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Combustion Turbines: Critical Losses and Trends

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Executive Summary

For underwriters some items and plants are more straightforward to insure than others. Combustion turbines are one of the most complex and difficult. For these turbines underwriting, risk management measures and loss adjustments are highly intricate and those undertaking them need to have sound experience.

IMIA's purpose is to give ideas and, if not direct recommendations, at least guidelines for the best insurance practice in the field. This paper discusses contemporary questions pertaining to combustion turbines. These turbines are critical for many reasons, the foremost being the fact that they stretch the upper limits of what certain components can endure as far as mechanical and thermal stresses are concerned. Furthermore, technical solutions in combustion turbines have a tendency to evolve at such a pace that machines often have features typical of prototypes, and in this sense represent unproven technology. Additionally, the service issues and replacement strategies of consumable parts are highly complex.

The paper discusses the statistical criticality of combustion turbines, recent developments in their use worldwide, major loss prevention means as well as contractual concepts between users, original manufacturers and insurers regarding service, spare parts and claims. Typical turbine damages are dealt with, and finally the paper presents examples of interesting failures from which one can learn.

1 Introduction

Half a century ago there was a need for a compact power source for peak load producing a megawatt scale output and gas turbines were the solution. These were mostly modified aero-engines able to start and shut down very fast so called “aero-derivatives”. Initially efficiency was not of primary importance.

In the years that followed, these peak load gas turbines were often powered by liquid fuel, as an alternative to gas, giving rise to the term combustion turbines as used in this paper. The units were also used for base power. The main reason for this was that they were compact, requiring much less investment by comparison with the alternatives such as a steam turbine, powered by steam produced in a boiler.

A plant with a combustion turbine is fast to build, as nowadays the turbines are delivered completely, or almost completely, pre-assembled. During the last decade the efficiency of the turbines has been enhanced by using higher firing temperatures. Steam turbines use temperatures in the region of 500-550 Cº, whereas in a combustion turbine, temperatures are in the region of 1200-1500 Cº. The use of combined cycle power plants with their excellent efficiency has furthermore increased the need for, and importance of, combustion turbines.

Higher temperatures require protective surfaces to be applied to the components that are exposed to them i.e. the combustion chamber, the vanes (nozzles) and the blades (buckets). Since the firing temperature is considerably higher than the solidification temperature of the metal alloys used, these components have normally to be coated with a thermal barrier. The metal core gives the structural stiffness to these critical parts. In order to keep the temperature down at the surface of these components, intricate cooling channels have been devised. All this results in components apt to melt down, if there is the smallest imperfection in the cooling, such as a clogged cooling channel.

The units have to be serviced and critical consumable parts changed after a specified number of hours calculated as “equivalent hours” and/or “equivalent starts”. Start ups and cooling periods are the most degrading periods of operation and therefore they make a disproportionate contribution to equivalent hours. A combination of prolonged use of the components, their replacement with original, refurbished or non-original spare parts, makes it difficult to determine when parts should be replaced. This determination is not helped by the fact that interpreting the results of non-destructive tests is a complex matter. Recent environmental requirements have led to water or steam injection in order to lower NO_x (Nitrogen Oxide) levels. This introduces potential problems of erosion.

Gas turbines are used in different ways. They can be operated in simple cycle or combined cycle mode. In combined cycle, they are used with a steam turbine. For this a heat recovery steam generator is utilized. Steam is led to the steam turbine and then back to the boiler after being cooled in a condenser. Combined cycle applications use either single or multi-shaft arrangements.

Both simple and combined cycle combustion turbine power plants can be operated as cogeneration plants. Waste heat from the combustion turbine generates steam for industrial process applications where steam is needed. A typical example is a power station producing district heating.

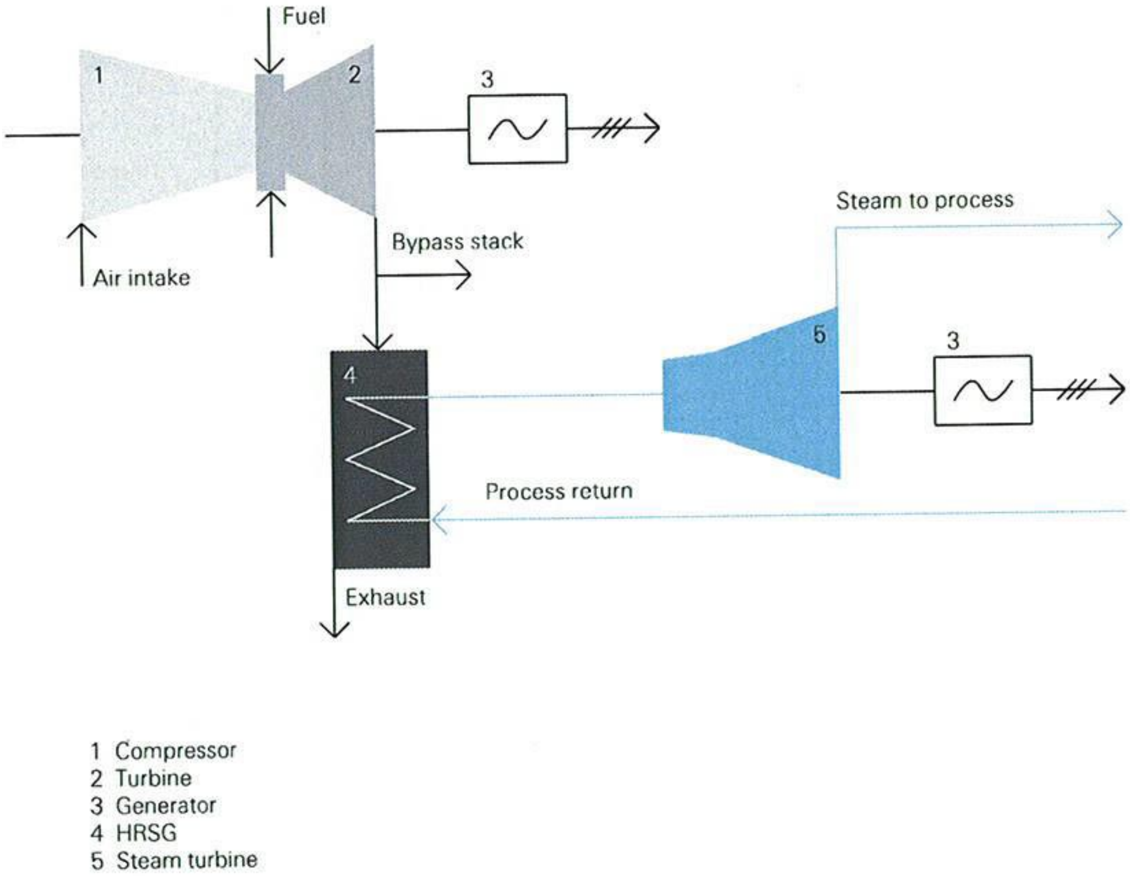

Figure 1: Combined cycle cogeneration plant
HRSG = Heat recovery steam generator. (M. Bommeli, 2003)

A sound understanding of the different combustion turbines, their types, components and operating principles is a prerequisite for good underwriting. The main underwriting principles have been thoroughly presented by Swiss Re in their publication: Insurance Aspects of Gas Turbomachines (M. Bommeli, 2003).

Combustion turbines employ technology at the limit of strength and temperature endurance of the materials used. Development of machines is fast, making almost every new design a prototype. This means that good underwriting and risk management procedures are crucial. The question of spare parts and the value of used components is complex. Claims concerning combustion turbines require high quality loss adjusting.

2 Statistical Criticality of Combustion Turbines

Power generation has seen a progressive move towards combustion turbine technology alongside the developments seen in the aero industry where small yet powerful turbines have proved to be the cost effective way forward.

The industrial power generation combustion turbine saw rapid development in the 1970s with impetus from new natural gas supplies such as the ‘dash for gas’ started in the UK during the 1980s which resulted in widespread construction of combined cycle gas turbine (CCGT) plants.

CCGT power stations were able to tempt plant operators with efficiencies well in excess of the traditional coal powered thermal plants. Unfortunately the expansion of the CCGT market was at the expense of losses and claims, technologically advanced designs being pushed to the limit resulting in a succession of spectacular failures.

There is now a significant proportion of power generated worldwide by combustion turbines and new designs are getting larger each year, the latest units to undergo testing having reached shaft outputs of 340 MW. The rate of increase in size and efficiency is slowing and we are seeing manufacturers concentrate their efforts more on reliability. There is a fine line between achieving high efficiency/power outputs and maintaining a consistent operation and it is clear that good and bad reputations have been created with some manufacturers during recent years.

Improved availability is good news but the huge and ever increasing repair costs for machinery of this type cannot be ignored. The insurer therefore has to be concerned that critical parts of combustion turbines are required to operate for longer and under more extreme conditions as turbine inlet temperatures creep higher and higher in search of improved efficiencies.

The CCGT market continues to grow at a fast pace and, even in times of recession the forecast for new combustion turbines remains largely unchanged due to superior (low) levels of emissions from natural gas fired plants when compared to coal fired plants.

The main manufacturers of large industrial combustion turbines are based in Europe, North America and Japan as follows:

Europe	Siemens and Alstom
North America	GE and Siemens (the 60 Hz models, previously Westinghouse)
Japan	Mitsubishi

No new manufacturers have emerged over recent years and it is unlikely that new contenders, say from China, will start designing and manufacturing from scratch due to the prohibitive research and development costs. Manufacturing under licence is however a possibility, an example being in Italy where Ansaldo have successfully built Siemens designed machines under their own brand name. Similar arrangements will undoubtedly spring up in China. The quality control for every critical part of a combustion turbine is such that new factories in emerging countries like China should be able to produce products equal to those sourced from the OEM factories, nevertheless insurers need to be vigilant especially since past experiences in this area have been poor.

Lack of engineering expertise with the operators and with the repair teams, is a concern. The complexity of combustion turbines increases with time, not only in respect of the materials used and methods of assembly, but also with the sophisticated control and monitoring systems. Specialists are required to provide the highest skills in assembly of turbines and in the interpretation of operational data stored on computers.

Great advances have been made as a necessity with remote monitoring of the instrumentation and this has allowed experts to oversee operations and detect developing problems in offices connected by satellite links on the other side of the world. This has been a truly remarkable advance by providing a watchful eye, identification of faults often being made remotely before the site becomes aware of a problem. Such expertise puts into question whether third party maintenance companies can maintain similar high levels of service capability in addition to keeping pace, in the long term, with all defects and manufacturers' modifications.

Combustion turbines now operate within such fine tolerances that advanced computer control is the only option. Condition monitoring is therefore necessary to control extremely complex problems such as those experienced with combustion dynamics. Often problems can be solved by expert interrogation of data on a remote laptop rather than by on-site manual adjustments. Therefore insurers are increasingly in the hands of the manufacturers for assurance that operation and maintenance is being carried out correctly.

The level of understanding required to make adjustments and interpret data is often beyond the capabilities of the site engineer or a third party maintenance provider. In this respect users and their insurers are very vulnerable to substandard repairs being carried out under service agreements with third parties who are not fully in touch with the intricacies of design – a dangerous situation. Moreover there is an extreme risk of rogue parts being fitted to turbines by third parties involved in maintenance. Parts traceability is of serious concern to all the major manufacturers. Sometimes highly stressed parts, such as blades, which have reached the end of their service life are refurbished and reverse engineered parts of dubious quality have found their way into machines only to fail because of defects or premature fatigue. Such failures invariably result in catastrophic events and very high insurance claims.

The lack of experienced engineers is a feature of this industry and mirrors the situation across all industries. In general, expertise emanates from the OEMs and this adds further weight to the need for caution regarding service agreements with third parties.

3 History and Future Evolution of Gas Turbines

3.1. The Historical Background

When one thinks about gas turbines, one usually associates them with modern technology like airplanes, helicopters, or state of the art electric power stations. But in reality, the concept of compressing air, injecting energy and then recovering mechanical energy in a turbine is not new. Karavodine and Holzworth built the first gas turbine unit at the beginning of the 19th century. In those days however, almost all the energy was absorbed by the Compressor which rendered the mechanical output insufficient for any practical application.

The first breakthrough in the gas turbine concept came later from Auguste Rateau in 1905. Auguste Rateau designed and incorporated a new component called the air centrifugal compressor. With this new component, he tested his first gas turbine in 1916. This was later used as a turbocharger in combustion engines.

In 1930, a Royal Air Force officer called Frank Whittle designed and patented the first turbo engine for airplanes. However, it was Hans von Ohain from Heinkel Company who tested the first jet engine-powered aircraft, which was later used in the Messerschmitt Me 262.

The features of the gas turbines in those days were:

- High output per kg of equipment
- Relatively quick warm-up when compared to diesel engines and particularly quick by comparison with steam plants
- Low to very-low efficiency
- Requirement for good quality fuel
- Limited maintenance when compared to diesel engines, but limited lifetime of the hot parts.

The first gas turbines were used for the propulsion of airplanes. Driven by the goal of quick military domination, the Royal Navy built and commissioned the first gas-turbine-propelled motor gunship in 1947. Until recently, the gas turbines on large warships were used in combination with diesel for transit until the operation zone (CODOG: Combined Diesel or Gas).

The first operational power station was built for the city of Neuchâtel in 1939. The output was 4 MW with an efficiency of 18%.

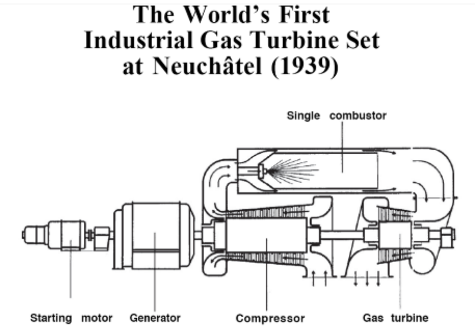

Figure 2: First Gas Turbine (1939)

The real take-off of gas turbines in electricity production happened in the early 1990's with the introduction of the so-called combined cycles. Combined cycles are composed of a gas turbine whose exhaust gases are directed into a heat recovery steam generator, which in turn feeds a steam turbine. The overall efficiency of such a combination is excellent, being 57-59% for the most recent plants. On the other hand, the open cycle efficiency, i.e. without heat recovery installation, is recorded at around 38% for most of the recent units.

3.2 Recent and Future Development of Gas Turbines

Improved Operational Flexibility

Apart from jet engines, which are not the topic of this paper, gas turbines are now mainly used in power generation. In addition to an ever increasing efficiency, due to also increased firing temperatures, manufacturers are now working on other parameters namely the efficiency at reduced load as well as fast "hot starts", which will enable the machine to reach its full capacity within a short time frame. Both improvements combined will enable the operators to leave the gas turbine unit running at a reduced load but at an acceptable efficiency and quickly ramp up when dispatched. This reduces the maintenance burden due to start-up.

Some designs handle this problem by having two separate and individually controlled combustors which allow an acceptable level of emission and a high level of efficiency at partial load. This is achieved by reducing the incoming air at the air inlet with variable guide vanes, thus allowing the same exhaust temperature to be maintained at partial load and at base load (See fig. 3). In this way, plants running at 15 -20% capacity can still achieve an efficiency of 35%.

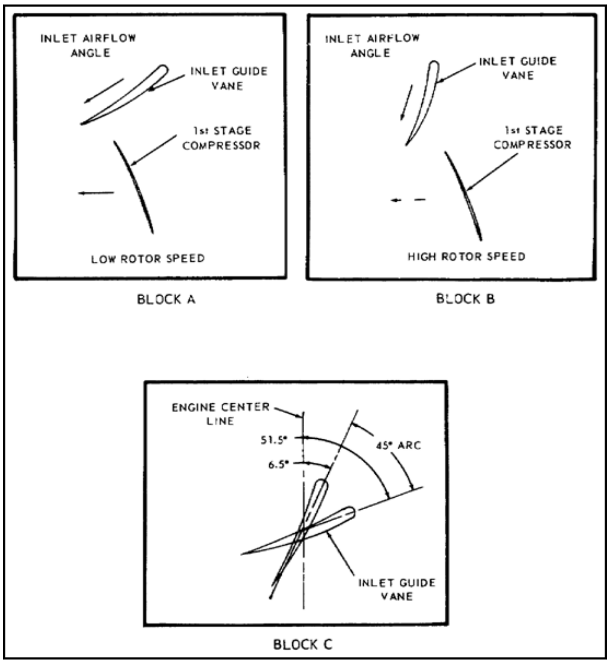

Figure 3: Angle of attack of inlet guide vanes according to rotor speed

Other designs tackle this issue with a modified heat recovery steam generator (HRSG), e.g. Benson type or Supercritical. Some plants allow hot starts to reach the full load within 40 minutes without maintenance penalties. In other plants, Engineers have developed a static frequency converter enabling the unit to reach 150MW within 10 minutes or the full load of 198MW within 12 minutes.

Other examples include machines whose major feature is their capability to reach the full load within 50 minutes during a hot start-up. These are Combined Cycle rated at 500MW, with steam cooled gas turbine rows 1 and 2 and with a remarkable 59.3% efficiency.

Steam Cooling

Increased firing temperatures of some of the models reached the point where the heat transfer characteristics of air were not sufficient to offer a proper cooling of the hot parts of the turbine. Hence the engineers developed steam cooling systems, one of the advantages of which is, primarily, much better heat transfer. Additional advantages are that there is more air available for the combustion, which in turn improves the level of emissions. Furthermore, after the cooling the steam is re-injected into the steam turbine intermediary stage, enabling it to recover the energy collected by the steam re-heat during the cooling process. This contributes to enhance the overall efficiency of the combined cycle.

Initial concerns about the reliability and the availability of such plants seem to lessen. For example, there exists now an operating fleet of 18 units covering both the 50Hz and 60Hz fields. Two units for 50 Hz have now more than 10 years of experience and each has achieved over 42,000 of actual operating hours. It should be noted that some technology concentrates the steam cooling on the fixed parts of the hot gas path. An additional concern relates to the chemical requirements of the cooling steam, but it seems that just normal steam turbine chemical standards are suitable for this use.

Micro Gas Turbine (MGT) Units

The race to miniaturization is reaching an advanced stage. This trend is driven by increasing consumer demand, both commercial and military, to use of electric-powered portable devices such as for example laptops as power generating units. Gas turbines have been part of this race, and the result has been the development of the so-called micro gas turbines. Their size ranged down to a portable unit producing less than a kilowatt of power. The basic components of this Unit include a Compressor, a Regenerator, a Combustion Chamber, a Turbine, and an Electric Generator.

Advantages of an MGT Unit are (1) compact size, (2) fewer moving parts, (3) relatively low maintenance cost, (4) light weight, (5) high reliability and durability, etc. The miniaturization of the gas turbine continues to pose tremendous technical challenges to their developers. The areas where challenges remain to be encountered include heat dissipation and high-speed bearings.

Figure 4: Micro gas turbine developed for US Department of Defence

4 Major Loss Prevention Means

4.1 Use of, Risk Based Maintenance and Inspection (RBMI) Programs

Original equipment manufacturers (OEMs) build up their recommended maintenance programs based on different types of risk based maintenance and inspection philosophies. They base their schedules on their experience of proven machine types and make predictions for unproven types.

Most turbine users devise their maintenance programs based on the recommendations given by the manufacturer. Usually three types of inspections are utilised:

- Combustion inspection
- Hot gas path inspection (minor overhaul)
- Major overhaul.

The intervals for these are based on a combination of the equivalent running hours and/or equivalent stops & starts of the unit, with each manufacturer providing equations/calculations for determining the service intervals of the machines.

The running up and also shutting down of the machines creates abnormal heat transient situations leading to thermal expansions and stresses. Every run up is apt to induce fatigue thermal cracks and to give the cracks the required energy to propagate.

Normally a combustion turbine running base load would need a combustion inspection after a year or after 8000 hours, a minor overhaul in the order of every three years and a major overhaul something like every six years.

By using additional monitoring systems, a machine can be operated closer to its safe working limits and the safety factors and redundancy can be reduced without increasing the operational risk level.

4.2 Use of Pro-active Maintenance Schedules

The schedules for normal overhauls are altered when so-called “extender programs” are used for the most critical and fastest degrading components or their specific parts.

The question of how long a component can be used safely can get complicated. This particularly applies when non-OEM spare parts have been used, or maintenance of used parts such as coating of the blades is undertaken with a new method compared to the original one. The same applies when it is done by somebody other than the OEM.

This situation requires a pro-active program for maintenance that takes into consideration these varying factors and the results of the NDT testing undertaken at the previous inspection. The results of the destructive testing of the structure of the material to be repaired are also considered. See Figs 5 and 6. Metallurgical tests show long term damage or show how far possible damage has developed to help engineers decide if a component can be reused or not. When parts are damaged and claims have to be adjusted, these complex questions have to be sorted out and solved. The contractual concepts that are then applied to the results are discussed in detail in this paper.

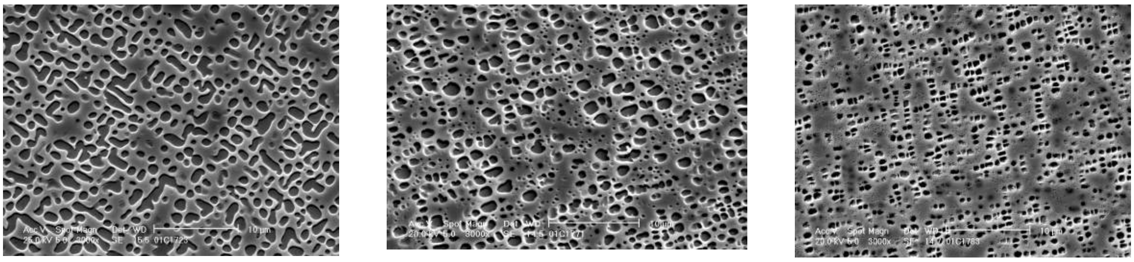

Figure 5: Microstructure of the gamma prime of a turbine blade. To the right a component with a normal microstructure. In the middle some coarsening and spheroidization can been seen indicating a small service damage and the structure to the left shows clearly long term temperature damage. Courtesy of The Technical Research Centre of Finland.

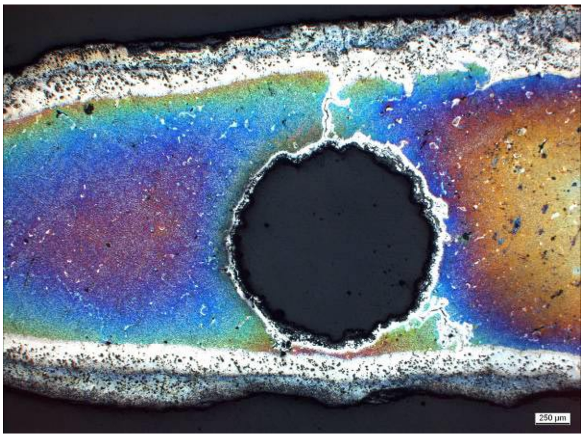

Figure 6: A magnification 10x of a gas turbine blade with a cooling hole. The structure has changed due to long term excessive temperature leading to internal oxidation of the protective layer (seen as the white region in the picture) on both sides of the blade and cracks on both sides of the cooling hole. Courtesy of The Technical Research Centre of Finland.

4.3 Diagnostic Monitoring

Many people incorrectly assume that diagnostic monitoring is limited to only vibration. While this technology has been used for decades, it is by no means the only method to monitor a combustion turbine. Proper machine diagnostics rely on accurate measuring and trending of the data to determine if a problem is developing. Typically machine diagnostic methods are listed below:

- use of human senses i.e. above all visual testing and analyses of sounds
- temperature measurements
- endoscopy
- vibration measurements and analyses
- thermography
- oil analysis

4.4 Endoscopy

Most turbines are today equipped with two or more holes for endoscopy. The reason for these is, of course, to be able to inspect the most stressed parts of components for damage like FOD (Foreign Object Damage) or IOD (Internal Object Damage). A typical FOD is presented in figure 7.

In many cases, there are not enough endoscope holes to give a complete picture of the critical components, such as all vane or blade rows. Inspectors try to inspect the first rows and the last ones and are thus able to make assumptions about components in between.

Endoscopes can nowadays be cooled by air allowing inspections to be undertaken on machines that have not yet cooled down completely. Also the endoscopes can be inserted around corners in all directions by the help of air jets.

All these features combined with the fact that the results of the inspection can be stored and comparisons made with previous inspection results means that endoscopy of turbines is very valuable.

Figure 7: Endoscopy of a compressor section in a gas turbine with foreign object damages (FOD)

4.5 Non Destructive Testing at Overhauls

The most commonly used NDT (Non Destructive Testing) methods and NDE (Non Destructive Evaluation) methods used in the maintenance and overhauls of combustion turbines are:

- Visual inspection, unaided or aided with the use of e.g. boroscopes or videoscopes, which will identify surface flaws
- Dye penetrant testing, e.g. searching for cracks and pores in materials such as blades, vanes and heat shields, will identify surface flaws
- Eddy current testing, e.g. searching for cracks in blades and vanes, which will identify sub-surface flaws

- Ultrasonics, e.g. thickness measurements and search for embedded discontinuities, which will identify internal defects
- Magnetic Particle Inspection (MPI), which can identify cracks, including fatigue cracks
- Hardness measurement (e.g. search for metallurgical changes in the material)

A more detailed description of the most commonly used NDT methods in engineering insurance can be found in the references list at end of this paper.

NDT-methods are constantly being developed so that they will function better and are easier and more reliable to use. The field that experienced the greatest achievements during the last decades is no doubt ultrasonic testing. Manual ultrasonic testing has always been complicated to perform and the results difficult to interpret. Reflections stemming from either discontinuities or geometric reflections in the structure are often hard to differentiate. Furthermore, the sizing of the discontinuities and especially their depth, which is critical for the strength of the component, is hard to establish. The testing has required very cumbersome and exact handwork and the sizing has depended on the reflective properties of the flaw and not solely on the geometrical size of the discontinuity. Nowadays two contemporary techniques have made a lot of progress and are on the point of moving from the laboratory to the field.

The first is, Time Of Flight Detection (TOFD), whereby the sizing of the flaws is made from real measurements of so called satellite pulses emerging from the tips of the crack. One can imagine a crack which is hit by sound as being a rope that starts to vibrate at the pace of the ultrasound. Its ends flap at the same time transmitting waves from the tips. These satellite pulses can be registered and the geometry plotted.

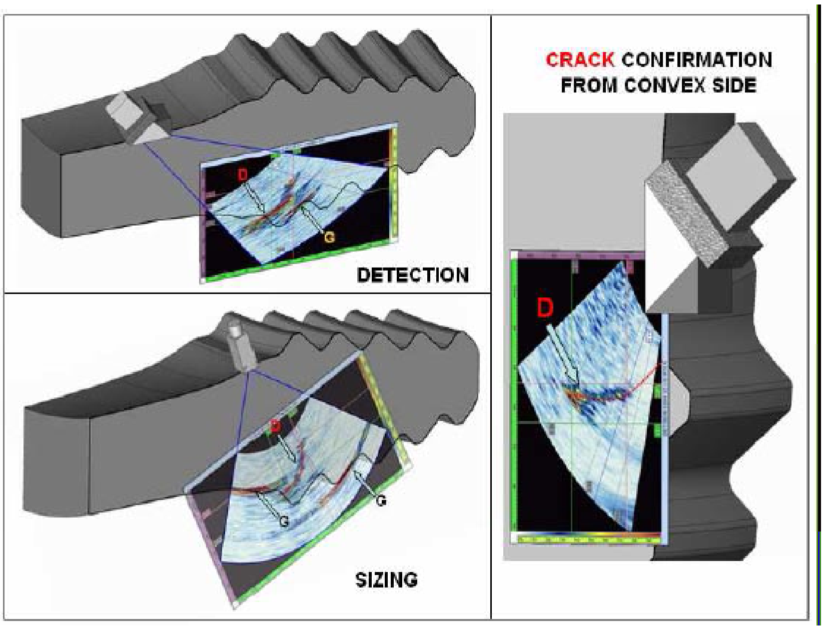

Figure 8: Example of Phased Array inspection features of a turbine blade for crack detection and sizing. P. Ciorau et al., 2008

Phased Array ultrasonic inspection has been used widely in the aerospace industry and has been applied to gas turbine component inspections. This form of NDT has been used for many years to evaluate disc integrity, especially around the blade serrations.

Phased Array NDT is a sonar based application used most commonly in medical diagnostics for examining foetuses in the womb. The technique emits the sound at different angles in front of the probe or scans perpendicular to the direction of the sound at the same time as the operator or manipulator is moving the probe. By combining the result with 2 D-or 3D - imaging a meaningful picture of the flaws in the component can be produced. See Figure 8.

When performing risk surveys of the level of machine diagnostics used at a plant with combustion turbines check-lists can be utilized for evaluating the quality of preventive maintenance practiced at the plant.

Typical questions to be answered could be as follows:

Checklist

1. Are all the safety devices on the turbo-set incorporated in the in-service maintenance program with systematic periodic function checks?
2. Are there several sensors for temperature, oil and steam pressure, and also for vibration that are connected to trip the turbine and not only connected to give a warning?
3. Do the operators of the turbo-set know the reason why the parameters measured are connected to trip the turbine or only connected to give a warning?
4. Are the maintenance overhauls in accordance with the recommendations of the manufacturer?
5. Has the maintenance program been adjusted according to earlier findings at the overhauls (proactively)?
6. Are the maintenance tasks and objects prioritized towards the highest prevailing risks (RBMI philosophy)?
7. Is the turbine equipped with holes for endoscopy and is endoscopy performed regularly e.g. yearly, every second year or every third year?
8. Are regular analyses of both the hydraulic and the lubricating oil in the turbine and the lubricating oil in the generator performed?

5 Contractual Concepts: Users - OEMs – Insurers

5.1 Service

Considering the advances in technology as well as the increased use of combustion turbines the way maintenance is undertaken continues to evolve. Technology and volume of repairs established more sophisticated processes by which the original equipment manufacturer (OEM) services the majority of their fleets.

Long-term equipment maintenance and service programs are known by many names such as contractual service agreements (CSA), long-term maintenance agreements (LTMA) or long-term service agreements (LTSA). For the purposes of this paper we refer to them generically as parts and service agreements. These agreements typically commit the original equipment manufacturer (OEM) to provide maintenance services for the equipment they manufacture. It is normally undertaken on an annual fixed-priced basis. This means that the OEM provides for a fixed price over a specified period of time:

- scheduled maintenance
- scheduled replacement of parts
- repairs during scheduled maintenance
- replacement of defective parts during maintenance if necessary
- provision of spare parts and availability of personnel

The alternative is maintenance and repairs handled on a per-incident basis.

Such a service agreement often binds the owner between 6 to 10 years and even up to 25 years.

As maintenance costs may be one of the few things owners can control, service agreements are attractive to them – especially regarding the predictability of relatively fixed long-term maintenance costs and contractually guaranteed or incentivised OEM support.

The main benefits of such service agreements for Owners are therefore:

- the reduced cash flow uncertainty
- the benefit of the latest technology innovations
- the risk-sharing
- the assurance on continuing support by the OEM and availability of spare parts
- the raised re-sale value of the plant.

The certainty and security provided by a long-term agreement is welcomed by banks, insurers and owners of small and mid-size turbines operating smaller fleets. Large fleet operators however are not keen to spend a large amount of money for the sake of certainty and/or a lack of flexibility.

Due to the complexity and wide range of such service agreements, there can be pitfalls for the Owner and Insurer. They can cause the Owner and Insurer to bear an inordinate amount of the risk or result in time-consuming disputes with the OEM.

The service agreement should clearly and completely define the OEM's scope of work with regard to the scheduled maintenance. It should include:

- a complete list of component parts which are subject to the OEM's scheduled maintenance obligations,
- definition of the OEM's scheduled maintenance obligations with respect to each part (inspect, repair, refurbish, replace, etc.),
- description of activities for each scheduled outage,
- definition of OEM's unscheduled maintenance obligations,
- definition of OEM's extra works.

Ideally the contract should also identify parts and activities that are not included in the OEM's scheduled maintenance works.

As a prerequisite it should be clearly defined in case of a loss or damage to part of the equipment causing an outage - which works belong to the OEM's warranty obligations or to the unscheduled maintenance obligations.

Unfortunately most of the agreements between the Owner and OEM are kept confidential and underwriters might not be aware of the full scope in the agreement.

For example, in a combustion turbine the individual parts are exposed to different forces and therefore replaced, repaired, refurbished after certain operating hours under a service agreement. Questions that might be asked are: how much of the life is left in each part and who owns the parts when a service agreement is in place? Does the OEM own them or do they belong to the machine and therefore to the Owner?

In case of a loss, the insurers are paying for the replacement parts. With a service agreement in place the parts may automatically belong to the OEM. Insurers might not be able to inspect the damaged part and recover any salvage value.

Often service agreements contain a waiver of subrogation and/or oblige the user to include the OEM as a named Insured under the policy, which should be taken into consideration during premium evaluation.

Even the Owners sometimes become dissatisfied with long term service agreements because they do not always do what the Owner thought they would. This can lead to a partnership with an Independent Service Provider (ISP) providing spare parts and/or maintenance services whose work the OEM will not warrant.

The intended usage of ISPs may provoke the OEM to threaten the Owner with cancellation of warranties and service agreements.

Trends and developments related to the combustion turbine equipment and service markets are highly dependent on the future development of combustion turbines, their usage and the type of Owners/Investors.

Within Europe, the UK is one of the fastest growing service markets driven by deregulation and the presence of Independent Power Producers (IPPs). By comparison in Germany, due to the historical strong allegiance between the big Owners and the OEMs, there is only a limited influence of Independent Service Providers.

Volatile gas and electricity prices are reducing long-term planning for power plant fleets. Lower electricity prices are reducing the investment in industrial plants and increasing the pressure to provide competitive services and spare parts. The increased requirements in terms of efficiency, flexibility and short term amortisation put an enormous pressure on OEMs and Owners.

5.2 Spare Parts

In the combustion turbine equipment market we can differentiate between three major levels of spare parts:

- OEM parts provided by OEMs
- non-OEM parts, which are new and manufactured under different patents or using improved design features by comparison with OEM parts to improve the operating life and performance
- grey market parts and also new or used parts that have been reconditioned (brown parts).

It is worth mentioning here that nearly every big OEM is also trying to capture a share of the repair and spare parts supply market from their competitors. As a result they are acting as an Independent Service Provider for the services and equipment of their competitors.

Combustion turbines contain highly sophisticated parts like rows of blades which are very expensive. No one would throw them away until all refurbishment options have been examined. Even if a refurbishment cannot be carried out, many companies would rather store these parts and wait for probable future enhancements of refurbishment technologies.

Major Power Companies and Manufacturers have started to redesign turbine blades to prolong their service life by reverse engineering. This is, to improve their operational efficiency, to increase the availability of spare parts and to save significant costs. The use of non-OEM parts for combustion turbines triggers a number of problems.

Conventional engineering, which produces a geometric model corresponding to the foreseen application suitable for manufacturing. By contrast, reverse engineering starts with the manufactured part and produces a geometric model. The quality of this model is highly dependent on the measurement techniques, data approximation errors, numerical methods, wear and tear of the object and ‘frozen-in’ errors. In addition for geometric models to achieve a positive solution, technical expertise and experience in the field of combustion turbine development and testing is absolutely essential.

One example of successful reverse engineering is the redesign of a combustion transition piece. The original part had a limited service life. A comprehensive operation and error analysis between new and refurbished parts was carried out followed by a test program on the redesigned part to determine the resonance frequency and oscillation modes. Based on the results the material was changed, the sealing was amended, the heat insulation improved and together with better wear-resistant connection elements and a different cooling system an alternative design solution with a much higher lifetime expectation was produced. In the meantime the OEM had also developed an upgraded combustion transition piece.

The above example shows that non-OEM spare parts can, under certain circumstances, be better than the original ones. OEMs can be forced into a challenging and creative competition with the non-OEM.

Where Owners use non-OEM spare parts, the manufacturers can cancel warranties and service agreements. Therefore the spare part market is bigger for smaller turbines than for larger ones.

Within the combustion turbine industry, non-OEM spare parts are generally of higher quality compared to other spare part markets.

The share of non-OEM parts in the equipment market is much higher for combustion turbines older than 5 years than for new models, upgrades and new parts because here the ISPs will not take the risk.

However, due to the fast growing service and equipment market not all of the ISPs can offer qualified services on highly sophisticated and complex machinery. Quality and durability problems have occurred on complex spare parts in the past.

Owners are mostly responsible on their own for verification and assessment of the quality of non-OEM service providers and non-OEM spare parts suppliers. There is no independent organisation to assist the Owner. Operators of smaller fleets are currently mainly dependent on the support of the OEMs, warranties and service agreements. An independent organisation would help them to get hold of ISPs more frequently. Large fleet operators are in a different and far better position to negotiate different contracts with the OEM.

The availability of spare parts is of utmost importance to the insurance industry. On the one hand it does not matter where the spare parts originate OEM or non-OEM parts might reduce a BI loss. On the other hand, Insurers/Reinsurers are not keen to pay for repairs and parts which might cause future severe damage to a combustion turbine.

Owners of larger utilities might buy spare parts and/or complete spare gas turbine/generators sets and store them to reduce downtime costs and expediting costs. If they did, the insurance premium for BI and consequential loss would be significantly reduced. Even operators of smaller fleets of identical combustion turbines could share a pool of spare parts which would help reduce their costs including insurance premiums.

Underwriting has to take into account the availability and location of spare parts even in remote areas.

For insurers/reinsurers the expense of buying, holding and managing spare parts on their own would tie up too much capital.

5.3 Other Contractual Issues

Members of the working group have come across issues between EPC contractors and owners regarding the handover of turbines. There have been instances where in gas turbine power stations under construction in various countries, the clients for these have been under such pressure to begin generating that they have required the contractor to connect parts of the station to the grid as soon as the turbines are ready but before the stations have been completed. This means the legal status of the turbines is uncertain since they still belong to the contractor/supplier having not been taken over by the client but they are operational in the middle of construction sites. In this regard, the contracts generally indicate that handover is achieved (and the onset of the maintenance period triggered) by virtue of the signature by the client of a formal certificate of provisional acceptance and nothing else. However, the policy will generally indicate that the construction/testing phase ends and the onset of the maintenance period is triggered upon a) completion of the works or testing, b) entry into service or c) expiry of the policy, whichever occurs first. In the event of damage being occasioned to a machine during this type operation a dispute could clearly arise as to liability and insurance. This could also complicate the calculation of the onset and termination dates for the maintenance coverage.

Checklist Parts & Service Agreements:

1. Which equipment components are part of the service agreement?
2. Which equipment components are excluded from the service agreement?
3. What are the OEM’s scheduled maintenance obligations?
4. What are the detailed maintenance obligations with regard to each part (inspect, repair, refurbish, replace, etc.)?
5. Description of the activities for each scheduled outage.
6. Which activities are excluded?
7. Definition of OEM’s unscheduled maintenance obligations.
8. Definition of OEM’s extra works.
9. Extent of warranty obligations and definition of consequent damage excluded from warranty.
10. Service Agreement for provision of spare parts and availability of OEM’s personnel only?
11. Waiver of Subrogation included?
12. In case of replacement of a damaged part: to whom belongs the damaged part? (salvage value)
13. Is the OEM to be included as Named Insured?

6 Typical Turbine Damages

Whilst damage to turbines attracts a lot of attention from insurers, damage is not common or frequently occurring. When it does occur, it can be expensive both in terms of physical repair damage costs and associated business interruption loss whilst units are out of service and repairs are being carried out. With large fleets of machines operating worldwide, periodic failures are almost inevitable with this type of equipment.

Accordingly, engineers, adjusters and industry claims professionals are accustomed to handling a wide variety of losses involving a wide range of gas turbine types. When analyzing losses, one possible focus could be the type of technology employed and the type and manufacture of machine, another the loss initiating components and yet a third the principal cause or triggering factor (IMIA WGP13 (00) E Large Gas Turbines - The Insurance Aspects (Update) Gerhard Müller, Martin Valk and Gregor Hosse. Presented by Helmut Heller).

Records of past failures provide a valuable source of information that can be used to devise measures to avoid future problems. Currently there is no comprehensive turbine loss register (despite efforts on the part of certain brokers to maintain statistics) and Insurers & reinsurers may feel that such a register should be set up and made publicly available. Care would be required to exclude commercially sensitive information on the equipment of individual OEMs. Owners, Operators, OEMs Insurers and Reinsurers are however likely to find a register useful.

6.1 Loss Analysis: Technology and Machine Type

Technology

From the technology standpoint, the turbine market can be segmented into prototype, unproven and proven technology, with some so-called proven technology on occasions still being regarded by the insurance industry as “problematical”.

Prototype

Insurance companies are extremely leery of underwriting such models; the insurers want to avoid subsidising the OEM’s R&D programs by paying for the consequences of failures. This is especially true today, as insurance markets harden. The first 2000 hours of operation seems critical to demonstrate the validity of component design.

Unproven

This category is reserved for units that have yet to achieve “proven” status based upon the nature of their operations. In addition, when a manufacturer makes what are deemed “substantial engineering changes” to a model, even a previously “proven” model can be reclassified as unproven. Although insurance is still available, terms and conditions as well as exclusions on certain components and consequential damages may involved until trouble-free operation is realized.

Proven

There are some differences of opinions in the insurance industry regarding the number of machines and the number of operational hours required before they can be considered as “proven” technology. However, some “proven” technology may still be regarded as problematic. Many major insurers have come to a common view concerning the technical risks associated with advanced CT models. Certain models had a poor reputation in the past. There are also broader business considerations based on whether such equipment is being included in a larger comprehensive package (EPRI combustion turbine experience and intelligence report: 2003).

Machine Types

Following wholesale reorganization of the gas turbine market in the last decade there are now really only four manufacturers of heavy frame industrial turbines (GE, Siemens, Alstom & Mitsubishi) and two main sources of aero-derived units (GE & Pratt and Whitney).

Heavy Frame Industrial Manufacturers

Models of particular interest include the more advanced F, G, and H class engines. The broker Marsh produced a list of these models in 2004 that is reported in the EPRI combustion turbine experience and intelligence report: 2005, available on the internet. The list outlines the main turbine types by manufacturer and indicates which models were, in Marsh’s experience at that time, regarded by insurers as prototype, unproven, proven or problematical.

This list is important because it illustrates the magnitude of the concern for CT failures from the new technology. The trend seems to be that the newer classes of turbines incur more failures due to “teething problems” and, furthermore, higher repair and replacement costs are expected because of their more sophisticated design and the metallurgy employed.

Aero-derivatives

The main competitors in the aeroderivative market are General Electric, Pratt & Whitney and Rolls Royce.

6.2 Loss Analysis: Loss Initiating Components

From a historical perspective, as reported in the EPRI combustion turbine experience and intelligence report: 2003, the major systems associated with a generic F-class combustion turbine failure are the compressor section (35 percent of failures), combustor (29 percent of failures), and turbine blading (28 percent of failures).

More recent figures suggest the following breakdown for newer models (EPRI combustion turbine experience and intelligence report: 2003):

• Rotating Blades & Parts of Turbine	42%
• Stationary Buckets & Parts of Turbine	21%
• Bearings	14%
• Rotating Blades & Parts of Compressor	12%
• Recuperators and Exhaust Pipes	5.8%
• Stationary Buckets & Parts of Compressor	5.3%
• Other	4.8%

Fittings Other Than Piping	3.4%
Fire Chambers and Hot Gas Areas	1.1%

Notwithstanding the foregoing figures, as reported in the Combined Cycle Journal Third Quarter 2006, compressor issues dominate podium time at user-group meetings these days. Every frame OEM has had its challenges, virtually all of which are resolved over time and at significant cost. Compressor problems probably should not be surprising given (1) the pressure on OEMs to deliver machines with the highest power ratings and efficiencies possible at the lowest possible prices, and (2) the cycling operating mode of most large frames today, which was not envisioned by OEMs and users when originally designed.

Turbine blade & vane failures continue to be a problem. Achieving higher combustion turbine efficiency by increasing rotor temperature requires improvements in the cooling systems of rotating blades and stationary vanes. At the same time, rotating blades in particular need the following:

- Better oxidation and hot corrosion resistance
- High thermal fatigue resistance, low-cycle fatigue resistance, and high-cycle fatigue resistance
- Excellent micro-structural long-term stability
- High creep resistance.

Such changes have motivated development of more sophisticated new substrate materials and protective coatings. For blades and vanes, polycrystalline materials are giving way to directionally solidified and single-crystal alloys. Also, thermal barrier coatings (TBC) are more commonly used in blades. Nevertheless, failures continue to occur.

6.3 Loss Analysis: Causative Processes

As mentioned above, all gas turbine losses are assigned to typical categories of causes. In this section we distinguish between 4 different loss categories:

- Technical & design
- Duty cycle, airflow, gas flow & fuel
- Quality assurance
- Operation & maintenance

As commented in the Combined Cycle Journal Second Quarter 2007, it must be stressed that often the assignment to the different categories is not quite clear and in many cases insurers' representatives, manufacturers and operators may have divergent views or assessments. In this respect, failure analysis is a term that can have a broad definition. For example, some might consider it identifying the damage mechanism; to others it might be determining both the damage mechanism and cause; still others will see it as determining the root cause of the damage. These certainly represent different levels of effort and cost. Assembling a root cause analysis (RCA) team that will be both collaborative and objective, as well as protect the interests of all parties, is a difficult task. The team should include representatives of the owner/operator, OEM engineers, the EPC and its subcontractors if still in warranty, insurance adjuster, and repair vendor. A RCA team comprised only of the OEM's personnel and its contractors should not be accepted by insurers or their adjusters - the OEM has commercial issues that cannot be overcome. Caution should be used if a parts and service agreement is in place. These agreements can restrict the accessibility of the offending hardware and limit the usefulness of any analysis. Keep in mind, too, that, in many cases, there may be no determination of a single root cause for the failure - the RCA team's output will be a weighted list of contributory causes.

Turbine technology continues to be in a state of almost continuous development as efficiency improvements are sought. As designs are fine tuned and operating parameters extrapolated unintended consequences can and have occurred leading to failures. There have even been instances where a modification designed to solve a fault has been the source of a secondary fault. Below in table A are examples of technical design problems that the authors of this paper have encountered.

A	**Technical & design**
1	Insufficient design clearance between rotor and stator blading in the compressor resulting in rubbing and detachment of material causing significant damage to components downstream.
2	Compressor first row blade distress, with downstream DOD
3	Material erosion of initial compressor stages associated with fogging or water injection, scale deposits on blading as well as mechanical blade failures due to airflow stalling or surging.
4	Gas turbine compressor contamination due to poor evaporative cooler design
5	Compressor diaphragm hook-fit wear and failure
6	Flame instabilities within the burner area of the combustion chamber leading to vibration and subsequent component cracking.
7	Flashbacks moving the burner flame front from its intended location impinging on components not designed for high temperatures and damage due to melting and detachment.
8	Gas turbine loss of stage 1 blades due to root seal pin locking up to change the resonant frequency
9	Cracking/liberation of first stage turbine disc
10	Failure and detachment of thermal barriers and insufficient blade cooling leading to thermal related damage associated with increased firing temperatures.
11	Gas turbine loss of latter stage vanes due to vane movement/erosion/liberation

Successful turbine operation is dependent upon the quality of the fuel that is burnt within it. For combustion to occur large quantities of air are also needed and problems with either the fuel or the air supply can have damaging consequences.

Furthermore, turbines are utilized to provide power on a continuous basis or just to satisfy peak consumer demand for a short operating period during each day. A unit that is operating on a continuous basis will incur few starts and stop thermal cycles. However a unit that is operating to meet daily peak loads will accumulate an increased number of starts and stop thermal cycles. The experience of these engines is different because of the significant variation of thermal fatigue damage cycles that are produced within the same actual operating hour period. The operator using the engine to satisfy peak loads will accumulate greater fatigue damage during the same operating hour period. Each startup-to-shutdown operation of the gas turbine duty cycle subjects the hot parts, particularly combustor hardware and row 1 blades and vanes to rapid changes in temperature and mechanical loading. A gas turbine unit that has frequent startup and shutdown duty applications (e.g. peaking and mid-range operators) will experience shorter hot parts durability than a base load duty operator. The effect of partial load cycling of the gas turbine will have an effect on parts durability. The effect of rapid and frequent load changes is analogous to that of frequent startup and shutdown cycling from the standpoint of hot parts durability. A trip from full load introduces an increase in the thermal strains in the part, which result in an increase in fatigue damage for this cycle.

The firing temperature level directly affects the operating metal temperatures and the resulting effects on the component due to oxidation, creep and fatigue. Combined cycle units are optimized for the overall efficiency obtained from the gas turbine cycle and steam bottoming cycle. The optimization results in relatively small variations in the firing temperature when the units are operating near base load operation because the maximum steam bottoming cycle efficiency is obtained at high gas turbine exhaust temperature. The airflow into the gas turbine is reduced at part load to maintain a high exhaust temperature, which therefore requires firing temperatures to be near base load operation. Load fluctuations in combined cycle operation result in minor fatigue damage resulting from small gas temperature excursions. However, a simple cycle unit only has a gas turbine and the firing temperature scheduling to base load is dependant upon the load. Units that operate in this fashion will incur increased fatigue damage as a result of load fluctuation demands in the electrical grid. It is therefore important to recognize the difference in operation characteristics of both simple and combined cycle operation on the fatigue damage that is introduced during partial load cycle effects. The latest models of "F" and "G" class gas turbines operate at almost 300 to 400°C (720°F) higher firing temperatures than the previous "D" class technology. Consequently, the thicker-wall turbine blades that were common practice in the industry for row 1 blade applications have been replaced by thinner wall blades in conjunction with more efficient internal blade cooling technology. As a result of the changeover to thinner wall designs the service expectancy is now more oxidation and fatigue life dominated rather than creep in the previous generation models.

Below in Table B are examples of duty cycle, airflow and fuel contamination problems.

B	**Duty cycle, airflow, gas flow and fuel**
1	FOD at compressor inlet
2	Corrosion at compressor inlet due to environmental factors, causing liberation of blades at compressor front end, with subsequent downstream damage
3	Dust particles drawn into the compressor as a result of insufficient air filtering causing damage throughout the machine.
4	Corrosion of stator parts in compressor at reverse Wilson line, causing liberation of blades, with subsequent downstream damage
5	Stall/flutter flow excitations contributing to blade and stator failures
6	Blade scaling or impingement causing excessive blade oscillation and resulting mechanical failures
7	Impurities in fuel and chemicals causing deposits, high temperature corrosion of combustor internals, chloride contamination, flame impingement and scaling in the turbine section.
8	Varying fuel quality or irregular fuel supply causing flame pulsation leading to mechanical damage which is aggravated by high temperatures and pressures.
9	Change in gas quality (sudden appearance of hydrocarbon fluid) causing flame pulsation in a units designed to run on either gas or liquid fuel
10	Blocked cooling passages leading to component overheating and severe damage.
11	High-temperature creep/oxidation and thermo-mechanical fatigue cracking of turbine blades leading to blade failure.
12	Gas Turbine hot corrosion due to poor fuel/water

Turbines are high precision machines operating at high temperatures pressures and speeds. Components therefore need to be manufactured to very tight tolerances if they are to operate correctly. Poor quality components can fail with disastrous consequences. Below in table C are examples of failures resulting from inadequate quality assurance.

C	**Quality assurance**
1	Use of inferior quality components resulting in substantial damage.
2	Use of non OEM or aftermarket components leading to voiding of manufacturer warranties
3	Vibration and blade rubbing due to rotor lifting shoes not removed following manufacture.
4	Explosion following failure of compressor rotor shaft on failure of compressor/turbine marriage bolts
5	Turbine multiple blade damage from detached inlet segment (repaired item had weld porosity)

For turbines to function properly over prolonged periods correct operation and maintenance is crucial. Operators need to know how to conduct normal operations without building up problems through repeating incorrect procedures. They also need to know how to react when alerted to a problem. Taking the wrong decision is an all too common cause of failures. Maintenance work is required from time to time with all machines. Despite well developed maintenance procedures mistakes are still made some of which have caused failures either immediately after maintenance work has been completed or months or even years later. Examples of loss associated with maintenance and operations are shown in Table D.

D	**Operations & maintenance**
1	Lack of experienced operating and maintenance personnel leading to failures in communication and omission of key steps.
2	Excessive start-up speed attributable to operating and/or control malfunctions resulting in severe rubbing and component failure through differential expansion.
3	Cooling air valves which remain closed following preventative maintenance, blocked or incorrectly connected lubrication system leading to severe damage.
4	Starting up a machine without the speed pickups connected by mistake
5	Loss of lube oil due to failure of backup system
6	Gas turbine over speed and generator catastrophic failure
7	Turbine multiple blade damage from transition piece debris resulting from high cycle fatigue
8	Turbine multiple blade damage due to failure of tbc due to blocked cooling holes
9	Rotor bearing damage due to failure of dc pump during trip shut down
10	Gas turbine lube oil system failure due to improper wiring on commissioning
11	Gas turbine coupling failure due to incorrect lubricant combined with misalignment
12	Gas turbine lube oil system failure due to insertion of flaw in control system logic during commissioning
13	Replacement rotor for damaged unit produced with too high blade clearances with casing

7 Examples of Interesting Failures

The final chapter of this paper includes a number of interesting failures:

7.1 Large gas turbine in a power generation application
7.2 Large frame gas turbine in a refinery – operates on gas and liquid fuel
7.3 Large frame gas turbine – operates in power plant with natural gas
7.4 Large frame gas turbine – evaporative cooled inlet filter house – natural gas
7.5 Aero derivative gas turbine in a power generation application – liquid and gas fired
7.6 Aero derivative gas turbine – heavy fuel oil fired in a power generation application
7.7 Large frame "Advanced" gas turbine – combined cycle application on natural gas
7.8 Large frame gas turbine – power generation application fired on natural gas
7.9 Large frame 50 cycle gas turbine – 200 MW power generation application
7.10 Large frame unit in combined cycle plant – natural gas fired
7.11 Large frame gas turbine in combined cycle facility
7.12 Large frame gas turbine – power generation application adjacent to a cement plant
7.13 Large frame gas turbine – combined cycle power generation application
7.14 Large frame gas turbine – combined cycle power generation application
7.15 Large frame gas turbine – combined cycle power generation application
7.16 Large frame gas turbine – combined cycle power generation application
7.17 Large frame gas turbine – open cycle peak lopping and load following power generation application.

Each example is described in three sections:

1. Description of Loss
2. Cause
3. Conclusion / Loss Amount.

Photographs showing the damages are included at the end of this section.

7.1 Large gas turbine in a power generation application

1. The gas turbine had been operating without vibration or other issues with temperature, such as exhaust spread. The unit tripped automatically on high exhaust temperature followed immediately by alarm on high vibration and fuel system trip. The coast down from full speed was much quicker than usual and it would not go onto barring gear. The unit was opened and damage was found in the combustion system as well as downstream in the turbine section.

2. The cause of the initial damage was found to be combustion dynamics that led to the release of a fuel nozzle tip which passed into the turbine section and started the cascading damage as seen in the photo.

3. The history of this unit revealed that there had been a number of experiences of high dynamics during fuel changeover and during starts at lower loads. The compressor section experienced rubbing which was able to be hand blended and no blades or vanes replaced. The unit was re-tuned after the loss and has operated well since. The property damage on the unit was over $15 million USD.

7.2 Large frame gas turbine in a refinery – operates on gas and liquid fuel

1. The gas turbine had been operating normally, but with a high exhaust temperature spread and reduced load. The temperatures were not excessive and the average was lower than normal, so it was considered safe to continue operation because of the lower temperatures. Without warning, the unit tripped on high exhaust temperature simultaneous with high vibration and the unit coasted down to zero speed and was placed on barring gear. Visual inspection of the exhaust plenum revealed that the turbine was damaged and had to be opened.

2. The exhaust temperatures, even if a low average, have differences in density of the hot gas passing through the inlet nozzle. This difference caused a pulse on each blade as it passed from the “hot” to “cool” areas and thus was operating with a resonance on the blades. This caused the airfoil to fail due to high cycle fatigue. The root cause of the exhaust temperature spread was blockage in some fuel nozzles due to poor quality fuel oil.

3. The exhaust spreads were in alarm, but were ignored until a better time could be planned for a shutdown to make the inspection. There was no compressor damage, so this failure was over $12 million USD.

7.3 Large frame gas turbine – operates in power plant with natural gas

1. The loss involved damage to the leading edges of many compressor blades due to a foreign object that entered the compressor inlet after an overhaul. The unit had been operating for the period needed to tune to combustion system and a final inspection of the inlet was made for acceptance of the unit. A scrape was found on the inlet and nicks and tears were found in the compressor.

2. Inspection of the inlet plenum revealed that debris was left in the area after welding was completed on the inlet silencers and other repairs to the inlet ducting. The piece or pieces that passed through were not located, but the location and depth of the nicks and impact sites were too large and low on the airfoils to hand blend.

3. The eventual repair required that the rotor be removed and shipped to a qualified shop to un-stack the compressor rotor to replace the blades. There was not

additional generation of debris by the material passing through the compressor section, such as bits being broken off downstream. Therefore, the compressor was the only section affected, not the combustion or turbine sections. The loss was over $6 million USD.

7.4 Large frame gas turbine – evaporative cooled inlet filter house – natural gas

1. The unit was shut down for a regular boroscope inspection that is completed every 6 months. There was no evidence of operational issues or efficiency problems in the compressor. The damage was found and because of the large dents seen here, there was concern about tears in the airfoils that could lead to vane liberation. The unit was opened and additional damage found.

2. This particular manufacturer installs shims between selected vanes and vane carriers to assure the spacing is proper and the vanes are tight during operation. Some of the larger shims were found to have migrated out, entered the air stream and caused impact damage to the blades and vanes.

3. The damage was concentrated in the compressor section and there was no damage or contamination that occurred in the combustor or in the turbine section. The compressor rotor was exchanged for another and the vanes were replaced on site. The loss was over $8 million USD with the exchanged rotor rather than a simple repair.

7.5 Aero derivative turbine in a power generation application – liquid and gas fired

1. The unit had been operating with poor, but not excessive exhaust temperature differentials, then changed such that one section became much cooler. The plant shut down the unit and inspected to find that there was splattering of metal in the last stages and the boroscope revealed breaching of the vanes of the inlet stage. The unit was removed from the compartment and shipped to a shop for inspection and repair. Inspection found melting and splatter in the hot gas path.

2. This loss occurred in the turbine hot gas path when the fuel system experienced contamination of the fuel nozzles and resulted in a poor flame pattern. This caused the wall of the annular combustor to melt by the flame impingement and the fuel nozzle to melt off, not as a single piece, but as a molten mass. This led to blockage of the inlet edge cooling holes, overheating of the nozzles and breaching of the vanes. This caused cooling air starvation to the other vanes and shut down as the exhaust temperatures varied over the limit.

3. The repair required that much of the hot gas path be replaced and the remaining portion repaired by stripping the molten material off the vane and blade surfaces. There was no damage to the compressor, but the combustor and fuel nozzles were replaced. The loss was over $2.5 million USD.

7.6 Aero derivative gas turbine – heavy fuel oil fired in a power generation application

1. The component seen in photo 7.6 was in operation for 4 weeks. The unit had operated normally after a major overhaul for 4 weeks and started experiencing exhaust temperature spread changes that quickly increased and before the unit could be run back (unloaded) the turbine tripped on high temperatures and high vibration. It was clear that something catastrophic had occurred and was removed and shipped to

a shop for inspection and repair. The damage was determined to be hot corrosion from contamination of the fuel.

2. An additive had been mixed with the fuel oil to reduce or eliminate the heavy metals, but apparently was not effective. The unit had operated for years prior with diesel and gas and the change to heavy oil was completed during the major outage 4 weeks earlier.

3. There was contamination and corrosion damage throughout the hot section. This was a small aero gas turbine, so the repair was the replacement of the HPT Module and the fuel nozzles. The loss was over $2 million USD.

7.7 “Advanced” gas turbine – combined cycle application on natural gas

1. Unit was operating normally with no signs of vibration, compressor efficiency or other issues. The unit came off line due to a compressor surge simultaneous with extreme vibration, then exhaust temperature spike. The rotor rolled down to zero speed quickly and could not be placed on barring gear. The inlet was inspected and found to be in good condition except for very small bits of debris on the floor of the inlet ducting and small impact sites on the leading edges of the visible blades. A boroscope revealed severe damage and the unit was opened.

2. The unit is close to an ocean and had evidence of pitting and corrosion on the vanes and blades. A crack had developed on a vane in the 4th stage which started at a pit and progressed across the airfoil by high cycle fatigue. The cause of the damage was the eventual loss of a stage 4 vane which caused further loss of blades and vanes that cascades through the compressor and resulted in the “corn-cobbed” condition in photograph 7.7 and on the rotor itself.

3. The damage to the unit included the entire set of blades and vanes in the compressor section. Also, due to the severe gouging on the interior of the compressor casing, it had to be replaced. There was severe debris that passed into the combustor, many of the smaller bits entering the turbine and causing impact damage to the blades. The cooling passages in the blades and vanes were both filled with fine metallic dust generated by the rubbing and resulted in replacement of half the hot gas path and repair to the remaining. The cost was over $19 million USD.

7.8 Large frame gas turbine – power generation application fired on natural gas

1. The loss event was a complete shut down without warning and tripping on high exhaust temperatures and high vibration of the turbine rotor, a common action when part of the turbine section has failed There was no warning condition such as an exhaust spread or increasing vibration, so the failure was most likely of a rotor component.

2. On opening, there was loss of blades in the turbine section and severe rubbing damage in the compressor. The eventual root cause was considered to be failure of a blade attachment due to cracking that had occurred in the attachment. The repair required that two turbine disks, all the blades and vanes and the compressor blades and vanes be replaced. Also, because of the debris generated by the rubbing in the compressor, the combustion system and the air cooling system were contaminated and required cleaning and overhauls.

3. The damage was to all sections of the unit. There was also contamination and some tube damage in the HRSG. The replacement of components and repair of those that were contaminated was concluded with a cost of over $25 million USD.

7.9 Large frame 50 cycle gas turbine – 200 MW power generation application

1. The unit had been operating normally, but had a history of Inlet Guide Vane sticking and the pins shearing on the operating arms. On the day of the loss event, the unit had operated well with no issues, when the vibration forced the unit out of service. It coasted down quickly and an inspection into the inlet revealed severe damage.

2. The cause was found to be loss of a single IGV that passed through the compressor, generating additional debris as the blades and vanes broke off bits downstream. The IGV was found to have fractured at the guide shaft, allowing the IGV to break away and pass into the compressor. This caused damage to the compressor, contaminated the combustor and caused splatter and impact damage in the turbine section.

3. The damage was extensive and after proposals were considered, the costs to repair the turbine were similar to those required for a replacement unit available from another project that had been cancelled. The time to install the replacement unit was less and the final decision was to replace with the upgraded unit rather than repair. The eventual property damage cost was $21 million USD.

7.10 Large frame unit in combined cycle plant – natural gas fired

1. Severe impact damage to the blades and vanes throughout the compressor section. The unit was shut down during a routine boroscope inspection and impact was found throughout. There was no change in the vibration signature of the unit nor was there any recorded change in compressor efficiency. The damage was discovered 6 months after the unit had experienced a major overhaul. Inspection of the inlet and areas around the inlet and the ducting showed it to be free of any damage or missing pieces that may have caused impact.

2. The cause was found to be at least three hex nuts that passed through the unit. Photograph 7.10 indicates a nut that was found in the outlet guide vanes that may have passed through the compressor during operation with the marks on the vanes and blades having the same shape as the nuts.

3. The nuts were simply considered to have been left in the unit by accident and were not considered as intentional, although many questioned that conclusion. The damage required only the replacement of vanes and blades of the compressor with nothing in the combustor or turbine because the foreign objects did not generate additional debris. The repair and replacement costs were over $7 million USD.

7.11 Large frame gas turbine in combined cycle facility

1. A claim was made for contamination that was found under the stage 1 blades during a hot gas path inspection. The same finding was found to have caused failure of blade airfoils about 1 inch above the platform. These blades were removed and inspected for cracking and the rotor was removed for cleaning. It was not a claim eventually.

2. The cooling air for the rotor exits the compressor, is cooled and reinjected into the rotor interior. The cooling air piping was made of carbon steel and had experienced

moisture that led to rusting of the interior. This fine rust during operation made its way to the rotor and under the blades to lock the sealing pins into position, then causing the blades to resonate at a node above the platform. There was no failure.

3. Since there was no accident because the rusting occurred over time and the fine debris was generated and passed into the blades over time, with no component failure, there was no accident, but was very close to having lost an airfoil on the stage 1 blades. However, notwithstanding the lack of policy cover, the work to clean the system and replace many blades was over $10 million USD.

7.12 Large frame gas turbine – power generation application adjacent to a cement plant

1. The unit had been operating for about 9 months since the last hot gas path inspection and was not experiencing any reported problems with output or efficiency other than the normal deterioration. Within a short period after the last change in inlet filters, the compressor began to lose efficiency and the exhaust temperatures began to show a spread that increased with time. Eventually, the output suffered and the unit was shut down for inspection. Boroscope revealed that there was severe contamination by a white powder and the cooling channels throughout the blades and vanes were blocked and many of the vanes were burned out as shown in the photograph 7.12.

2. The material in the cooling passages and on the compressor components was from the cement plant adjacent to the facility. When asked about the filters, the records showed that they were changed regularly and the boroscope reports showed no contamination. However, further discussions revealed that the filters were changed on a specific date, but the records showed that the plant was at full load all that same day. The filters were changed at load and the debris was allowed to fall off the filters and entered the unit.

3. The powder from the plant had solidified on the compressor components to the extent it could not be removed. The combustion system and all the vanes had the same problem with the solidified material blocking cooling holes. The cooled blades and shrouds in the turbine could not be cleaned and had overheated. A replacement rotor and all new stationary components were installed after significant cleaning with a cost over $27 million USD.

7.13 Large frame gas turbine – combined cycle power generation application

1. The unit was operating normally when the operators control screens froze. After consultation by telephone with the Original Equipment Manufacturers (OEM) it was decided to bring the unit offline. The turbine emergency stop buttons were operated without effect. The operators then considered cutting the supply of gas to the burners. However, they were concerned this could lead to a motorisation of the generator. The plant staff then considered that the best way to stop the machine was to manually open the main unit breaker. When the main circuit breaker was opened, isolating the generator from the grid with a full load throw off, the machine went into an overspeed condition, effectively self destroying.

2. The underlying root cause was the freezing of the control systems. However, the intervening cause was the operators' decision to open the main unit breaker at full load. If a major problem with the control/monitoring of the unit occurs, the generator circuit breaker must not be opened under load - since it is unknown if the speed governor and overspeed protection will function. The connection to the grid is the only means to avoid an overspeed. The operators should have manually closed the

gas valves and then opened the generator breaker when the load was < 0 MW (in the event this didn't happen automatically by the reverse power protection).

3. Damage to the turbine was complete or almost complete and significant damage was occasioned to the compressor section. The generator suffered both electrical and mechanical damage and an oil line was severed starting a fire within the turbine enclosure. A replacement unit was sourced and the approximate property damage was $35 million USD.

7.14 Large frame gas turbine – combined cycle power generation application

1. The unit was being taken out of service for a routine 24,000 hours combustor inspection. Load was gradually reduced to approximately 10 MW. The unit main circuit breaker was then tripped manually to isolate the unit from the grid. The operator then proceeded to perform an overspeed test, apparently per manufacturer's recommendations, prior to stopping the unit. Approximately 3 seconds after the operation of the overspeed trip, high vibrations were noticed and the trip for high vibrations operated on all bearings. This coincided with a loud noise emanating from the compressor section of the turbine.

2. It was eventually concluded that there had been entrance of excess quantities of foreign material (dirt) through the filtration system. The build up of material caused loss of clearance and increased friction between the variable guide vane inner cylinder-sealing surfaces and inlet cylinder casing in the "O" rings – resulting in increased torsional loading on the variable vanes and shear loading on the retaining spring pins. This, in turn, resulted in the failure of the spring pin on one vane, allowing that vane to settle into a position out of alignment with the remaining vanes, causing an abnormal loading of the row 1 blades; each time they passed the out of alignment vane – a "once per rev excitation". This caused development of high cycle fatigue cracking on the compressor row 1 blades to the extent that one blade eventually broke off during the overspeed test causing catastrophic downstream damage.

3. Blades and vanes in all rows of the compressor were total losses. All of these components were replaced in the repair. There was some material carry over (metal splatter) into the turbine section. Damage was seen to the first and second rows of blades and vanes as well as ring segments of all four rows – as was anticipated the majority of these components would prove to be capable of repair. The property damage loss amount was $10 million USD.

7.15 Large frame gas turbine – combined cycle power generation application

1. While operating at full load the gas turbine tripped off line following a reported high vibration incident. This coincided with a loud noise emanating from the compressor section of the turbine. Inspection undertaken at the bellmouth intake adjacent to the plenum chamber revealed significant impact damage to all of the inlet guide vanes (IGV's) with the metallic remains of many of the IGV's lying on the floor of the plenum chamber and several metallic particles embedded in the acoustic insulation of the chamber. Inspections also revealed significant damage to the first two stages of compressor blades that were visible from the bellmouth.

   The following sequence of events took place:

   - Water soluble corrosive elements entered the turbine.
   - Leading edge corrosion pitting occurred on the first row blades in the compressor.

- The corrosion pitting caused a local stress raiser, reducing the Goodman properties of the blades and allowing fatigue crack initiation on the leading edge of the blades, just above the blade platform.
- The cracks then propagated by a high cycle fatigue mechanism under engine order excitation and/or start up & shut down stresses.
- Eventually one blade failed causing downstream damage.

2. The cause was, thus, principally attributable to the aggressive environment in which the plant operated – in an industrial complex in a marine environment. However, there was some discussion with the OEM regarding possible lack of damage tolerance in the blade design & possible harmonics issues and/or rotating stall on start-up and shutdown.

3. Blades and vanes in all rows on the compressor sustained significant damage, to the extent that all constituted total losses. All of these components were replaced in the repair. There was some material carry over (metal splatter) into the turbine section. Damage was caused to the first and second row HGP components, which were beyond repair. The property damage loss amount was $16 million USD.

7.16 Large frame gas turbine – combined cycle power generation application

1. The gas turbine tripped off line following a reported high vibration / low compressor discharge pressure incident. As soon as was possible, an inspection of the compressor was undertaken with a boroscope. This revealed significant damage to blades from all stages of the compressor, from rows 2/3 onwards that were visible with the boroscope. Also, damage was noted to turbine hot gas path components.

2. A 4th row compressor rotor blade failed and was carried down in the air stream, causing impact damage to all subsequent compressor rotor blades and stator vanes. Material was carried over through the combustion section impacting turbine blades and vanes. The cause of the blade failure was established as high cycle fatigue, initiating at a corrosion pit formed by corrosion of the stator parts in the compressor at the reverse Wilson line.

3. Blades and vanes in all rows on the compressor sustained significant damage, to the extent that all constituted total losses. All of these components were replaced in the repair. There was some material carry over (metal splatter) into the turbine section and non-repairable damage was seen to the first and second rows of blades and vanes as well as ring segments of all four rows. The property damage amount was $16 million USD.

7.17 Large frame gas turbine – open cycle peak lopping and load following power generation application

1. The unit was synchronised and ran on base load for three days, following which it tripped from load on a high vibration alarm (generator bearing, turbine side) as well as exhaust gas high temperature alarm. Boroscope inspection and subsequent detailed inspection after removing the covers indicated a failure of a blade in the first stage of the hot gas path section. At the time of the event, the machine had not accumulated enough equivalent operating hours or equivalent starts to reach its first combustor inspection from new. Cracks observed on the leading edge pressure side airfoil and platform of 1st stage turbine blade.

2. A blade of the first stage of the turbine cracked and subsequently failed due to a low cycle fatigue mechanism. The cracks initiated from the leading edge cooling holes

where they join the main serpentine cooling channel. Other than the failed blade, other blades exhibited cracks in the same position on the airfoil. On all blades an excessive amount of red dust (corrosion products) was seen in the cooling channels and locking pin grooves. Almost all blades in the first row of the turbine exhibited cracks in the blade platform indicative of thermal cycling. It seems there were two contributing factors operating together, namely (1) Poor functioning of cooling holes, due to red dust plugging (corrosion products incoming from the compressor) creating a situation where the blades were operating too hot, and (2) Thermal cycling due to the fact the unit was operating on open cycle for peak lopping and load following.

3. There was severe domestic object damage to all major components of the hot gas path of the turbine. The OEM initially recommended full replacement of these components and all required miscellaneous hardware. In addition the OEM quoted for replacement of fuel nozzles, combustor baskets, transition ducts and transition seals, although there was no incident related damage to these items. Further analysis demonstrated that many of the damaged blades, vanes and ring segments could be repaired. The property damage amount was $11 million USD. A similar loss occurred at another plant, where the extent of the damage was much more severe, resulting in property damage of $19 million USD.

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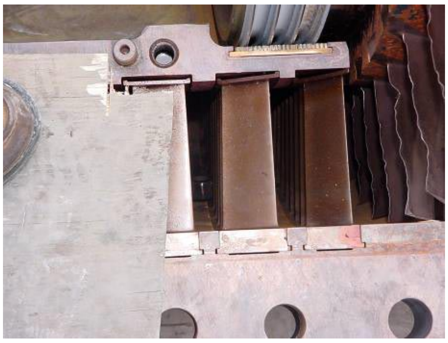

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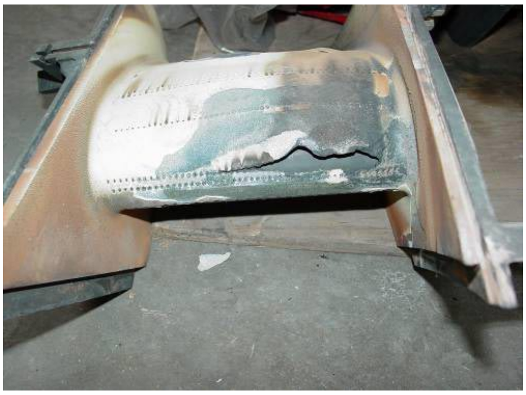

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