III.- PROLOGUE

The current world requires increasingly efficient and less polluting industrial and energy processes, which force us to look for increasingly advanced technology based on the performance and experiences recorded over decades in multiple industrial plants located worldwide, a product of the lessons learned and the best engineering practices in each productive sector of each country, required in the most critical areas of the world economy, such as the oil, gas, and petrochemical industry and in power generation.

In a world looking for more and more efficiency and less polluting energies, at the same time more safety, there is a focus on eliminating the energies producing high contaminants like Carbon (CO, CO2 greater pollutants) and to keep the economy in the countries using efficient industrial processes in order to avoid them through cleaner fuels such as natural gas and less polluting liquid fuels (such as clean gasoline and diesel with a low sulfur content), as well as now in these days, preparing to use in the near future, the hydrogen and other less polluting synthetic gases, while cleaner and renewable energies such as wind energy, solar energy, hydraulic energy can be developed and improved to benefit the pollution all over the world.

Nuclear energy is a separate issue since, although it is clean, it requires very risky and dangerous processes, which have proven to be very harmful and dangerous worldwide due to the hazardous effects caused by the presence of radioactivity during the process and the sequelae it produces on living beings, humans, and nature. This book tries to achieve the possible improvements at the level of the world industry, using the most efficient and the least polluting energy being available and cheap, which is derived from the fossils (i.e., not in the case of non-renewable energy being in development). The oil and natural gas industry was developed a century ago, has a good infrastructure and improved performance, and is more efficient and safer in industrial processes now in our days, improving the quality of human lives, looking for also minimizing any possible negative effects on nature.

These industrial processes in many facilities worldwide require using highly efficient and reliable machinery through multiple chemical and thermodynamic processes to treat raw fuels such as crude oil and natural gas. There are very important critical steps in the development and operation of these oil and gas treatment plants, where the correct design and selection of mechanical equipment (in this case applicable to rotating equipment) are vital to obtaining the final products that the international market and economies require in order to maintain a satisfactory world economy and the best living standards for people in this world, not being in the highest and effective level in these days.

Among the rotating equipment that is required to be used in industrial plants to obtain the commercial fuels (liquid and gas) that move the economy around the world, some of them are as follows, hydrocarbon pumps, air and gas compressors, gas and steam turbines, air and gas blowers, gearboxes, electric motors (fix speed or VFD), gas engines, and some others, where each one alone represents a variety of complex and critical designs and divers utility consumptions associated, that complement it in order to have a reliable and functional operation, reaching the objectives and goals with the final product demanded by the society.

Each of the different types of rotating equipment required in the industrial world has been developed through very complex and effective technical specifications, which for several decades have been continuously reviewed and improved through the good and bad experiences in the operation and maintenance of process plants and taking into consideration the lessons learned and through the advances in the newest and more reliable technologies developed by different engineering entities and manufacturers in the case of rotating equipment.

Some of them, the industrial plants designed for the processing of crude oil and natural gas (through the Licensors/Process Technologists), the owner/purchaser/user who operate and maintain these critical and complicated plants (by oil and gas companies, Power Generation, Petrochemical companies), and the periodical revision among the users, such as the owners operating plants and the world-class turbomachinery manufacturers of this critical equipment, in severe services sometimes.

In addition, we have the Contractor or Designer in this case applicable about Engineering, Procurement and Construction, and also through the Oil & Gas Institutions in charge, having the compromise to meet the best specialists and getting their field experiences and lessons learned, in periodically time (some of these institutions have carried out technical meetings every 5 to 10 years approximately), in order to improve the reliability, maintainability, availability, quality, and safety in each mechanical equipment, in this case about the rotating equipment like the centrifugal compressors treated in this book.

All these technical specifications generated in those technical meetings, coordinated by important Institutions in charge, with senior specialists over the world, and with the experiences acquired in so many years (with their own "know-how"), have been used in the industry for the technical development of this class of equipment and how to fight with their exigent processes, where the Contractor (in charge of Engineering-Procurement-Construction) is who finally applies it in new projects, where its own experience learned in the past and the knowledge of new tools and applications, based on the best technology being available (also known by turbomachinery manufacturers), can be applied in order to complete the planning and actions to execute any project.

It’s also important to have in mind the reliability since the original concept or vision till its final execution is reached when the machine is built (i.e., passing through the conceptual engineering, basic engineering for design, detailed engineering, procurement, manufacturing, assembly, inspection, testing (in the factory and the site), shipment, preservation, installation, commissioning, start-up, reviewing such as planned in order to comply with the expected guarantees/warranties in the future operation (in the process plant)).
In addition (but not less important) in the design and new technology application, it’s made by the mechanical equipment manufacturer, who designs the equipment depending on the service type in order to comply with a minimum warranty and guarantee conditions as required in most of the chemical and thermodynamic process used to transform the raw fuels (usually to get a useful life cycle of the equipment and the industrial plants of 30 years), in clean and less contaminated fuels, in the best reliable and possible safe way, but always following the best engineering procedures, technical specifications, which are based in international codes/regulations being available all around the world.

As mentioned, those codes/regulations are constantly in revision and improvements based on new knowledge, studies, simulations, and technology to be applied in the equipment by the world-class level manufacturers, where the focus is to produce cleaner fuels or derivates of them, as required by the end user, who through scheduling periodical technical meetings (with serious and specialized engineering Institutes and manufacturers through its specialists) in order to increase the benefits economically, generating the most appropriate technical specifications for the mechanical equipment already mentioned (in this case the rotating case). This has been used in industrial plants with the highest world-class level in quality (oil and gas companies, petrochemical, and power generation, among others).

Due to the extensive technical specifications that allow a reliable and safe design of rotating equipment in industrial plants, they would be separated into separated sections, depending on each specific type of machinery (in this case gas turbines), also among others rotating equipment (requiring different books or volumes to clarify each particular case technically), where the intention is to give the maximum possible technical details about how to design and manufacture in these days, and how each equipment can be operated and maintained, so we can increase the performance in efficiency, safety and also reducing the environmental impact and pollution that could cause the fuels produced in process plants like oil, gas and petrochemical companies, using this class of equipment. Besides, it is important to mention improving the auxiliary parts involved in the machinery operation and the utility consumptions, which together form the equipment package. This implies having a single responsible or coordinator in the entire engineering and manufacturing process (on each side, by

Owner, Contractor & Manufacturer), so we can reach the minimum guarantees and performance required to comply with the service for which it has been destined within the industrial plant.

In addition to its complexity in design and manufacture, the gas turbine packages must be integrated with advanced control systems and complex auxiliary systems included as part of the package. This means we require the presence of different engineering disciplines for its adequate completion with a high-quality standard. In this case, engineering disciplines such as Process, Mechanical, Piping, Civil, Structural, Flexibility and Stress Piping, Electrical, Instrumentation and Control Systems, Industrial Safety, Fire & Gas Metallurgical, and Corrosion, Welding, Architecture, Quality Assurance (especially during the Certification, Inspection, and Testing), Installation, Commissioning, Start-up, Construction on site, as well as those about the Procurement and Project Control. In addition, it is necessary to interchange the technical issues during the project with their respective responsible counterparts (by disciplines) as planned for the project by the Client/ Purchaser to whom the project must be carried out.
The best intention with my contribution in knowledge and experiences in this technical book (or others related to rotating equipment in the future) is to share the lessons learned in these 4 decades (since the early 80s till now) in the conceptual design, basic and detailed engineering for the selection, design, procurement, installation, operation and maintenance about the compressors through its useful life cycle in the plant.

My technical contribution has been shared 50% of the time (20 years) in the phase of the design and selection engineering, and the other 50% (20 years) assisting and coordinating in the facilities at the field in the process plants directly, being in contact with the operators and maintainers in the aspects related to the reliability, maintainability, availability, and safety in the correct operation and maintenance, in order to recommend the best to reach higher operational and mechanical performance, and also reaching the longest possible useful life in that class of equipment over the process plants.

The book also includes information in text, different diagrams, drawings, and photos to facilitate the understanding of the technical issues being addressed, to make it easier, and as a reference or clarification for the reader.

It also should be noted that, in addition to the technical specifications being applied these days by world-class level companies, there are sections where the reliability, maintainability, quality, and safety can be better followed based on a comparative review of the specifications for machinery (gas turbines in this case) between those used by the Purchaser and those recommended mainly by API Institute Specification (American Petroleum Institute) regarding the basis to design and select the machinery.

Besides, there are other important technical documents (related to the operating conditions, material details, manufacturing process, accessories, auxiliary and control systems as required, the scope of procedures for inspections and testing, the new technology available in turbomachinery these days, and some others about how to apply the scope and how to analyze the failures and typical damage in gas turbines affecting the reliability, and some technical tools about how to improve the reliability in this type of machinery through a risk analysis).

Utility consumables are critical in these turbines, such as the cooling water system, air/gas or purge for sealing, and fuel conditioning systems, steam or water injection systems and chiller systems, electrical consumption for the main drivers, and for devices and actuators (also pneumatics devices through the air where be applicable) regarding the gas turbine package, gas/oil heater conditioning systems (electrical or steam water), instrument air for pneumatic action in auxiliary systems, oil lubrication/oil control systems for bearings and in operational control systems, and on each auxiliary service and in accessories being part of the package.

In addition, at the beginning of the project, it is necessary to define the instrumentation and piping diagrams (P&ID) for the correct operation of the compressor package, as well as the drawings for the general arrangement of the compressor package; besides, it is important to review the foundation's diagrams as required, in order to adapt the physical spaces available in the process plant (the size and spaces inside the plant are defined before the selection of the rotating equipment to be installed).

It is also relevant to have, from the beginning, the procedures and acceptance criteria required for the inspection and test plans (required for the Factory Acceptance Test, FAT, and those required for the Site Acceptance Test, SAT) applicable for the major components in the rotating equipment (gas turbine package) and approved by each part in the project before installing the machinery in the plant. It's also required to receive memories of calculus and different technical studies and operational and mechanical simulations (including rotodynamic studies) to finally get a reliable design and performance in the selected gas turbine

On the other hand, the control architecture and the philosophy about operation and control must be clearly defined during the execution and development phase of the project. The whole technical documentation must be reviewed in the first 8 months of starting the detailed engineering in the project, so the Contractor can accept to start the manufacturing process and the assembly in the Factory about the major and critical parts in the gas turbines.

In the phase before providing the purchase order, before buying the gas turbine with the final selected Supplier/ Manufacturer (through a comparative technical evaluation of different bidders), and after having multiple technical meetings for clarification related to aspects such as the scope of supply, optional items, mechanical and operational performance, inspection and testing procedures, control systems architecture, about the turbine package, is when it is decided about the scope of the supply as agreed to be provided by the Supplier/Manufacturer of the equipment, and when be agreed the delivery time expected to complete the engineering and manufacturing project according to the project schedule, related to the time when to move the compressor package from the Factory to the process plant at the site (reception/preservation at the site before the installation).

It is worth to mention about the integrity and compromise by my side with the work team and support by different specialists and consultants, about all the information as presented and commented in this book, is not related to any particular Oil & Gas Company or Gas Turbine Manufacturer, so I clarify the intention is to look for the best way to get high reliability, availability, maintainability and safety issues, so this means to use information coming from different technical subjects. I have reviewed and consulted regarding available information about technical papers, technical magazines, proceedings in Conferences or Symposiums, technical meetings in specialized organizations, etc., in order to get a better explanation or understanding how to evaluate and detect the causes or reasons affecting the machine, so we can take the best actions to avoid the severe or critical failures and the consequences of the damage in gas turbines (even in the case when the failure is not considered severe, such as degraded fails or incipient fails).

The material in this book includes different aspects based on the Manufacturing experience and technology available at the project moment by Manufacturers, and as agreed among the parts before assigning the purchase requisition in order to comply with all the quality issues regarding the experiences and lessons learned by each technologist or licensor involved in the process, related to the gas turbine operators in the Oil, Gas, and Petrochemical Plants, including the thermal power plants and combined cycle, regarding the different national or international standards, codes or regulations that could be agreed in each project and that must be applied in a good manner by the EPC (project contractor). The idea is to comply with the goals of quality assurance in the different phases from the beginning of the project till their final installation, commissioning, and start-up, expecting to cover the minimum and maximum operational and mechanical guarantees as requested, for which they have been designed.

I intend that all this knowledge in the area of rotating equipment could serve as a reference for turbomachinery engineers in current and future generations in the industrial world, and that will also be the basis for the improvements and technological changes that will surely occur in the future about the turbomachinery, due to the conditions of the world economy and the infrastructure existing today in many countries.

This allows us to predict that this infrastructure will be in force for at least 25-30 more years (i.e., till 2050 as my best estimated) since the world's reserves of crude oil and natural gas, and fossil fuels statistically reflect this scenario. In this period of time, the minimum infrastructure to use renewable energy and non-polluting energy such as hydro, wind, solar, nuclear (not so reliable in these times), and some others in the development process (hydrogen, capture and collection of CO2 through underground wells, synthetic gas, among some others) will be developed satisfactorily in next 2 or 3 decades in order to be cheaper, safety and more reliable compared with the energy being now derived from the fossil fuels.

Technological advances have been the key in the rotating equipment going from control components issues, passing the mechanical to pneumatic, and then the hydraulic and currently to electronic systems, which are proven to be increasingly efficient, effective, and reliable as well as safe for the current world economy, significantly reducing the possible risks and dangers could be caused by fossil fuels and their processing to human beings themselves and the impact on the environment, such as it has occurred before in the facilities.

Besides, the useful life cycle of the equipment and its most critical components have been significantly increased with new studies, simulations, special software, tools and technologies and with the increasingly resistant and lightweight materials used today. In summary, the machinery has been improved compared to the past few decades since it is lighter, more efficient, more reliable in requirements with more critical services and processes, with higher or lower pressures, temperatures, flows, capacity, and composition in gases (affecting the fuel gas / liquid combustion systems in gas turbines, speed control and protection systems, improvements in metallurgy and materials in direct contact with the air and gas burned, improvement in the analysis and studies about failures, risks and rotodynamic being applied to smaller or bigger turbomachinery in this case in gas turbines, among some others relevant issues).

All of this can be measured and decide the corrective actions to take in order to increase the level of reliability in the turbomachinery (occurring fewer and less severe failures during operating time), about high availability (increasing the operating time), high maintainability (improvement in active and inactive repair time), and in the safety and quality issues about the personnel, equipment, and facilities (i.e., less severe failures and fewer unforeseen or unscheduled shutdowns or downtimes, fewer fires or explosions, fewer spills or leakages, fewer environment or human impacts, or production loss in time and costs, etc.).

These factors and improvements related to rotating equipment have also been developed and applied for other types of mechanical equipment such as static machinery (among others, these are the pressure vessels, heat exchangers with cooling by water or by air, treatment towers, columns, in direct fire equipment (such as burners, process furnaces, steam boilers, heat recovery steam generators, etc.), surface condensers, systems with ejectors, for injection of chemicals (corrosion inhibitors, etc.), as well as many others being part of the facilities in the Process and power generation plants. However, they are not part of this book since it is up to the static technical specialists in this type of mechanical equipment to describe, evaluate and analyze the technology being available and recent improvements made in reliability in the last few decades in that kind of equipment.

I close this prologue with the illusion in mind that these 40 years of learning and knowledge acquired in the development, operation and maintenance of rotating equipment, with the experience accumulated during this time, and with the support received from great companies and senior specialists in turbomachinery with which I have had the opportunity to face the challenges day by day, both in the Facilities in process and thermal power generation plants and the phase regarding the design, selection and during the execution of small and mega projects, it could be part of the knowledge and learning that can be consulted by turbomachinery engineers who are now being responsible to provide good engineering in rotating equipment, those senior specialists requiring actualization about knowledge, and, first at all, to those engineers starting in this complex area of knowledge in process and power generation plants and those who will enter soon in the industrial world, and for the future engineering generations. To all of them, I wish you reach your goals in this area, as I think I have met my own goals and objectives in this regard. Enjoy the lecture of this book.

Alberto Mtz Llaurado, 2022

IV.- OBJECTIVES AND GOALS IN RELIABILITY FOR GAS TURBINES

The main objective to achieve the highest profitability for an industrial company that aspires to be world-class level is to have the highest levels of reliability, availability, safety, and maintainability, among other aspects of value, which are achieved based on the experiences and lessons learned about the design, manufacture, installation, operation, and maintenance of rotating equipment, and in this case that applies to us here, in gas turbines.

Among the different existing tools for this purpose, we must mention (among others) the application of continuous improvements in the development of the technical specifications of the equipment and its facilities, the contributions accumulated by various studies and cases analyzed from the analysis of the failures and the correct diagnosis in said analyzes for each case, as well as the collection of statistical and probabilistic data of the different type of failures being analyzed through the few decades by the specialists and technicians present in the industry worldwide.

The profitability of industrial companies (oil & gas process plants or in thermal power generation plants) that want to reach a world-class level must comply with strict protocols and standards that are part of the specifications of the final product, as it is in this case for the compressors, the objective being the achievement of continuous operations without failures or unforeseen or unscheduled shutdowns or downtimes, operating in the widest range of design and production capacity (for greater productivity and feasibility), and without affecting the environmental issues and human issues in community environment where the industrial activity is carried out or developed.

Going into more detail, in the development of the book, the most appropriate different technical tools and processes for the achievement of these objectives will be indicated, which make companies leaders to follow worldwide, in an increasingly competitive and demanding world in these times, where aspects such as climate change and its consequences force us to implement increasingly demanding and challenging rules and procedures in this decade and the rest of XXI century.

A primary tool for the achievement of these objectives and goals is the application of technical specifications in the design phase of any industrial project since it is the moment when they are reviewed and decided based on the experiences lived and the learning obtained in the area of rotating equipment and in this particular case of gas turbines, based on the particular operating conditions required in the process and power generation plants to which the turbomachinery will be required as much as possible during its useful life cycle, which is estimated around 30 years.

In general, it is expected that, during that stage or useful life cycle, there will be no unforeseen or severe failures or downtimes while operating at the highest possible or rated capacity (or according to the criteria or strategy conceived in this regard in the company), always with the highest levels of efficiency in order to have the highest business profitability and feasibility in the world market.

The scope of the technical specifications for gas turbines is generated through different entities and technical institutions based on their own criteria and the experiences lived during the operation in the different industrial plants where they are required, taking into account that their scope may vary depending on the type of service, the physical conditions of the plant site, the regulatory limitations of the country or by Purchaser, the technology developed or available to the current date, as well as other factors (tangible or intangible) derived from the available budget and the strategies of the government in this regard, the specifications required in the final product of the plant, the degree or level of minimum acceptable quality in the process, which must comply with the minimum standards of any class company worldwide, where the installation, operational and maintenance risks and uncertainty are as low as possible.

The scope of the technical design specifications are generated by institutions such as the technologist or licensor of the process plant (same licensers or gas turbine manufactures in case or combined cycle or thermal power generation plants) that is required to be applied, the standards and codes of the client or user of the plant or facilities, the EPC-ist (project designer) who will develop the project, as well as some of the existing international institutions that are recognized for this purpose, that depending on the location of the plant, may vary (in the case of projects at the American level, standards such as APIs, ASME, ASTM, NFPA, ISO, AWS, IEC, IEEE, among others), taking into account the rules and regulations of the country where this equipment would operate.

An appropriate method to achieve this goal is to see, over time, the technological advances or changes made, as well as the own companies experiences and lessons learned along the way (from the last of 20 to 30 years, if possible) regarding the installation, operation, and maintenance of this equipment in existing facilities.
In this case, the text includes particular cases of the different technical improvements made in the specifications, aiming to have a greater degree of reliability, safety, availability, maintainability, and operational efficiency in the equipment and its facilities.

Due to the extensive and complex technical specifications in gas turbines, in this case, we consider the most relevant or critical aspects that may affect these factors (especially reliability, maintainability and safety) to achieve the highest possible operational capacity with the best possible efficiency.

Among the cases to be analyzed, we could highlight the following:
• Specifications of the technologist /process licensor (oil & gas or power generation plants).

In this particular, the different standards generated for gas turbines and those of their auxiliary lubrication, control, fuel, cooling and sealing systems are taken into account, as they are the most important in the design and reliability of this type of equipment.
• Technical specifications of the user or client of the physical facilities where this equipment will be installed.
• Technical specifications of the designer (EPC-ist) applied to gas turbines.
• Technical specifications developed by international institutions applied to compressors (such as API, ISO, IEC, IEEE, etc.).
• Technical specifications developed by world-class private companies in projects for gas turbines, especially for the oil, gas, and petrochemical industry, including the thermal power generation plants.
• Particular technical complements that apply as improvements in the area of gas turbines.

In addition to the technical specifications, another way to improve the issue of reliability in this equipment is by applying statistical and probabilistic studies according to the different failure patterns seen for the area of compressors and studies carried out by serious institutions created for this purpose, as it is in one of the cases, OREDA (Offshore and Onshore Reliability Data) among others. In our case, the data and analysis carried out by OREDA has been taken to have a good base of reference in this regard.

Other technical tools are used to achieve the goal of increased reliability, including failure mode analysis and fault diagnosis related to gas turbines (with procedures such as RCA, FMEA, FMECA, Hazop, SIS, among others).
Another important aspect of improving the equipment's reliability is the risk-based management applied to gas turbines. In this case, API and ISO have developed some documents like recommended practices associated with this equipment, so we can refer to them or review them as part of this book.

Different technical studies and papers about gas turbines failures that affect reliability are also included, as well as particular cases that occurred in world-class projects in the area of gas turbines, especially for the oil, gas, and petrochemical industries and thermal or combined cycle in power generation plants.
Some serious studies are also analyzed and concluded recommendations to be applied, taking care of different technical aspects that improve the reliability and safety of the equipment.

There is a section with information about the manufacturers of gas turbines (mechanical drivers or electrical power generation drivers), which highlights the latest in technology as developed by each one, as well as the technical and operational characteristics of each new design.
As a starting point, a brief basic description of the types and classes of existing gas turbines being available in the world, and, of course, and the industrial applicability is also shown and commented on.

V.- INTRODUCTION

The gas turbine engine is a machine delivering mechanical power using a gaseous working fluid. It is an internal combustion engine like the reciprocating Otto and Diesel piston engines with the major difference that the working fluid flows through de gas turbine continuously and not intermittently. The continuous flow of the working fluid requires the compression, heat input, and expansion to take place in separate components. For that reason a gas turbine consists of several components working together and synchronized in order to achieve production of mechanical power in case of industrial applications, or thrust, when those machines are used for aeronautical purposes.
During gas turbine operation, air is taken from the atmosphere and is sucked by the first row of compressor blades. From there, the working fluid receives mechanical power from the compressor causing that pressure and temperature increase rapidly. In that particular moment, air has the proper conditions to be send to the combustion chamber; component responsible for mixing the incoming air with fuel, creating combustion and producing high-temperature-flue-gases with temperatures up to 1400oC – 1500oC. The achievement of that high window temperature means that materials and design of those components requires special attention; Due, the region located between combustion chamber outlet and the turbine's inlet, is considered as the most sensible and challenging design point for gas turbines technology.

When flue gases have been released from the combustion chamber, they are driven to the turbine rows; components responsible for extracting energy from the gases in form of mechanical-rotational-power, which is used to drive the compressor and producing extra power to drive machinery or generating thrust. Later on, flue gases are liberated to the atmosphere through the exit nozzle having temperatures around 550 oC.

The primary function of the turbine is to extract power from the pressure and kinetic energy of hot gases coming out of the combustor. A large portion of this power, in the neighborhood of 75 per cent, is expended in driving the compressor, with the remainder producing the thrust in an aero-engine or electrical power in an industrial power generation turbine. The drive power to compress the air is as high as 100,000 horsepower in larger engines. The load imposed on a single rotating blade can be gauged from the amount of power, 250 to 300 horsepower, as the
hot gases flow over the airfoil, roughly the same as that produced in an eight cylinder automobile engine. But the space needed and the weight of a single turbine blade is much less than that of an automobile engine.

Turbine blades and vanes constitute a considerable portion of the total cost of the equipment, given the fact that thousands of airfoils are used in any turbo-machine. Accurate determination of operating life of turbine and compressor blades plays a central role in the design of aircraft power plants. The rotating parts must be retired prior to failure, but must still possess adequate life to be commercially acceptable to airline operators. Life estimation using stress-based theories is a multi-faceted technology, and calls for calculation of mean steady stresses, dynamic stresses, failure surface, load history and cumulative damage.

A major cause of breakdowns in gas turbines is the failure of turbine blades. Blade failures arise from metal fatigue as a consequence of resonant vibrations. Dynamic loads arise from many sources, the predominant one being the source of the operating principle itself on which the machine is designed. When a rotor blade passes the stationary vanes of the nozzle, it experiences repeated fluctuating lift and moment loads at a frequency dependent on the number of vanes and the speed of the machine. The rotating airfoils are flexible members, and possess a number of natural frequencies of vibration about their torsional axis and bending in and out of the plane of rotation of the disk. In addition to the steady centrifugal forces arising from its mass, the airfoil must also withstand the dynamic loads due to the aerodynamic excitation.

Although the blades are designed to avoid resonance at its design speed, resonant vibrations are still encountered as an aircraft engine accelerates from ground to flight idle, cruise and takeoff speeds. Even in power generation turbines operating at a near constant speed, it is not infrequent to find major shutdown of the machine due to failure of the blades.

At least in the past twenty years, maintenance has suffered a great evolution. Due to the exponential increase in the diversity of the industrial equipment, new techniques and methodologies have been developed to manage the assets and at the same time improve the existing ones.
Nowadays, the survival of the companies does not only depend on the economic demands, but also in the manner on they do not affect the environment and the society. There are several legislations to punish the companies that do not attend these expectations.

Along the economic and environment aspects, the necessity to maintain the equipment in normal conditions of operation and to maximize its performance and efficiency, makes today's companies to be more concerned with developing maintenance plans to prevent or to fix some failures. To do that, some techniques are used and in this work it will be followed the Failure, Mode, Effects and Criticality Analysis (FMECA) technique with application of the concepts of Reliability Centered Maintenance (RCM) and Life Cycle Cost (LCC), as well.

Talking about the power plants, different specialists have analyzed the situation about the importance about the gas turbines such as the following...
The gas turbine is a power plant that produces a great amount of energy depending on its size and weight. The gas turbine has found increasing service in the past 60 years in the power industry among both utilities and merchant plants as well as the petrochemical industry throughout the world. Its compactness, low weight, and multiple fuel application make it a natural power plant for offshore platforms. Today there are gas turbines that run on natural gas, diesel fuel, naphtha, methane, crude, low-BTU gases, vaporized fuel oils, and biomass gases.

The last 20 years have seen a large growth in gas turbine technology. The growth is spearheaded by the growth of materials technology, new coatings, new cooling schemes, and the growth of combined-cycle power plants. This, with the conjunction of increase in compressor pressure ratio from 7:1 to as high as 45:1, has increased simple-cycle gas turbine thermal efficiency from about 15% to 45%.

Table 1.- Economic Comparison of Various Generation Technologies*

Technology Comparison	Diesel Engine	Gas Engine	Simple Cycle Gas Turbine	Micro Turbine	Fuel Cell	Solar Energy Photovoltic Cell	Wind	Biomass	River Hydro
Product rollout	Available	Available	Available	Available	Available	Available	Available	Available	Available
Size range (kW)	20–100,000+	50–7,000+	500–450,000+	30–200	50–1,000+	1+	Up to 5,000	Up to 5,000	20–3,000+
Efficiency (%)	36–43%	28–42%	21–45%	25–30%	35–54%	NA	45–55%	25–35%	60–70%
Gen. set cost ($/kW)	125–400	250–600	300–600	800–1,200	1,500–3,000	NA	—	NA	NA
Turnkey cost No-heat recovery ($/kW)	200–500	600–1,000	400–850	1,200–2,400	2,500–5,000	5,000–10,000	700–1,300	800–1,500	750–1,200
Heat recovery added cost ($/kW)	75–100	75–100	150–300	100–250	1,900–3,500	NA	NA	150–300	NA
O&M cost ($/kW h)	0.007–0.015	0.005–0.012	0.003–0.008	0.006–0.010	0.005–0.010	0.001–0.004	0.007–0.012	0.006–0.011	0.005–0.010

*The above information is based on data obtained from several sources such as manufacturers and technical magazines.

Table 1 gives an economic comparison of various generation technologies from the initial cost of such systems to the operating costs of these systems. Because distributed generation is very site specific, the cost will vary and the justification of installation of these types of systems will also vary. Sites for distributed generation vary from large metropolitan areas to the slopes of the Himalayan mountain range. The economics of power generation depends on the fuel cost, running efficiencies, maintenance cost, and initial cost, in that order. Site selection depends on environmental concerns such as emissions, noise, fuel availability, size, and weight.

Regarding economic and operational aspects in power plants with gas turbines, there are some issues as follow.

Table 2 Economic and Operation Characteristics of Plant*

Type of Plant	Capital Cost ($/kW)	Heat Rate BTU/kWh (kJ/kWh)	Net Efficiency	Variable Operation and Maintenance ($/MWh)	Fixed Operation and Maintenance ($/MWh)	Availability (%)	Reliability (%)	Time from Planning to Completion (Months)
SCGT (2500 °F/1371 °C) Natural gas fired	300–350	7582–8000	45	5.8	0.23	88–95	97–99	10–12
SCGT oil fired	400–500	8322–8229	41	6.2	0.25	90–96	95–98	12–16
SCGT crude fired	500–600	10,662–11,250	32	13.5	0.25	75–80	90–95	12–16
Regenerative gas turbine natural gas fired	375–575	6824–7200	50	6	0.25	86–93	96–98	12–16
Combined-cycle gas turbine	600–900	6203–6545	55	4	0.35	86–93	95–98	22–24
Advanced gas turbine CCPP	800–1,000	5249–5538	65	4.5	0.4	84–90	94–96	28–30
Combined-cycle coal gasification	1,200–1,400	6950–7332	49	7	1.45	75–85	90–95	30–36
Combined-cycle fluidized bed	1,200–1,400	7300–7701	47	7	1.45	75–85	90–95	30–36
Nuclear power	1,800–200	10,000–10,550	34	8	2.28	80–89	92–98	48–60
Steam plant coal fired	800–1,000	9749–10285	35	3	1.43	82–89	94–97	36–42
Diesel generator-diesel fired	400–500	7582–8000	45	6.2	4.7	90–95	96–98	12–16
Diesel generator-power plant oil fired	600–700	8124–8570	42	7.2	4.7	85–90	92–95	16–18
Gas engine generator power plant	650–750	7300–7701	47	5.2	4.7	92–96	96–98	12–16

*The above information is based on data obtained from several sources such as manufacturers, technical magazines, as well as data obtained by the author.

Table 2 depicts an analysis of the competitive standing of the various types of power plants, their capital cost, heat rate, operation and maintenance costs, availability, reliability, and time for planning. By examining the capital cost and installation time of these new power plants, it is obvious that the gas turbine is the best choice for peaking power. Steam turbine plants are about 50% higher in initial costs of $800–$1000/kW than combined-cycle plants, which are about $400–$900/kW.

Nuclear power plants are the most expensive plants. The high initial costs and the long time in construction make such a plant unrealistic for a deregulated utility.

Efficiency and heat rate are interchangeable, as they represent the efficient conversion of fuel to energy. The following relationship gives the easy conversion from heat rate to efficiency.

$$\text{Efficiency} = 3412.2/\text{BTU}/\text{kWh} = 2544.4/\text{BTU}/\text{HPh} = 3600/\text{kJ}/\text{kWh}$$

In the area of performance, the steam turbine power plants have an efficiency of about 35% when compared with combined-cycle power plants, which have an efficiency of about 55%. Newer gas turbine technology will make combined-cycle efficiencies range between 60% and 65%. As a rule of thumb, a 1% increase in the efficiency could mean that 3.3% more capital can be invested. However, one must be careful that the increase in the efficiency does not lead to a decrease in the availability. From 1996 to 2000, we have seen a growth in the efficiency of about 10% and a loss in the availability of about 10%. This trend must be turned around since many analyses show that a 1% drop in the availability needs about 2–3% increase in the efficiency to offset that loss. The larger gas turbines, just due to their size, take more time to undergo any of the regular inspections, such as combustor, hot gas path, and major overall inspections, thus reducing the availability of these turbines.