AN ANALYSIS FOR FAILURE MODES OF REFRIGERATION SYSTEMS RECIPROCATING COMPRESSORS

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Abstract: *The most used refrigeration system is based on the vapor compression cycle. In this cycle, the compressor is the most complex and expensive component, specially the reciprocating semi-hermetic type, which is widely applied in the food products conservation. This component is very sensitive to variations in its operation conditions. If these conditions reach unacceptable levels, failures are practically inevitable. Therefore, maintenance actions should be taken in order to maintain a good performance of such compressors and avoid undesirable stops of the system. In order to achieve such goal, one has to evaluate the reliability of the system and/or the components. Reliability means the probability that some equipment can not perform their requested function for an established time period, under defined operation conditions. One of the tools to perceive actions to improve the component reliability is the Failure Mode and Effect Analysis (FMEA). This paper proposes to use the methodology of Failure and Effect Mode Analysis as a tool to evaluate the main failures found in semi-hermetic reciprocating compressors used in refrigeration systems.*

Keywords*: refrigeration, compressors, reliability.*

1. INTRODUCTION

The use of refrigeration systems becomes almost indispensable in several activities in the modern society. The range of application of such systems goes from providing thermal comfort in office buildings to maintaining low temperatures in refrigerated chambers (-25 to 0ºC) in order to keep food products in healthy conditions. For those systems, one of the main components is the compressor.

The main function of the compressor is to aspirate a certain amount of refrigerant vapor produced by the evaporator and increase its pressure and, consequently, its temperature. Afterwards, the refrigerant vapor is liquefied in the condenser. After the condenser, the refrigerant flows through the expansion valve and comes out as a two-phase mixture, moving into the evaporator in order to be evaporated again. In this last step, heat is transferred from the controlled temperature environment to the refrigerant. Therefore, failures and/or poor functioning of such component can result in losses due to the products deterioration or thermal discomfort (Stoecker (1994)). According to Stoecker (1994), the main types of compressors in the refrigeration industry are: reciprocating, scrolls vanes and centrifugal types. Among them, the most common type in the plants with capacities up to 1,000 kW are the reciprocating and scroll types.

For the reciprocating types, there are variations in their constructions where the open, semi-hermetic and hermetic should be pointed out. In our study, the focus is the semi-hermetic reciprocating compressor. For this compressor, the shell has, in its interior, the compressor itself and electrical motor. Usually this type of compressor operates with halogenated fluids that flow in direct contact with the motor parts which promotes the electrical motor cooling.

A growing concern is the efficiency of the refrigeration system that can be achieved through proper maintenance actions contributing for the energy consumption reduction. Also the faulty operation and failures of the components promote a high loss of energy (Tassou and Grace (2003); House *et al* (2003)).

A maintenance program can be considered a strategic function inside a company because it is responsible for keeping the systems operating in its nominal capacity or even higher than the minimum required for activity that this system is designed for (Cardoso (2004); Cardoso and Souza (2004)).

2. RELIABILITY

The term reliability has its origin in the failure analysis of electronic equipments for military use in the 50s in the United States. One of the many definitions found in the open literature is from the UK Ministry of Defense:

"The ability of an item to execute , or be able to execute, a certain function over specific conditions without failing for a established period of time or of operation expressed in terms of a probability" (UK Ministry of Defense, 1979 apud Carter(1986)).

Equipments are designed according to a specification, e.g., equipments are designed according to a basic function that they will perform. Maintenance actions are capable of restoring part of the original performance of an equipment, however, it does not increase its performance above its original level.

Leitch (1995) proposed that the actions which assure the maintainability of a equipment are different from those which assure reliability, "…. Maintainability is the probability of an equipment to be restored to its functional state, in a given time and environment". In other words, maintainability is the study of maintenance periods.

The concept of availability is then proposed as the time that an equipment, system or plant is available to operate or to be able to produce. One of the tools that allow evaluating actions that will increase the reliability and the availability is the Failure Mode and Effect Analysis (FMEA). Basically, FMEA is based on the analysis of the definition of the function of the systems and subsystems. Afterwards, the failures that affect each system function and its mains failures modes are evaluated. For each failure mode, the defects are analyzed and actions are proposed in order to reduce, eliminate or simply control the undesirable effects of a possible occurrence of such failure. FMEA is a logical system where the potential failures are scrutinized and it provides recommendations for preventive actions. It is a formal process that uses specialists dedicated to analyze the failures and how to solve them (Pinto and Xavier(2005)).

FMEA has general guidelines that should be followed when its method is applied to any system. Therefore, it is necessary, in order to elaborate a FMEA study, to answer the following five questions related to the system or equipment (Cardoso(2004)):

- How can each component of the system fail? or Which are its failures modes? By answering this question a failure mode can be understood as a set of factors and demands imposed to a certain equipment during its operation. Those factors and demands will promote the end of the equipment life cycle or they also can be the mechanism that provokes that equipment to fail.
- Which are the effects of such failure over the system? Here one has also to answer:
  - Which are the evidences that failure has occurred? (if there is any)
  - In which way is the failure a threat (if there is any) to safety or the environment?
  - How does the failure affect (if it really affects) the production or the operation of the equipment?
  - Which is the physical damage caused by the failure? (if there is any)
  - How critical are those effects?
- How can one detect the failure?
- Which are the actions that should be implemented to avoid, prevent or minimize the effects of that failure?

2.1. Reliability distributions

Reliability can be expressed as a statistical function or curves. Its type is chosen based on the characteristics of failures. One of the most common curves is known as the bathtub curve (see Fig. 01) that represents the failure rate of an equipment during a long period of time. During the equipment life cycle, this curve can represent the behavior of an electrical or a mechanical equipment and its shape is determined on statistical studies.

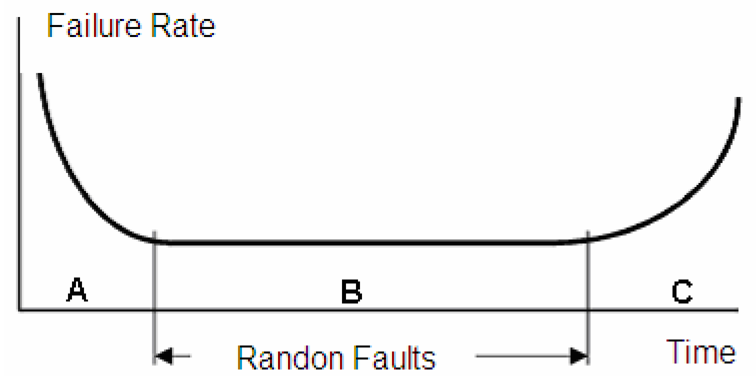

Figure 1 - Bathtub curve

The bathtub curve has three defined sections:

- Child mortality: there is a high occurrence of failures of the components due to poor application and/or installation errors. The failure rate decreases as time goes by.

- Random: this section is characterized by a very low and constant failure rate. The failure is provoked by less controllable factors such as overcharge fatigue or accelerated corrosion. Therefore the prediction/prevention of such failures is a lot more difficult.
- Aging or degeneration: there is an increase of the failure rate due to the natural wearing (friction and corrosion) that increases as time goes by.

This curve was considered for a long time as a standard for failure analysis of components, equipments and systems. However, due to the need of better evaluation of equipment before its operation, mainly in the design stage, other curves were proposed. The main reliability distributions are the normal, lognormal, exponential and Weibull.

The normal distribution (see Fig. 02), also known as Gaussian, is widely used to describe the behavior of natural materials and biological phenomena (O´Connor (2002) and Carter (1986)). Lewis (1987) attributes this distribution to represent equipments that suffer from increasing wearing.

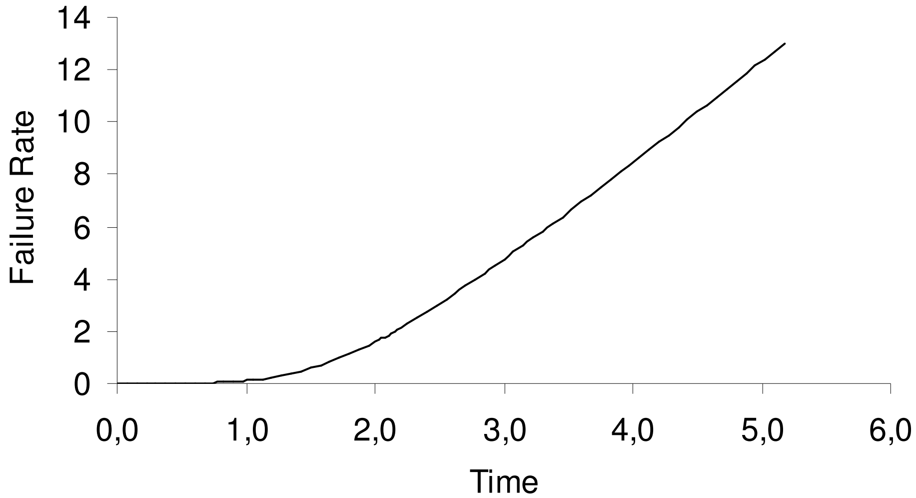

Figure 2 – Normal distribution for failure rate.

The exponential distribution (see Fig. 03) represents a situation in which the failure rate is constant. This distribution corresponds to the constant section of the bathtub curve. Carter (1986) also considers that the behavior of electronic equipments or systems is well represented by such distribution.

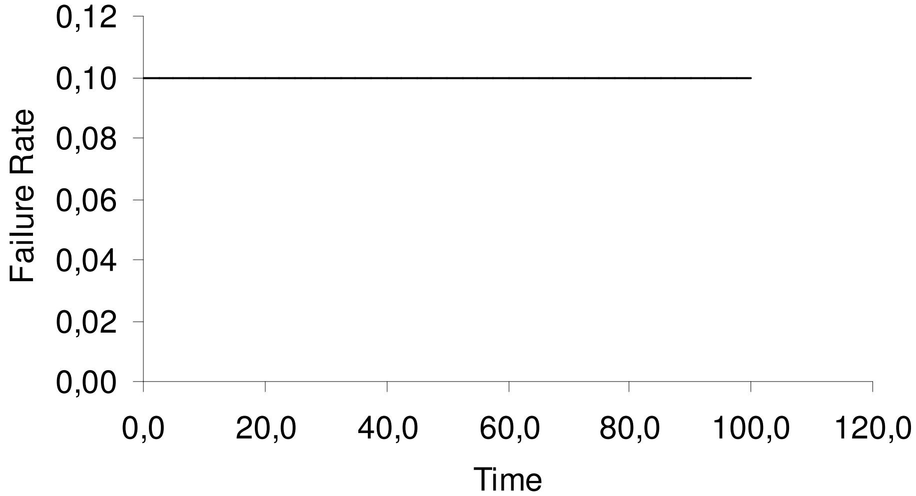

Figure 3 – Exponential distribution for failure rate.

The lognormal distribution (see Fig. 04) is quite used to characterize the life cycle of semiconductors in which the failure mechanism involves chemical interactions such as corrosion, electrical charges accumulation, contacts degradation. This distribution also describes fairly well failure behaviors of equipments caused by fatigue (Freitas and Colossimo (1997); Carter(1987)).

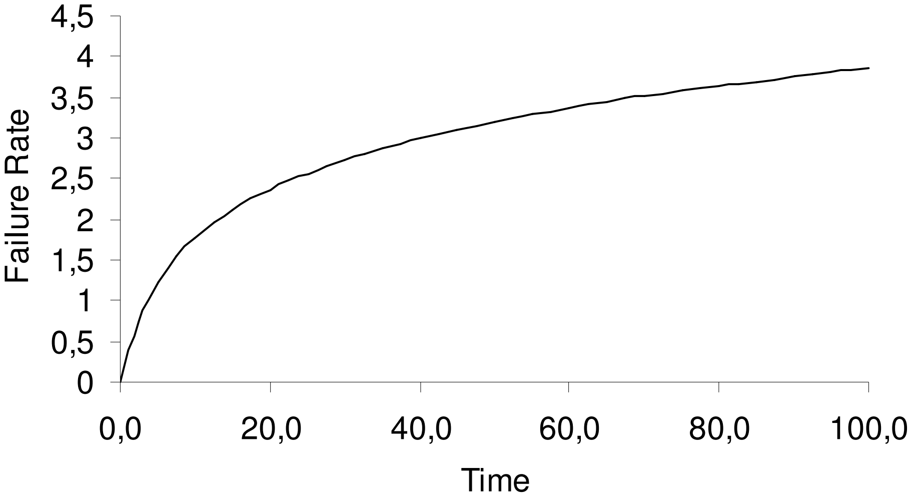

Figure 4 - Lognormal distribution for failure rate

The Weibull distribution (see Fig. 05) was proposed originally by W. Weibull in 1951 when he was studying the failure period due to fatigue in materials. One of the many advantages of the Weibull distribution is that it can represent a wide variety of failure rates behaviors with a common basic characteristic: the failure rate function is monotonic. This means that the curve can be monotonically increasing, decreasing or constant. Carter (1986) mentioned that the Weibull distribution “is quite useful, because one can have a distribution that can represent any failure rate in time”. The parameter β, called shape constant, in the Weibull distribution is responsible for controlling the form that the curve will have.

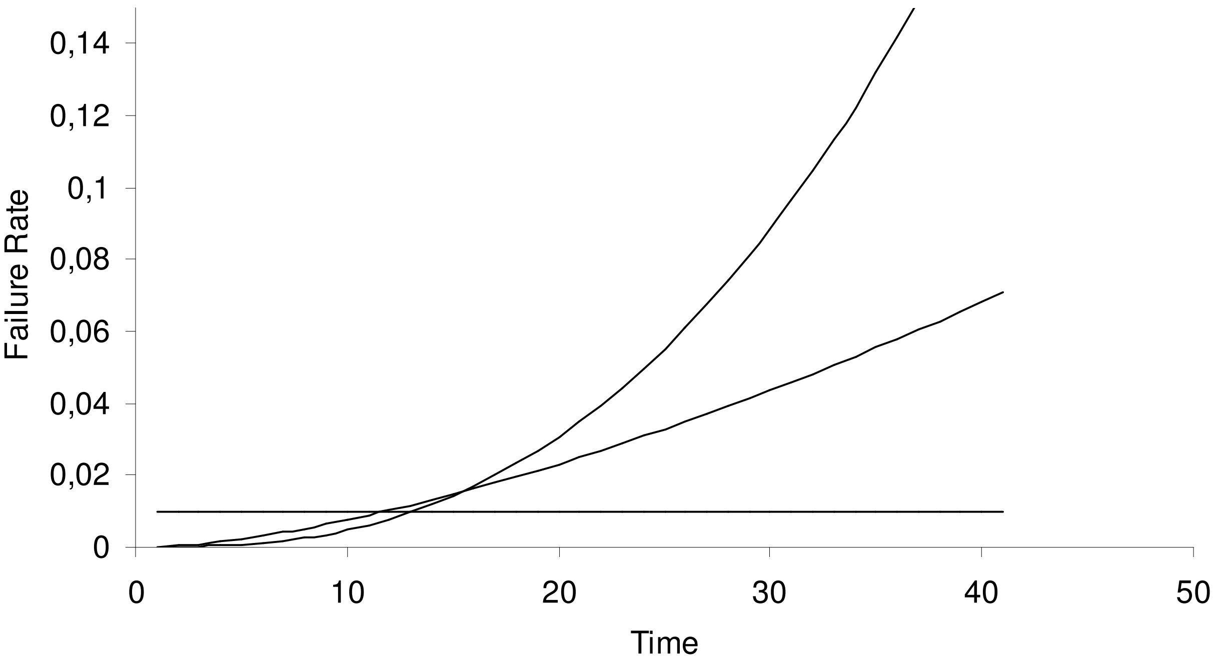

Figure 5 - Lognormal distribution for failure rate.

3. METHODOLOGY

For the objectives of this paper, FMEA study was applied to failure modes of reciprocating compressors used on refrigeration system. In order to perform this study, a database was built based on an analysis of a set of 600 reports of the occurrence of failures in reciprocating compressors of refrigeration systems. This database was provided by a maintenance company and corresponded to a three year period of maintenance service. This analysis allowed performing a detailed evaluation of the main failure modes for reciprocating semi-hermetic compressors during its operation.

Regarding the description and analysis of the failure modes in reciprocating compressors for refrigeration systems, there are few works in the open literature. Among them, the most relevant are the works of Copeland (2004) and Silva (2004). In those works one can find a good description of the several failures related to reciprocating compressors and their possible causes. Breuker and Braun (1998) presented a study in which reciprocating compressors used in air conditioning roof top system were analyzed. In this study the authors found out that the failures in the compressors represent 5% of the total failures occurrences for those equipments but they also represent 24% of the maintenance total cost, reinforcing the importance of further studies to minimize the failures in the reciprocating compressors.

Jourdan (2004), Gauge (2003), Tomezyk (2003A and B), Schaub (2001) showed several characteristics and effects of some of the failure modes in reciprocating compressors and presented some actions in order to prevent and/or eliminate those failures.

Based on the analysis of the reports and literature, it was established that the reciprocating compressors can produce several modes of failures. This can be inferred because these equipments are composed by electrical and mechanical components that can fail independently and affect the whole equipment. Therefore, due to the variety of failures modes, the Weibull distribution was applied because of its flexibility in representing well all the failures rate curves. In order to calculate the proper Weibull distributions, the software Weibull++ from Reliasoft was used for the failure modes analysis. This software was developed to perform a life cycle analysis using several distributions such as parametric Weibull, mixed Weibull, generalized gama, etc. (Reliasoft (2006)). For the proposals of this paper, the authors chose to perform a failure mode and life cycle evaluations using the technique of right-censored tests. On those tests, the equipment life cycle is determined by analyzing, for a determined period (in this case, one year after the production of the equipment), the amount and type of failures that occurred and determine the warranty period for that equipment.

Observing the created database, one can find seven types of compressors with different constructive characteristics that will be named from now on A, B, C, D, E, F and G. This classification is based on the following criteria: application (frozen or refrigerated products); compressor block, cylinders number and a ratio between the piston length and diameter. The latter one is directly related to the compressor compression ration. Based on such criteria, Tab. 01 showed each type of compressor and its characteristics. Afterwards, the main failure modes were analyzed in each type and also a separation of such failure effects were done. Fig. 6 shows the failures effect distribution for each compressor type.

Table 1. Compressor types and its characteristics

Model	Compressor block	Cylinders number	Application	Geometrical ratio
A	Compact	4	Frozen products	1,40
B	Compact	4	Frozen products	1,27
C	Compact	4	Refrigerated products	1,27
D	Standard	4	Refrigerated products	1,36
E	Standard	4	Frozen products	1,55
F	Standard	4	Refrigerated products	1,55
G	Standard	6	Refrigerated products	1,36

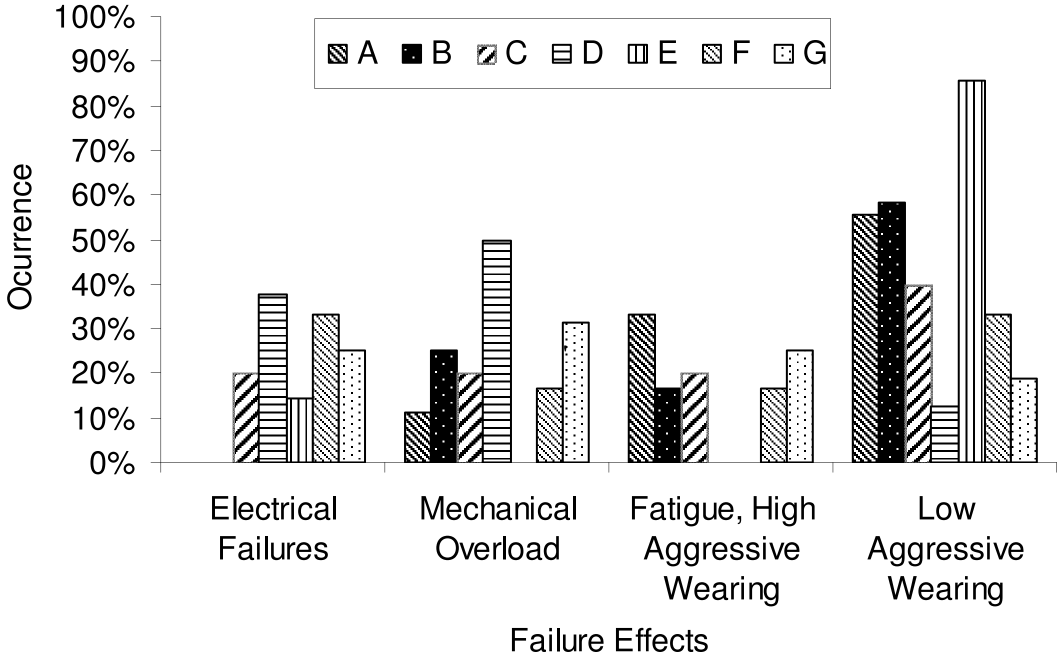

Figure 6 - Distribution of failure effects for each compressor type.

The authors consider that failure effects such as fatigue and high aggressive wearing are produced by refrigerant migration to the compression chamber and liquid refrigerant flood back. Production defects, contamination produced by air and/or moisture and excessive superheating were considered low aggressive wearing effects. Liquid stroke in the compression chamber was considered a mechanical overload effect. Electrical failures were defined as random effects and they can be originated by poor electrical energy supply or even a technician error (defects on the electrical installation of the equipment). Along the analysis it was observed that some of those failure effects could be produced for more than one problem. For example, in some cases, low aggressive wearing effects, such as contamination, can increase its influence in the system provoking a liquid stroke that caused the compressor to fail. The problem started as a low aggressive one but changed to something more aggressive and on the analyzed reports this kind of failure source separation was difficult to do. In order to properly separate the effects, the authors understand that a system technical evaluation should be carried on for the systems where the failed compressor was installed. Unfortunately, for the database in hand, this type of evaluation was not possible to be done and therefore an uncertainty due to the proper source of the failures will be inherent in this study. By introducing the collected data in the Weibull++ software, the reliability and failure rate distribution curves were produced for each compressor and the results are shown in Figs. 7 and 8.

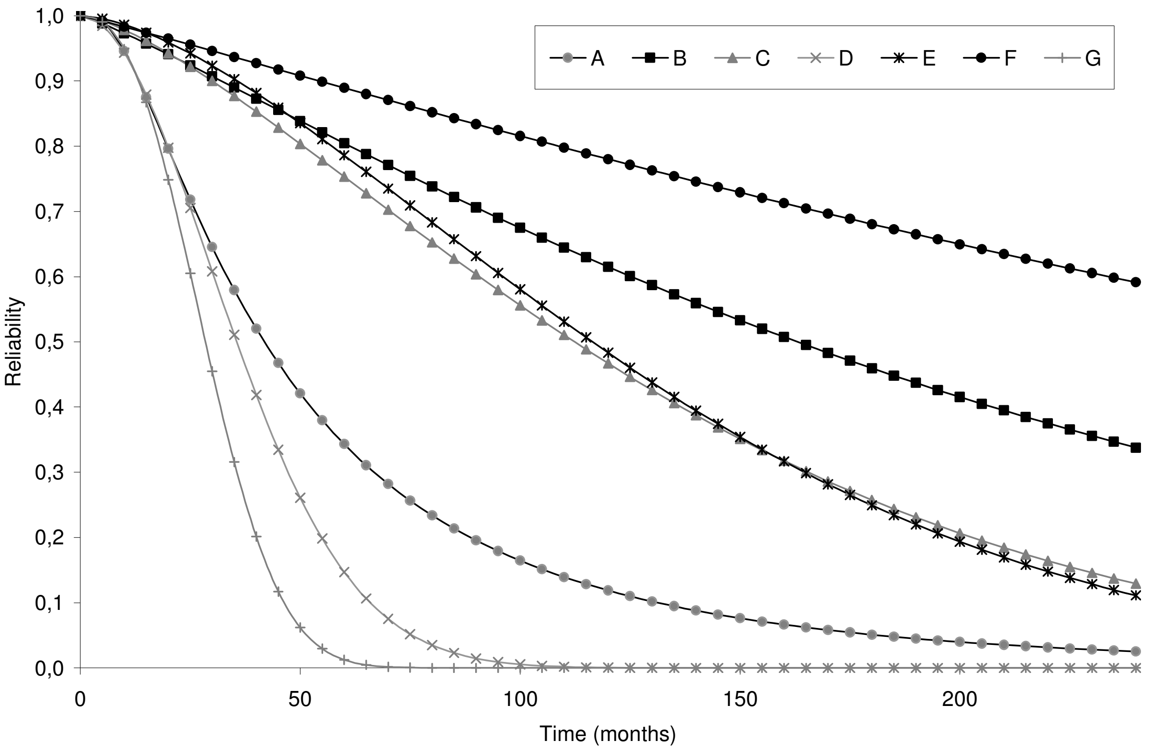

Figure 7 – Compressors reliability curves.

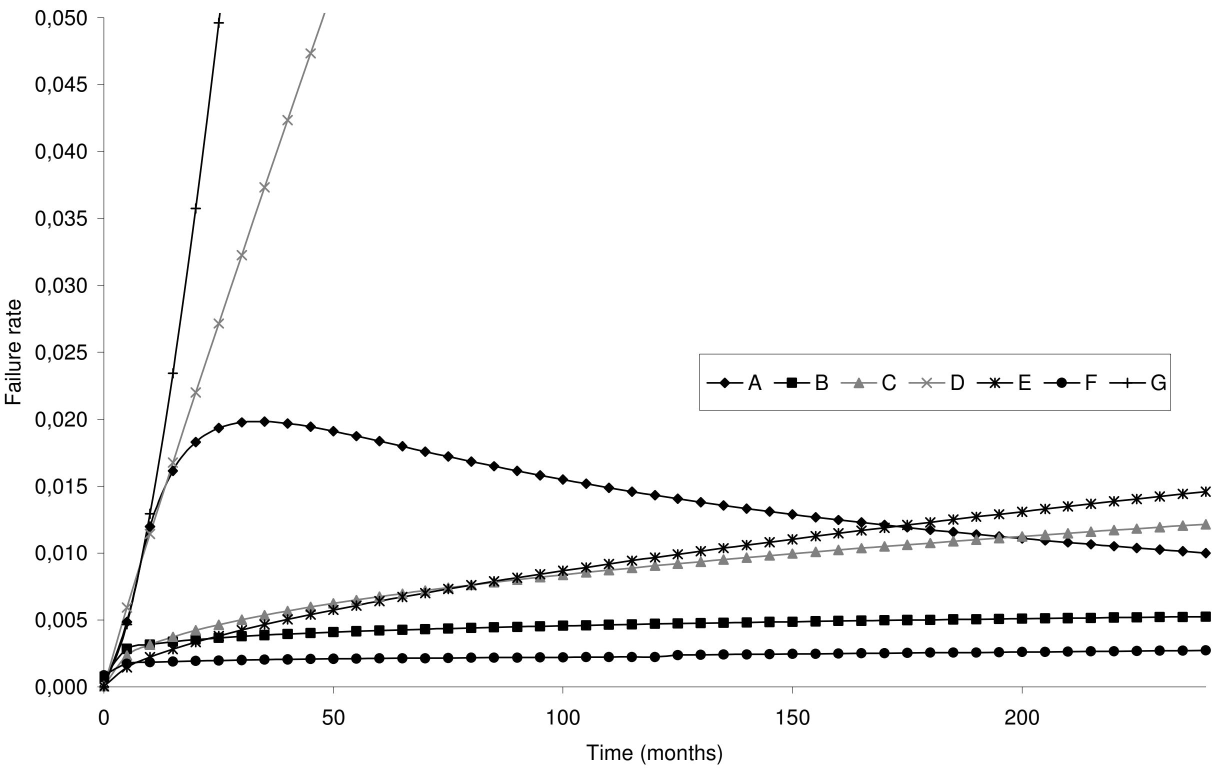

Figure 8 – Compressors failure rate curves.

In order to facilitate the analysis, these compressors were separated in 4 groups based on their compression ratio: group 1: compressor A; group 2: compressors B and C; group 3: D and G and group 4: compressors E and F.

Group 3 (compressors D and G), with the same compression ratio, shows similar behavior for both distribution curves. The higher failure rate and the lower reliability in compressor G can be explained by the occurrence of high aggressive effects such as fatigue.

Even though compressors E and C belong to different compression ratio groups and also present different failures effects distribution, they have the closest similarity in their distribution curves among the compressors analyzed in this paper. This can be explained by the fact that the Weibull distribution is calculated based on the failure occurrence and not in the type of failure. In the case of compressors E and C, their failure distributions in time are almost identical; therefore their Weibull distribution curves become very similar.

Compressor A has liquid refrigerant flood back as its main failure effect and it has a similar distribution curve comparing to compressor D and G curves. This can be explained by the fact that these three compressors have the same field application, e.g., refrigerated product systems. This implies that they work with denser refrigerant which promotes higher probabilities of liquid stroke occurrence, leading to a behavior similar to the child mortality section of the bathtub curve.

Compressors B and F have no similarities in any of the studied parameters but they both have a well spread failure mode effect distribution along the period in which this study was conducted, leading to a random behavior in the failure rate curves. This is easily noted in the compressor F curve due to the fact that most of its failures (around 70%) are on the electrical and low aggressive failure effect. In the case of compressor B, it has most of its failure also in the low aggressive effects inducing for a more random behavior but it gets a lower reliability curve than F due to the fact of a higher occurrence of high aggressive effects especially for the mechanical overload.

4. CONCLUSIONS

There are very few studies of reliability for refrigeration semi-hermetic compressor mainly due to its model complexity. But, based on the information available, it was possible to organize a database in order to provide a reliability study for such equipments.

Based on the reliability analysis for the warranty period (one year), it was possible to evaluate that, for those compressors, the behavior of the reliability parameters are highly disturbed by the design and operation of such compressors. Besides that, it was found out that the best curve that represents the reliability behavior of such equipments is the failure rate curve in which the constructive characteristics, failure mode and the application of such compressors are all taken into account. On the other hand, the reliability curve better represents the compressors behavior when only the constructive characteristics, such as the compression ratio, are taken into account.

The reliability curves also demonstrate that, in many cases, the compressors will hardly achieve the end of the life cycle evaluated in the design stage without maintenance.

The authors believe that such kind of study can improve the performance of the refrigeration compressor by better understanding its failures and also providing more qualified information for the maintenance staff.

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