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Failure Analysis of Feedstock Preheater Unit of the Kaduna Refinery using Failure Modes Effects and Criticality Analysis (FMECA)

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ABSTRACT
The use of failure modes effects and criticality analysis (FMECA) as a failure or reliability analysis tool, checks the probabilities that an item will perform a required function under stated condition(s) when operated properly.Failure analysis of process equipment is an important issue in any process industry. This study aims at analyzing the failure of feedstock preheater unit of the Kaduna Refining and Petrochemicals (KRPC), Fluid Catalytic Cracking Unit (FCCU), using the failure mode, effects and criticality analysis (FMECA). The unit failure and its effects were identified through seven sub-units (fresh feed surge drum, heavy naphtha exchanger, light cycle oil exchanger, heavy cycle oil exchanger, fractionator bottom exchanger, feed preheater and fresh feed charge pump), using the failure mode effects analysis (FMEA). Both quantitative and qualitative criticality analyses (CA) were used for failure analysis of the unit (feedstock preheater). For the qualitative analysis, items risk priority number (RPN) were computed and it was found that, four sub-units (heavy naphtha exchanger, main fractionator bottom exchanger, feedstock preheater, and fresh feed charge pump) had their Risk Priority Number (RPN) greater than 200, these sub-units are said to be critical. Three of the sub-units (fresh feed surge drum, light cycle oil exchanger, and heavy cycle oil exchanger) had their RPN less than 200, these sub-units are said to be less critical. For the quantitative analysis, items criticality number (Cr) were computed and it was found that most of the sub-units had their Cr>0.002. In addition, the results of the criticality matrix showed that, eight out of the sixteen failure modes identified were above or closely below the criticality line. Finally, FMECA was effectively used for failure analysis of the feedstock preheater andpredictive maintenance was recommended.

Keywords: *FCCU, Feedstock Preheater, Failure Analysis, FMEA/FMECA, Risk Priority Number, Criticality Number, and Criticality Matrix.*

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I. INTRODUCTION

The feedstock preheater is a train of heat exchangers used to preheat the fresh feed normally the heavy gas oil (HGO) and vacuum gas oil (VGO) at a temperature range of 300 – 330°C. Heat from the product which is to be cooled, is recovered by the feedstock preheaters. The feed heat is further increased by the feed furnace and then introduced into the base of the riser (Chiyoda[1], 1980 and Hendrix[2], 2011). The failure of this unit is of great concern, because it may lead to complete shutdown of the FCCU. Therefore, the failure analysis of this unit (feedstock preheater) using the FMECA cannot be over emphasized. FMECA was one of the first systematic techniques for failure analysis.It is a technique used to identify, prioritize, and eliminate potential failures from the system, design or process (Rausand[3], 2005). FMECA methodologies were designed to identify potential failure modes for a product or process before the problems occur, to assess the risk (Sultan[4], 2011 and Maley[5], 2012). This tool was used byThangamani, et al[6], 1995 to assess the reliability of a FCCU, and from their results, the reliability was found to be low.Masoud, etal[7], 2011 applied this tool for failure analysis ofan oil industry in Iran. Also, Flecher[8], 2012 used this tool to assess the risk of Sinopec X'ian branch FCCU. His result showed that reactor-regenerator systems have the highest potential hazard. In addition, Mahendra[9], 2012 applied FMECA for ensuring reliability of process equipment. At the end of his work, highly critical systems and failure modes were identified and that the duration for which the equipment is out of work is reduced significantly. Ibrahim, et al[10], 2015 used the tool for the reliability of a reactor – regenerator unit. Similarly, Ibrahim, et al[11], 2016 used the tool to assess the reliability of fractionation column. Their results showed that the reliabilities of the units were found to be low.

II. METHODOLOGY

2.1 FMEA Methodology

The method adopted for FMEA is as shown in figure 1. It is a step by step process of identifying and analyzing failure in the feedstock preheater. Failure modes, failure cause, failure effect, detection method, compensation provision and severity of each of the item of the sub-units were identified and analyzed.

2.2 FMECA Methodology

The method adopted for FMECA is as shown in figure 2. For both quantitative and qualitative criticality analysis, the information in FMEA serves as the basis for criticality analysis.

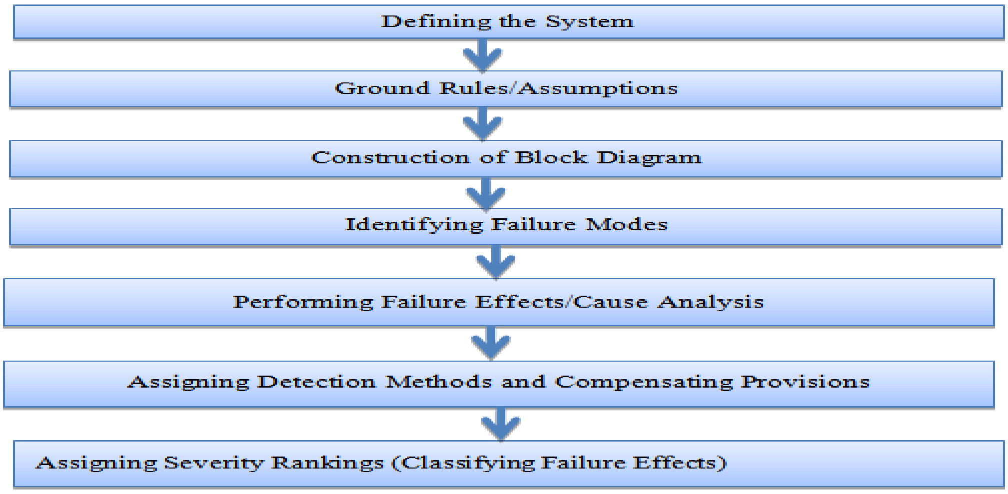

Fig 1: A FMEA Block Diagram

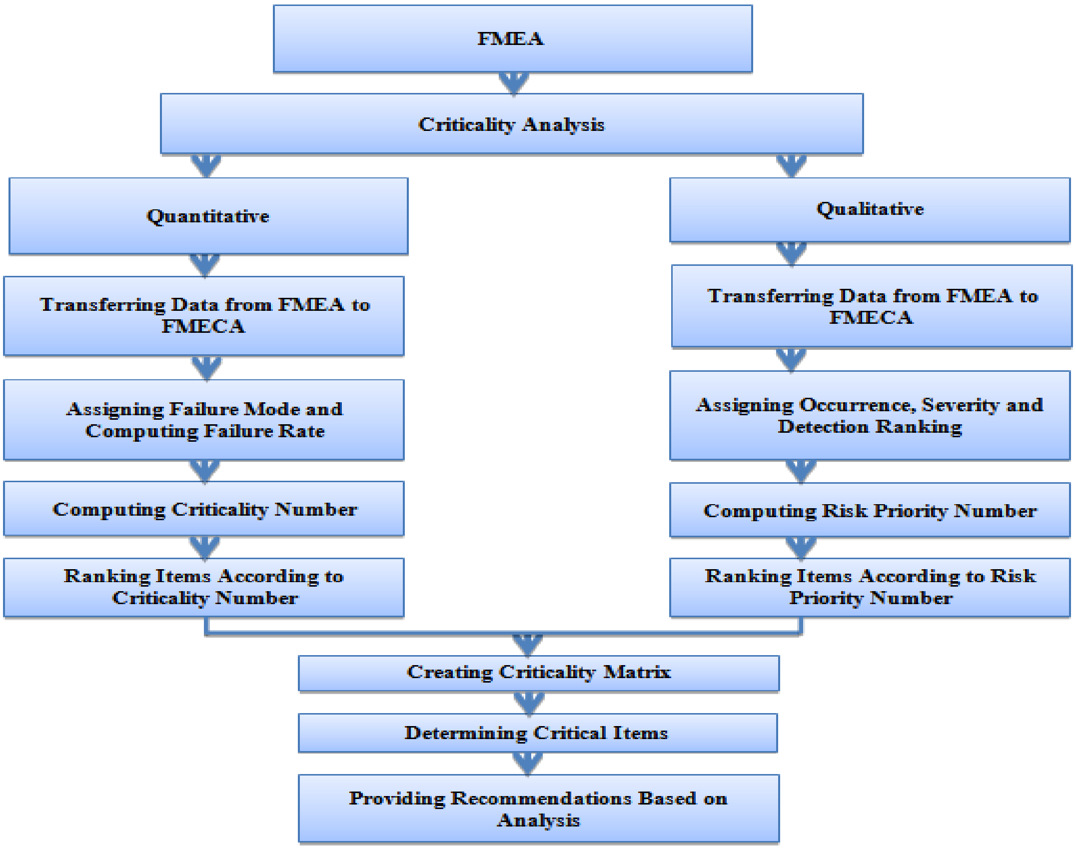

Fig 2: A FMECA flow diagram

III. RESULTS AND DISCUSSIONS

3.1 FMEA Result

Table 1 is the FMEA result for feedstock preheater. The table shows the potential failure modes, failure mechanism, failure effects, detection method, compensation provision and severity of the feedstock preheater via its seven sub-units (fresh feed surge drum, heavy naphtha exchanger, light cycle oil exchanger, heavy cycle oil exchanger, fractionator bottom exchanger, feed preheater and fresh feed charge pump). The severity of the sixteen failure effects of the sub-units were above average, between four to nine. That is, from a failure that might cause minor injury, minor property damage, or minor system damage which will result in delay or loss of sub-unit (marginal), to a failure which might cause death or lack of ability to carry out operation without warning (catastrophic).These values and descriptions of the failures above were in conformity with the RAC[12], 2005, Technical Manual [13], 2006 and Ibrahim,et'al[10], 2015.

Table 1: A FMEA sheet for Feedstock preheater

	FAILURE MODE EFFECT ANALYSIS (FMEA)						
	STUDY AREA: Area 3 (KRPC)						
	SYSTEM : Feedstock Preheater						
	OBJECTIVE: To heat the long chain hydrocarbon molecules and recycle slurry oil						
ITEM ID	FUNCTIONAL ID	FAILURE MODE(S)	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHOD	COMPENSATION	SEVERITY
D15	fresh feed surge drum	low level in the drum	supply line blokage	leads to P01 cavitation	level sensor	level indicator	4
		drum perforated	corrosion	pump will tripped off	flow sensor	flow indicator	2
E02A/B	heavy naphtha exchanger	Tube fouled	tube blockage	in effective heat exchange rate	alarm temperature sensor	SCADA* Indicator	4
		leakage	tube rupture	low outlet temperature	alarm temperature sensor	SCADA Indicator	5
		loss of vacuum	tube rupture	compressor might trip off	alarm temperature sensor	SCADA Indicator	6
		accumulated dirt	filament blockage	lube oil flow restriction	alarm temperature sensor	SCADA Indicator	7
E03	light cycle oil exchanger	Tube fouled	tube blockage	in effective heat exchange rate	alarm temperature sensor	SCADA Indicator	4
		leakage	tube rupture	low outlet temperature	alarm temperature sensor	SCADA Indicator	4
E04	heavy cycle oil exchanger	Tube fouled	tube blockage	in effective heat exchange rate	alarm temperature sensor	SCADA Indicator	5
		leakage	tube rupture	low outlet temperature	alarm temperature sensor	SCADA Indicator	5
E05	fractionator exchanger	Tube fouled	tube blockage	in effective heat exchange rate	alarm temperature sensor	SCADA Indicator	4
		leakage	tube rupture	low outlet temperature	alarm temperature sensor	SCADA Indicator	5
H02	feed preheater	heating of empty tube	tube buckling	high heater outlet temperature	alarm temperature sensor	Redundant System	7
		failure to line-up	Tube coking	low outlet temperature	alarm temperature sensor	Redundant System	7
		leakage	tube rupture	oil leak will occur to heater fire box	alarm temperature sensor	SCADA Indicator	8
P01	fresh feed charge pump	low level in surge drum	pump tripped	low flow across feed train	interlock system	Redundant System	6
		low discharged pressure	tube blockage	catalyst slumping in the riser	interlock system	Redundant System	2
		low suction head pressure	cavitation in pump operation	coking of H02 tubes	interlock system	Redundant System	9
		power failure	voltage drop	production distruption	interlock system	Redundant System	2

*SCADA: Supervisory Control and Data Acquisition

3.2 Qualitative FMECA Result

The qualitative FMECA for the feedstock preheater is presented in Table 2. From the table, four sub-units (heavy naphtha exchanger, main fractionator bottom exchanger, feedstock preheater, and fresh feed charge pump) have their Risk Priority Number (RPN) greater than 200.These sub-units are critical and have low reliabilities. Three of the sub-units (fresh feed surge drum, light cycle oil exchanger, and heavy cycle oil exchanger) have their RPN less than 200. These sub-units are said to be less critical and have moderate reliabilities.

Table 2: A qualitative FMECA for feedstock preheater

QUALITATIVE FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)						
	STUDY AREA: Area 3 (KRPC)					
	SYSTEM : Feedstock Preheater					
	OBJECTIVE: To heat the long chain hydrocarbon molecules and recycle slurry oil					
ITEM ID	FUNCTIONAL ID	SEVERITY	OCCURRENCE	DETECTION	RPN1	RPN2
D15	fresh feed surge drum	4	1	9	36	60
		2	2	6	24	
E02A/B	feed/ heavy naphtha exchanger	4	2	7	56	384
		5	3	7	105	
		6	1	8	48	
		7	5	5	175	
E03	feed/ light cycle oil exchanger	4	1	8	32	68
		4	1	9	36	
E04	feed/ heavy cycle oil exchanger	5	1	8	40	85
		5	1	9	45	
E05	feed/ main fractionator bottoms exchanger	4	4	8	128	248
		5	8	3	120	
H02	feed preheater	7	1	3	21	219
		7	2	5	70	
		8	4	4	128	
P01	fresh feed charge pump	6	8	2	96	322
		2	2	6	24	
		9	3	6	162	
		2	4	5	40	

Table 3 shows the prioritized items for corrective action based on their RPN. Item with the highest RPN is the item to be considered first for replacement, repair or maintenance. This is to ensure safety and reliability of the unit. The heavy naphtha exchanger has the highest RPN of 384. This means highest priority for corrective action.The order follows up to fresh feed surge drum with the least RPN value of 60. This means least priority for corrective action. However, in terms of selection criteria for maintenance program, Puthillath,et'al[14], 2012 also adopted this system of item ranking.

Table 3: A qualitative FMECA item ranking for Feedstock preheater

	ITEM RANKING QUALITATIVE (FMECA)	
	STUDY AREA: Area 3 (KRPC)	
	SYSTEM : Feedstock Preheater	
ITEM ID	FUNCTIONAL ID	ITEM RPN
E02A/B	feed/ heavy naphtha exchanger	348
P01	fresh feed charge pump	322
E05	feed/ main fractionator bottoms exchanger	248
H02	feed preheater	219
E04	feed/ heavy cycle oil exchanger	85
E03	feed/ light cycle oil exchanger	68
D15	fresh feed surge drum	60

3.3 Quantitative FMECA Results

Table 4 presents the quantitative FMECA for feedstock preheater. The following data (item failure rates, failure mode ratio, and item criticality number) were computed for the seven sub-units (feed/heavy naphtha exchanger, fresh feed charge pump, feed/main fractionator bottoms exchanger, feed preheater, feed/heavy cycle oil exchanger, feed/light cycle oil exchanger, and fresh feed surge drum). The criticality number (Cr) describes the reliability and availability of each of the sub-unit. The higher the criticality numbers the more the risk involved and the lower the reliability and availability of each of the sub-unit. Four of the sub-units (feed/ heavy naphtha exchanger, fresh feed charge pump, feed/ main fractionator bottoms exchanger, and feed preheater) have their Cr> 0.002. The remaining three sub-units (feed/ heavy cycle oil exchanger, feed/light cycle oil exchanger, and fresh feed surge drum) have their Cr < 0.002. Similar data were obtained by RAC[12], 2005 and Technical Manual[13], 2006 in assessing the reliability of their defense equipment.

Table 4: A quantitative FMECA for feedstock preheater

	QUANTITATIVE FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)								
	STUDY AREA: Area 3 (KRPC)								
	SYSTEM : Feedstock Preheater								
	OBJECTIVE: To heat the long chain hydrocarbon molecules and recycle slurry oil								
Item ID	**Functional ID**	**time (hr)**	**Occurrence**	**Failure rate □**	**Item □**	**□***	**□****	**Cr*** **	**Item Cr**
D15	fresh feed surge drum	17280	1	5.78704E-08	1.7361E-07	1	0.33	0.00033	0.00167
		17280	2	1.15741E-07		1	0.67	0.00134	
E02A/B	heavy naphtha exchanger	17280	2	1.15741E-07	6.3657E-07	1	0.18	0.00036	0.00352
		17280	3	1.73611E-07		1	0.27	0.00081	
		17280	1	5.78704E-08		1	0.1	0.0001	
		17280	5	2.89352E-07		1	0.45	0.00225	
E03	light cycle oil exchanger	17280	1	5.78704E-08	1.1574E-07	1	0.5	0.0005	0.001
		17280	1	5.78704E-08		1	0.5	0.0005	
E04	heavy cycle oil exchanger	17280	1	5.78704E-08	1.1574E-07	1	0.5	0.0005	0.001
		17280	1	5.78704E-08		1	0.5	0.0005	
E05	bottoms exchanger	17280	4	2.31481E-07	6.9444E-07	1	0.33	0.00132	0.00668
		17280	8	4.62963E-07		1	0.67	0.00536	
H02	feed preheater	17280	1	5.78704E-08	4.0509E-07	1	0.14	0.00014	0.003
		17280	2	1.15741E-07		1	0.29	0.00058	
		17280	4	2.31481E-07		1	0.57	0.00228	
P01	fresh feed charge pump	17280	8	4.62963E-07	9.838E-07	1	0.47	0.00376	0.00546
		17280	2	1.15741E-07		1	0.12	0.00024	
		17280	3	1.73611E-07		1	0.18	0.00054	
		17280	4	2.31481E-07		1	0.23	0.00092	

*failure effect probability, **failure mode ratio, ***criticality number

Table 5 depicts the quantitative FMECA item ranking for feedstock preheater. From the table, criticality numbers were used to rank items according to their risk level. The main fractionator bottoms exchanger has the highest criticality number of 0.00668 while the light and heavy cycle oil exchangers have the least criticality number of 0.001 each. Therefore, sub-unit (main fractionator bottoms exchanger) with the highest criticality number would be considered first in terms of maintenance, repair or replacement.

Table 5: A quantitative FMECA item ranking for feedstock preheater

	ITEM RANKING QUANTITATIVE (FMECA)				
	STUDY AREA: Area 3 (KRPC)				
	SYSTEM : Feedstock Preheater				
Item ID	**Functional ID**	**Operating time (hr**	**Failure rate λ (/hr)**	**Failure effect probability**	**Item criticality number**
E05	feed/ main fractionator bottoms exchanger	17280	6.94444E-07	1	0.00668
P01	fresh feed charge pump	17280	9.83796E-07	1	0.00546
E02A/B	feed/ heavy naphtha exchanger	17280	6.36574E-07	1	0.00352
H02	feed preheater	17280	4.05093E-07	1	0.003
D15	fresh feed surge drum	17280	1.73611E-07	1	0.00167
E03	feed/ light cycle oil exchanger	17280	1.15741E-07	1	0.001
E04	feed/ heavy cycle oil exchanger	17280	1.15741E-07	1	0.001

Figure 3 is the criticality matrix for the feedstock preheater. From the figure, the plot of criticality number against severity was used to identify those critical failure modes related to the sub-units. The criticality lines on the figures were used to differentiate between critical, semi- critical and highly critical items. Eight out of the sixteen failure modes identified were above or closely below the criticality line while eight values of the failure modes were below the criticality line. Those values above and closely below the criticality line showed how critical those failure modes were with respect to the unit (feedstock preheater). However, it means that the reliability of those sub-units is low; therefore, preventive maintenance is recommended. Ibrahim, et al [11], 2016 and Rooney, et al[15]1988 also recommended preventive maintenance for high risk, because it may eventually result in substantial reduction in production periods.

Table 6: A Criticality Matrix data for Feedstock Preheater

ITEM ID	SEVERITY	Criticality number
D15	4	0.00033
	2	0.00134
E02A/B	4	0.00036
	5	0.00081
	6	0.0001
	7	0.00225
E03	4	0.0005
	4	0.0005
E04	5	0.0005
	5	0.0005
E05	4	0.00132
	5	0.00536
H02	7	0.00014
	7	0.00058
	8	0.00228
P01	6	0.00376
	2	0.00024
	9	0.00054
	2	0.00092

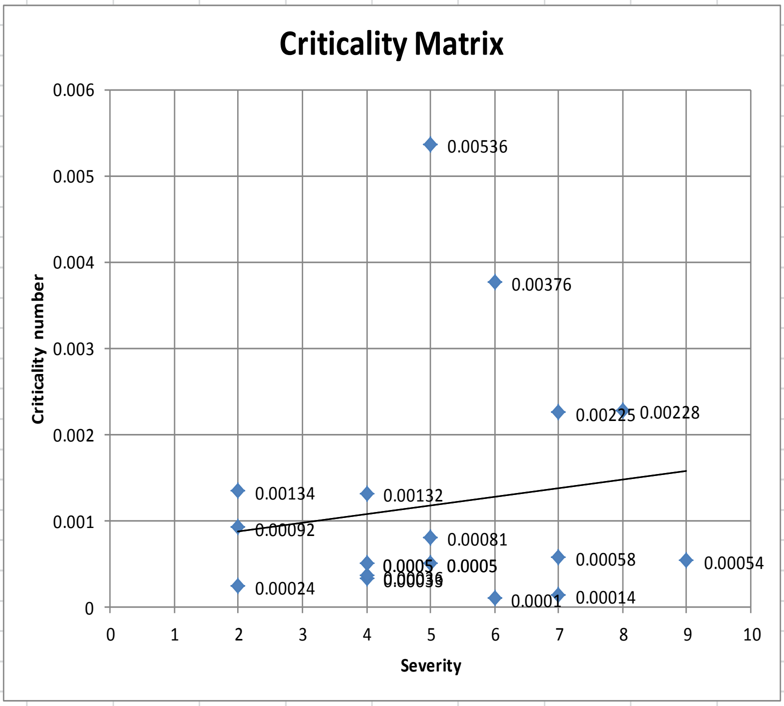

Fig3: A Criticality Matrix for Feedstock Preheater

IV. CONCLUSION

The failure analysis of the feedstock preheater via its sub-units (feed/ heavy naphtha exchanger, fresh feed charge pump, feed/ main fractionator bottoms exchanger, feed preheater, feed/ heavy cycle oil exchanger, feed/ light cycle oil exchanger, and fresh feed surge drum) was done using FMECA. From the analysis, the reliability was found to be low.

Preventive maintenance was recommended for the high risk failures because these failures eventually results in substantial reduction in production periods. The reliability tool (FMECA) used was efficient in failure analysis of each sub-unit of the feedstock preheater.

The use of FMECA to conduct the failure analysis of the feedstock preheater will help to reduce financial losses as a result of equipment damage, injury to personnel and above all loss of life.

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