Economic Risk Analysis for Gamma Irradiator

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Abstract: Gamma Irradiators are facilities that provide decontamination, disinfection and sterilization services for commercial products 24 hours a day. A failure that delays this service greatly affects its productivity. Therefore, there is a need to perform an economic loss analysis due to the delay in the production process. In this study, a reliability analysis was performed on the systems of an irradiator category IV through the application of a Probabilistic Safety Assessment methodology and the calculation of economic losses due to failures. Economic losses were determined based on real failures that occurred in a certain time frame and a comparison was made with the possible economic losses based on the failure rate of the components. These results allowed the improvement of the irradiator service through a more efficient maintenance management.

Keywords: Gamma Irradiator, Economic Risk Analysis, failure rate, economic losses.

1. INTRODUCTION

Gamma irradiators (GI) are facilities that operate with radioisotope sources where the most used radionuclide is ^{60}Co. Its objective is to provide a service of decontamination, disinfection, and sterilization of products that require treatment to reduce their microbiological level [1-4].

There are 3 categories for industrial irradiators with gamma sources: (i) Category II (Panoramic irradiators with dry storage of the radioactive source) (ii) Category III (underwater irradiators) and Category IV (Panoramic radiators with storage of the source in water). They have particular characteristics according to the product to be treated, transportation mechanism and shielding source. GIs work with high doses between 105 and 106 Gray (Joule/kg). Safety is an important factor in the operation and performance of the personnel who work daily in these facilities [5,6].

On the other hand, the calculation of economic values in a company facilitates the evaluation of its performance during a specific period, as well as optimizing the process and driving the application of measures that improve the synergistic relationship between customers, management, and the process.

In the production or service costs, there are elements of expenses that include the planned disbursements associated with the necessary maintenance to maintain the functional capacity of the installation, in order to achieve a safe, reliable and stable operation.

These costs can be identified by the different maintenance strategies: preventive, predictive, and corrective analysis. The first two can be planned with adequate accuracy based on the existing information. In the latter case, there is generally no notion of when it will happen or its magnitude, it is manifested by failures in the production process or service in a certain period of time, causing an unexpected interruption of production, causing a reduction in the economic results of the installation that deviate from those already planned.

According to the literature consulted [7,8], the cost of planned maintenance, whatever its variant, includes two components: the cost of the necessary replacements and the human labor associated with that process. Because there is no information that determines the magnitude of the work required to recover the operational capacity of the facility, the two components cannot be specified previously, which causes the cost of corrective maintenance to have a high degree of uncertainty. Also, in this case, another component must be included that contemplates the plant's downtime due to the failure that occurred, causing an "economic loss" that will lead to expenses and included in the cost of corrective maintenance. These costs can not be precisely defined, hence the need to associate them with the probability of failure of components and include it within the potential costs of the facilities. This is particularly important in irradiation facilities that use radioactive sources since these independently of their exploitation have a decay (exponential) which directly decreases productive efficiency.

Given the concern about safety and economy due to detaining the production process. Probabilistic Safety Assessment (PSA) can be used to do safety analysis as a first stage and economic analysis as a final phase. This will identify the components that most affect the irradiator's production process when it will be necessary to replace them as well as if it will be necessary to reduce the time between maintenance.

As proof of concept, this paper presents, the calculation of economic losses due to failures in a category IV irradiator in order to improve its service through a more efficient management of maintenance.

1.1. Gamma irradiator category IV

Category IV GIs, have 5 mains systems to carry out the irradiation process: (i) safety systems, (ii) external transportation systems, (iii) the source lift system, (iv) internal transportation system and (v) the system of driving compressed air to the equipment that needs it.

The safety systems are responsible for monitoring that there is no parameter under surveillance other than the pre-set values and avoids the irradiation of the personnel that operates the irradiator. The external and internal transportation systems are responsible for moving the products inside and outside the irradiation chamber. The source lifting system is responsible for moving the source and placing it in any of its two preset positions, irradiation position or shielded position.

The workers do not have access to the irradiation zone while the source is in the irradiation position, this area is only accessed if the source rack is in the safe position. To prevent operators from accessing the irradiation chamber while it is carrying out the process, the irradiator has safety and protection systems founded on the basic principle of defense in depth.

The GI uses containers to move the products while they are inside the transportation system These containers are moved either by roller chambers or rails that allow free passage throughout the process. Its movement is stopped only by the existing physical barriers, which provide the directionality of the movement [6].

The transportation of these containers are carried out by pistons that use compressed air from compressors installed outside the irradiation chamber. The movement of the pistons and the containers is monitored by a control panel. The control panel is programmed to operate all the processes that occur within the irradiation chamber, the external conveyor, and the compressed air system.

A failure of any system can lead to stopping the production process due to the active and passive actuation of the safety systems, hence the importance of continually monitoring the systems and components.

The control of the process is carried out by dosimeters (instruments that measure the absorbed dose in a certain range) that are placed in different positions within the containers before the irradiation process begins. This analysis is performed to validate the dose absorbed by the product for quality reasons.

The price of the services is established by irradiated container, weight or product volume. The price of each service varies according to the speed with which the customer needs the product:

urgent> semiurgents> normal. The facility also provides dose services: A, B, C, D,...... N and the charge per dose increases as the time it takes each container within the irradiator increases: N> E>......> A.

2. ECONOMIC RISK ANALYSIS METHODOLOGY

Economic Risk Analysis (ERA) is based on the calculation of economic losses due to malfunction of the systems that make up the production process of an installation that is able to stop it. The fundamental objective of this analysis is to transform the values of service inactivity to economic values through the monitoring of failures and improvements in maintenance programs.

ERA gives an estimated value of the losses that have existed during the work period of the installation or that may exist in the future. The analysis presents a closed cycle of 7 stages (Fig. 1) (each one dependent on the previous one) that allows evaluation and continuous improvements to the installation.

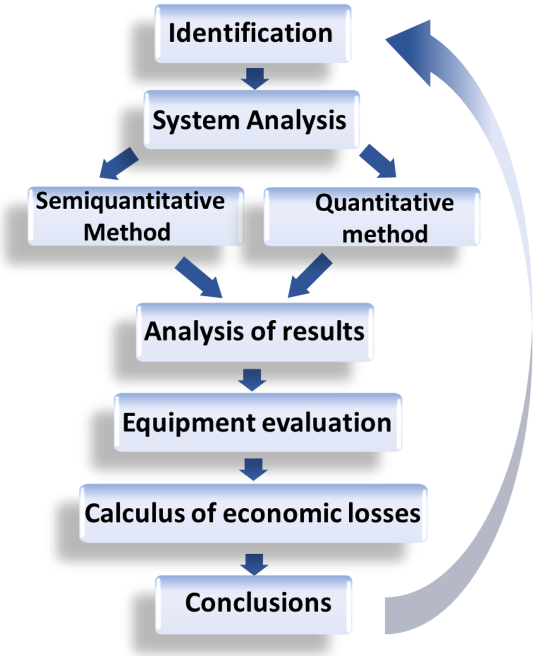

Figure 1. Stages of Economic Risk Analysis

-The first stage is the identification of the irradiator according to its category, systems linked to the process, human resources, management processes, quality and other fundamental factors to obtain basic knowledge about the irradiator operation.

-The second stage is the systems analysis. A detailed study of the systems directly involved in the production process is carried out, which allows indirectly obtaining the most critical systems and components that affect the proper functioning of the irradiator and its possible causes.

- The third stage is the reliability analysis based on different methods that can change depending on the personnel or structure of the installation. Two types of analysis must be carried out: one qualitative or semiquantitative and the other quantitative. In the first case, primary information of the key elements of the system and its failure modes is obtained, as well as a semiquantitative classification based on criteria of the analyst. In the second analysis, the probabilities of failures are introduced to quantify which components are most critical for the process, as well as to determine the minimum combinations of equipment out of service that can lead to disruption of the productive process.

The most used methods are: What if, FMEA, Check List, FMECA and HAZOP, and the fault tree method for quantitative analysis [9-13]. In this work, the methodology of failure mode, effect and criticality analysis (FMECA) was used, following the next steps [14-18]:

1. Define system boundaries for analysis. Identify the Asset / Maintainable Unit or system being analysed.
2. Collect information on historical failures.
3. Define failure/success criteria for the system.
4. Determine each Asset / Maintainable Unit /item potential failure modes.
5. Determine the causes and effects of failure mode.
6. Establish Asset / Maintainable Unit/item failure mode severity Severity (S) score of the failure consequence (Table 1).
7. Determine item failure mode (frequency) occurrence (O) (Table 2).
8. Determine item failure mode detectability (D) (Table 3).
9. Assess the risk priority for each failure mode.
10. Risk Priority Number (RPN) Score – S x F x D.
11. Review actions, currently being taken, for dealing with the failure modes.
12. Develop remedial measures to eliminate or mitigate the potential failure.

Table 1. Severity Criteria

Rank	Severity Criteria	Systems	Staff	Company
1 Minor	Failures that delay the production process less than 20 min	Loss of functional capacity less than 20min.	-	Small production losses
2 Marginal	Failures that delay the production process for 20min-1hour.	Loss of functional capacity for 20min-1 hour.	Injury.	Minor production losses
3 Moderate	Failures that delay the production process for 1-5 hours.	Loss of functional capacity for 1-5 hours.	Injury.	Moderate production losses
4 Crítical	Failures that delay the production process more than 5 hours.	Loss of functional capacity more than 5 hours.	Injury.	Large production losses.
5 Catastrophic	Destruction or large-scale degradation of the facility's functions.	Total loss of the functional capacity of the facility.	Lose the life.	Irradiator closure.

Table 2. Occurrence Criteria

Rank	Ocurrence	Occurrence (Irradiator cycles)	Failures per hour
1 Unlikely	It is not reasonable to expect this failure mode to occur	1/100,000	-
2 Very Low	Low number of failures	1/10,000	<0.0001
3 Low	Occasional failures	1/1000	0.0001 a 0.001
4 Medium	Frequent failures with long cycle intervals.	1/100	0.001 a 0.01
5 High	Frequent failures with short cycle intervals.	1/10	0.01 a 1.0

Table 3. Detectability Criteria

Rank	Detectability Criteria	Probability %
1 Very high	Very high probability of detecting the failure before it occurs. Usually preceded by a warning.	80-100
2 High	High probability of detecting the fault before it occurs. Sometimes preceded by a warning.	60-80
3 Moderate	Moderate probability of detecting the failure before it occurs.	40-60
4 Low	Low probability of detecting the fault before it occurs. Always comes with little or no warning	20-40
5 Remote	Remote probability of detecting the failure before it occurs. The pre-failure warning does not exist.	0-20

The fault tree is a deductive procedure. It is used to determine the different combinations of components of a system, which could trigger the undesired events specified at the beginning of the analysis.

The result is a logic graphical model with different combinations of simultaneous failures that lead to the occurrence of the unwanted event or top event. Examples of failures include human errors, component failures. For the modeling of the fault tree in this study, we used the Saphire program.

- The fourth stage is the analysis of results where information is obtained on the equipment, components, and systems that must be considered during the economic analysis, due to their influence on the production process.

- The fifth stage is based on quoting the prices of equipment, components, and tools necessary for corrective, preventive and predictive maintenance.

- The sixth stage is the calculation of losses and is made knowing the characteristics of the installation, the way of charging for the service, the duration of the interruption and the dose received by the product at the time of failure.

To calculate the economic losses the next steps were followed:

1. Calculate the cost of the duration of service interruption

The cost of losses of service time is based on two fundamental factors: the number of containers that stopped leaving and the duration of the interruption. Taking into account that during the same failure you can find containers with different services inside the irradiator:

$$\mathrm{Cpi} = \frac{\mathrm{Ti}}{\mathrm{Tci}} * \mathrm{Ts} \qquad (1)$$

Where:
Cpi: Cost for service losses of component i (USD).
Ti: Unavailability time due to component failure i (h).
Tci: Console time at the time of failure (h).
Ts: Type of service (USD).

Console time is the interval (in time) that a container takes to exit after its predecessor has left.

$$\text{Ts: Type of service,} \qquad \mathrm{Ts} = \begin{cases} \text{Normal} \\ \text{Semiurgents} \\ \text{Urgent} \\ \text{Combination of the above} \end{cases}$$

At the moment of the failure, more than one type of service can coexist, which is why it is considered a combination of the costs. This combination is expressed as the sum of the types of services that are affected during the fault, depending on the time the same as the distribution of containers within the irradiation chamber.

The cost for service losses of component (i) (Csi):

$$Csi = \sum_{i=1}^{n} Cpi \tag{2}$$

2. Calculate the cost of repair

The cost of repair is based on the analysis of the necessary equipment to do effective the maintenance of the failed component (i) and the labor required for the performance of the task that can be classified as light or complex, depending on the magnitude of the failure and the possibilities of the installation to face the solution of this failure.

$$\mathrm{Fi} = \begin{cases} \mathrm{L} \\ \mathrm{C} \\ \mathrm{L + C} \end{cases} \tag{3}$$

Where:
Fi: Cost of labor for maintenance of component i (USD).
L: Light (USD).
C: Complex (USD).

The light workforce includes the maintenance that is carried out by the workers of the facility, so no external help is needed while the complex workforce is one in which the maintenance is carried out by personnel other than the installation and finally, a combination of the above is required when the maintenance work is a larger scale.

The cost of repair of a component is given by the relationship between the labor force present during maintenance and the cost of the component in case of any replacement. The cost of repair of component (i) due to failure is:

$$Cri = Cci + Fi \tag{4}$$

Where:
Cri: Cost of repair of component i (USD).
Cci: Cost of component i (USD).

The total cost of repair of component (i) during the period of the evaluation:

$$Ctri = \sum_{i=1}^{n} Cri \tag{5}$$

The productive process not only fails the component (i) but also the components j, k,......., n can fail, the equations from before become:

From (2) the cost of total irradiator losses per service stop:

$$Cts = Csi + Csj + Csk \ldots\ldots\ldots.. + Csn \tag{6}$$

From (5) the total repair cost:

$$Ctr = Ctri + Ctrj + Ctrk \ldots\ldots\ldots.. + Ctrn \tag{7}$$

3. Calculate of economic losses

For the calculation of economic losses, the total cost of repair, the cost of loss per service and customer demands were analyzed.

$$Pe = Ctr + Cts + Cl \quad (8)$$

Where:
Pe: Economic losses (USD).
Cl: Customers.

The demands of the clients are the complaints which are analyzed by the installation and which tribute in legal problems or in the increase of the service for free, which causes economic losses that were not contemplated in the process.

Economic losses per hour (USD/h):

$$Peh = \frac{Pe}{T} \quad (9)$$

Where:
T: Analysis time (h)

The 3 previous steps are used to calculate economic losses only when real data can be posted for failures in a facility during a study period.

4 Calculate the expected value of economic loss due to failures

An estimate of economic losses can be made by calculating the expected value of economic loss due to failures. This value takes into account the cost of the component that may fail, the failure rate of the component to be analyzed and the cost per service proposed by the analyst when assessing economic losses. The latter is an estimated data, which is associated with a value of economic losses due to failures during a period.

$$Vei = (Cc + Cs) * \lambda i \quad (10)$$

Where:
Vei: Expected value of economic losses per hour of component i (USD/h).
λi: Failure rate of component i (1/h).
Cs: Cost of estimated service losses (USD).
Cc: Cost of the failed component (USD).

From (10) the expected value of total economic losses is:

$$Ve = Vei + Vej + Vek \ldots\ldots\ldots.. + Ven \quad (11)$$

The economic calculation was made on the components that most influenced the unavailability of the system and those that required long maintenance times. The analysis did not take into account the complex workforce since all the maintenance of the installation is carried out by the operators and maintenance managers. In addition, there were no claims from customers that accrued in economic losses.

The result from step 4 will be used as a comparison with the three previous steps to obtain knowledge about the operation of the facilities. If Peh > Vei then the irradiator can reduce the economic losses if Peh ≤ Vei then the operation of the installation is adequate, therefore no changes in operation or maintenance are required.

- **The seventh stage** concludes the analysis of the economic losses, which allows making recommendations about a change of components, variations in the maintenance program or other suggestions that optimize the irradiator's production process

A reliability analysis was carried out on the systems of a category IV irradiator for 18 months, where the economic losses were analyzed according to the real failures that occurred in that period, using the first three steps of the sixth stage. A comparison was made with the possible economic losses based on the failure rate of the components, calculated in the 4th step of the sixth stage of the methodology.

3. ANALYSIS AND DISCUSSION OF RESULTS.

From the analysis of each system using the FMECA and fault tree methodologies, it was found that the most important system for safety is the lifting system, and the most influential in the production process is the internal conveyor, the horizontal pistons being the components that most contribute to the failure of the system. Other systems that contribute to the economic risk are shown in Figure 2.

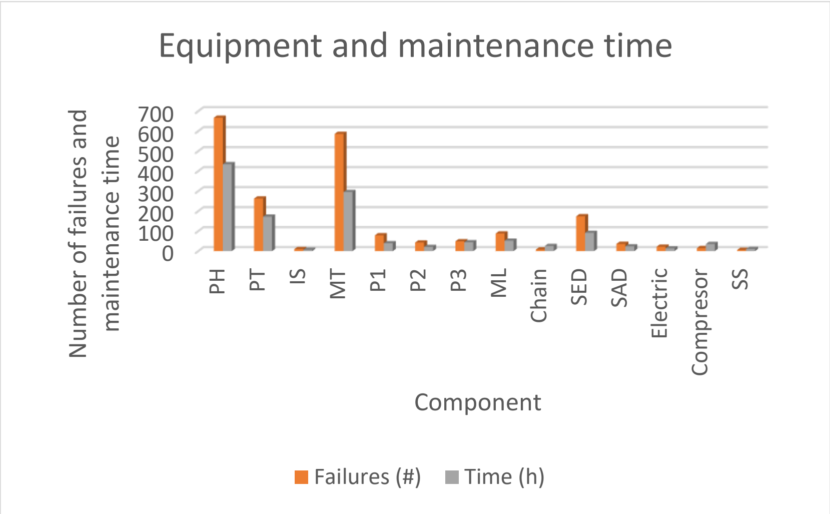

Figure 2. Most common component failures and their maintenance time.

PH: horizontal pistons, PT: transverse pistons, IS: internal stuck, MT: Mechanical conveyor, P1, P2, P3: Pistons number according to the case, ML: mechanical link, SED: stuck in the front door, SAD: stuck in the exit door, SS: safety systems.

Table 4 shows the values obtained from the calculation of economic losses during the study.

Table 4: Most common component failures and their maintenance time.

Failures	Csi (USD)	Ctri (USD)	Pe (USD)	Peh (USD/hour)
PH	65912.97	393.49	66306.47	5.12
PT	34308.87	196.72	34505.59	2.66
IS*	1004.81	-	1004.81	0.08
MT	49962.41	37.14	49999.55	3.86
P1	5953.02	618.02	6571.04	0.51
P2	3140.82	556.22	3697.04	0.29
P3	6724.01	741.63	7465.64	0.58
ML	7893.13	777.14	8670.27	0.67
Chain	3873.89	3428.57	7302.46	0.56
SED*	13852.47	-	13852.47	1.07
SAD*	3608.47	-	3608.47	0.28
Electric	2022.26	297.14	2319.40	0.18
Compresor	5371.62	800.07	6171.69	0.48
SS	189.59	280.00	469.59	0.04
Total (USD)	203818.33	8126.16	211944.49	16.35

*IS, SED and SAD do not have repair costs since the failure is produced by containers stuck inside or outside the irradiation chamber, so there is no repair. This failure is directly linked to the sizing of the products that enter the irradiation chamber.

During the 18 months of the study, the irradiator presented an economic loss from failures of $ 211,944.49 USD, which is equivalent to $ 16.35 per hour. The horizontal pistons, the transverse pistons and the components of the mechanical conveyor are of greater economic impact. Figure 3 shows the economic losses by components.

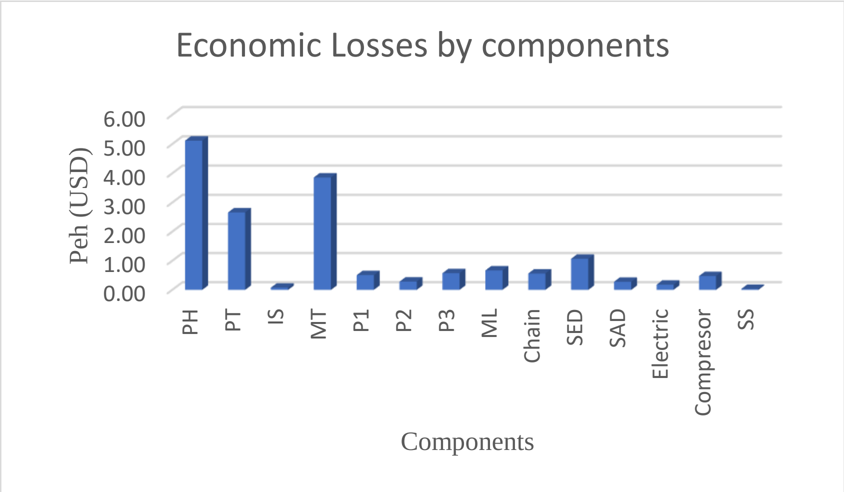

Figure 3. Cost of failure per hour of the components.

Table 5 shows the economic losses taking into account the fourth step of the sixth stage of the methodology. For this evaluation, the maximum permissible time of the out-of-service equipment due to failures was taken as an approximation for the calculation of the unavailability time due to failures of each component. The maximum allowable time establishes the moment, with a minimum of economic losses, in which the equipment or components must be replaced due to continuous failures. This value was obtained through surveys with operators and other specialized personnel of the plant. Some failure rates were obtained from the facilities and others from OREDA [18].

Table 5. Values obtained from the calculation of economic losses.

Failures	Cs (USD)	Cc (USD)	λ (1/hour)	Vei (USD/hour)
PH	2262.06	164.40	0.00111209	0.34
PT	890.78	155.46	0.00157	0.27
IS	104.02	-	0.00087222	0.09
MT	1702.72	171.43	0.000511	0.96
P1	202.88	164.40	0.000624	0.23
P2	107.04	164.40	0.000624	0.17
P3	229.15	164.40	0.000624	0.25
ML	269.00	102.86	0.00076755	0.29
Chain	132.02	6857.14	0.00013083	0.91
SED	472.09	-	0.000514	0.24
SAD	122.98	-	0.00151766	0.19
Electric	68.92	205.71	0.00033946	0.09
Compresor	124.92	14403.61	0.00014392	2.09
SS	52.77	942.86	0.000157	0.16
Total (USD)	6741.35	23496.65		6.27

The fourth step of the methodology demostrated the need to replace the equipment during the production process when the economic loss of the installation is $ 6.27 USD per hour which translates into $ 81,259.2 USD during the 18 month evaluation period. Figure 4 shows the values of Vei.

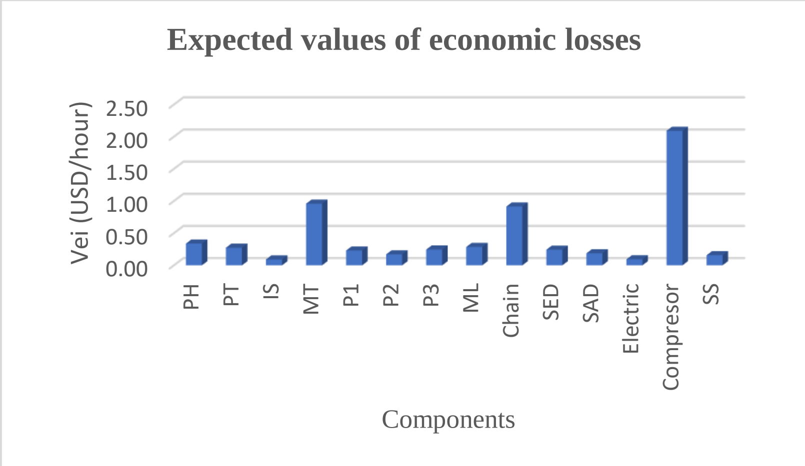

Figure 4. The expected value of economic losses.

Figure 5 shows the difference between the analyses. Vei shows the economic losses be due to failures if component changes were made at the recommended limit. Peh shows the real values of the economic losses during the study period.

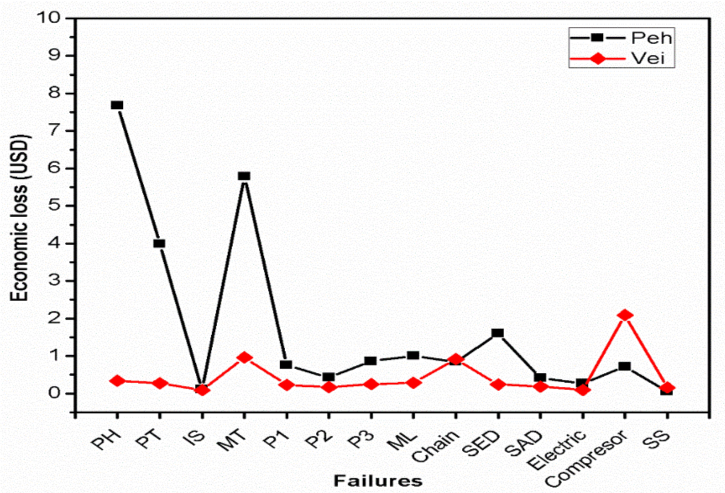

Figure 5: Comparison between economic losses with real and expected values of failures.

In this way, the fourth step of the methodology was used to establish a comparison between the economic losses calculated according to real failures, obtaining economic parameters that allow estimating when it would be necessary to increase the frequency of maintenance and on wich components.

The total economic losses per hour of Vei were of $ 6.27 USD, wich is set to be the maximum allowable value of losses due to the production process during this period. The values of components obtained by Peh that exceed those obtained by Vei predict that they must be replaced. When the general economic losses reached $ 6.27 USD; or when a specific component reached its expected value of economic losses per hour, the irradiator could have saved approximately $ 130,685.29 USD.

As a result of the analysis, the need to improve the production process could be achieved by reducing the time between maintenance or replacing of the horizontal pistons (PH), the transverse pistons (PT), as well as the transportation element (MT) of the input and output of products.

4. CONCLUSIONS

A reliability analysis was carried out on the systems of a category IV irradiator for 18 months using the FMECA and fault tree methodologies to quantitatively evaluate the components that are directly linked to the production process and for which their failure affects the performance of the facilities. In this stage the components, equipment, and systems that most affected the production process were: horizontal pistons, transverse pistons, compressors, safety systems, hauler, parrots, input and output pistons, the transportation chain and the different processes of jamming of the products inside the irradiator.

The economic losses taking into account the actual failures revealed losses of approximately $ 211,944.49 USD. On the other hand, the economic analysis obtained by the expected value for failure showed that: a timely change of equipment at an economic loss rate of $ 6.27 USD reduces costs from reasons failures by $ 81,259.2 USD, which is equivalent to 38.34% of the actual economic losses of the irradiator.

This economic calculation tool allowed an improvement in the maintenance evaluations, focusing the efforts on the components that most favor the detention of the productive process and associating them with a maximum value of economic losses due to failures during a determined period. This maximum value is directly associated with the change of the equipment or component that allows improving the production process.

Acknowledgments

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