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Gas Turbine

Short and Long Term Operation and Failure Mechanisms

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1 ABSTRACT:

In the last decades, gas turbine technology has evolved in pursuit of higher efficiency and increased flexibility. These objectives impose higher operating temperatures, higher pressure ratios and faster ramp rates. These tougher operating conditions impose increased stresses on the gas turbine components affecting their durability. In addition, longer operating intervals between scheduled inspections increase the risk of component deterioration and failure with potential secondary damage.

Under these circumstances, detection of issues and their subsequent correction is fundamental to enhance the reliability of new or modified gas turbines. This process is part of the validation process applied to gas turbines prior to offering them to potential clients. The process can be divided into short and long term validations where different failure mechanisms and defects become apparent.

Short term validation allows quick detection of unexpected issues resulting from difficult to estimate or simulate phenomena or from secondary effects overlooked during the design stage. Positive results from short term validation represent a "green light" for long term validation, where the time and temperature effects on durability can be evaluated.

Low cycle fatigue, erosion, corrosion and fretting are among time/start-stop dependent phenomena while creep and aging of Thermal Barrier Coatings are among those phenomena that depend on time and temperature. These effects are very difficult to estimate based on a few hundred hours of operation and require long term validation in the order of thousands of hours. The long term effects mentioned above are commonly mentioned in typical Root Cause Analysis

reports of significant component failures with associated downstream damage and must therefore be detected and corrected prior to commercial introduction.

This paper discusses several deterioration mechanisms that can be detected during short and long term exposure to different operating modes and presents examples of issues that can be detected only during long term validation.

2 ABBREVIATIONS:

AOH Actual Operating Hours (Clock hours)

EOH Equivalent Operating Hours (Hours that are factored for LTSA calculation purposes)

COD Commercial Operation Date

CTE Coefficient of thermal expansion

DOD Domestic Object Damage

FOD Foreign Object Damage

LCF Low Cycle Fatigue

LTSA Long Term Service Agreement

RCA Root Cause Analysis

RMC Remote Monitoring Center

RPM Revolution per minute

TBC Thermal barrier coatings

TGO Thermally grown oxide

T-Point Mitsubishi Hitachi Power System Validation Power Plant in Takasago, Japan

YSZ Yttria Stabilized Zirconia

3 INTRODUCTION

Testing of prototype machinery is widely used in different industries. The automobile companies run factory tests where the vehicle drive system is tested by rollers without actually moving the vehicle. These “static” tests are typically followed by track runs and finally prolonged usage on real roads during different climate conditions for performance, endurance, reliability and comfort verification. All these tests allow engineers and designers to identify and fix design issues and optimize the total design for long term operation and reliability before the new car goes into mass production.

Like cars, gas turbine prototypes must also be thoroughly tested to identify and fix issues that could impact their reliable operation in the field. Similar to the automobile testing example, gas turbines are initially tested under similar “static” conditions where their functionality is tested OFF the grid prior to the final and prolonged test on the grid where the reliability and power generating capabilities are confirmed under differing loads and ambient conditions. The latter is particularly important because the gas turbine performance is greatly affected by the site and seasonal environmental conditions as well as operational deterioration. The initial “static” tests are typically performed disconnected from the grid in an effort to verify the equipment behavior under different rotating speeds and accelerations (off frequency behavior).

OFF the grid tests allow gas turbine – generator operation at rotating speeds different from synchronous speeds for off frequency verification, however, the range of RPMs are typically restricted by blade frequency excitation concerns. The operating ranges are clearly defined by Campbell Diagrams analysis that clearly identifies harmonics. Figure 1 shows an example of a Campbell diagram.

The Campbell diagram represents the natural frequency of the blades as a function of the rotating speed. The inclined lines show potential excitation harmonics. This diagram is drawn for individual rotating blade rows. The blades have several natural frequencies, such as 1st mode, 2nd mode and so on. For example, if the upstream turbine nozzle count is 32, the rotating blade is hit 32 times per rotation. In this case, the frequency is 60Hz x 32 = 960Hz at 3600rpm. In the event the blade natural frequency is 960Hz (red circle in the diagram) it will be exposed to resonance with the excitation harmonics, and can quickly fail due to high cycle fatigue. Therefore, in blade design, care is needed to avoid excitation harmonics within or near the range of grid frequency variation.

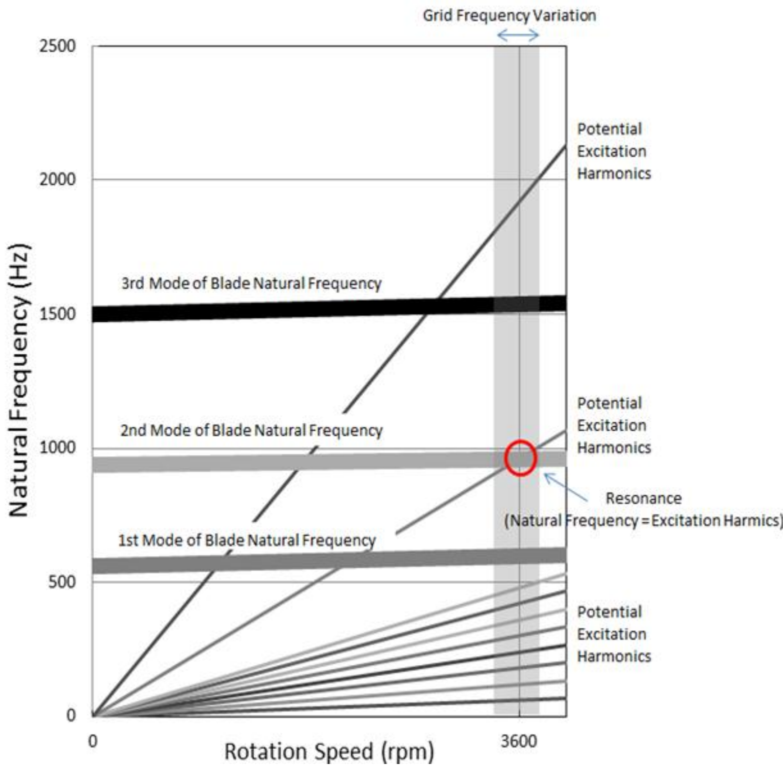


Figure 1. Campbell diagram illustration.

Protective control systems typically restrict the rotating speed of the GT by implementing routines that will open the breaker or trip the unit when a preset frequency range and timers are exceeded to prevent sustained operation at high risk RPMs. In other words, OFF frequency tests are necessary but cannot be freely sustained outside of the preset range of RPM.

The OFF frequency tests must be followed by long term validation, connected to the grid under very different dispatching conditions to verify long term behavior of the equipment.

Based on claim records presented by the Insurance Community, it is clear that many complex failures develop after prolonged operation and are affected by numerous contributing factors. Experience shows that detection of these issues and the subsequent introduction of design enhancement involves iterations and explains the initial low reliability of the prototypes prior to long term validation.

4 HISTORY OF INDUSTRIAL GAS TURBINE VALIDATION

Large industrial gas turbines consume large amounts of fuel while operating under high loads. This is recognized by the Insurance Community, as stated in reference [1] by Marsh & McLennan "Validation and testing new designs will ideally involve replicating the likely operating and demand conditions, which is an extremely expensive process".

A 40% efficiency large frame gas turbine will burn 8,530 BTU per kW-hr, resulting in very high validation costs and therefore imposing enormous constrains on the validation duration. Additionally, OFF the grid simple cycle validation provided with energy dissipation equipment generates in excess of 1,000 lbs of CO_2 per MW-hr without any energy benefit (more than 100 tons of CO_2 when running at 200MW). For all the above reasons, shop test rigs are commonly used for only a few hours as a first step to validate prototype gas turbines.

Prolonged validation requires a continuous revenue stream that allows sustained operation. In the 1990s Mitsubishi Heavy Industries (MHI) decided to build a high efficiency combined cycle power plant inside Takasago Machinery Works premises capable of dispatching the generated power to the local utility. This plant, shown in Figure 2 allows MHPS to sustain thousands of validation hours prior to commercial introduction under variable demand requested by the local utility.

In the 17 years following T-Point COD, more than 12,000 GW-hrs have been dispatched while validating the M501G, M501G1, M501GAC and currently M501J.

Figure 2. T-Point Validation Combined Cycle Power Plant.

5 ROTOR-BEARING SYSTEM VALIDATION

The rotor-bearing behavior of a power train depends on the final configuration of the installed gas or steam turbine, its foundation and the coupled equipment. T-Point features a Mitsubishi Hitachi standard multi-shaft 1:1 configuration, where each turbine is coupled to their respective generator. Figure 3 shows the gas turbine and generator layout.

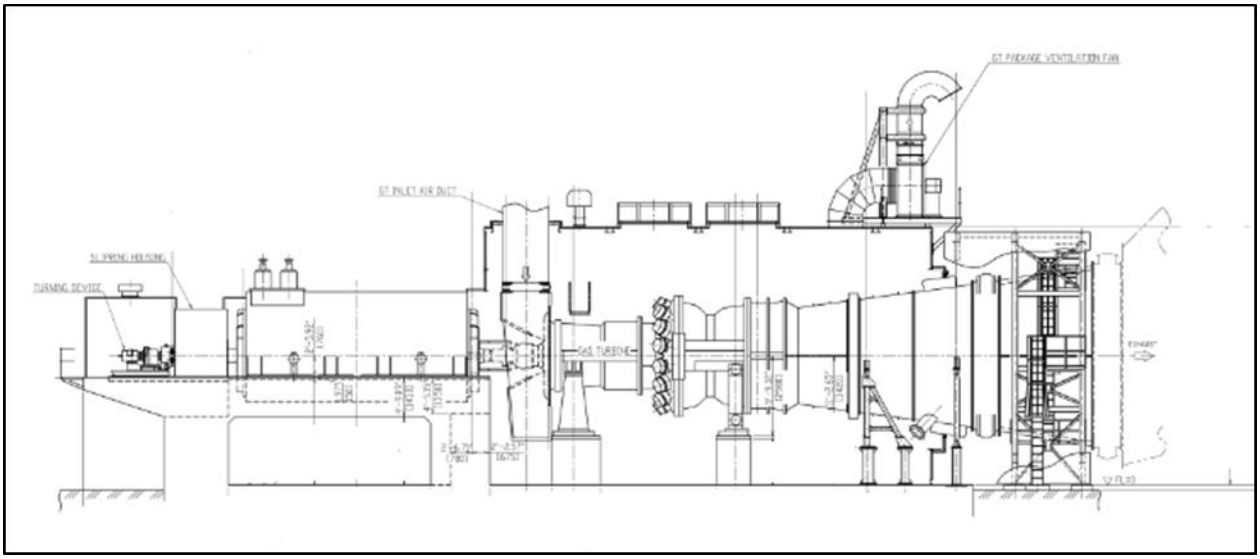


Figure 3. T-Point Gas Turbine-Generator layout

The rotor dynamics and natural frequencies of the gas turbine generator train depend on the stiffness and damping of the supports, foundations, coupling type and axial distance between bearings. By using the standard Mitsubishi Hitachi configuration at T-Point, the validation is effective in detecting vibration issues, including torsional behavior that will not become apparent in a temporary test rig with different supports, foundations or configuration of the coupled equipment.

6 SHORT TERM VALIDATION

T-Point is used to perform both short and long term validation. The short term validation is effective to detect problems associated with the turbine being tested, which may include manufacturing or assembly workmanship issues, or prototypical design issues that are not time or cycle dependent.

Short term validation is sometimes misrepresented by long schedules that simply depict the time the prototype unit has been installed in the test facility regardless of the actual fired hours clocked during actual tests. The use of LTSA definitions such as EOH instead of AOH can also be misleading as they describe time intervals that are longer than clock hours, especially when numerous start stop sequences are applied.

The following are examples of issues that can be detected during short term validation.

6.1 Blade tip rubbing

The clearance of gas turbine components is highly influenced by transient operating conditions. Start-up and shut-down sequences impose uneven heating or cooling of moving and stationary components that can temporarily close the clearance and induce rubs. This becomes more noticeable in high efficiency designs that target tight clearances. This risk can be mitigated by advanced clearance control techniques but the initial runs could unfold design estimation errors.

6.2 Vibrations

Vibration and blade tip rubbing can also occur if the rotor-bearing system design is prone to excitations. This could be detected during short term testing provided that the test stand replicates the gas turbine and driven equipment support and foundation design to be used in commercial applications as described above. It is also possible to have excitations triggered at certain loads, hardware temperature and/or lube oil temperature conditions.

One advantage of OFF frequency validation is the detection of excitation issues that would occur at off frequency conditions. Nevertheless, there are constrains imposed by physics and represented in the Campbell diagram for OFF frequency cumulative operation that might be tolerated.

7 LONG TERM VALIDATION

There are failure mechanisms that are clearly linked to operational time or cycles, or time and temperature such as low cycle or thermal fatigue, corrosion, erosion, creep, high temperature oxidation, etc. There have been enormous academic and industrial efforts applied to try to predict initiation and estimate the progression of these mechanisms but most of the conclusions for these efforts are based on controlled test conditions in laboratories and under isolated loading conditions that are very far from the complex loadings experienced by gas turbine components. Long term validation at T-Point offers a practical and realistic way to detect these complex stress exposures when the issues actually occur allowing their identification and correction. The load and temperature loading is imposed on the unit being tested by variable and real demand. The temperature exposure is changed as a result of demand oscillations, frequent start stops and variable vanes manipulation to sustain high exhaust temperatures at part load.

The following are examples of issues that can be detected during long term validation.

7.1 Low Cycle Fatigue

LCF issues are commonly mentioned in gas turbine component’s RCAs and it is not uncommon to find it as one of the most probable contributors in somewhat inconclusive failure investigations. Start and stop cycles are the predominant source of cycles.

7.2 Thermal Fatigue

Among the Low cycle fatigue, thermal fatigue is also mentioned in gas turbine component's RCAs and pointed out as one of the most probable contributors in failure investigations. Thermal effects of start/stops or load changes are the predominant source of thermal cycles.

7.3 Corrosion/Erosion

Corrosion is defined as gradual degradation of material by chemical reaction with its surrounding over a period of time. The chemical reaction proceeds due to a difference in electrochemical potential between the material and an oxidation/reduction reaction under influence of an environment containing oxygen. This results in the formation of rust or pits on the surface of the material potentially inducing crack initiation and when undetected could result in catastrophic failure under high stresses or loads.

In industrial gas turbine applications, apart from hot section components, the primary alloys used for fabrication are Fe-based alloys which include small amounts of other elements such as Cr and Ni. These alloys fall into a category called martensitic or austenitic stainless steel. It is been reported that corrosion can play an important role on the life of components such as compressor blades when erosion causes loss of protective coatings. This particular phenomenon does not happen instantaneously but typically over extended periods of time.

7.4 Deterioration of Thermal barrier coatings

Figure 4 shows a historical gas turbine temperature increase trend starting in the mid 60s. Modern gas turbines rely on TBCs for a greater efficiency achieved with higher operating temperatures.

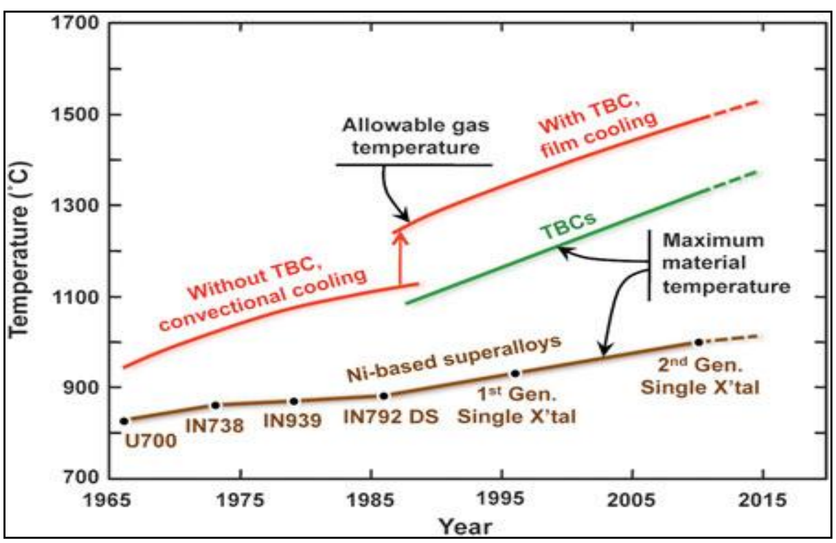


Figure 4.Historical gas turbine inlet temperature and types of alloy and introduction of TBCs. Based on a diagram from the late professor Tony Evans (UC Berkeley).

Superalloys used in these engines offer structural integrity to hot components, however it is the combination of TBC and sophisticated cooling schemes that allow operating temperatures exceeding the typical limits of superalloys (1300 °C). TBC coatings have evolved for 50 years introducing different chemistry, processing techniques and physical appearance.

The degradation of these coatings is highly dependent on GT operating time and start/stop cycles. The degradation mechanisms are complex and include:

a) Coating delamination under cyclic thermal strain due to CTE mismatch
b) TGO growth and sintering in the ceramic layer resulting in micro-cracking and top coating sintering.

Figure 5 below shows the TGO separation mechanism when residual stresses are present in the interface as a result of compression. [2,3,4,5]

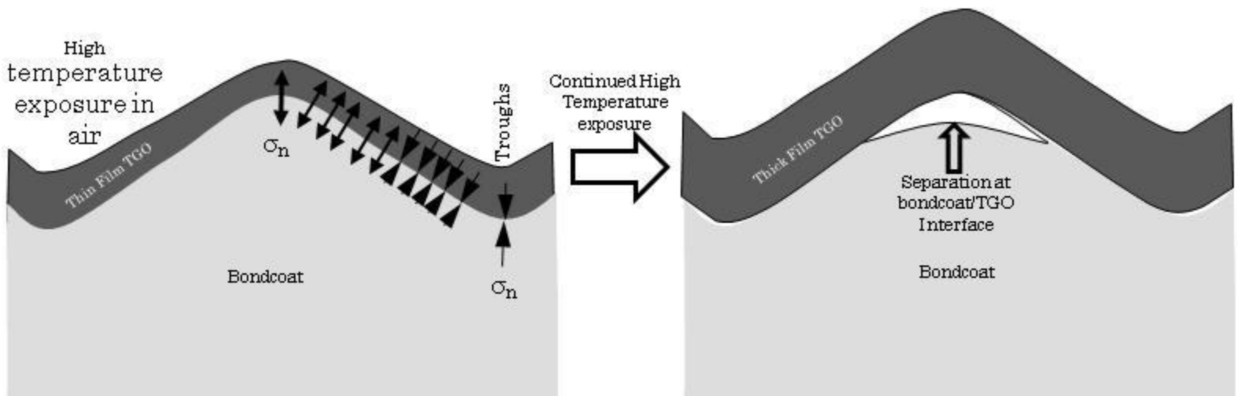


Figure 5. Schematic representations of local separation between TGO and bondcoat

Figure 6 shows progressive bond coating crack initiation due CTE mismatch and out of plane tensile stresses in the TGO driving a crack within the YSZ and at the TGO/bondcoat interface.

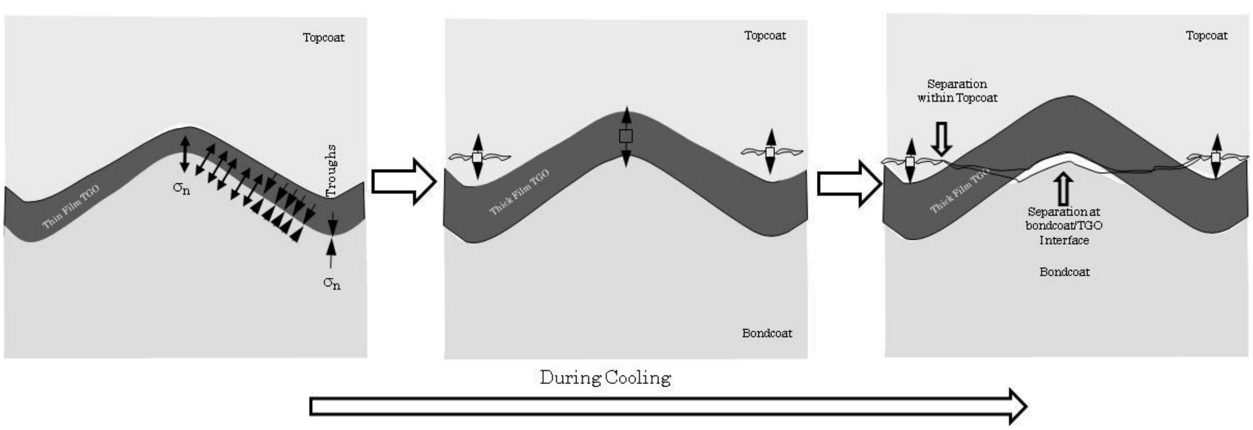


Figure 6. Progressive crack initiation in the topcoat

7.5 Creep

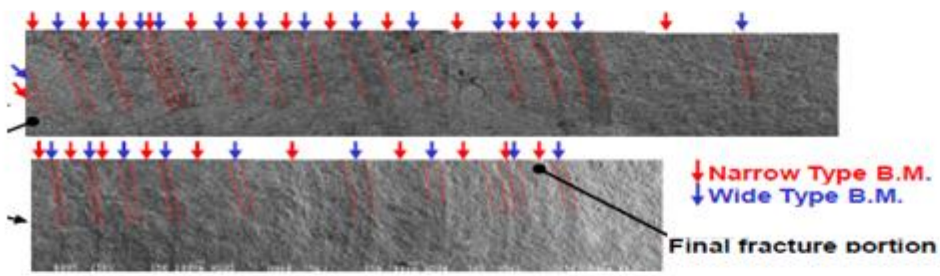
Creep affects materials that are subjected to high temperature for long periods. The creep strength has been improved using Ni-based alloy. Larson-Miller type analysis is commonly used in laboratory test under controlled loading but it is not effective to replicate complex stress conditions involved in gas turbine components.

8 COMPLEXITY OF GAS TURBINE FAILURE MODES

Failure mechanism analysis of gas turbine components is challenging due to their exposure to complex stress loads. This makes identification and prediction of failures inaccurate. Compressor components can be subject to unstable aerodynamic loading, environmental effects such as erosion or pitting. The turbine section is also exposed to high temperatures, fuel contaminants and other effects.

Root Cause Analysis (RCA) of gas turbine component failures frequently leads to identification of the most probable cause or combination of causes of a failure.

Data from Remote Monitoring Centers (RMC) provides valuable information to narrow the potential causes and very frequently help identify the duration of the failure from initiation to operational disruption by the effect of the final failure. Figure 7 shows an example of a gas turbine component exposed to fatigue and the RMC records demonstrate the crack propagation took several months to develop.



Beach marks (BM) clearly show the progressive crack propagation

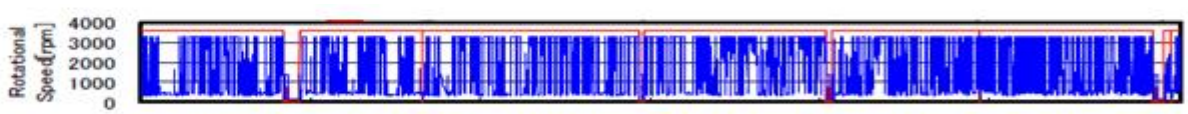


Figure 7. RMC data demonstrates the fatigue crack took several months to propagate to the rupture point

9 INSURANCE COMMUNITY EXPOSURE TO GAS TURBINE FAILURES

The insurance community has an enormous wealth of knowledge about gas turbine failures and their root cause analysis. Table 1 and Table 2 show two different summaries of common gas turbine failures reported during the 42nd Annual Conference of the International Association of Engineering Insurers. [6]

The expectation of validation is to be able to detect these failures at the prototype stage, either during short or long term validation and modify the design accordingly to prevent recurrence prior to commercial introduction.

It is worth mentioning that there are failure mechanisms that present a higher probability of occurrence after gas turbine performance deterioration has progressed under long term operation. Combustion dynamics and flash backs are good examples.

Table 1. Summary of frequent failures associated with design deficiencies [6]

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 air flow 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 combustion chamber leading to vibration and subsequent component distress/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 barrier coating and insufficient internal cooling leading to thermal related damages associated with increased firing temperatures.
11	Gas turbine loss of latter stage vanes due to vane movement /erosion/liberation.

Table 1 lists common GT Insurance claims that are associated with design deficiencies. Failure 1 constitutes a clear example of failures that could be detected during short term validation. Failures 2, 3, 6, 7 and 10 could happen during either short or long term validation. It is worth mentioning that 6 & 7 could be a non-issue until certain ambient conditions, fuel composition or performance deterioration degrades to the point where combustion instabilities are triggered. Failure 3 could be separated into two different scenarios with two different trigging mechanisms. Stalling and surge could happen early if the design and the surge margin are marginal but their occurrence is also affected by long term compressor fouling. Erosion and scale deposits are typically developed during long term operation. Failures 4, 5, 8, 9 and 11 can mainly be detected during long term validation.

Table 2. Summary of frequent failures associated with duty cycle [6]

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 in mechanical failures
7	Impurities in 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 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

Similarly Table 2, The FOD mentioned at the top of the table should be detected very soon after starting short term validation, with the exception of a very uncommon case that the foreign object is held in position until released. Failures 2, 3, 4, 6 and 11 can mainly be detected during long term validation while 5, 7, 8, 9, 10 and 12 could happen during either one. Failure 10 could happen in short term if the cooling passages were clogged during manufacturing of the failed component but it will typically correspond to long term in cases where the clogging is induced by dust or rust unless poor system cleaning has been applied during commissioning.

10 SUMMARY

1. The cost associated with fuel consumption during Large Frame Gas Turbine validation at high loads is extremely high and constitute a hard limit to prolonged validation.
2. Prolonged validation can be sustained with an efficient validation plant connected to the grid and competitively dispatching the generated power.
3. Short Term validation allows detection of issues that are not physically associated with long term exposure to cycles and/or temperatures. It is also effective to evaluate off frequency behavior of the gas turbine.
4. The RPM range used during OFF frequency testing is restricted by blade excitation concerns; therefore this validation is performed within allowable frequency boundaries.
5. Study of individual mechanical or thermo-mechanical failure mechanisms are typically restricted to controlled test conditions in laboratories, while gas turbine complex loading and consequent failure mechanisms are very complex and difficult to predict.
6. Prolonged (Long Term) validation is effective in detecting issues that are physically associated with long term exposure to cycles and temperatures such as LCF, creep, corrosion, erosion, embrittlement, etc.
7. Common failures compiled by the Insurance Community based on common and very expensive claims show many failure mechanisms that can only be detected by sustained long term validation.
8. There is a complex interaction between gas turbine design changes targeting improved performance and reliability. The Combined Cycle Validation Plant in Takasago has been in commercial operation since 1997 and has generated in excess of 12,000 GW-hrs, playing a fundamental role to leverage the experience of proven designs and thorough validation for producing high efficiency gas turbines with high and validated reliability.

11 REFERENCE

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