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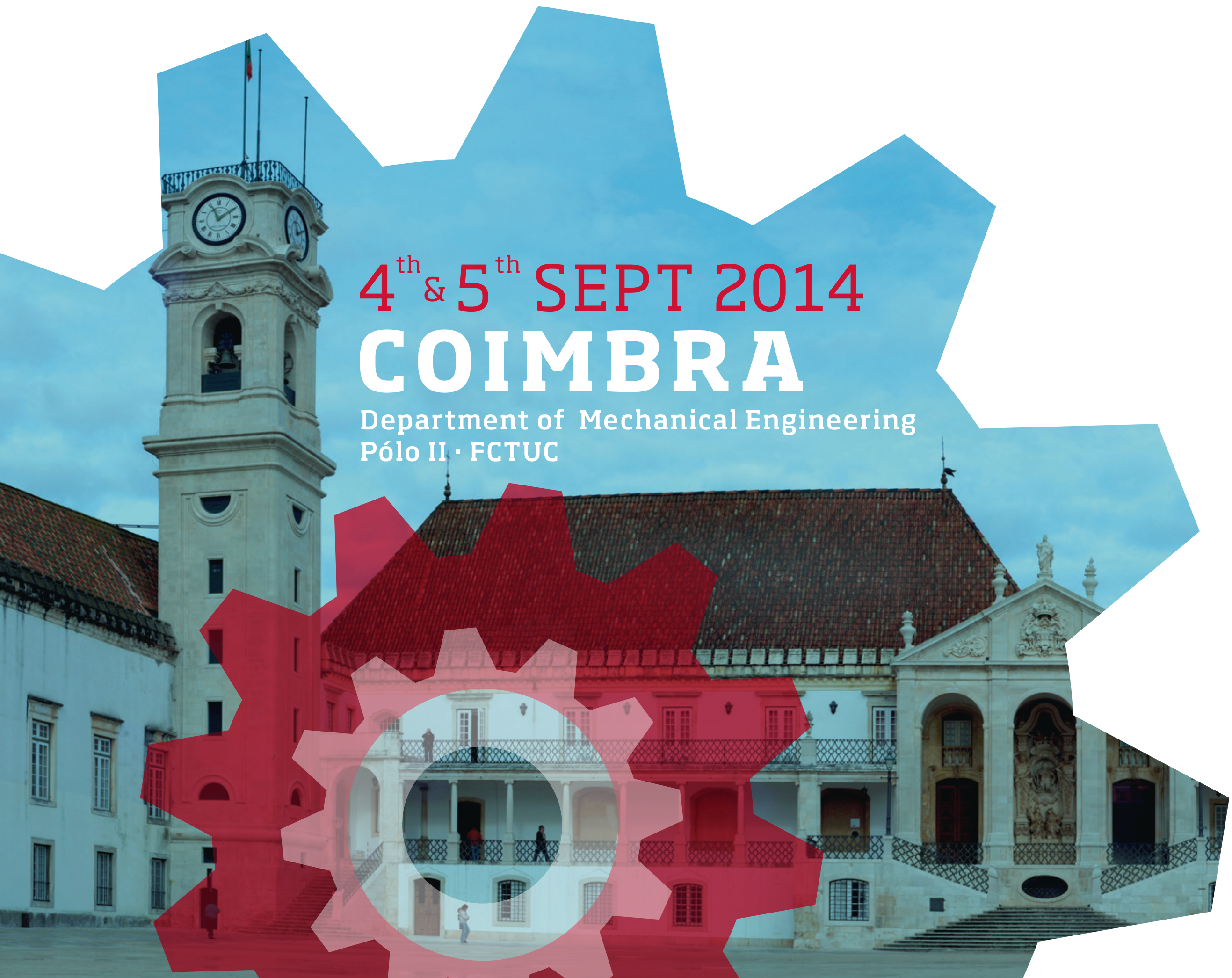

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Risk-based Maintenance: Relationship between the risk and the environment of operation

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Abstract

The risk-based maintenance is sustained in the mapping of the risk of the assets failure in an organization. The failure risk of an asset depends on the consequence of a specific failure and the probability of occurrence of such a failure. The maintenance tools based on risk assessment allow to reducing the risk of assets failure and contribute to the life cycle optimization. Being the failure risk of an asset affected by the environment of its operation, the corresponding maintenance management should be adapted to this specific environment to keep the failure below the pre-defined maximum risk criterion. Hence, the main goal of this paper is to demonstrate how the operating environment of an asset relates with its failure risk. Thus, the failure risk of a known system operating in normal conditions and in a hostile environment will be evaluated. In the end, it's expected to be known what criteria which contribute to the risk calculation we should be aware to recalculate the failure risk and review the maintenance plan.

Keywords— Risk-Based Maintenance; Risk; Life cycle costs optimization; Assets failure; Maintenance management..

I. INTRODUCTION

The risk-based maintenance has been a tool used in industry to reduce the risk of assets failure that have been growing in complexity and dimensions.

Since the seventy decade, one has been assisted to a growth of complexity and dimension in industrial plants. With the growth of industrial plants the list of hazard material has been increasing. The practice of learning by mistakes was no longer acceptable, and the risk analysis had gained a new importance. It started to identify the consequences of a failure by quantification methods.

There are many examples of industry disasters that have contributing for risk analysis development. The Flix borough disaster was an explosion at a chemical plant close to the village of Flixborough in England, on 1 June 1974. This disaster resulted in 28 deaths and 36 seriously injured. This accident had a lot of media coverage and had awakened the population for industry risks. Others accidents, continued occurring. Like the Seveso disaster in Italy on 10 July 1976 in a small chemical manufacturing plant that had affected the nearby populations.

Others more recent, like the Piper Alpha in the North Seal oil production platform on 6 July 1988.

After all this occurrences, the mentality had change and nowadays there are guidance and legislation that control the risk acceptance.

The risk can be variable since its factors are the probability and the consequence of occurrence. If for any reason, the failure consequence it's not the same, then the risk of failure has to be reevaluated.

Many developments have been taken to find the best methodology for risk-based maintenance. It will be done some review of the most significant methods.

In 1998, Harnly developed a procedure, which assigns priorities to repairs, based on risk of non-accordance that was identified in inspection procedures on chemical installations of Exxon. The procedure prioritizes the equipment´s based on an index that is the relationship between the potential failure and the consequence. The general risk of the plant is reduced minimizing the risk index of the components that most contribute to the general risk level. [1]

In 2003, Kan and Haddara, developed a risk-based methodology for inspection and maintenance [2]. They applied the method in an HVAC system and developed a maintenance program. In this methodology the risk incorporates economic, safety and environment components [2]. Such a method has three steps: Risk Estimation; Risk Evaluation; and Maintenance Planning [2].

Wang *et al.* [3] defined the consequence of failure in three components: Personal security effect, environment threat, and economical lost. For the risk assessment the authors have been used the following strategy: 1. Identification of the scope; 2. Risk Assessment; 3. Risk evaluation; 4. Maintenance planning [3]. For this author, the risk of failure results from the product of the following three parcels: the personnel safety risk, the environmental impact and the economic losses [3]. In this article the authors used a FMEA methodology to quantify the severity of personnel injury and environment pollution. To prove their methodology they used a case study of a continuous catalytic reforming plant [3].

In this paper it will be analyzed the risk of failure of an air conditioned system installed on a frigate from the Portuguese Navy. After analyzed the risk of failure for each failure mode, it will be analyzed the risk of the same failure modes but in a hostile environment for the system.

To achieve the risk of each failure mode, will be used the FMEA methodology to decompose the system, analyze its failure modes and calculate the risk associated to each failure mode.

This paper is organized in three main parts, in the first is presented the risk-based maintenance methodologies, where will be explained how can be calculated the risk of each failure mode. The second part presents the case study, with a resume of the system and with the application of the chosen methodology to the case study. The third part analysis the results, where we have the comparison between the risk in normal working conditions and when the system is working in a hostile environment. The results are towards recommendations to reduce the risk of the chosen system when working on a considered hostile environment. The last section provides some concluding remarks.

II. Risk-Based Methodology

The FMEA (FMEA – Failure mode effects analysis) methodology helps the maintenance management people to identify the failure modes of complex systems as an entire plant, and use them to select the correct maintenance tasks, to avoid the failure of the plant. [4] The methodology consists of listing all components of a system, and finding the failure mode for each component. [5].

To do a correct risk assessment there is definitions that have to be clarified. The next definitions will be assumed for the entire paper.

Moubray [4] define **failure** as: "Failure is defined as the inability of any asset to do what their users want it to do." In this definition, Moubray centered the failure on the asset function.

An asset can have more than one function, then, it can have more than one failure. So, it's important to define what a **functional failure** is. Moubray [4] defined functional failure as: "A functional failure is defined as the inability of any asset to fulfill a function to a performance standard of that is acceptable to the user."

The use of FMEA analysis is important to define what a **"failure mode" is**. Moubray [4] defined failure mode as "A failure mode is any event which causes a functional failure".

Identifying the failure mode is the way to know what we can do to avoid the failure. Identifying the entire failure modes of a plant can be a hard work. But in the day-to-day basis, the maintenance team focuses in the failure mode, the team discusses about what have been failed, what caused them and what can be done to repair and avoided them.

A failure mode can has many levels of description. If it is known the failure function, like "pump set fails" we can advance in levels of description of the failure mode. We might stop in the level where is possible to identify an appropriate failure management task. On the other hand, we shouldn't stop in a level that is not possible to describe the failure mode enough that we can't find the appropriate task to cope with the corresponding failure.

Risk is the relationship between the probabilities of a failure occurrence versus its consequence. In maintenance, the occurrence is our failure probability.

When the risk-based maintenance is used in the maintenance optimization, the maintenance engineer pursues the answer to the following questions [2]:

- What event can happen to cause the system failure?
- How can this event happen?
- What is the probability of occurrence of this event?
- What would be the consequences for the organization from this event?

Then we'll want to know, how we can reduce the risk of failure, or to maintain a low risk and optimize the maintenance costs.

The methodology of risk-based maintenance, studies all equipment components failure modes and determines the risk associated to each failure mode.

Khan [2] present a risk-based maintenance based on three general steps that it will be explained as follows (risk estimation, risk evaluation and maintenance planning):

A. Risk Estimation

In this step is calculated the risk associated to each failure mode.

There are quantitative or qualitative methods for risk estimation. The quantitative approach is done by the estimation of each failure mode frequency and its consequences. This method is appropriate when is reasonable and practicable. The most common problem when we talk about quantifying the risk is the historical data surveys [6].

Qualitative risk assessment can be applied when the risk is small and well known [6]. In this methodology is quantified the parcels of risk-based on severity and occurrence matrix that are evaluated by the maintenance engineer.

Identification of scope

The first sub-step is to identify each failure mode associated with the equipment. There are many tools to find each failure mode related to a specific equipment. It can be used a fault tree analysis, which permit to identify the basic events and how to achieve the top event. The fault tree, with the necessary data, allows calculating the probability of a top event occurrence from the probability of basic events.

Other tool that can be used to decompose the system components it's the FMEA – failure mode and effects analysis. FMEA is a process that allows understanding how a component, from a complex system, contributes to the overall failure mode. The methodology consists of listing all components of a system, and finds the failure mode for each component [5].

The FMEA methodology has the following steps:

- It has to be identified all items of a system and defined how they can failure (the failure mode).
- It has to be evaluated the occurrence severity of those failure modes.
- It has to be evaluated the occurrence probability of the failure mentioned above.
- It has to be evaluated the corresponding detectability.
- Finally it's calculated the RPN – risk priority number.

In the end is possible to use the RPN as a quantification of the risk of each failure mode.

Consequence analysis

The consequence is evaluated as a failure severity classification. That provides a qualitative measure of the worst potential consequences resulting from the failure of a specific item.

In this paper will be used a matrix to quantify the severity of each failure mode. This matrix was pointed out by Khan [2] and gives a number between 1 and 10 that allows prioritizing equipments and their components. Usually the severity has three components: the system performance loss; the financial loss; and the human health loss [2]. However, the severity matrix determination could be simplified based on the criteria presented on Table I not including all the three severity components previously mentioned. This last approach has been followed in the studies described in this paper.

TABLE I : Quantification for severity index

Classification	Description
9 to 10	Very important for system operation. Failure would cause system to stop functioning.
7 to 8	Important for good operation. Failure would cause impaired performance and adverse consequences
5 to 6	Required for good operation. Failure may affect the performance and may lead to subsequent failure of the system.
3 to 4	Optional for good performance. Failure may not affect the performance immediately but prolonged failure may cause system to fail.
1 to 2	Optional for operation. Failure may not affect the system's performance.

Failure probability

The failure probability can be calculated by using probability methods if exists sufficient historical data about the system performance [4].

However, for the sake of simplicity the work described below has been based on a matrix to quantify the probability of occurrence. Such a matrix was obtained using the information included in Table II. This approach induces a loss of accuracy but is based on the operators experience in working with the equipment and allows reaching some conclusions without having logged huge amounts of data corresponding to the operational variables of the system. This methodology is suitable to estimate the risk of new systems due to the lack of data about such a systems functioning. The probability is quantified as a number between 1 and 10, as can be seen in Table II.

TABLE II: Quantification for probability index

Classification		Description
9 to 10	Frequent	A high probability of occurrence during the item operation time interval.
7 to 8	Reasonably probable	A moderate probability of occurrence during the item operating time interval.
5 to 6	Occasional	An occasional probability of occurrence during item operating time interval.
3 to 4	Remote	An unlikely probability of occurrence during item operating time interval.
1 to 2	Extremely Unlikely	A failure whose probability of occurrence is essentially zero during item operating time interval.

Detectability evaluation

As defined in the military standard of USA Department of Defense [7], “Procedure for performing a failure mode, effects and criticality analysis”, the detection mechanism, are methods by which a failure can be discovered by an operator under normal system operation or can be discovered by the maintenance crew by some diagnostic action.

To evaluate the detectability level, was used the matrix represented in the table III to quantify the possibility to identify the failure before the failure occurs.

TABLE III:Quantification for detectability index

Classification		Description
1	Easily detectable	Automatic detection of the failure before it occurs
2	Moderately detectable	Detection of failure by inspection
3	Hardly detectable	Detection with advanced diagnosis methods
4	Impossible to detect	It's not possible to detect the failure mode before the failure occurs

Risk estimation

Doing the product of the consequence with the probability of occurrence and the detectability we have the risk priority number, which represent the risk of failure for each failure mode. This number will allow making the risk evaluation and reaching the objective of the work described in this paper. Hence, the risk index could be achieved using the following equation:

$$R = D * O * S \tag{1}$$

The following nomenclature is used: R- Risk index; D-Detectability; O – Occurrence, or failure probability; S-Severity.

B. Risk Evaluation

In this step it will be defined the acceptance criteria, which will indicate the failure modes that have or not acceptable risk of failure.

The literature presents different methods for such criteria definition. The most known and used is the ALARP (As Low As Reasonable Practicable). The ALARP definition says that should be taken all the measures to reduce a risk, that are out of the tolerable zone, until the cost of risk reduction is disproportionate to the benefit [5].

In the case study described below, it has been assumed that the failure modes that have more or equal than 70% of the maximum risk possible will not be acceptable. This interval is called the **”non-acceptable risk”**.

The failure modes between 70% and more or equal than 40% of the maximum risk possible will be within the “**tolerable risk”** criteria.

The failure modes with less than 40% of the maximum possible risk are in the “**acceptable**” interval.

C. Maintenance Planning

In this phase, maintenance techniques to reduce the risk of failures are applied to the failure modes that are within the “non-acceptable” risk criteria. To reduce the risk of a failure mode the risk index of (at minimum) one of the parameter should be reduced. There are three ways to achieve that:

- Reducing the occurrence probability by increasing the preventive maintenance tasks.
- Reducing the severity through the installations of redundant components.
- Or increasing the detectability before the failure occurs through the implementation of advanced condition monitoring techniques.

In the work carried out was not considered the detectability as influencing the risk index and the severity has been considered to be unchangeable, since it is considered that the equipment could be used in severity conditions without time to engineering modifications. So it will be analyzed how the risk can be controlled handling only the probability of a failure occur.

III. CASE STUDY

A. System description

The system chosen as test bed of the proposed methodology is an air conditioned chiller unit from a vessel. Its major function is to chill water to the ventilation system. Such a system includes a compressor, an electric motor, the chilled water system, the sea water system, the electronic unit for command and control and auxiliary components.

In Table IV it can be seen, as an example how was apply the FMEA methodology to one of the systems of the air conditioned chiller, the electrical motor. This table was extrapolated for the rest of the equipment systems and sub-systems.

This system is always working since the vessel is on duty and can be used in situations not foreseen in its project.

In the last year, the chosen system worked during five months with sea water temperature around 32ºC. These working conditions are out of the corresponding maker specifications and it has been observed an increasing of operational temperatures and pressures by each hour of operation. The increased temperatures and pressures could induce premature failures and, hence, the maintenance program and the spares kits should preview such an abnormal situation.

The extreme working conditions mentioned above will be defined as hostile operation condition. From the experience observed for this work the number of failures in the hostile condition has raise in comparison with the normal working conditions.

B. Risk estimation

To achieve the aim claimed above by the author, the methodology previously described for risk-based maintenance assessment, has been adopted in the current work. Considering the normal equipment working conditions and for abnormal working situation mentioned above. The comparison will determine the maintenance plan that should be taken to preview premature failures.

Thus, to estimate the risk of each failure mode has been used the FMEA methodology.

The complete system was divided into 35 components. To each component was specified its function. For each function was defined the functional failure and for each functional failure was developed the failure modes. A failure mode should consist of a noun and a verb being the most consistent and precise as possible [4].

Occurrence probability

It was analyzed failures data recorded since 2009, on a total of 40272 working hours. The existing data are from failures of the system that shutdown the system for more than 3 hours. In order to consider the other failures the qualitative method was used to evaluate the failure occurrence probability. In this methodology the expert opinion was used taking into consideration the most probable failures even without correct data recording.

The matrix used to evaluate the failure occurrence probability was the one represented in Table II. To determine the scale in the mentioned table was calculated the failure rate of each failure mode that had occurred during the observation time. With this failure rate, even if is 0, was possible to achieve a scale index according to the one included in the mentioned Table. Furthermore, it was considered the expert opinion that has been considered very important to tune the index in accordance with his experience. Then, the quantification of the failure occurrence probability is a number in a scale from 1 to 10.

The results of this analysis can be seen in the column “O” on table V.

TABLE IV : FMEA of electric motor

NR	System/sub-system	Function	Functional Failure	Failure Mode	Corrective Maintenance
Electric Motor					
1	Motor (rotor and stator)	Produce rotation with electrical supply	Not run	Damaged cables	Replace cables
2	Bearings	Ensure the rotation of the shaft evenly without adding stress to the electric motor	The motor heats up, makes noise and increases consumption	Seized bearings	Bearings replacement
3	Coupling	Ensure equal rotation between the motor shaft and compressor	Only moves the electrical motor	Damaged coupling	Coupling replacement

Based on the failures historical records, of this equipment working on the specific conditions described before as "hostile environment", was reviewed the level of occurrence probability to each failure mode, and was constructed a new FMEA with this specific data. The results can be seen in column "O'" on table VI.

Severity analysis

The analysis of the severity was performed according to Table I. It was based on the expert experience in working with the previously described equipment who have been accompanied this system since 2011, including the time that the system worked in the hostile environment.

The severity analysis took into consideration the scale of Table I, aiming to determine how each failure mode could contribute to the system unsatisfactory performance. Thus, the severity quantification is a number in a scale of 1 to 10.

The severity level for the normal working conditions and for the abnormal working condition was considered constant. Once the severity index is function from the system arrangement, which is not changed in this case study. The results of severity analysis, can be seen in column "S" on tables V and VI.

Detectability Evaluation

The evaluation of detectability for each failure mode was performed according to the Table III. The detectability range is from 1, to failures easily detectable, until 4, to failures impossible to detect before it happens.

The detectability index, is also independent of the operation conditions, so this index will be constant independently of the environment.

To determine the detectability value was taken into consideration the actual maintenance program. The results can be seen in column "D" on tables V and VI. The table VII shows how the risk can be reduced with the improvement of detectability index, this possibility will be analyzed later.

Risk estimation

The risk estimation is not more than the multiplication of the occurrence, severity and detectability indexes for each failure mode. The quantification of the risk of failure is a number in a scale taking the value 1 to the minimum possible risk and 400 to the maximum possible risk.

The "RPN" column on Table V shows the initial risk of failure for the failure modes out of the defined criteria. The "RPN'" column on Table VI shows the failure modes that had increased the failure risk during the "hostile operation". The "RPN''" column shows the failure risk reduction obtained improving the detectability.

C. *Risk evaluation*

After the risk estimation, it should be defined the acceptable criteria. It was used the intervals defined in the section II. In accordance with the acceptance criteria defined, it will be used the next intervals:

Less then 160 (RPN)	Acceptable
Equal or greater then 160	Tolerable
Equal or greater then 280	Non-acceptable

Thus, in Table V is shown the failure modes that are out of the acceptance criteria.

In the Table VI is shown the failure modes that had increased risk index when the system was working in the hostile environment. There are two failure modes (the nr 23 and 24) that increased the risk value from a situation of "acceptable risk" to "tolerable risk".

Those two failure modes were acceptable, but with the failure historic analysis during hostile operation, the "occurrence" index had increased their values and the RPN had also increased to non-acceptable values.

D. *Maintenance planning*

After the risk index has been assessed for the normal working period and for the hostile working period, it is possible to know how the risk varies, if varies, and how can be accommodated the increasing risk to guaranty the most efficient system operation.

Analyzing the failure modes on Table VI, can be selected the failure modes that should be watchful. There are two situations:

- Failure modes that are already in those levels of concern, like the failure modes 6 and 12. In these cases, the risk is already worrying and the methodology to reduce risk should be taken independently of the working environment.

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TABLE V : Failure modes in the tolerable risk and non-acceptable risk index

NR	System/sub-system	Function	Functional Failure	Failure Mode	O	S	D	RPN
Compressor								
6	Suction and compression valves	Ensure the intake and exhaust the FREON in correct timing	Doesn't make the intake or exhaust the FREON	Broken Valves	9	10	4	360
7	Cylinders	Ensure the compression and expansion the FREON	Doesn't make the compression or expansion	Damaged cylinders	6	10	4	240
Command and control automatism system								
12	Command and control automatism (electronic components)	Receiving information from the sensors, make an emergency stop of the compressor and manage the phases of compression of each compressor	System doesn't work	System has no command	5	8	4	160
FREON circuits								
33	Tubing	Ensure the tightness of the circuit	Low suction pressure of the FREON	FREON leakage	6	8	4	192

TABLE VI : Failure modes that had increased the risk In the hostile environment

NR	System/sub-system	Function	Functional Failure	Failure Mode	O´	S	D	RPN´
Compressor								
6	Suction and compression valves	Ensure the intake and exhaust the FREON in correct timing	Doesn't make the intake or exhaust the FREON	Broken Valves	10	10	4	400
7	Cylinders	Ensure the compression and expansion the FREON	Doesn't make the compression or expansion	Damaged cylinders	6	10	4	240
Command and control automatism system								
12	Command and control automatism (electronic components)	Receiving information from the sensors, make an emergency stop of the compressor and manage the phases of compression of each compressor	System doesn't work	System has no command	6	8	4	192
Sea-Water cooling system								
23	Bearings	Facilitate rotation	The pump heats up, makes noise and increases consumption	Seized bearings	6	7	4	168
24	Water retainer	Ensures the tightness of the pump	Water leakage from the shaft	Damaged retainer	8	5	4	160
FREON circuits								
33	Tubing	Ensure the tightness of the circuit	Low suction pressure of the FREON	FREON leakage	7	8	4	224

TABLE VII : Failure modes that had improved the detectability factor

NR	System/sub-system	Function	Functional Failure	Failure Mode	O´	S	D´	RPN´
Sea-Water cooling system								
23	Bearings	Facilitate rotation	The pump heats up, makes noise and increases consumption	Seized bearings	6	7	3	126

- There are two failure modes that rose from a situation of "acceptable risk" to "tolerable risk" when the equipment was working in the hostile environment. In those situations are recommended to implement maintenance management techniques to reduce the failure risk.

To demonstrate that the detectability improvement can reduce the failure risk, the Table VII quantifies the RPN in hostile environment with the appliance of advanced techniques of failure diagnosis. Applying this techniques, the detectability index reduces from 4 to 3 in the failure mode nr 23 and consequently the RPN reduces turning this failure mode as "acceptable".

IV. CONCLUSIONS

The maintenance management can't be a static theory with closed methodologies. For each situation, for each system, the assets management requires a suiting policy that contributes to the most efficient exploitation of these assets.

The work carried out was based on well-known methodologies to advise a real case of an asset that have different necessities of maintenance during its period life cycle.

In the final analysis of the system considered were identified two failure modes that weren't failure modes of concern in normal working conditions but in a very specific environment they turn into failure modes of concern and, thus, it should be adopted suitable maintenance techniques for the components corresponding to those failures.

There were other two failure modes that were already case of concern with high level of failure risk, furthermore in the specific hostile environment considered, their risk increases. For the components corresponding to this failure modes, should be taken into consideration the adoption of monitoring techniques with a high frequency, due to the high severity of failures or high probability of occurrence.

With the failure modes out of acceptance criteria, was simulated the possibility of applying advanced techniques of diagnosis and one of the failure modes that as increased its RPN to non-acceptable has been reduced to acceptable.

For the future is important to validate these conclusions with data corresponding to more failures and like is quoted before, the analysis needs to evolve in time to guarantee a more reliable system.

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