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ESTIMATION OF RELIABILITY AND LIFETIME OF COMPOSITE OVERWRAPPED PRESSURE VESSELS ADOPING POTENTIAL FAILURES ASSESSMENT AND ACCELERATED TESTS APPROACH

Maryam Gholami Arjenaki[1], Dr. Mahdi Karbasian[2*], Amin Kazemi Manesh[3], Mohammadreza Jafari[4]
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[1] University of Technology-Shahin Shahr Campus, Shahin Shahr, Isfahan, Iran.
[2*]Malek Ashtar University of Technology, Tehran, Iran.
[3]Islamic Azad University- Ahar branch, Ahar, Iran.
[4]Islamic Azad University-Zahedan Branch, Zahedan, Iran.
[1]maryamgholami6677@gmail.com, [2*]mkarbasian@yahoo.com, [3]kazemimaneshamin@gmail.com,
[4]Jafari6340@gmail.com

Abstract

Aim. *Compressed air vessels are responsible for injecting compressed air to the mechanical flying device. It should be noted that the pressure level inside these vessels is very important in conducting all operational stages successfully; therefore, it is of high significance to be assured of the quality of the vessels being used. This study was done in 2017 in order to calculate and estimate the reliability of compressed air vessels in mechanical flying device system with proposing a potential failures assessment and accelerated test approach taking into consideration the current methods.* ***Methods.*** *The paper uses methods of Fault Tree Analysis, Failure Mode & Effect Analysis and Accelerator tests. Initially, the interactions among the components were identified using the Design Structure Matrix in order to design a matrix to help estimate the reliability; consequently, improve equipment performance. Next, failures root recognition was done using Fault Tree Analysis diagram, then, failures reasons prioritization was done using Failure Mode & Effects Analysis tables. Accelerator tests were designed and applied on failure mechanisms such as leakage by pressure on vessels, corrosions on steal head, nipples, O-ring creeping, O-ring ozone cracking and liner chemical degradation. After that, the average of failure rates was calculated within the taking after stage for each test. Within the conclusion, the result of failure rates from the accelerator tests was compared with the result of failure rates from the process approach. Consequently, the most elevated amount of these two approaches was defined as the total failure rate; product reliability and lifetime were calculated utilizing this amount.* ***Results.*** *The following finding were obtained using the proposed methods. When Windy Liner was used, vessel lifetime was six years and half and vessel reliability in ten years was 0/22. Whereas, when Rotational Liner was used, vessel lifetime was eight years and three months and vessel reliability in ten years was 0/3.* ***Conclusion****.The approach proposed in the paper allows accelerator degradation test can also be used instead of accelerated test in order to calculate the reliability of failure mechanisms. In the event that high-quality and legitimate O-rings are used, vessel reliability and lifetime can be increased.*

Keywords: Reliability, Accelerator Life Tests, Composite Overwrapped Pressure Vessel, Failure Modes and Effects Analysis, Fault Tree Analysis.

1- Introduction

Product reliability is an essential aspect of customer expectation. The expectation to increase reliability at the lowest cost has become an important issue for companies in offering competitive products [1]. Product reliability is about promoting the product to the needed quality over time, which is absolutely important in creating fame and maintaining competitive advantages for companies [2]. Traditional reliability evaluation methods were always based on failure data which were obtained from product lifetime, i.e., it was not possible to calculate the reliability as long as the product was functional. This lifetime failure data was obtained almost impossibly in a very short period of time for products with high reliability and extended lifetime. To solve this problem, creating quantitative data is absolutely significant and it can be achieved by evaluating the potential failures approach. Furthermore, using accelerator tests to estimate reliability in real conditions is considered to be practical [3].

Products with high reliability and lifetime are used extensively in spacecraft, aviation, and other fields, so, how to evaluate the reliability and predict their lifetime is one of the most important topics [4]. Pressure vessels inject compressed air into the mechanical flying device. The pressure level inside these vessels is very important in order to successfully proceed all operational sections. It is necessary to have these vessels always ready to operate with operating pressures (approximately 280 bars). It is highly essential for the user to know how many years the vessels will be functional with this operating pressure [4].

The used composite overwrapped pressure vessels (COPV), are made of metal or polymer core and is wrapped by low-density composite layers. The interior layers are responsible for providing the original structure, strength, rigidity and appropriate surface in contact with the gas inside the vessel. Composite coating is wrapped around the core with the aim of ensuring the mechanical strength of the inner layers against high levels of pressure as well as resisting against scratch, impact and other possible damages [5]. In terms of ratio of strength to density, due to severe decline in weight, COPV have noticeable advantages compared to the metal pressure vessels. However, some difficulties such as high production costs diminished this superiority [6].

Since by default, COPV were designed for flying machine equipment; high reliability and safety are considered in their design. But the safety considered in the design phase cannot be trusted because incidents and damages in composites have caused explosions due to the release of high energy of the compressed gas in the vessels. It is true that the possibility of such incidents occurring is rare, but if we consider the severity of the disaster; especially, in aerial and human-related projects, the high amount of reliability seems to be necessary [7].

This study was conducted in one of the flying machine device manufacturing industries in 2017 and the purpose of this study was to calculate the reliability of these compressed air pressure vessels in these systems.

2- Methods

Initially, the interactions among the components were identified using the design structure matrix [8]. Furthermore, failure roots recognition was done using fault tree analysis (FTA) diagram [9]. Occurrence and severity numbers were defined by experts using failure modes and effects analysis (FMEA) tables; eventually, risk priority number (RPN) was calculated [10]. As a result, priority of failure causes was clarified. Critical failure factors were then specified after designing risk analysis matrix.

Furthermore, accelerator tests were designed and performed. Next, the failure rate was calculated for each test. At the end, the failure rates average from the accelerator tests were compared with failure rates of the process approach. After that, the highest number derived from this comparison was the final failure rate of the product; consequently, product reliability and lifetime were calculated (Fig. 1).

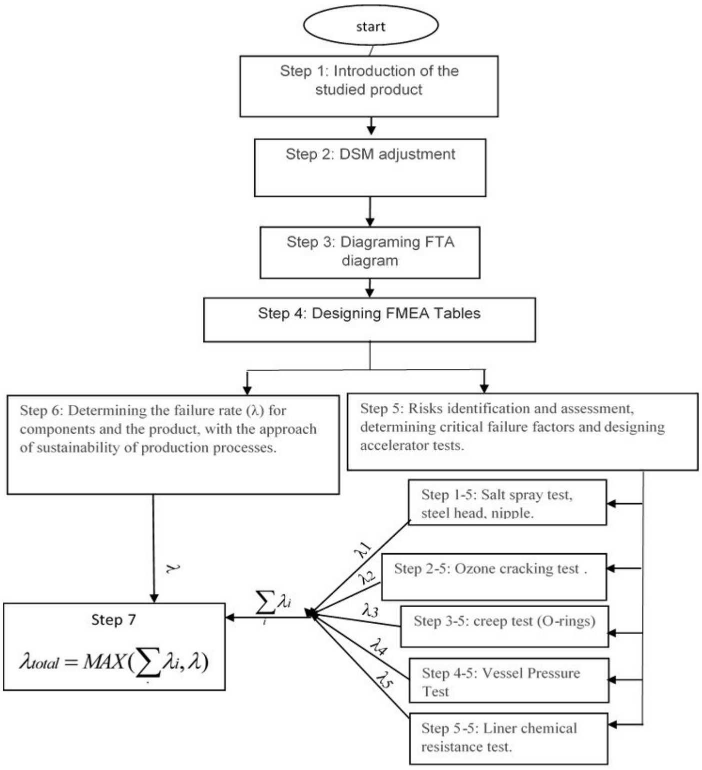


Figure 1: Research steps chart

2-1- Design Structure Matrix (DSM)

At the heading row and the body row of DSM, the product components are mentioned in the chart and the relations among them were clarified [supporting table 1].

2-2- Fault tree analysis (FTA)

In this stage, FTA was demonstrated for each part of the vessel's components. The example of fault tree for O-ring parts and steel head can be seen in figures 2 and 3. Also, a fault tree was drawn for the nipple, composite, rotary and wind liner parts accordingly.

2-3- Failure Modes and Effective Analysis (FMEA)

FMEA tables, in the next stage, were designed for FTA diagrams which were then designed for product components [supporting table 2]. FMEA table was completed according to the data from FTA diagrams; the top events in FTA diagrams were placed under potential failures column, and other forms of failures in FTA were placed under potential causes column according to their stage.

Kim et al. (2013) used FMEA tables in an article entitled 'A new reliability allocation weight for reducing occurrence of severe failure effects'. To complete FMEA tables, they used the standards which had been designed by the US Army. By the dedication of occurrence and severity number to potential failures in FMEA table, formula 1 can be used to calculate the failure rate of each potential failure [11]. According to brainstorming sessions and consultations with industry experts, risk priority number, severity and occurrence numbers were defined between 1-10. RPN was calculated by multiplying severity by occurrence. In FMEA tables, a special made-up code was given to every potential failure cause. This would not only make future analysis easier, but also would help to avoid explanations.

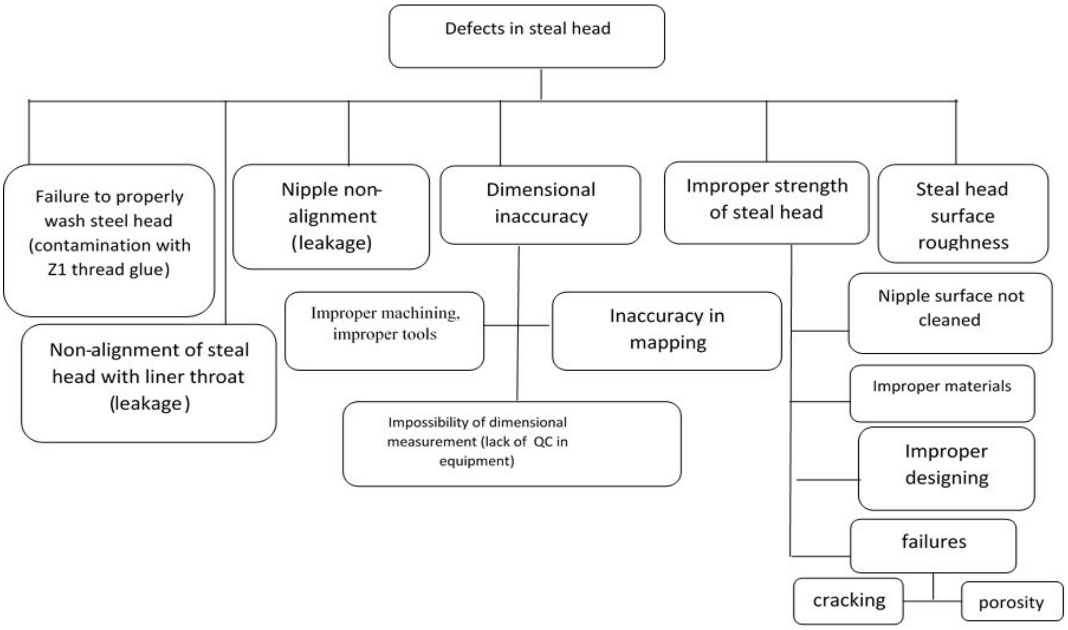


Figure 2: Steal head Fault Tree

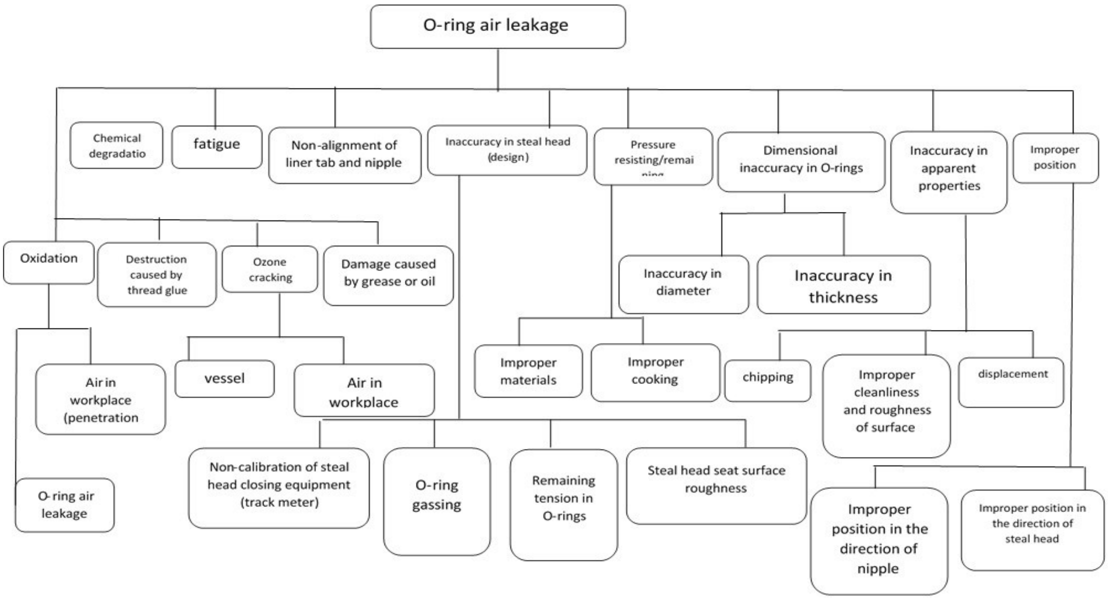


Figure 3: O-ring Fault Tree

$$\lambda = \mathrm{EXP}\ (-9.993+0.7702^{*}\mathrm{O}) \qquad (1)$$

In formula 1, O is Occurrence, and EXP is Exponential Function. λ as a failure rate was calculated based on any failure cause with occurrence number. Time unit for FMEA tables is 10 years [12].

2-4- The development of accelerator tests

After completing the risk analysis table, failure codes in the critical area of risk analysis table and potential failures with the highest score received in RPN were identified, therefore, wherever possible, accelerator tests were designed and performed on these mechanisms. Accelerator tests can be performed on mechanisms such as: leakage caused by pressure on vessels, corrosion on the series of steal and nipple components, creeps in O-rings, Ozone cracking in O-rings, liner chemical degradation. In the next step, accelerator tests for the aforementioned mechanisms were designed; it is significant to realize that the samples were in 3 stress levels and in each level, three samples were evaluated and the overall of 9 samples for each test were examined. Selection of test parameters were based on product material, geometric tolerance and environmental conditions.

2-5- Salt Spray Test for Steel Head and Nipple

The Salt Spray Test is intended in corrosion-related failure mechanisms of the steel head and nipple. Formula 2 can be used to calculate the lifetime of steel head and nipple using the data derived from the corrosion.

$$A = \frac{TFop}{TFstress} = \exp\left[a.(RHstress - RHop)\right] * \exp\left[\frac{Ea}{Kb}\left(\frac{1}{Top} - \frac{1}{Tstress}\right)\right] \tag{2}$$

In formula 2, TFop is time to fail in normal condition, TFstress is time to fail under stress, a is constant and is equal to 0.1 (RH-1). RHstress is humidity under stress; RHop is humidity in normal conditions. Ea is activation energy in terms of electron volt. Kb is Boltzmann constant which is equal to 8.61*10-5 [12] [supporting table 3].

2-6- Ozone cracking test

In order to find failure in O-rings, Ozone cracking test was designed. In this test, to determine the accelerator factor, when temperature is not the main cause of acceleration, formula 3 which is reverse exponentiation relation is used.

$$AF = \left(\frac{\xi_{stress}}{\xi_{op}}\right)^{n} \tag{3}$$

In formula 3, ξ_{op} and ξ_{stress} are operational stress and stress under accelerated conditions, respectively. And n is power derived from the exponentiation law model. According to formula 4 and 5, lifetime or Time to Failure (TF) is calculated in operational conditions [12].

$$AF = \frac{TF_{operation}}{TF_{stress}} \tag{4}$$

$$TF_{operation} = AF \times TF_{stress} \tag{5}$$

2-7- Creep test for O-ring

Creep test was designed for failure-related creep mechanism in O-rings. O-ring lifetime is calculated based on formula 6 under creep condition.

$$TF = t_0^{\gamma\sigma} e^{(u \quad /RT)} \tag{6}$$

TF is the destruction time caused by creeping. t_0 is constant and is equal to 10-12 per second. u is active energy in fracture process. Ɣ is a constant material structure. R is molar gas constant and is equal to 8/314 j/mol0k. T is absolute heat degree and σ is constant stress [12] [supporting Table 4 and 5].

2-8- Pressure test

Pressure test is designed for failure leakage due to pressure on vessel. Pressure and heat are the two failure factors used in pressure test. When the failure reason is pressure, formula 3 is used to calculate accelerator factor; whereas, when heat is the failure reason, formula 7 is used to calculate accelerator factor. In general, acceleration coefficient can be defined for either heat stress or non-heat stress, then formula 8 can be used for the accumulation of stress in equipment. After calculating AF, formula 5 can be used to calculate lifetime in operational conditions [12][supporting Table 6 and 7].

$$AF_1 = EXP\left(\frac{Ea}{Kb}\left(\frac{1}{T2}-\frac{1}{T1}\right)\right) \tag{8}$$

$$AF = AF_1 \times AF_2 \times \ldots \times AF_n$$

2-9- Chemical resistance test for liner

Chemical resistance test is designed for failure mechanisms in chemical degradation of liner. Formulas 3 and 4 are used to calculate liner lifetime in chemical resistance test. ξop demonstrates PH in normal environment and $TF_{operation} = AF \times TF_{stress}$ shows PH in stress environment[12] [supporting Table 8].

2-10- Calculation of reliability and failure rate

Failure rate is calculated after acceleration tests are done. According to the assumption by which the product lifetime function follows exponential distribution, after calculating the lifetime in operational conditions, formula 9 can be used to calculate failure rate. Mean Time to Failure (MTTF) is the calculated number in operational lifetime. By using this formula, failure rate in accelerator tests can be calculated [12].

$$MTTF = \frac{1}{\lambda} \rightarrow \lambda = \frac{1}{MTTF} \tag{9}$$

In this study, the Lussar's Law was used to calculate failure rate in products and failure rate in product manufacturing process.

2-11- Calculation of reliability, failure rate and vessel lifetime.

In order to calculate the failure rate in mechanical components in FMEA table, all failure rates in the table must be summed up so that the total product failure rate is derived. For example, to calculate the total failure rates in steal head, all failure rates in FMEA table related to steal head were summed up. To calculate failure rate resulting from the accelerator tests of all vessel components, when using the wind liner, failure rates from 5 accelerator tests were summed up. On the other hand, when the rotary liner was used, all accelerator tests except pressure test were calculated since pressure test was used for wind liner test.

Finally, to calculate the total failure rate of vessel components, failure rates resulted from the FMEA tables were summed up. Then, the maximum of these two numbers, after summing up the failure rates in accelerator tests and comparing them with the total failure rate of FMEA, were considered as the total failure rate of vessels.

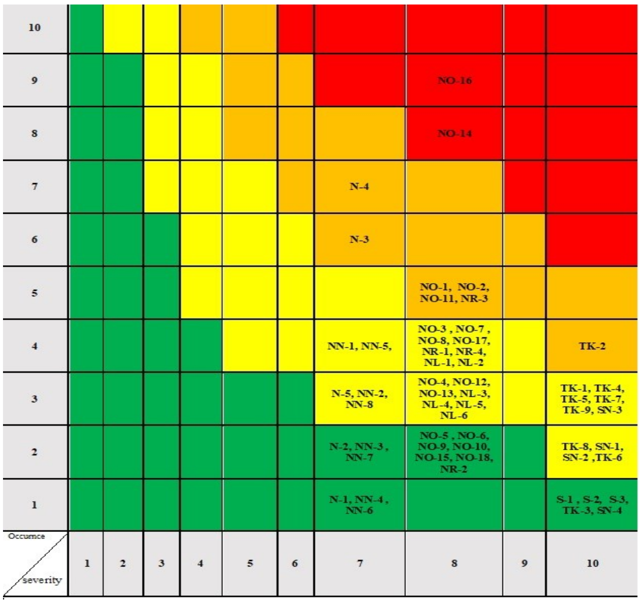
Then, total Reliability (total) (R(t)) was calculated using formula 10 and lifetime was calculated using formula 9. It is needless to mention that since the duration of this study was 10 years, 1 is replaced by t in formula 10 [12].

$$R(t) = EXP(-(\sum \lambda) * t) \tag{10}$$

3- Result

3-1- Calculation of failure codes, RPN and failure rate

FMEA tables were completed for different parts of the vessel. Failure codes NR-3, TK-2, NO-1, NO-2, NO-11, N-3, N-4, N-14 and N-16 had the highest RPN among vessel failure codes, respectively. Accelerator tests, then, were designed and performed. In table 1, samples of- failure code, RPN and failure rate were calculated for O-ring. More tables can be seen in supporting tables. According to risk matrix analysis in figure 4, N-16 and N-14 were of the only failure codes placed in critical area.



10										
9								NO-16		
8								NO-14		
7							N-4			
6							N-3			
5								NO-1, NO-2, NO-11, NR-3		
4							NN-1, NN-5,	NO-3 , NO-7 , NO-8, NO-17, NR-1, NR-4, NL-1, NL-2		TK-2
3							N-5, NN-2, NN-8	NO-4, NO-12, NO-13, NL-3, NL-4, NL-5, NL-6		TK-1, TK-4, TK-5, TK-7, TK-9, SN-3
2							N-2, NN-3 , NN-7	NO-5 , NO-6, NO-9, NO-10, NO-15, NO-18, NR-2		TK-8, SN-1, SN-2 ,TK-6
1							N-1, NN-4 , NN-6			S-1 , S-2, S-3, TK-3, SN-4
Occurnce / severity	1	2	3	4	5	6	7	8	9	10

Figure 4: Risk analysis matrix for failure code sets of vessel components.

3-2- Calculation of accelerator test for potential failures

After performing the accelerator tests, according to the aforementioned formulas, operational component lifetime for each section was calculated in the methods section.

3-3- Salt Spray Test on Steal Head and Nipple

Operational lifetime was calculated by inserting the parameters listed in salt spray test parameters table into formula 2 [supporting Table 3]. Then by inserting the calculated lifetime in formula 9, the failure rate of salt spray test was calculated.

3-4- Ozone cracking test

By inserting the parameters listed in the ozone cracking test parameters table into formula 3, the number for accelerator factor (AF) was calculated [supporting Table 4]. Then by inserting AF into formula 4, the operational lifetime was calculated. The failure rate of ozone cracking test was derived by inserting the calculated lifetime into formula 9.

3-5- O-ring creep test

By inserting the parameters listed in creep test parameters table into formula 6, the operational lifetime was calculated. Then by inserting the derived amount of lifetime into formula 9, the failure rate of creep test was calculated [supporting Table 5] [Table 2].

3-6- Pressure test

By inserting the parameters listed in pressure test parameters (pressure failure factor) table into formula 3, the number for AF2 was calculated [supporting Table 6]. Then by inserting parameters into pressure test parameters (temperature failure factor) table, AF1 was calculated [supporting Table 7]. Next, by inserting the amount for accelerator test into formula 8, the amount of AF was calculated. Following that, by inserting AF into formula 4, the amount of lifetime was calculated; furthermore, by inserting the calculated lifetime into formula 9, the failure rate in pressure test was calculated.

3-7- Liner chemical resistance

By inserting the parameters related to liner chemical resistance test into formulas 3 and 4, the operational lifetime was calculated [supporting Table 8]. So, by inserting the calculated amount of lifetime into formula 9, the failure rate for chemical resistance was derived.

3-8- Calculation of vessel reliability, failure rate and lifelong

Table 3 shows failure rate derived from FMEA tables and accelerator test for vessel components. The reliability result, failure rate and total amount of lifetime for all vessels are shown in table 4.

***Table 1:** Design of FMEA table for O-Ring*

Potential Failure	Severity	Failure Code	Potential Failure Reasons		Occurrence	RPN	Failure Rate
			Stage 1	Stage 2			
O-ring air leakage	8	NO-1	Improper positioning in the direction of the steal head		5	40	0.002150618
		NO-2	Improper positioning in the direction of the nipple		5	40	0.002150618
		NO-3	Displacement (defects in apparent coordinates)		4	32	0.000995565
		NO-4	Defects in surface smoothness and cleanliness (defects in apparent coordinates)		3	24	0.000460867
		NO-5	Chipped (defects in apparent coordinates)		2	16	0.000213345
		NO-6	Dimensional defects in O-rings	Thickness inaccuracy Diameter inaccuracy	2	16	0.000213345
		NO-7	Improper cocking (pressure resisting/remaining)		4	32	0.000995565
		NO-8	Improper materials (pressure resisting/remaining))		4	32	0.000995565
		NO-9	Roughness of steal head seat surface (defects in steal head (design))		2	16	0.000213345
		NO-10	Remaining tension in O-ring (defects in steal head (design))		2	16	0.000213345
		NO-11	O-ring biting (defects in steal head (design))		5	40	0.002150618
		NO-12	Non-calibration of steal head closing equipment (track meter) (defects in steal head (design))		3	24	0.000460867
		NO-13	Non-alignment of the liner tab and nipple		3	24	0.000460867
		NO-14	Fatigue		8	64	0.021679243
		NO-15	Damage caused by grease or oil (chemical degradation)		2	16	0.000213345
		NO-16	Ozone cracking (chemical degradation)	Air in workplace Vessel	9	72	0.046831464
		NO-17	Damage caused by thread adhesive (chemical degradation)		4	32	0.000995565
		NO-18	Oxidization (chemical degradation)	Air in workplace due to the penetration through threads O-ring air leakage	2	16	0.000213345

Table 2: *Lifetime results of salt spray, ozone cracking, creep, pressure, liner chemical resistance test*

Salt spray test lifetime results					
TFop	Rate Failure				
72.6504467	0.01376454				
ozone cracking test results					
Failure Rate	TF Op (year)	TF Op (h)	AF		
0.0057239	174.707	1530432.236	5101.4408		
Creep test results					
TF	Failure Rate				
11.5796	0.086358622				
Pressure test results					
AF2	AF1	AF	TF(month)	TF(year)	failure rate
28.88254	2.784722	80.42985	643.4388	26.80995	0.0373
liner chemical resistance test results					
AF	TF Op (month)	TF Op (year)	Failure Rate		
162.4221671	32484.43341	88.9984477	0.0112362		

Table 3: *Vessel components accelerator tests and FMEA table failure rates*

Vessel components	Failure rate from FMEA in 10 years	Failure rate from tests in 10 years
Steal head	0.015667846	0.137645403
Nipple	0.004523398	0.137645403
Wind liner	0.0038346	0.11236151
Composite	0.003825354	0
O-rings	0.081855017	0.92082495
Rotary liner	0.004355093	0
Total (rotary)	0.110226709	1.196115756
Total (wind)	0.109706216	1.494975179

***Table 4:** Reliability results, failure rates and lifetime of the entire vessel assembly*

	MAX(λ FMEA,λ ALT)	Reliability in 10 years	Lifetime(years)
Total (rotary)	1.196115756	0.302366399	8.360394843
Total(wind)	1.494975179	0.224254171	6.689074266

4- Discussion

While being extremely high, O-ring failure rate is one of the main reasons in increasing failure rate in vessels. The sum of two failure rates in creep accelerator tests and ozone cracking test increases the failure rate in O-rings. This high failure rate made O-rings a critical component for the vessel set, and without having a plan to cope with failure triggers in O-rings, they are potent to reduce the amount of vessel reliability. The method used to calculate vessel reliability and lifetime; especially, in using and combining several diverse accelerator tests results increased the accuracy and precision of the quantitative information.

By studying previous researches, we realized that according to the method and the selected model, they first identified the factors affecting failure rates by using tools such as FTA, FMEA, etc. Second, they designed and performed accelerator tests in accordance with these factors. Then, based on the previous recognition of the system, they assumed the lifetime distribution. Finally, to estimate the related parameters in lifetime distribution, they either used the least square estimation or the maximum probability estimation methods. Then by using these distributions, they obtained the amount of reliability, failure rate, average time to failure, lifetime, etc.

When wind liner was used, vessel reliability was calculated to be 6.6 years, lifetime was 0/22 in a ten-year period, while, when rotary liner was used, vessel reliability and lifetime were calculated to be 8.3 years, and 0.3 in a ten-year period, respectively, which demonstrated a perspective in how to use the components available. It is also important to identify which component plays a significant role in lowering reliability amount.

In this system, the failure rate in O-ring is calculated very high and this can be very effective in modifying the design for future productions in order to produce a product with higher reliability.

By reviewing various articles, we found that in most researches done so far, different accelerator tests were used to calculate reliability and lifetime in other devices, needless to say, only one accelerator test was conducted.

For example, Regattieri et al. 2017 “Reliability assessment of a packaging automatic machine by accelerated life testing approach” presented a way to evaluate the reliability of an automatic packaging machine using both the accelerated life test (ALT), the Weibull distribution method and the maximum probability method [13]. The result of this study indicates that the accelerated life test is effective for predicting the life of the product through a short-time test, which is in line with the results of the current research.

Yunfeng Li 2017 studies titled 'A range for aircraft accelerator life test based on quasi -mechanical analysis' which provided theoretical foundations for selecting work parameters and forming final judgment of failure rate in the accelerator life test. Using accelerator test along with FTA to spot failure, and quasi-dynamic analysis to determine different working conditions, made it possible to determine the equipment lifelong range [14].

Boro et al., also conducted a research in 2017 ' Strength and Reliability Analysis of Metal-Composite Overwrapped Pressure Vessel'. In order to calculate reliability in the composite layers, creep and fatigue damage were calculated based on experimental models. Especially, in the creep calculation, the use of accelerated life tests is more accurate than experimental diagrams [15]. For the samples used in performing accelerator tests, it would have been better if more samples were used to increase the accuracy of the output information, but due to the limitation in sample availability, 9 samples were used. The purpose of the study was ultimately to calculate the lifetime and reliability of the vessel. Although the mentioned results are appropriate, by modifying the O-ring in vessel, the amount of lifetime and reliability can definitely increase.

5- Conclusion

The study team concluded that when wind liner was used, vessel reliability was calculated to be 6.6 years, and lifetime was 0/22 in a ten-year period, while, when rotary liner was used, vessel reliability and lifetime were calculated to be 8.3 years, and 0.3 in a ten-year period, respectively, which demonstrated a perspective in how to use the components available.

For failure mechanisms, accelerated destruction tests can be used instead of accelerated life tests. Also, in choosing the O-ring for the vessels, O-rings with higher quality and more reliability can be used to increase reliability and lifetime in equipment.

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