

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 world industry 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 derivatives 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 centrifugal compressor, also in 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 compressor 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 compressor package 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 40 years (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, directly 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 an 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 centrifugal compressors 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 compressors affecting the reliability, and some technical tools about how to improve the reliability in compressor through a risk analysis).

Utility consumables are critical in these centrifugal compressors, such as the cooling water system, air/gas or purge for sealing, and nitrogen barriers in sealing systems, steam water systems and oil seal systems (when applicable), electrical consumption for the main drivers, and for devices and actuators (also pneumatics devices through the air where be applicable) regarding the compressor package, gas/oil heater 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 (compressor package) and approved by each part in the project before installing the compressor 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 centrifugal compressor.

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 6 to 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 centrifugal compressor.

In the phase before providing the purchase order, before buying the compressor 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 compressor 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 mentioning that the integrity and compromise by my side, about all the information as presented and commented in this book, is not related to any particular Oil Company or Compressor Manufacturer, so I clarify the intention is to look for the best way to get reliability, availability, maintainability and safety issues, so this means to use information coming from different technical subjects, I have consulted before being available in technical papers, technical magazines, proceedings in Conferences or Symposiums, etc., in order to get a better explanation or understanding how to evaluate and detect the causes or reasons affecting the compressor, so

we can take the best actions to avoid the severe or critical failures and the consequences of the damage in centrifugal compressors (even in the case when the failure is not considered severe, such as deterioration 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 compressor operators in the Oil, Gas, and Petrochemical Plants, 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 compressors, due to the conditions of the world economy and the infrastructure existing today.

This allows us to predict that this infrastructure will be in force for at least 25-30 more years (i.e., till 2050 as 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 decades in order to be cheaper and safety and 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, as 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, 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 gas sealing systems in compressors, speed control systems in turbines, improvements in metallurgy and materials in direct contact with the process gas, improvement in the analysis and studies about rotodynamic applied to smaller or bigger rotors in centrifugal compressors, among some others issues).

All of this can be measured through the level of reliability in the compressor (occurring fewer and less severe failures during operating time), availability (increasing the operating time), maintainability (improvement in repair time), and in the safety and quality issues about the personnel, equipment, and facilities (i.e., less severe and fewer unforeseen or unscheduled shutdowns, fewer fires, fewer spills, fewer explosions, or production loss time, etc.).

These factors and improvements related to rotating equipment have also been developed and applied for other types of mechanical equipment such as static parts (among others, 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, etc.), surface condensers, systems with ejectors, for injection of chemicals (corrosion inhibitors, etc.), as well as many others that are part of the facilities in the Process 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 available and recent improvements made in the last 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 rotating equipment, with the experience accumulated during this time, and with the support received from great companies with which I have had the opportunity to face the challenges day by day, both in the Facilities in process plant and the phase regarding the design, selection and during the execution of small and big projects, it could be part of the knowledge and learning that can be consulted by engineers who are now being responsible

for providing good engineering in rotating equipment, those specialists requiring actualization about knowledge, and, first at all, to those engineers starting in this area of knowledge and those who will enter soon in the industry and for future generations. To all of them, I hope you reach your goals in this area, as I think I have met my own goals and objectives in this regard.

Alberto Mtz Llaurado, 2022

IV.- OBJECTIVES AND GOALS IN RELIABILITY FOR CENTRIFUGAL COMPRESSORS

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 centrifugal compressors.

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 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, operating in the widest range of design and production capacity (for greater productivity), and without affecting the environmental and 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 in the area of rotating equipment and in this particular case of centrifugal compressors, based on the particular operating conditions required in the process to which the equipment will be subjected during its useful life cycle, which is estimated around 30 years.

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

The scope of the technical specifications for centrifugal compressors 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 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 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, 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 experiences seen and lessons learned along the way (from the last 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 of the equipment and its facilities.

Given how extensive the particular specifications of centrifugal compressors are, in this case, we consider the most relevant or critical aspects that may affect these factors (especially reliability 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.
In this particular, the different standards generated for centrifugal compressors and those of their auxiliary lubrication, control, 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 compressors.
- Technical specifications developed by international institutions applied to compressors (such as API, ISO, etc.).
- Technical specifications developed by world-class private companies in projects for centrifugal compressors, especially for the oil, gas, and petrochemical industry (Fluor, Shell, BP, etc.).
- Particular technical complements that apply as improvements in the area of centrifugal compressors.

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 Reliability Data) among others. In our case, the data and analysis carried out by OREDA are taken to have a good base 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 centrifugal compressors (with procedures such as FMEA, FMECA, Hazop, and SIS, among others).

Another important aspect of improving the equipment's reliability is the risk-based management applied to compressors. In this case, API has developed some documents recommending practices associated with this aspect, so we can refer to or review this in the book.

Different technical studies and papers about compressor failures that affect reliability are also included, as well as particular cases that occurred in world-class projects in the area of centrifugal compressors, especially for the oil, gas, and petrochemical industries.

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 centrifugal compressors, 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 theoretical description of the types and classes of existing compressors is available in the world, and, of course, in the case of centrifugal compressors, and the industrial applicability is also shown and commented on.

V.- INTRODUCTION

As an introduction to the area of centrifugal compressors, it is important to understand that this family of equipment represents a critical component in crude oil processing plants and other processing plants of natural gas or other related gases due to the gas service with a high level of risk and criticality.

Because of the high technology and complexity required to develop its engineering, it's critical to get a reliable and safe design, procurement, manufacturing, inspection, and testing in the factory, as well as in its subsequent process of preservation and storage on site, also due to the very demanding procedures of installation, very complex commissioning and to comply with difficult operational guarantees with severe penalties in cost for the manufacturer.

This makes centrifugal compressors very expensive equipment, with a long delivery time and that, if they present failures in their design and selection, generate high impacts on the production of the plants where they operate, with high risks of impact on personnel and facilities, due to risks of leaks with fires, toxic spills, explosions, severe environmental impact, among others, which demand the greatest possible attention when it comes to their operation and maintenance.

Making a little history about this type of compressor, you have to Centrifugal compressors are second in the number of machines in service. Compressors have been around for quite some time. They were originally used in process applications at relatively low pressure and high-volume service. In the early 1930s, the main application was in the steel industry, where it was mainly used as an oxidation air compressor for blast furnaces.

The compressor displaced the reciprocating compression equipment being used at the time. It was used in the coal-to-coke conversion process, where it was used to extract gas from coke ovens. In the late 1930s, the implementation of air conditioning for cinemas, department stores, and later office buildings led to a generation of small centrifugal equipment that gained the upper hand due to its smaller size and the absence of agitation forces.

These forces were difficult to contain when using a reciprocating compressor of comparable capacity in a populated environment. The design of the smaller compressor was able to penetrate the overall market of the process plant that had historically belonged to the reciprocating compressor.

The plant size and the availability of low-cost power helped bring the centrifugal compressor to prominence in the 1950s. As the compressor grew in popularity, developments were initiated to improve reliability, performance, and efficiency. As energy costs rose in the mid-1970s, efficiency improvements shifted from the latter to the first priority in allocating development funds.

Before this turn of events, most developments had concentrated on making the machine reliable, a goal that was reasonably well achieved. The execution time between revisions has become five years or more, with execution times of six years that are not unusual. As the size of the plant increased, the pressure to maintain or improve reliability was very high due to the large economic impact of unscheduled or unforeseen shutdowns. This being the case, even with the greatest emphasis on efficiency, there is no interest in energy compensation versus reliability. Operating groups tend to assess reliability first, with energy cost as a secondary factor.