

Availability Analysis of Gas Turbines Used in Power Plants

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Abstract

The availability of a complex system, such as a gas turbine, is strongly associated with its parts reliability and maintenance policy. That policy not only has influence on the parts' repair time but also on the parts' reliability affecting the system degradation and availability. This study presents a method for reliability and availability evaluation of gas turbines installed in an electric power station. The method is based on system reliability concepts, such as functional tree development, application of failure mode and effects analysis to identify critical components for improvement of system reliability, and reliability and maintainability evaluation based on a historical failure database. The method also proposes the application of Reliability Centered Maintenance concepts to improve complex system maintenance policies aimed at the reduction of unexpected failure occurrences in critical components. The method is applied to the analysis of two F series gas turbines, each with an output of 150 MW, installed in a 500 MW combined cycle power plant. The reliability and availability of the turbines are simulated based on a five-year failure database. The availability analysis shows different results for each turbine, one presenting 99% and the other 96% availability, indicating differences in their systems installation and operation.

Keywords: Availability, gas turbines, maintainability, RCM and reliability simulation.

1. Introduction

The use of combined cycle power stations has increased in recent years due mainly to the development of high nominal output gas turbines. The high temperature exhaust gas from the Brayton cycle is used as a heat source for the Rankine cycle, which increases the power plant global efficiency.

Reliable gas turbine operation can be considered critical for the combined cycle operation. The gas turbine transforms the thermal energy generated by fuel combustion into mechanical energy to rotate the electrical generator's shaft. The exhaust gas is used to produce steam in a steam generator that is part of the steam cycle. In case of a gas turbine failure the power plant is fully shut down since the Rankine cycle is dependent on the gas turbine availability. Bearing in mind the great importance of the gas turbine for plant operation, its availability should be carefully evaluated in order to anticipate the performance – technical and economical - of the plant.

Availability measures are concerned with the fraction of time a unit is capable of providing service. Most power plants use the index proposed by IEEE std. 762 (1987) to define availability. That index represents the percentage of a given period of time, expressed in hours, that the unit is in service (including reserve shutdown state). A reduction in availability is caused by planned maintenance and unplanned maintenance actions. The index, usually evaluated monthly, is reported in a Generating Availability Data System (GADS) and can be used for comparison between different generating systems.

That index is deterministic and can only be used for maintenance efficiency management. In order to improve maintenance efficiency and to reduce maintenance costs, Eti et al. (2007) proposed the use of reliability and maintainability concepts to define an availability index

expressed by the ratio of the mean time to failure to the sum of the mean time to failure plus the mean time to repair. Those authors indicate that the mean time to failure, calculated from the failure records, can be improved through the study of root-cause failure analysis and system reliability analysis.

The availability of a complex system, such as a gas turbine, is strongly associated with the parts reliability and the maintenance policy. That policy not only influences the parts' repair time but also the parts' reliability affecting the system degradation and availability.

Most of the maintenance tasks of power plant equipment are based on manufacturer's recommendations. Those recommendations are not always based on real experience data. Many manufacturers get very little feedback from users of their equipment after the guarantee period is over. Fear of product liability claims may perhaps also influence the manufactures' recommendations.

In a large enterprise, such as a power plant, keeping asset reliability and availability, and reducing costs related to asset maintenance, repair, and ultimate replacement are at the top of management concerns. In response to these concerns, the Reliability Centered Maintenance (RCM) concept was developed. RCM has been formally defined by Moubray (1997) as "a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context".

The RCM methodology is completely described by the following four features:

- i) Preserve functions;
- ii) Identify failure modes that can defeat the functions;
- iii) Prioritize function need;

- iv) Select main monitoring systems to evaluate critical component degradation to allow the definition of maintenance actions before the occurrence of functional failure.

This paper presents a system reliability-based method used to identify the most critical components in a gas turbine. The criticality is associated with the component failure effect on the turbine operation condition. The higher the criticality of the component, the more technical and financial resources should be expended in the maintenance activities to keep the gas turbine available for operation. The RCM concepts are used as a guideline for ranking the maintenance policy priorities for the critical components aiming at the overall gas turbine operation availability.

2. Method Development

The method is based on system reliability concepts.

The method's first step consists in the elaboration of the turbine functional tree that allows the definition of the functional links between the equipment subsystems. Although all gas turbines possess essentially the same subsystems, such as compressor, combustion chamber and turbine, there are differences between the technologies used by the manufacturers, therefore the functional tree must be developed for each specific gas turbine model.

The next step is the development of the Failure Mode and Effects Analysis (FMEA) of each turbine component in order to define the most critical components for turbine operation. FMEA provides a lot of valuable qualitative information about the system design and operation, since its goal is to identify, concisely, the failure modes and mechanism of interest. The quantitative treatment of failures will be carried out in the analysis' third step, using reliability concepts instead of FMECA approach (where the "C" stands for "criticality").

The analysis is based on the evaluation of the component failure effect on the turbine operation (Lewis, 1987). For the definition of the system degradation, the FMEA analysis uses a numerical code, usually ranking from 1 to 10. The higher the number the higher is the criticality of the component that must be evaluated for each component failure mode. For the present analysis that index

is classified into three main severity levels: marginal, critical and catastrophic. Each level is split into three other sub-levels to express some variety of failure effects. A criticality scale between 1 and 9 is proposed. Values between 1 and 3 express minor effects on the turbine operation while values between 4 and 6 express significant effects on the turbine operation. Finally, failures that cause turbine unavailability or environmental degradation are classified by criticality values between 7 and 9. The description of the effects associated with the highest criticality index is presented in Table 1.

The method's third step involves a reliability analysis based on the 'time to failure' data recorded during the gas turbine operation. The failures should be classified according to the subsystem presented on the functional tree. The reliability of each subsystem is calculated based on the failure data and the gas turbine reliability is simulated through the use of a block diagram. Considering the 'time to repair' data and the preventive maintenance tasks associated with the equipment, the gas turbine availability is evaluated using the block diagram.

Once the critical components are defined a maintenance policy can be proposed for those components considering the RCM concepts.

This maintenance policy philosophy is focused on the use of predictive or preventive maintenance tasks that aim at the reduction of unexpected failures during the component's normal operation (Smith and Hinchcliffe, 2004).

For complex systems, such as gas turbines, the occurrence of unexpected component failures drastically increases maintenance costs associated with corrective tasks not only for the direct corrective costs (spare parts, labor hours) but also for the system unavailability costs.

The reliability block diagram analysis allows the prediction of a possible availability improvement considering the application of new maintenance procedures, expressed by the reduction of corrective maintenance repair time.

In Figure 1 a flowchart is used to illustrate the method main steps.

Table 1. Criticality Index Description for FMEA Analysis.

Criticality Index	Effects on the Turbine Operation
7 (Severe)	This severity ranking is given when a component potential failure mode can cause unavailability of the equipment but does not cause damage to other equipment components, possibly affecting: i) the equipment operation, since it must be stopped; ii) the environmental in a severe manner; iii) the compliance with government requirements. The failure also causes the need for repair and/or replacement of the failed component. The plant is unavailable for a short period of time.
8 (Very Severe)	This severity ranking is given when a component potential failure mode can cause unavailability of the equipment but does not cause damage to other equipment components, possibly affecting: i) the equipment operation, since it must be stopped; ii) the environmental in a very severe manner; iii) compliance with government requirements. The failure also causes the need for repair and/or replacement of the failed component. The plant is unavailable for a long period of time.
9 (Hazardous Effects)	This severity ranking is given when a component potential failure mode can cause severe damage to other components and/or to the equipment, possibly affecting: i) the equipment operation, since it must be stopped; ii) the environmental safety, including leakage of hazardous materials; iii) the safe power plant operation; iv) the compliance with government requirements. The failure also causes the need for repair and/or replacement of a great number of components. The plant is unavailable for long period of time.

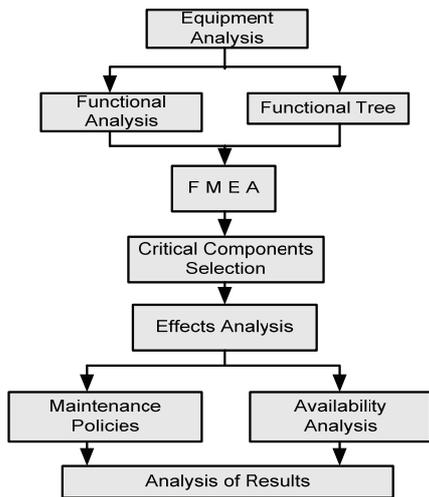


Figure 1. Flowchart for Complex System Availability Evaluation.

3. Application

The method is applied to the analysis of two identical heavy-duty F series gas turbines, with a 150 MW nominal power output, installed in a 500 MW combined cycle power plant located in Brazil. The reliability and availability of the turbines are simulated based on a five-year failure database.

3.1 Functional Tree

The functional tree for the power plant is presented in Figure 2 and was divided into seven main systems: gas turbine, steam turbine, and electrical generator, heat recovery steam generator, cooling water system, water treatment system and electrical station.

The functional tree for the gas turbine is presented in Figure 3. The equipment is divided into six main subsystems: trunnion, air inlet, compressor, combustion, turbine and turning gear (start/stop subsystem). Those subsystems are divided into components, each one performing a specific function in connection with the subsystem main function. A failure in a component at the bottom of the tree affects all subsystems above it, causing a possible degradation in the turbine operation, represented by any reduction in the nominal power output or even environmental degradation. The tree was developed according to the operation manual furnished by the manufacturer.

3.2 Failure Mode and Effects Analysis

Although there are many variants of FMEA, it is always based on a table, as shown in Figure 4. In the left-hand column the component under analysis is listed; then in the next column the physical modes by which the component

may fail are provided. This is followed, in the third column, by the possible causes of each of the failure modes.

The fourth column lists the effects of each failure mode that are classified according to the criticality scale, which expresses the degradation degree in the turbine operation.

The FMEA analysis was performed for each component listed in the end of a given branch of the functional tree. In Figure 4 the analysis for the trunnion support is partially presented as an example.

The failure modes for the components were developed according to manufacturer's information and other failure analysis available in the open literature, (Black & Veatch, 1996), (Park et al., 2002), (Baumik, 2002), (Burgazzi, 2004), (Chang et al., 2003), and (Guan, 2005).

The analysis pointed out that the most critical components for the turbine are:

- compressor: blades, vanes and shaft;
- bearings: oil heat exchanger, pump, piping and filter;
- combustion subsystem: combustion chamber, ignition and transition duct;
- turbine: blades and vanes refrigeration system, shaft and exhaust;
- turning gear: gear box.

These systems are regularly submitted, according to manufacturer recommendation, to a detailed maintenance policy based on predictive or preventive techniques, including annual inspections.

3.3 Maintenance Tasks Recommendations

The maintenance policy of gas turbines is typically based on five or six year cycles. During the first two years some annually based basic preventive tasks are performed. In the middle of the cycle a more complex inspection is performed. After that the basic tasks are performed annually and at the end of the cycle overhaul maintenance is performed.

Based on the results of the FMEA analysis, the RCM concepts can be used to recommend maintenance tasks to those components that have a criticality index greater than 6. The failure of those components can cause severe degradation in the gas turbine's performance, significantly reducing the power output of the generator coupled to the turbine shaft which affects the gas turbine main function.

The gas turbine presently analyzed has a complex monitoring system based on temperature, pressure and vibration gauges. That system can be used to monitor the real-time performance of the critical components of the gas turbine allowing the use of condition-based maintenance policy to improve the equipment availability. Those data can be used to define the trend in the equipment performance and a limit value must be selected as a potential failure indicator.

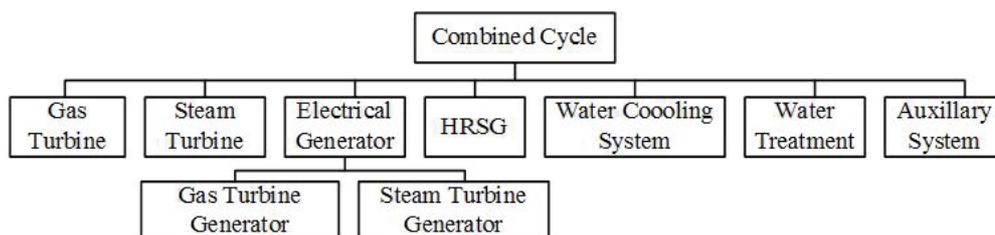


Figure 2. Combined Cycle Power Plant Functional Tree.

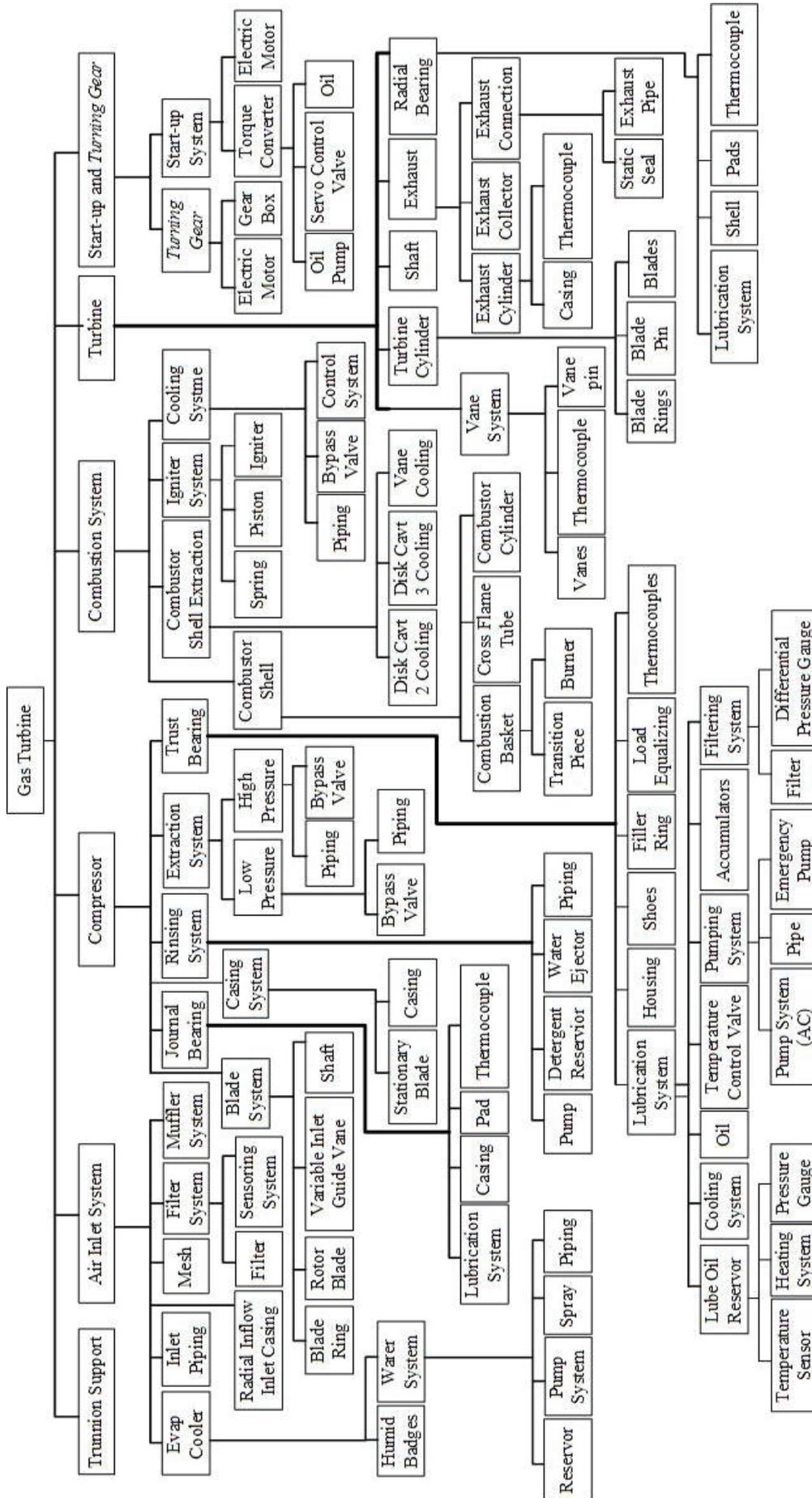


Figure 3. Gas Turbine Functional Tree.

Function	Failure Mode	Failure Causes	Failure Effects	Criticality
Support Turbine housing	Achieve Ultimate limit state	Fatigue failure, fracture, Buckling	Loss of structural support, extensive damage to the turbine	9
	Achieve operational limit state	Plastic deformation due to overloading, existence of fatigue crack	Loss of structural stiffness, possible turbine vibration.	8

Figure 4. Failure Mode and Effects Analysis: Example – Trunnion Support.

That value allows identification of the alert level, providing information to schedule maintenance tasks before functional failure occurs. The analysis is the basis for the implementation of the predictive maintenance policy recommended by RCM philosophy. Moreover, most of the critical components of the gas turbine can be assisted with predictive maintenance tasks although, according to manufactures' recommendation, other critical components are assisted with preventive maintenance tasks.

For some critical components the authors detected that there is no monitoring system that could indicate the evolution of a given failure mode. For those components the authors suggest the following measures aiming at the reduction of their failure probability:

i) The pressure and temperature magnitude in the combustion chamber are monitored allowing the on-line diagnosis of the combustion process. As a consequence, corrections in the turbine operational conditions can be rapidly implemented;

ii) Regarding the sliding bearing systems (radial and thrust), the lubrication oil pressure and temperature are monitored at the bearing inlet. Based on the trends of the sensors registers the lube oil system operational condition can be monitored but not the bearing material degradation. For that analysis the authors recommend that periodically an oil sample should be analyzed in order to detect the presence of metallic particles in the fluid. The time history of those particles' volume and chemical composition can be used as indicators of bearing material degradation allowing the planning of maintenance actions before the bearing failure;

iii) Only the thrust bearing has an axial vibration monitoring system. Although the trend in the thrust bearing vibration pattern can be used to characterize a potential failure development in the sliding bearings, the monitoring system could be improved through the use of vibration sensors in the radial sliding bearing. With that improvement more information about the rotating parts of the gas turbine should be recorded supporting preventive or predictive maintenance tasks planning;

iv) The filtering systems installed in the air inlet and in the lubrication oil circuit are monitored through the use of differential pressure gauges. Any change in the differential pressure trend can be used as an indication of the presence of solid particles in the filter cartridge. The authors recommend that the solid particles removed during the cartridge cleaning operation could be analyzed to check if there are metallic materials in the particles that can be used as an indication of turbine parts deterioration;

v) The sliding and thrust bearings lubrication oil pumps do not have any monitoring system. As any degradation in those pumps' performance can affect the bearings operational condition that could even cause the turbine to trip, the authors recommend the use of non-destructive techniques to check their performance. The thermograph technique can be used to check the pump electric motor

operational condition and a vibration monitoring system can be used to check the pump performance. The trends in those registers can be used to support on condition maintenance tasks planning avoiding any degradation in the bearings performance;

vi) The lubrication oil refrigeration system must be also considered in the predictive maintenance planning since its performance degradation has consequences on the turbine bearings operational condition. The cooling water pumps should be monitored with vibration gauges and some flow meters can be used to check the water flow in the oil /water heat exchange system.

The use of monitoring systems allows the evaluation of failure development only for mechanical components. Nevertheless, to allow any trend evaluation, one needs to define the signature pattern representing the component operational performance in the normal condition defined in the design specifications. A recorded signature pattern associated with each monitored component is compared to the trends presented by the signal registered by the sensors allowing the maintenance tasks planning before the equipment functional failure.

3.4 Reliability and Availability Analysis

Reliability can be defined as the probability that a system will perform properly for a specified period of time under a given set of operating conditions. Implied in this definition is a clear-cut criterion for failure, from which one may judge at what point the system is no longer functioning properly. For the gas turbine the failure criterion is any component failure that causes incapacity of generating the nominal power output.

The reliability analysis is performed for each of the two gas turbines installed in the power plant, submitted to the same commissioning process and starting to operate at the same time. The reliability analysis is based on the time to failure data analysis.

Probably the single most used parameter to characterize reliability is the mean time to failure (MTTF). It is just the expected or mean value of the failure time, expressed as:

$$MTTF = \int_0^{\infty} R(t) dt \quad (1)$$

where:

$R(t)$ reliability at time t
 T time period [h]

Random failures (represented by the exponential probability function) constitute the most widely used model for describing reliability phenomena. They are defined by the assumption that the rate of failure of a system is independent of its age and other characteristics of its operating history. In that case the use of mean time to failure to describe reliability can be acceptable once the

exponential distribution parameter, the failure rate, is directly associated with MTTF.

The constant failure rate approximation is often quite adequate even though a system or some of its components may exhibit moderate early-failures or aging effects. The magnitude of early failures is limited by strict quality control in manufacturing and aging effects can be sharply limited by careful predictive or preventive maintenance.

In the beginning of the operational life of complex equipment such as a gas turbine, the presented failure modes are not usually random and cannot be represented by an exponential reliability distribution. The equipment's initial performance depends on commissioning and operational procedures and even on environmental conditions that can induce the occurrence of early failure modes.

When the phenomena of early failures, aging effects, or both, are presented, the reliability of a device or system becomes a strong function of its age.

The Weibull probability distribution is one of the most widely used distributions in reliability calculations involving time related failures. Through the appropriate choice of parameters a variety of failure rate behaviors can be modeled, including constant failure rate, in addition to failure rates modeling both wear-in and wear-out phenomena.

The turbine is modeled as one block. For that block the reliability and maintainability distributions are estimated based on failure reports presented by the plant operator.

The two-parameter Weibull distribution, typically used to model wear-out or fatigue failures is represented by the following equation:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (2)$$

where:

- $R(t)$ reliability at time t
- t time period [h]
- β Weibull distribution shape parameter
- η Weibull distribution characteristic life [h]

The distribution parameters are estimated through the use of parametric estimation methods that fit the distribution to the 'time to failure' data. There are procedures for estimating the Weibull distribution parameters from data, using what is known as the maximum likelihood estimation method. For the gas turbine reliability analysis the software Weibull++ (Reliasoft, 2003) was used for parameter estimation.

Table 2 shows the Weibull distribution parameters for the two gas turbines.

Table 2. Weibull Distribution Parameters for Turbine Reliability Calculations

System	Parameters
Gas Turbine 1	$\beta=0,58$ $\eta=1014,56$
Gas Turbine 2	$\beta=0,44$ $\eta=497,24$

Both gas turbines have reliability distributions with shape parameters less than one. When $0 < \beta < 1$, the distribution has a decreasing failure rate.

Turbine 1 presented 15 failures that caused equipment unavailability in the analysis period. Several of those 11

failures occurred in the first two operational years. Most of them were related to high temperature in the combustors or excessive vibration on the bearings. The failure root-cause was sensor calibration problems. In the last three years there were two failures due to high temperature in the exhaust collector caused by combustor failure.

Turbine 2 presented 24 failures in five operational years and 12 of them occurred in the first two years. Three of those failures were related to calibration problems of pressure gauges located at the exhaust collector and the other three failures were related to fuel filters premature cleaning due to premature clogging caused by poor natural gas quality. In the last three years, the main problems were related to the lubrication oil system, mainly the oil feeding pressure.

The failures that may affect turbine availability were associated with components listed at the bottom of functional tree branches presented in Figure 3 and were considered as critical in the FMEA analysis.

For the gas turbines, the early failure stage, defined by the large failure concentration in the first two operational years, is mainly associated with the adjustment of control systems.

The shape parameter of the turbine 1 reliability function is higher than the same parameter estimated for turbine 2. This fact indicates that the first turbine is getting close to the period of random failures characterized by a shape parameter equal to one.

The reliability distribution curve for turbines 1 and 2 are presented in Figure 5. The points presented in the graphic represent the median rank plotting reliability estimate for each of the time to failure data, arranged in increasing order. Those points are used to verify the adherence of the reliability distribution to the failure data.

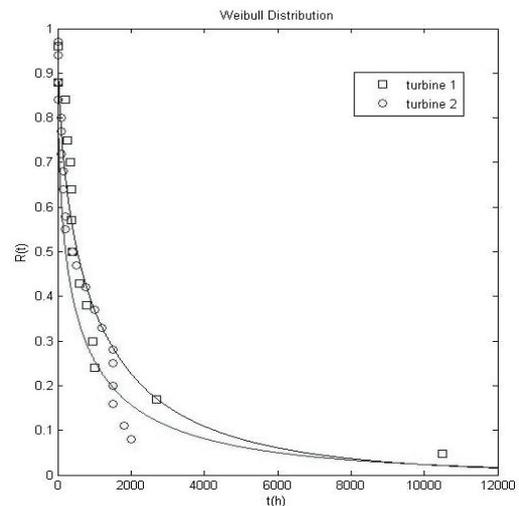


Figure 5. Turbines 1 and 2 Reliability Distribution.

For complex systems, the concern about reliability starts in the early design stages to achieve the required functional requirements. The manufacturer defines the basic characteristics in which the system is to function such as the range of air temperature and humidity, the concentration of dust or other contaminants in the air as well as the quality of fuel.

From such requirements a conceptual design is formulated that in broad form outlines how the system is to function and provides a general plan for its construction. The conceptual design must be converted into a detailed set of drawings and specifications from which the system can

be built and maintenance requirements and procedures are also likely to take shape in a detailed form. In the later stages of the design process, prototypes are built and the reliability tests may be performed. In the design of equipment for power plants, such as gas turbines, the data gained from subsystem prototype reliability tests provide a valuable understanding of failure modes and may suggest refinements that would increase overall system reliability.

Unfortunately, usually the gas turbines manufacturers do not perform detailed end product reliability analysis due to test program cost and difficulties to simulate in a laboratory environment the operational requirements of a gas turbine.

So the equipment reliability estimative is usually based on system reliability analysis methods, including information on subsystem reliability and failure data collected in the field during regular operation of similar gas turbine models.

The subsystem parts manufacturing process is monitored and controlled by the methods of statistical quality control in order to eliminate problems in manufacturing that could affect parts, and consequently, system reliability.

Although the design process and subsystem parts manufacture planning are based on reliability concepts aiming to achieve a given gas turbine reliability requirement defined in the design stages, the reliability of the end product is dependent on the final installation process in the power plant site, including set up and testing activities. The gas turbines are likely to be assembled under field conditions that are more variable than those found in a manufacturing plant and there is more cause for concern that the reliability may be compromised. Very stringent acceptance criteria on components (including reliable packaging design to avoid both damage in shipment and deterioration in storage), careful supervision and control of the assembly and often an elaborate set of proofs or acceptance tests are necessary in such situations.

The differences in reliability of turbines 1 and 2 can be attributed to some slight differences in the assembly and set up processes causing a great number of failures in the first two years of operation, mainly those related to sensors calibration.

Once the turbine has failed a corrective maintenance procedure is performed to return the equipment to the normal operation condition as soon as possible. The time to repair is also a random variable since it is dependent on the nature of failure, on the ability to diagnose the cause of failure and on the availability of equipment and skilled personnel to carry out the repair procedure.

The probability that an equipment will be repaired in a given period of time is defined as maintainability and described by a probability distribution. Typically the lognormal distribution is used to model the time to repair distribution of complex systems. The maintainability can be expressed according to equation (3):

$$M(t) = \Phi\left(\frac{\ln t - \mu}{\sigma}\right) \quad (3)$$

where:

$M(t)$ maintainability at time t

μ lognormal distribution mean value

σ lognormal distribution standard deviation

$\Phi(\bullet)$ standard normal distribution cumulative function

Based on the time to repair database for both gas turbines and using the software Weibull++ (Reliasoft, 2003), the lognormal distribution parameters for maintainability modeling were calculated and are presented in Table 3.

Table 3. Lognormal Distribution Parameters for Turbines' Maintainability Calculation.

System	Parameters
Gas Turbine 1	$\mu = 1,52 \quad \sigma = 1,12$
Gas Turbine 2	$\mu = 1,88 \quad \sigma = 1,95$

The graphical representation of the maintainability probability distribution for turbines 1 and 2 are presented in Figure 6. As for turbine reliability, the points represent the median rank plotting of each time to repair, arranged in increasing order.

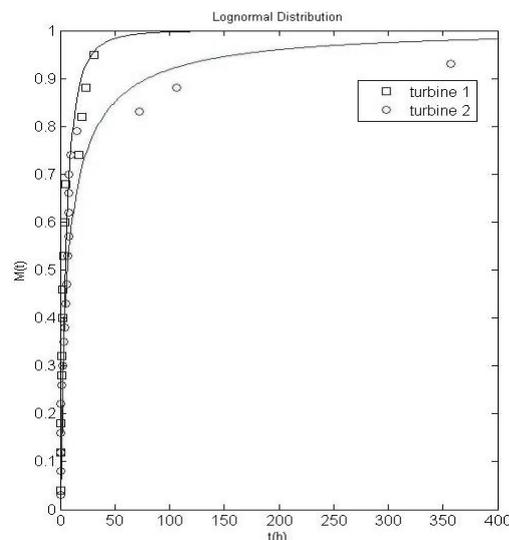


Figure 6. Turbines 1 and 2 Maintainability Distribution.

Turbine 1 has a mean time to repair smaller than turbine 2. This fact is explained through the analysis of the failure database.

Turbine 1 has had simple failures, usually in association with sensors or control system devices that require a short time to repair, while turbine 2 presented a failure in the lubrication oil system that required a time to repair greater than 1000 hours. That value has a great influence on the mean time to repair estimate.

For complex electrical-mechanical systems such as gas turbines, the determining factors in estimating repair time vary greatly.

In mechanical components, the causes of failure are likely to be quite obvious. The primary time entailed in the repair is then determined by how much time is required to extract the damage parts and install the new components. In contrast, if an electronic device (such as sensors or control units) fails, maintenance personnel may spend most of the repair procedure time in diagnosing the problem, for it may take considerable effort to understand the nature of the failure well enough to locate the part that is the cause. Conversely, it may be a rather straightforward procedure to replace the faulty component once it has been located.

Once the reliability and maintainability parameters are calculated the system availability can be estimated.

Availability is a measure of the percentage of time that a plant is capable of producing its end product at some

specified acceptable level. In the case of a gas turbine in a power plant, availability is a measure of the fraction of time that it is generating the nominal power output.

In a simple way, availability is controlled by two parameters:

- ◆ Mean time to failure (MTTF) which is a measure of how long, on average, the gas turbine will perform as specified before an unplanned failure will occur, being associated with equipment reliability;
- ◆ Mean time to repair (MTTR) which is a measure of how long, on average, it will take to bring the equipment back to normal serviceability when it does fail.

Although reliability can be at least estimated during the gas turbine design stages, its availability is strongly influenced by the uncertainties in the repair time. Those uncertainties are influenced by many factors such as the ability to diagnose the cause of failure or the availability of equipment and skilled personnel to carry out the repair procedures. In the case of a gas turbine, the same equipment model can present different availability in different sites due to differences in the skill of personnel responsible for maintenance.

Applying the Monte Carlo simulation method, the availability can be estimated for an operation time.

That procedure uses a uniform distribution in the interval (0,1) to generate a random time to failure or random time to repair, drawn from the reliability and maintainability distribution. The equipment first time to failure (T_{F1}) is a random number drawn from the reliability distribution. Once failed, the time to repair the equipment is drawn from its repair distribution (T_{R1}). The equipment is restored by time ($T_{F1}+T_{R1}$). The second time to failure, randomly generated, is T_{F2} and the subsequent time to repair is T_{R2} . The time when the system is restored is $[(T_{F1}+T_{R1}) + (T_{F2}+T_{R2})]$. This process is repeated over the entire simulated operational time. The availability is the ratio of the system uptime divided by the total simulated time.

Considering the gas turbines operating over one year, corresponding to 8760 hours, and using the reliability and maintainability probability distribution presented in Tables II and III, respectively, the availability for turbine 1 is 99.35% and for turbine 2 is 96%. Availability is an index dependent on reliability and maintainability and considering that turbine 1 has higher reliability and smaller mean time to repair than turbine 2, clearly it must be more available than turbine two. Using the method proposed by Eti et al. (2007), the turbines availability are 99.46% and 91%, respectively for turbines 1 and 2, close to the values defined by simulation.

For turbine 2 the simulated availability is higher than the value estimated by the formula proposed by Eti et al. (2007). The difference is caused by the use of mean time to repair to define availability once that value is strongly influenced by the 1000 hours time to repair associated with one failure presented by turbine 2.

The North American Electric Reliability Corporation (NERC, 2006) keeps available a reliability database based on North America power plants' performance that can be used as a benchmark for power plants availability analysis. According to that database the average availability of gas turbines with nominal output higher than 50 MW, within the period between 2002 and 2006, is 93.95%. The gas turbines analyzed in the present study have higher

reliability than the values presented in the NERC database. That comparison should be used only for initial evaluation of the gas turbine performance since that database does not clearly define the availability for heavy-duty gas turbines and the average age of the turbines used in the database are higher than the equipment evaluated in the presented paper. Nevertheless, the performance of the gas turbines analyzed in the present study can be considered satisfactory as far as the availability index is concerned.

Considering that the failure rate of both gas turbines is decreasing one can expect that the frequency of failures can continue to decrease until the equipment reaches the random failure stage. Based on the reduction of the failure frequency, caused by maintenance policies or even operational procedure improvement, an availability increase can be expected.

The simulation results show that for complex electric-mechanical systems, such as gas turbines, the availability can be different for identical equipment located in the same site. This difference can be associated with the operational profile of the equipment, mainly the number of trips presented during the operational life, and the nature of failures – associated with mechanical or electrical devices.

3.5 Availability Improvement

The maintenance policy of gas turbines must follow very stringent recommendations defined by the manufacturer. Most of the maintenance procedure tasks, involving periodical inspection and replacement of parts, are related to parts submitted to very high temperature and located in the hot gas path (combustion chamber plus turbine). The parts that compose those subsystems can present severe wear, affecting gas turbine performance. For those parts the manufacturer did not allow any maintenance procedure change once they are defined in maintenance contracts involving equipment warranty. The periodic inspection schedule is based on the number of equipment start-ups and operational hours.

For auxiliary systems, such as the lubrication oil system, the manufacturer recommends periodic inspections but does not clearly define what kind of maintenance policies could be applied to the components of those systems.

The results of the RCM analysis, listed as maintenance tasks recommendations in Section 3.3, were presented to the manufacturer who agreed to allow changes in the lubrication oil system maintenance policy aiming to achieve the power plant owner's availability requirement.

That system is initially chosen once its failure has a great impact on turbine operation, causing the equipment trip to protect the sliding bearings.

In order to verify the feasibility of the changes in lubrication oil maintenance procedures, the system installed in turbine 2 (the one that presents the lowest availability) had its design changed. Sensors were installed in the oil pump to allow the use of a monitoring system to check oil pump vibration and oil temperature and flow. Also a bi-monthly oil analysis was implemented in order to check for the presence of metallic particles in the fluid that could be an indication of possible bearings parts wear. The trends in those registers supported on condition maintenance tasks planning to avoid wear-out failures in the pump and unplanned outage of the gas turbine. Those monitoring improvements were made during the five year overhaul maintenance tasks.

After that change, gas turbine 2 operated for another two years. The ‘time to failure’ and ‘time to repair’ databases of those two years are used to define the turbine reliability, maintainability and availability, using the same procedure presented in Section 3.2. The turbine was considered ‘as good as new’ after the overhaul maintenance, and the failures of the first five operational years are not considered in the new reliability analysis.

In Table 4 the reliability and maintainability probability distributions parameters are presented. The reliability distribution is presented in Figure 7 and the maintainability distribution is presented in Figure 8. The estimated mean time to failure of turbine 2 increased to 2627 hours. The shape parameter (β) of the Weibull distribution used to represent turbine 2 reliability is close to 1 indicating that the equipment is presenting random failure.

Table 4. Reliability And Maintainability Distribution Parameters For Turbine 2 After Maintenance Procedure Modification.

System	Parameter of Interest	Probability Distribution Parameter
Turbine 2	Reliability (Weibull distribution)	$\beta = 0,95$ $\eta = 2562,05$
	Maintainability (lognormal distribution)	$\mu = 1,4$ $\sigma = 0,86$

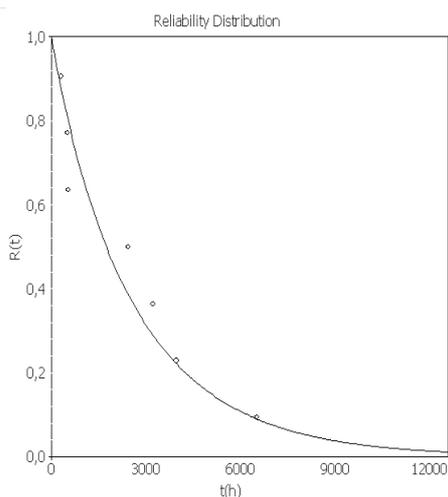


Figure 7. Turbine 2 Reliability Distribution after Maintenance Procedure Improvement.

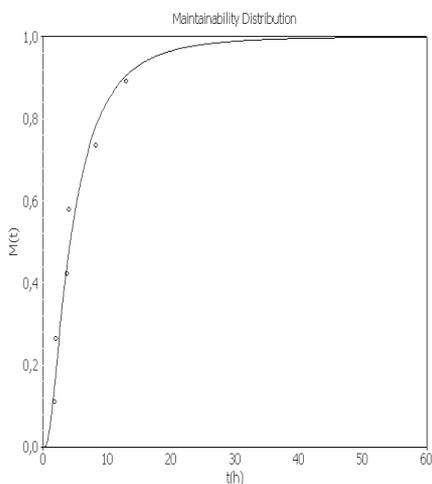


Figure 8. Turbine 2 Maintainability Distribution after Maintenance Procedure Improvement.

During those two years the oil pump had not presented any unexpected failure proving the effectiveness of the use of a condition based maintenance policy for critical gas turbine components. All maintenance tasks could be planned, reducing the number of unplanned or emergency trips of the gas turbine.

The availability of gas turbine 2 was increased to 99.76% (estimate for one operational year), close to the value calculated for turbine 1.

During those two years there were no more sensors early failures, although there were failures regarding the air inlet filtering system, blocking of inlet gas filters, and overheating of some combustion chambers.

The results of the changes in the maintenance procedure for turbine 2 lubrication oil system were approved by the manufacturer and in the future will be extended to turbine 1.

4. Conclusions

In the design of few-of-a-kind systems, such as heavy duty gas turbines, the designers and manufacturers’ experience and the use of standards and codes of good practice are most beneficial in eliminating potential failure mechanisms and modes from the system. Those facts help to guarantee that the system may achieve a given reliability performance.

For these kinds of systems only a few prototypes are built (sometimes only one) and the preliminary reliability tests are performed. Although the number of prototypes available may not allow enough units of the final design to be tested to failure to gain statistically meaningful predictions of reliability, the failures that do occur are valuable in that they add to the understanding of the failure mechanisms and thus provide a basis for improving reliability by modifying the design or through maintenance procedures.

In the case of heavy duty gas turbines, the reliability behavior can be quite different from the predicted values. The turbine on-site installation process, operator’s skills, maintenance crew training, environmental variables (air temperature, humidity and solid particles concentration) and gas quality, for example, can affect the reliability behavior predicted theoretically and/or experimentally.

The data collected on field failures are particularly valuable because they are likely to provide the only estimates of the reliability and availability that incorporate the loadings, environmental and maintenance procedure effects found in practice. On both component and system levels such a database is valuable for predicting on site reliability and availability.

The proposed method for reliability and availability analysis seems to be suitable for complex systems since it allows not only the identification of critical components for maintenance planning but also defines quantitatively the system reliability and availability.

The development of the system functional tree is important for the understanding of the functional relation between system components. Based on the functional hierarchy, the FMEA analysis is performed considering the failure modes associated with the components listed in the end of each branch of the functional tree, identifying the effects of component failure on the system under analysis. Once the critical components are identified, based on the failure effects classification, a maintenance policy can be formulated to reduce their occurrence probabilities.

The maintenance policy aims to reduce the system unavailability through the use of predictive or preventive maintenance tasks for critical components. This policy allows the reduction of unexpected failure occurrences that cause the system unavailability and are usually very expensive to repair. For gas turbines the use of predictive or preventive tasks seems feasible providing that a complex monitoring system is applied.

The maintenance policy proposed by the turbine manufacturer can be improved through the use of predictive tasks in some auxiliary systems, such as the bearings lubrication systems, since their failures can cause the gas turbine trip. That improvement is feasible once most of the auxiliary systems present some monitoring device.

Based on time to failure and time to repair data, the method allows one to carry out system reliability, maintainability and availability analyses.

For the case under analysis, which considered two identical turbines installed in the same power plant, the reliability was calculated considering a five-year operational database. Both turbines have their reliability represented by a Weibull probability function and are still presenting a decreasing failure rate. Most of the failures occurred in the first two operational years, associated with sensors faults.

The reliability and availability are different for both turbines. Turbine 1 presented a small number of failures that were rapidly repaired having a small effect on system availability. Turbine 2 presented almost twice the number of failures of turbine 1 and had a high time to repair, reducing the equipment availability. The availability of turbine 2 was improved with the change of the maintenance policy for the lubrication oil system, mainly through the use of condition based maintenance.

The availability and reliability of the turbines presented in the present study reflect on site behavior, including the effects of changes in auxiliary systems maintenance policy. Both gas turbines' reliability and availability estimates can be considered as preliminary. The equipment is designed for a long operational life, more than 20 years, and the analysis is based on the first five operational years. For that period the operation personnel was still learning how to deal with the equipment and the maintenance crew was still getting used to the maintenance procedure. The improvement of 'time to failure' and 'time to repair' databases during future operational years (with the addition of more failure and repair data) will allow more reliable estimates of the turbines reliability and availability. Nevertheless those estimates can be used to check design and maintenance procedures in order to adapt them to the gas turbine local operational condition that may be different from the average condition considered in the equipment design. Those estimates can also be used for benchmarking in order to compare the performance of the same gas turbine model operating in different sites.

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