2008-5435/09/11-20-25
INTERNATIONAL JOURNAL OF OCCUPATIONAL HYGIENE

IJOH 1: 20-25, 2009

ORIGINAL ARTICLE

The Reliability of a Tunnel Boring Machine

MOHAMMAD JAVAD JAFARI*, NOR-ALLDDIN GHARARI, HAMID REZA SHEIKHI

Department of Occupational Health, Faculty of Health, University of Shahid Beheshti (MC), Tehran, Iran.

Received February 26, 2009; Revised May 24, 2009; Accepted June 7, 2009

ABSTRACT

Greater levels of complexity in tunnelling with Tunnel Boring Machine (TBM) allow higher chances of failures that may increase the potential hazardous risks. This paper presents the results of a study on TBM reliability using risk analysis. Machinery Failure Mode and effect analysis was applied to analyze the risks of a TBM using QS9000 and SAE J1739 recommendations. For this purpose, 48 failure modes were postulated for the TBM main systems and all subsystems. Afterwards, the effects of every failure were listed. Safeguards or controls that might prevent or mitigate the effects of each failure were also listed. In the final step, essential remedial actions to prevent or mitigate the failure were recommended. Risk Matrix was developed for each possible failure to be used for risk ranking. For this, the Risk Priority Number (RPN) was estimated for each failure mode for pro and post application of control measures to identify the most critical failures. The results revealed that 7 failure modes had risk priority numbers higher than 80 therefore, they were categorized unacceptable. Cutter head stop due to bad rock condition with RPN=240 was the significant critical failure. The results also showed that 3 failure modes in TBM required modification due to high severity rate. The findings from this study were applied to a long tunnel under construction and significantly reduced the accidents during the next two years tunnelling period. It can be concluded that, MFMEA is a superb tool for TBM reliability evaluation and promotion.

Keywords: *Risk, Tunnelling, Analysis, Hazard, Tunnel Boring Machine*

INTRODUCTION

Failures during tunnel and mine excavation may lead to serious human, property and investment losses. Risk management is therefore, essential in these projects [1, 2].

Accidents in tunnel, mine and underground space works may lead to catastrophe, if they are not precisely predicted and effectively controlled in advance. In 1949 in north-east China, 1549 miners lost their life in one accident. During 2004, in China 6300 miners were killed in accidents. In 2003 in the BobNizo mine located in south east Iran, 9 miners were killed in an explosion incident. In 2006 in a tunnel excavation in west Iran, 4 people died from deadly hydrogen disulfide (H_2S) gas emission when the ventilation system failed. In the work of a dam project in the south of Iran started in 2005, 22 workers died in 2 years in different accidents [3]. In 2009, 12 miners lost their life in a mine accident, in south east Iran. Other countries experience similar ever increasing awareness of hazardous risks that need to be managed. This includes hazard identification, risk assessment and risk management [3-5].

Many of the hazards may be identified by conducting a Process Hazard Analysis (PHA), such as Hazard and Operability Analysis (HAZOP), What If/Checklist or FMEA. At the identification stage there is no clear or concise picture of what this danger might be or how often it might occur. At this stage, it may be felt that the use of a risk matrix of severity versus likelihood provides an adequate pseudo-measure or approximate gauging of risk so that a full quantification of the risk would not be necessary.

FMEA is a widely used methodology to identify hazards [5]. It is used to analyze specific systems or items of equipment that are best handled as objects rather than by the use of parameters or operations. FMEA is also used for analyzing items of equipment having interactive mechanical and/or electrical components. Many authors, including Hyatt believe that FMEA is very good for analyzing complex equipment items where the failure of a component may have major consequences [4]. Some authors believe that FMEA

***Corresponding author:** M J. Jafari, Email: Jafari1952@yahoo.com

Table 1. Likelihood ranking used in the present study (QS9000)

Rank	Failure Occurrence	Failure Rate
10	Very high, failure almost certain.	MTBF≤1 hr
9	Very high number of failures likely.	2 hr<MTBF≤10 hr
8	High number of failures likely.	11 hr<MTBF≤100 hr
7	Moderately high number of failures likely.	101 hr<MTBF≤400 hr
6	Medium number of failures likely.	401 hr<MTBF≤1000 hr
5	Occasional failures likely.	1001 hr<MTBF≤2000 hr
4	Few failures likely.	2001 hr<MTBF≤3000 hr
3	Very few failures likely.	3001 hr<MTBF≤6000 hr
2	Rare number of failures likely.	6001 hr<MTBF≤10000 hr
1	Failure highly unlikely.	MTBF>10000 hr

Different standards including MIL STD1629A, SAE ARP 5580 and SAE J1739 describe the methodology for applying FMEA [3, 6, 7]. Some institutions have it as a part of their mandate along with other PHAs.

There are six types of FMEA namely machinery FMEA, design-FMEA, system-FMEA, process-FMEA, application-FMEA, and product-FMEA. The nature of the study and the stage of the process life cycle when it is conducted, determines the type of FMEA to be used. Each FMEA follows the same approach. The nature, purpose, and scope of the study dictate which type of FMEA and to what extent of detail is used.

In order to modify the safety of operator, reliability and operability of machinery systems such as present study, MFMEA (Machinery FMEA) is a standard technique for equipment failures assessment. Machinery Failure Mode and Effect Analysis (MFMEA) is specifically invented for machinery hazard identification. Unlike other methods it uses 3 parameters of severity, detection, and likelihood of each hazard which is its main advantage over other hazard identification methods. This technique fits well with the objectives of the present study to assess the reliability of the tunnel boring machine.

From 1993 to 2005, in Iran, many researchers, including, Pourparand, Kakavandi, Ali Mohammadi, Azar Barzine, and Naderi applied FMEA to assess safety status of different manufacturing processes [3]. In all of these studies Risk Matrix was used for risk ranking. For this purpose RPN was estimated to identify the most critical failures. None of these studies applied to tunnelling.

In other countries different studies were used FMEA to analyze the safety of different processes [8-17]. None of these processes included tunnelling. In most of these studies RPN was calculated and then the safety status was assessed. In 2004 Working Group 2 of the International Tunnel Association issued guidelines for tunnelling risk assessment [1]. These guidelines are considered for the risks integrated with other systems and are useful for both consultants and contractors.

The Tehran–North freeway is one of the largest road projects in Iran. Many tunnels, including the longest national road tunnel are under construction in this project. This tunnel, called Alborz, is located at 2400 m higher than sea level and is 6350 m in length with maximum 850 m of over burden. The tunnel consists of 3 bores, two main tunnels with a pilot tunnel between them. The pilot tunnel is under excavation using TBM to gather geotechnical data for the main tunnel design. The pilot tunnel will be used as a service tunnel during the tunnel operation.

Pro-excavation geological data showed that, gas emission and water flow was expected in the tunnel. Methane (CH_4) and hydrogen disulfide (H_2S) emissions in very high concentrations were recorded before applying this risk analysis. TBM stop due to bad rock condition was also expected. The TBM used in this project was not originally designed for such a hard condition. Therefore, MFMEA was applied to assess the reliability of the TBM used in the Alborz Tunnel.

MATERIALS AND METHODS

MFMEA were applied to identify failures, evaluate the effects of the failures and prioritize the failures of a TBM. For application of MFMEA, pertinent information e.g. site plans, charts, operations information, procedures, relevant data, and design plan were collected. In the next step the purpose, scope, depth of the study, associated costs, expertise, experience available, and so on were established. The TBM was broken into 4 main systems including mechanic, hydraulic, pneumatic, and electric systems.

All potential failure modes for each system were identified. The causes of each failure mode were determined. All current controls were identified and listed. A rating for severity, occurrence and detection of each failure was assigned. All correction actions were determined. In the final step, the recommendations were carried out.

Risk Matrix was used for prioritizing of the risks. Risk Matrix was developed using severity, likelihood and detection parameters. Risk Priority Number (RPN) was determined using these parameters. The Mean Time between Failures (MTBF) was used for likelihood ranking (Table 1)[4, 6].

The severity parameter was ranked according to QS9000 and SAE.J1739 recommendations (Table 2). Risks were categorized using RPN. RPN was calculated using the following equation.

$$RPN = Sev\ Num \times Lik\ Num \times Det\ Num \qquad (1)$$

Risk Matrix was developed using likelihood and severity parameters. The Risk Ranking was categorized according to the RPN calculated for each failure.

Table 2. Severity Ranking used in the present study (QS9000 & SAE.J1739)

Rank	Effect	Measure: Severity Effect
10	Maximum Severity	Injury or harm to operating personnel. Failure resulting in hazardous effects almost certain. Non-compliance with government regulations.
9	Extreme Severity	Failure resulting in hazardous effects highly probable. Safety and regulatory concerns.
8	Very High Severity	Significant downtime and major financial impacts. Product inoperable but safe. User very dissatisfied, e.g. TBM stops for longer than 30 days
7	High Severity	Significant downtime. Product performance severely affected. User very dissatisfied, e.g. TBM stops for 10 -30 days
6	Severe	Disruption to downstream process. Product operable and safe but performance degraded. User dissatisfied, e.g. TBM stops for 24 hr -10 days.
5	Moderate	Impacts will be noticeable throughout operations. Reduced performance with gradual performance degradation. User dissatisfied, e.g. TBM stops for 10 to 24 hr
4	Minor	Local and/or downstream process might be affected. User will experience minor negative impact on the product. e.g. TBM stops for 1 to 10 hr.
3	Slight	User will probably notice the effect but the effect is slight e.g. TBM stops for less than 1 hr.
2	Very Slight	No downstream effect. Insignificant / negligible effect e.g. parameter variation is in control range, adjustments or controls are essential.
1	None	Might be noticeable by the operator. Improbable/not noticeable by the user e.g. parameter variation is in control range, adjustments or controls are not essential or it can be checked during maintenance shift.

Table 3. Detection Ranking used in the present study (QS9000 & SAE.J1739)

Rank	Effect	Measure: Severity Effect
10	Extremely Unlikely	Controls will almost certainly not detect the existence of a defect, or there are no controls on the equipment.
9	Remote Likelihood	Controls have a very low probability of detecting existence of a defect.
8	Very Low Likelihood	Has lowest effectiveness in each applicable category.
7	Low Likelihood	Has low effectiveness for detection.
6	Moderately Low Likelihood	Has moderately low effectiveness for detection.
5	Medium Likelihood	Has medium effectiveness for detection
4	Moderately High Likelihood	Has moderately high effectiveness for detection.
3	High Likelihood	Has high effectiveness for detection.
2	Very High Likelihood	Controls have very high probability of detecting existence of failure.
1	Extremely Likely	Controls will almost certainly detect the existence of the defect.

The detection was ranked using QS 9000 & SAE J1739 recommendations (Table 3).

Different measures were considered to decide whether it is necessary to intervene for modification or prevention of failures. Review of failure characteristics including critical condition, controlling possibilities, safety or severity and an acceptable RPN was considered as a measure of decision making for modification or prevention of failures.

Acceptable RPN varies from a plant to plant. Naderi considered it to be 100 for analysis of a lift. The number was obtained from multiplying 4×5×5. Ulrich Hussels used the RPN of 108 as an acceptable level in a vehicle cooling system analysis. This number was obtained from 3×4×9 [3]. According to engineering decisions, regulatory restrictions, safety standards, financial status of the organization and etc, an acceptable RPN of 80 was determined in the present study. The acceptable RPN was based on multiplying 5×4×4 = 80. Failure modes with higher RPN were categorized critical failures then.

RESULTS

A total number of 48 potential failure modes were identified and studied for all 4 main systems (Table 4). For each system and subsystem a tabular form similar to Table (A) in the appendix was completed. The modification and control actions applicable to reduce the RPN of each failure recommended by the related expertise team with its effect on final RPN were also listed. The severity, likelihood and detection rating for each failure at existing condition and after recommended control actions taken were estimated. Risk Priority Number of each failure mode was then calculated.

Electric system. Sixteen failures were identified in electric part of TBM (Table 5). No voltage and low voltage failures at the transformer with risk priority numbers of 9 and 90 had the minimum and maximum risks in electric system respectively. The high standard deviation of 21.4 in comparison with the low average risk priority number of 36 represented a scattered RPN in TBM electric system.

The results revealed that the low output voltage at the transformers was the only unacceptable failure in TBM electric system (Fig. 1).

According to Fig. 2, three failures of high voltage supplied by the generators, high voltage leakage from transformers and missing dynamo layers of transformers need to be redesigned mainly due to their high severity rate of more than five.

Table 4. Studied TBM systems and subsystems

System	Code	Subsystem	Code	Component	Code
Electric System	1	Generator	1.1		
		Transformer	1.2		
		Control Board	1.3		
		Power Board	1.4		
Hydraulic System	2	Reservoir	2.1		
		Piping	2.2		
		Pump	2.3		
		Feeding Pump	2.4		
		Oil Cooler	2.5		
Pneumatic System	3	Compressor	3.1	Filter Outlet Valve	3.1.1 3.1.2
		Electromotor	3.2		
		Air Tank	3.3	Relief Valve	3.3.1
		Air Screw Pump	3.4		
Mechanical System	4	Grab	4.1		
		Cutter Head	4.2		
		Conveyor	4.3		

Table 5. Risk Priority Numbers of TBM Systems

Failure Mode	Existing Condition				After Control			
	Elec	Hydr	Pneu	Mech	Elec	Hydr	Pneu	Mech
Min	9	12	16	48	6	8	3	24
Max	90	96	108	240	60	40	54	120
Average	36	34.4	43.9	100.8	16.5	14.7	17.1	49.7
Standard Deviation	21.4	23.6	24.8	68.2	14.2	12.8	14.6	37.0
N	16	10	14	8	16	10	14	8

Hydraulic system. A total number of 10 potential failure modes were identified and studied in TBM hydraulic system (Table 5). According to this Table, minimum, maximum, and average risk priority numbers of all failures in hydraulic system are very similar to those obtained for electric system. The failures of leakage from piping and starting in hydraulic pumps had the minimum and maximum risk priority numbers respectively.

According to Fig. 1, the failure of pressure supplier to start (RPN=96) was the only unacceptable failure in TBM hydraulic system. Fig. 2 shows that none of the failures in hydraulic system require redesigning.

Pneumatic system. As it is shown in Table 5, a total number of 14 failures were identified and studied in pneumatic system. The results revealed that, defective opening of high pressure tank has the maximum RPN (e.g. 108) while, the shorting coil in electromotor with a RPN of 16 has the lowest risk.

According to Fig. 1, failing of the air tank relief valve to open, with a RPN of 108 is the only unacceptable failure. Fig. 2 shows that 3 failures of compressor electric coil breakdown, failing of the compressor to start, and failing of the air tank relief valve to open need to be redesigned mainly due to their high severity rates.

Mechanical system. Eight failure modes were identified in TBM mechanical system. Table 5 shows the maximum, minimum, average, and the standard deviation of RPN of failures in mechanical system.

The results showed that cutter head stop had the highest RPN. Two failures of Grab inlet tap breakdown and Electric tap breakdown have the minimum Risk Priority Number.

According to Fig. 1, 4 failures in TBM mechanical system have unacceptable RPN (e.g. RPN>80), which need to be modified. According to Fig. 2, three parts need to be redesigned mainly due to high severity rates of their failures.

DISCUSSION

Addressing the modification and controlling methods of the failures and quantification of their influences on the final risk priority number of each failure by the expertise team was the novelty of the present study.

Seven failure modes with RPN>80 were categorized unacceptable failures. Fig. 1 shows these failure modes with their codes. The results show that even after modification and applying control measures, the cutter head stop failure mode will still have a RPN of higher than 80.

It is believed that when the range of severity, likelihood and detection is from 1 to 10 a risk with its RPN ≥100 is a high risk failure and if the severity is more than 5, then modifying the design work is essential [3]. According to this conception, 9 failure modes had severity numbers higher than 5 but only 3 of them had a RPN of higher than 100. Systems with RPN>100 need to be redesigned (Fig. 2).

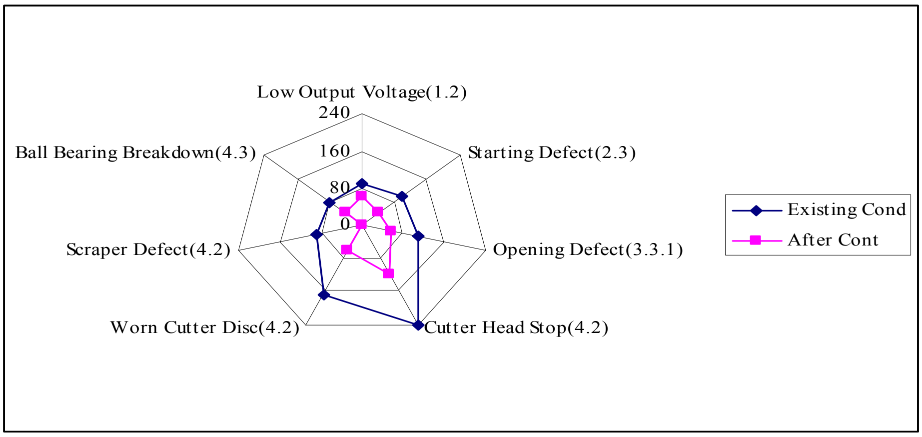

Fig. 1. Unacceptable failure modes (RPN>80)

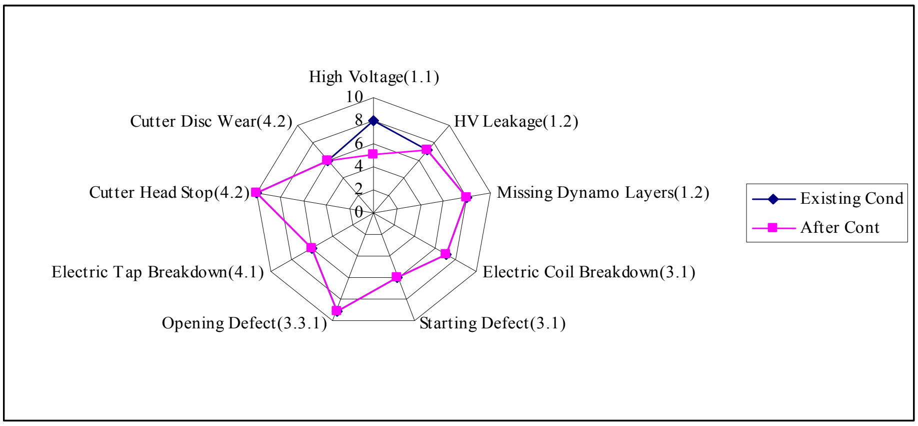

Fig. 2. Failures which require redesigning (SV>5)

The accidents occurred in next two years were tracked. The results revealed that, modification of the process and equipment reduced the accidents significantly. Three TBM stops due to bad rock condition were the major accidents occurred during next two years. The consequences of these accidents were negligible. The comparison of the accidents (numbers and consequences) with similar projects shows that this project was successful in accident prevention.

Electric system. Power generator, short circuit in secondary windings of the transformer, high voltage drop along the power distribution line or getting high current from the system may lead to a low output voltage.

This failure can effect electric consuming subsystems or burn the transformer and finally stop the TBM. It can be prevented or discovered through applying voltage control relays, breakers sensitive to voltage in main circuit breakers, and phase controlling relays. The related expertise team suggested applying Programmable Logic Circuit (PLC) for design modification and controlling this failure mode. The application of PLC will reduce the detection number from 3 to 2. This will reduce the RPN from 90 to an acceptable level of 60 (Fig. 1). The application of this controlling measure will not influence the severity and likely hood numbers.

Hydraulic system. According to the results, in TBM Hydraulic system, all failure modes except the starting defect of pressure supplier (RPN=96) were low risk failure modes. The high likelihood number of this failure means that the probability of its occurrence is relatively high. This failure mode that can stop the TBM may be caused mainly due to defective electromotor, defective circulation pump problems in main circuit or lose fittings. The related expertise team recommended an appropriate preventive maintenance program in order to control this failure. The application of an appropriate preventive maintenance is expected to reduce the likelihood number from 8 to 5 and the RPN from 96 to 40.

Pneumatic system. The results reveal that, considering RPN, defective opening of high pressure tank is the only high risk failure mode in the pneumatic system. Corrosion, humidity and any obstacle in the tap may lead to this failure. The failure will increase the pressure of the tank and burst it which will finally stop the TBM. At present, the pressure gauges on air tanks and in TBM control rooms are used to detect this failure.

The MFMEA expertise team recommended preventive maintenance, periodical checks, and punctual replacement of the appropriate parts to control this failure. The application of these recommendations is expected to reduce the RPN of this failure mode from 108 to 54. The control actions will not reduce the severity number. A modification design for the opening mechanism of the high pressure tank is required to reduce severity number.

The results also show that in the TBM pneumatic system 3 failure modes had severity numbers higher than 5. They included electric coil breakdown, starting defect of air supplier and opening defect of pressure tank. If the electric coil of air supplier breaks down, it will not have any local effects but it will stop the compressor which will consequently stop the TBM. At present, PLC is applied to detect this failure. The expertise team believed that an appropriate preventive maintenance program will reduce its likelihood and detection numbers leading to a reduction of RPN from 56 to 14. The control actions will not reduce the severity number, thus modification of electric coil design seems to be essential.

Starting defect in air supplier will not have a local effect, but it will stop the compressor which will consequently stop the TBM. Any defects in PLC, burning of contactor blades, sulfating, dust and any electrical or mechanical failures in electromotor may lead to this failure mode. Presently, PLC is used to detect this failure. Preventive maintenance is suggested to reduce RPN from 54 to 24, but it will not reduce the severity number. A modification of starting design is recommended to reduce severity number.

Mechanical system. Cutter head stop is the most severe and highly risk failure mode in this system. High severity and likelihood numbers are the special characteristics of this failure mode. This failure leads to stop the TBM.

Bad rock condition is the main reason the cutter head stops. Core drilling is recommended to identify rock condition in advance. This will reduce the likelihood number from 8 to 6 and the detection number from 3 to 2 which all together will reduce the RPN from 240 to 120. This suggestion was applied and reduced the cutter head stop due to rock condition from then on.

Cutter disc wear is the next failure mode with a high RPN and severity number. It may lead to TBM stop. Bad Rock condition and non-standard disc material are the main reasons for this failure. The expertise team recommended using standard discs and periodical checks to prevent this failure. These actions will reduce the likelihood number from 4 to 2 and the detection number from 7 to 5 which will totally reduce the RPN from 168 to 60.

The third failure mode with a RPN higher than 80 is scraper defect (break down and wear). This failure mode will stop the TBM. This failure has a relatively high detection number. Thus, periodical checks may help to detect it easier. The team did not make any recommendations.

CONCLUSION

MFMEA is a superb analyzing tool to evaluate the reliability of a TBM. Prediction of the risk priority numbers considering the controlling measures applied to the system provides very useful guidelines for loss control due to accident prevention.

ACKNOWLEDGEMENT

The authors wish to appreciate the University of Shahid Beheshti (MC) and Talon Company for their sincere contribution in this work. The authors declare that they have no conflicts of interest.

REFERENCES

1. Eskesene SD. Guidelines for Tunnelling Risk Management: International Tunnelling Association, Working Group No 2. *Tunnelling and Underground Space Technology*. 2004; 19:217-37.
2. Khouty GA. Eu Tunnel Safety Update. *Tunnel and Tunnelling International*. 2005; 37(2):56-67.
3. Gharari N. Risk Assessment in Tunnelling with TBM Using FMEA Method and Temporary Ventilation Design [Research]. Tehran: Shahid Beheshti (MC); 2007.
4. Hyatt N. *Guidelines for Process Hazards Analysis, Hazards Identification and Risk Analysis*, 3rd edition. 3 ed. Dyadem press, Ontario, Canada: 2003.
5. Brauer RL. *Safety and Health for engineers*. 2nd edition. 2nd ed. Hoboken, New Jersey, USA: John Wiley 2002.
6. SAEJ1739. *Potential Failure Mode and Effects Analysis in Design (Design FMEA), in Manufacturing and Assembly Process (Process FMEA), and for Machinery (MFMEA)*. Society of Automotive Engineers, USA 1994.
7. MIL-STD-1629A. *Procedures for Performing a Failure Mode, Effects and Criticality Analysis*. Department of Defense, USA 1998.
8. Abdul-Nour G, Beaudoin H, Ouellet P, Rochette R, Ambert SL A. Reliability Based Maintenance Policy; A case study. *Computers Ind Engng*. 1998; 35 (3-4):591-4.
9. Pinna T, Caporali R, Cambi G, Burgazzi L, Poucet A, Porfiri MT. Failure Mode and Effect Analysis on ITER heat transfer systems. *Fusion Engineering and Design*. 1998; 42:431-6.
10. Sankar NR, Prabhu BS. Modified Approach for Prioritization of Failures in a System Failure Mode and Effects Analysis. *Int J Qual Reliab Manage*. 2001; 18 (3)(3):324-35.
11. Scipioni A, Saccarola G, Centazzo A, Arena F. FMEA Methodology Design, Implementation and Integration with HACCP System in a Food Company. *Food Control* 2002; 13:495-501.
12. Price CG, Taylor NS. Automated Multiple Failure FMEA. *Reliability Engineering and System Safety* 2002; 76:1-10.
13. Seung JR, Ishii K. Using, Cost Based FMEA to Enhance Reliability and Serviceability *Advanced Engineering Informatics* 2003; 17:179-88.
14. Seyed-Hosseini SM, Asgharpour MJ, Safaei N. Reprioritization of Failures in a System Failure Mode and Effect Analysis by Decision Making Trial and Evaluation Laboratory Technique. *Reliability Engineering and System Safety* 2006; 91:872-81.
15. Dominguez – Garcia A, John K, Schindall J. Reliability Evaluation of the Power Supply of an Electrical Power net for Safety – Relevant Applications. *Reliability Engineering and System Safety* 2006; 91:505-14.
16. Burgazzi L, Roberta F, Barbara G. Safety Assessment of a Lithium Target. *Nuclear Engineering and Design* 2006; 236:359-67.
17. Eti MC, Ogaji SOT, Probert SD. Development and Implementation of Preventive Maintenance Practices in Nigerian Industries. *Applied Engergy* 2006; 83:1163-79.