On further investigation, it was discovered that the bolts in all of the affected machines were traced to one supplier producing substandard components. Improved quality assurance procedures have now been introduced to help prevent reoccurrence.

Operational Issues
Correct operation of these machines is an important issue. Many problems have been caused through poor procedures leading to failure in communications and important steps of operations being skipped. Cooling air valves have been left in the incorrect position after maintenance activities, lubrication systems have been left out of service prior to start up and pre-start checks have been carried out incorrectly.

All of these issues may in themselves only seem minor failings, but it only takes moments of running a high speed turbine with little or no lubrication to cause extensive damage to bearing surfaces and overheating of equipment components.

Gas turbine internals are relatively fragile. Cleanliness is critical to prevent damage to machine blading, burners and other internal areas, as one small foreign particle can have disastrous consequences.
Improperly controlled maintenance activities can also lead to problems. Bolts can be left untightened, tools can be left in the machine and auxiliary systems may not be recommissioned correctly. Debris or foreign objects left following maintenance activities, or loose components can become detached, and prevent the correct operation of machine controls. In more severe cases, these may be drawn into the turbine causing great damage as they pass through the compressor/turbine blading leaving a path of destruction.

Use of correct components and properly designed spare parts are of equal importance during maintenance activities and manufacturer’s guidelines should be properly adhered to.

In 1997, a gas turbine was fitted with a set of refurbished turbine blades and was put back into normal service. The manufacturer advised that the refurbished blades had a reduced life-span, but the operator ran the machine to and beyond the recommended service limit. The blades subsequently failed due to a fatigue mechanism, which resulted in the total destruction of the machine.

The Way Forward

It is a business desire to continue improving and there are larger risks associated in not doing so. Within the power generation business arena, the manufacturers of gas turbines have been forced to remain competitive by pushing the technology barrier to build larger and more efficient machines to meet customers’ demands.

Historically, the use of any new technology has always been beset by failures and upsets in the initial stages, but over time these ‘teething problems’ have been rectified. In the case of the gas turbines, these developments have proved to have come, perhaps, too rapidly, and consequently at a high cost.

However, despite all the problems encountered by some gas turbine models, these are continuously being addressed and significant progress has been achieved on many fronts by the manufacturers.

Drawing from past experiences in other engineering fields, as efficiencies approach an upper plateau, there is an expectation that a greater normalisation is being achieved in this industry.
Insurance

There are many issues affecting the insurability of gas turbine based power plants, not only from the equipment itself, but as a result of the changing regulatory environment.

Equipment Issues
As mentioned earlier within this report, many of the gas turbine manufacturers are being driven to release larger, more efficient machines as a result of market pressures, which in turn lead to a number of new and improved machines being put into commercial operation before they have been fully tested.

This has led to mechanical problems occurring during power plants’ testing and commissioning and/or early operational phases, which have resulted in claims against insurers. In some cases, the length of the business interruption loss has been increased by the need for the manufacturers to modify the equipment to correct design faults.

As a result, it is now standard practice to classify a new model of machine as unproven (or prototype) technology until the first three lead machines of each design type have run trouble-free for at least 8,000 equivalent operating hours. A modification to a proven model will usually mean the reclassification of that model as unproven, requiring it also to fulfil the 8,000 hours test before it can again be considered proven. Much of the latest generation of gas turbine plants has yet to move from the unproven technology designation to being considered proven, and is therefore subject to significant scrutiny by insurance underwriters.

As the equipment manufacturers strive to become market leaders by releasing ‘new improved’ models, it is unlikely that the criterion of 8,000 trouble free operating hours will ever be met by all of a manufacturers’ models, meaning there will always be unproven technology in the marketplace.

Business Issues
As a result of deregulation in the electricity generation industry throughout the world, a new kind of electricity generator has arisen, known as Independent Power Producers (IPPs). As their name implies, these are privately owned, non-utility generating companies making extensive use of gas turbine technology.

IPPs fall into two categories:
- those that trade under long-term power purchase agreements (PPAs) with electricity users or off-takers
- merchant power plants, which sell their output on the open market and/or under short/medium-term contracts.

These create different risks and problems for insurers, especially when it comes to business interruption. A PPA may contain provision for penalties as a result of failure to supply or unavailability of generation equipment, and may oblige the IPP to purchase replacement power if it is unable to meet its obligations through its own generation.

For merchant plants, the difficulty will be in proving its loss in the event of an outage. One of the fundamental principles of business interruption insurance is that the Insured must prove his loss, which in the case of a power station means proving when the station would have generated and the revenue that would have been earned. While this should not present a problem for plants with a PPA, it is far more difficult for merchant plants, as these would have to prove what they would have sold, and the revenue they would have earned, following a lengthy outage.
Both types of IPP may have Take or Pay liabilities under fuel supply agreements (FSAs), which they may seek to insure. Many FSAs contain a ‘truing up’ mechanism over subsequent contract years, which extends the period in which the business is affected beyond the policy maximum indemnity period, and which further complicates the adjustment of a claim.

**Insurance Market Practice**

Many insurance carriers are reluctant to underwrite unproven technology equipment based on the mechanical breakdown and business interruption risks, partly because the lack of historical performance-based information on the equipment makes it difficult to estimate future performance, and partly because of the experience of failures among improved or prototypical equipment.

For most insurers, it is now standard practice to impose a variety of design defects exclusions to the insurance of unproven technology turbines. While the cost of rectifying such defects may be covered under the manufacturers’ warranties, any ensuing damage to non-warranty items and the consequential loss of revenue and/or other costs (such as replacement power costs) will be left with the power station owners.

In addition, it is usual for insurers to cap the indemnity available under business interruption policies, especially for merchant plants, to a *per diem* or *per mensem* amount, to avoid the possibility of a disproportionate amount of the business interruption sum insured being payable during a relatively short outage, which might otherwise be the case if the outage coincides with a period of high spot market prices.

The minimum business interruption deductible available for power generators is (with few exceptions) 60 days, and deductibles of 90 days or more might be applied if the technology is unproven.

Insurers also require detailed business interruption underwriting information, including worksheets breaking down revenue and expenses on a month-by-month basis to enable them to identify seasonal variations.

Much progress has been made by manufacturers and operators of gas turbines, and all sides have learned from mistakes of the early years of development.

In the short and medium terms, we can however continue to expect much unease from insurance and reinsurance carriers in respect of all the exposures involving the new generations of gas turbines.

The provision of very detailed technical information, and the demonstration of thorough quality assurance procedures will *inter alia* remain a key success factor for completing the broadest available risk transfer programme.