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RELIABILITY ANALYSIS OF REACTOR-REGENERATOR UNIT OF THE KADUNA REFINERY USING FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)

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ABSTRACT

The neglect of most process industries to assess the reliability of their process equipment had led to high financial losses.As a result, this study aims at systematically analyzing the effectiveness and reliability of the Reactor-regenerator 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 effect were identified through twelve (12) sub-units (air heater, riser, disengager, regenerator, stripper, spent catalyst plug valve, regenerator catalyst plug valve, flur gas slide valve, fresh catalyst drum, wash water pump, used catalyst drum, and fractionator primary condenser), using the failure mode effects analysis (FMEA). Both quantitative and qualitative criticality analysis (CA) were used to determine the effectiveness and reliability of the unit (reactor-regenerator). For the qualitative analysis, items risk priority number (RPN) were computed and it was found that, five (5) of the sub-units (air heater, riser, spent catalyst plug valve, regeneration catalyst plug valve, and flue gas slide valve) had their RPN>300, with air heater having the highest RPN of 724. 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, sixteen (16) out of the twenty four (24) failure modes identifiedwere above or closely below the criticality line. Therefore, the effectiveness and reliability of the unit is low. As such, sub-units with RPN>300 and failure modes above or closely below the criticality line were recommended for replacement or predictive maintenance.

Keywords: FCCU, Reactor-Regeneration, Reliability, FMEA/FMECA, Risk Priority Number, Criticality Number, and Criticality Matrix.

I. INTRODUCTION

The reliability of a system is the ability of the system to perform it required functions under stated conditions for a stated period of time. The consequence of industries not assessing the reliability of their process equipment had led to high financial losses across the globe (Judith, H. 2011); this is as a result of equipment failure. Therefore, the need to assess the reliability of process equipment cannot be overemphasized. In Nigeria today, the failure rate of FCCU is high resulting to huge financial losses (Hamisu, 2011). FCCU is one of the most important conversion processes used in petroleum refineries. It is widely used to convert high-boiling, high-molecular weight hydrocarbon fractions of petroleum crude oils to more valuable gasoline, olefinic gases, and other products. The feedstock to an FCC is usually heavy gas oil (HVGO) from atmospheric distillation or vacuum distillation. It has an initial boiling point of at least 340 °C at atmospheric pressure and an average molecular weight ranging between 200 to 600. The cracking is done in a converter (Reactor-regenerator) in the presence of a finely divided catalyst which is maintained in an aerated or fluidized state at a temperature and pressure of 700 °C and 2.4bar respectively (Handrix, 2011). The failure of the reactor-regeneration unit will lead to shutdown of the entire unit, as such, the reliability analysis of the unit is of great importance. The basic input for finding the optimal maintenance tasks comes from Failure mode, effects and criticality analysis (FMECA) of the equipment (Mahendra, P. 2012). FMECA is a step-by-step approach for identifying all possible failures in a design, manufacturing or assembly process, product or service (Malay, N. 2012). It identifies and carries out corrective actions to address the most serious concerns. Information gained by performing FMECA can be used as a basis for troubleshooting activities, maintenance, manual development and design of effective built-in test techniques (Sultan, L.L. et'al, 2011).The analysis is characterized as consisting of two sub-analyses, the first being the failure modes and effects analysis (FMEA), and the second, the criticality analysis (CA).

The method is widely used and accepted throughout the military and commercial industries (Rausand, M. 2003).Historically, FMECA is contained in the 1949 Military Procedure MIL-P-1629 as a reliability evaluation technique to determine the effect of system and equipment failures (Technical manual 2006).This tool was used by Thangamani, G. et'al, 1995 to assess the reliability of a FCCU. Also, Flecher, P. 2012 used this tool to assess the risk of Sinopec X'ian branch FCCU. And his result showed that reactor-regenerator systems have the highest potential hazard. In addition, Mahendra, P. 2012 apply 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. Similarly, Masoud. H. et'al 2011 in their research "The application of FMEA in the oil industry in Iran: The case of four litre oil canning process of Sepahan Oil Company". The aim of their research was to show how FMEA could be applied to improve the quality of products at Sepahan Oil Company.However, after implementation of the improvement actions from FMEA, the can scrap percentage was reduced from 50000 to 5000 ppm and the percentage of the oil waste was reduced from 1 to 0.08%.Therefore, the use of FMECA to assess the reliability of FCC reactor-regeneration unit will help to minimize huge financial loses as a result of equipment failure.

II. METHODOLOGY

FMEA was used to identify potential failure modes, failure mechanism, failure effects, detection method, compensation provision and severity of the reactor-regeneration unit. The FMEA data were generated from the failure logbooks, operating manuals, equipment maintenance manuals and questionnaires. After FMEA analysis, both quantitative and qualitative criticality analysis (FMECA) were performed. According to Keller, P. 2014, RAC 2005, and technical manual 2006 equations (1), (2), (3) and (4) were used for the quantitative criticality analysis, while according to Puthillath, B. et'al 2012, Yelmaz, M. 2009, Sydney Water 2010 and Sultan, L.L. 2011 equation (5) was used for the qualitative analysis.

$$Cr = \alpha * \beta * \lambda_i * t - (1)$$

Where,

α is the failure effect probability

$$\alpha = \frac{\lambda_i}{\bar{\lambda}} \tag{2}$$

$$\bar{\lambda} = \sum_{i=1,2,3\ldots}^{n} \lambda_i \tag{3}$$

β is the failure mode ratio

λ_i is the failure rate

$$\lambda_i = \frac{Occurrence}{Operating\ time} \tag{4}$$

t is the operating time

$$RPN = D * O * S \tag{5}$$

Where,

D is the detection

O is the occurrence

S is the severity

A criticality matrix was then computed from the plot of criticality number and severity using MS-Excel spread sheet. This was used to identify critical items which were then ranked according to their level of criticality.

III. RESULTS AND DISCUSSION

The result of FMEA for the reactor-regenerator (converter) is shown in Table 1. It generally indicates the potential failure modes, failure mechanism, failure effects, detection method, compensation provision and severity of the sub-units (air heater, riser, disengager, regenerator, stripper, spent catalyst plug valve, regenerator catalyst plug valve, flur gas slide valve, fresh catalyst drum, wash water pump, used catalyst drum, and fractionator primary condenser) under the converter. The twelve sub-units under study had twenty nine failure modes, twenty nine failure mechanism and twenty nine failure effects. The detection method involve either the use of alarming systems, flowsensors or inspections. While the compensation provision involve the use of either Supervisory Control And Data Acquisition (SCADA) indicators, redudant systems or operation overide. The severity of the twenty failure effects of the sub-units is above average, between four to nine. That is, froma failure which may 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 may cause death or lack of ability to carry out operation without warning (catastrophic).

Table 1: A FMEA Sheet for Converter

FAILURE MODE EFFECT ANALYSIS (FMEA)						
STUDY AREA: Area 3 (KRPC)						
SYSTEM : Reactor-regeneration (Converter)						
OBJECTIVE: To convert the higher molecular weight hydrocarbon into lighter and more valuable gases						
FUNCTIONAL ID	POTENTIAL FAILURE MODE(S)	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHOD	COMPENSATION PROVISION	SEVERITY
Regenerator	over heating of catalyst	high air rate or slurry recycle	over cracking of feed	alarm system	SCADA Indicator	3
	in sufficient combustion air	PV-1 low pressure air grid	cracking distruption	alarm system	SCADA Indicator	4
	K01 air blower failure	low regenerator pressure	distort catalyst regeneration	alarm system	SCADA Indicator	8
	afterburning	excessive air in the regenerator	equipment damage	alarm system	SCADA Indicator	8
Stripper	stripping steam injection failure	trapped hydrocarbon in the regenerator	catalyst over heating	alarm system	SCADA Indicator	3
	low strpper bed level	slide valve blockage	spent catalyst with high hydrocarbon entrainment	alarm system	SCADA Indicator	8
Disengager	high attrition of product on cyclone	cyclone erosion on the surface	poor seperation and catalyst entrainment	alarm system	SCADA Indicator	3
	ineffective feed/ catalyst seperation	cyclone blockage	high sludge in 16C01 bottom	alarm system	SCADA Indicator	8
Riser	low riser feed rate	riser feed nozzle blockage	long residence time leading to over cracking	alarm system	SCADA Indicator	3
	low riser temperature	MP steam leaks	under cracking	alarm system	SCADA Indicator	7
	high riser temperature	riser deposit	overcraking	alarm system	SCADA Indicator	8
Fractionator primary condenser	ineffective cooling of overhead product	tube blockage	low gasoline yeild	flow sensor	Redundant System	3
	fan failure	no supply voltage to motor	low gasoline yeild	flow sensor	Redundant System	2
Air heater	vessel leakage	vessel rupture	fire eruption	interlock system	Redundant System	9
	less heat flow	controller faulty	less cracking	interlock system	Redundant System	7
	high temperature	controller faulty	excessive cracking	interlock system	Redundant System	8
Spent catalyst plug valve	hydrualic oil system failure	hooking of plug valve	affects catalyst movement	flow sensor	Redundant System	8
	valve not responding	valve blockage	pressure distortion	flow sensor	Redundant System	9
Regenerated catalyst plug valve	hydrualic oil system failure	hooking of plug valve	affects catalyst movement	flow sensor	Redundant System	8
	valve not responding	gear teeth distortion	rise the stripper bed level	flow sensor	Redundant System	8
Flue gas slide valve	hydrualic oil system failure	hooking of plug valve	affect flue gas discharge pressure system	flow sensor	Redundant System	6
	steave mechanism	gear teeth distortion	reduction in reactor pressure	flow sensor	Redundant System	8
Fresh catalyst storage drum	low carrier air or purge air pressure	blockage of catalyst loading line	catalyst over use leading to under cracking	Inspection	operator action and overide	4
	drum perforated	drum leakage	catalyst wastage	Inspection	operator action and overide	4
Used catalyst storage drum	low carrier air or purge air pressure	blockage of catalyst loading line	catalyst over use leading to under cracking	Inspection	operator action and overide	4
	drum perforated	drum leakage	catalyst wastage	Inspection	operator action and overide	4
Wash water pump	low level in surge drum	pump cavitate	pump mechanical seal may damage	flow sensor	Redundant System	3
	no level at all	pump heat up	pump mechanical seal may damage	flow sensor	Redundant System	2
	leakage	pump rupture		flow sensor	Redundant System	3

Table 2 represents the qualitative FMECA for the reactor-regeneration unit. From the Table, five sub-units (air heater, riser, spent catalyst valve, regenerated catalyst plug valve and flue gas slide valve) have their RPN greater than 300 these sub-units are critical and have low reliabilities. Seven of the sub-units (disengager, regenerator, fresh catalyst drum, wash water pump, used catalyst drum, stripper and fractionator primary condenser) 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 Converter

QUALITATIVE FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)					
STUDY AREA: Area 3 (KRPC)					
SYSTEM : Converter					
OBJECTIVE: To convert the higher molecular weight hydrocarbon into lighter and more valuable gases					
FUNCTIONAL ID	**SEVERITY**	**OCCURRENCE**	**DETECTION**	**RPN1**	**RPN2**
Regenerator	3	1	3	9	153
	4	2	5	40	
	8	1	7	56	
	8	1	6	48	
Stripper	5	2	4	40	75
	7	1	5	35	
Disengager	4	5	5	100	164
	8	2	4	64	
Riser	2	1	9	18	410
	7	2	8	112	
	8	5	7	280	
	3	3	6	54	74
Fractionator primary condenser	2	5	2	20	
	9	5	6	270	724
Air heater	7	6	7	294	
	8	4	5	160	
	8	8	2	128	353
Spent catalyst plug valve	9	5	5	225	
	8	8	1	64	304
Regenerated catalyst plug valve	8	5	6	240	
	6	8	2	96	256
Flue gas slide valve	8	5	4	160	
	4	3	5	60	140
Fresh catalyst storage drum	4	4	5	80	
	4	3	5	60	124
Used catalyst storage drum	4	4	4	64	
	3	6	3	54	132
Wash water pump	2	3	5	30	
	3	4	4	48	

Table 3 shows the prioritized items for corrective action based on their RPN. Item with the highest RPN showed item to be considered first for either replacement, repair or maintenance. This is to ensured safety and reliability of the unit. The air heater has the highest RPN of 724 this means highest priority for corrective action, the order follows up to fractionator primary condenser with the least RPN value of 74. This means least priority for corrective action.

Table 3: A Prioritized Item Ranking for Converter

ITEM RANKING QUALITATIVE (FMECA)	
STUDY AREA: Area 3 (KRPC)	
SYSTEM : Reactor-regeneration unit (Converter)	
FUNCTIONAL ID	**ITEM RPN**
Air heater	724
Riser	410
spent catalyst plug valve	344
regenerated catalyst plug valve	312
flue gas slide valve	304
Disengager	164
Regenerator	153
fresh catalyst storage drum	140
wash water pump	132
used catalyst storage drum	124
Stripper	75
fractionator primary condenser	74

The quantitative FMECA for reactor-regenerator unit is as shown in Table 4.From the Table, item failure rates, failure mode ratio, maintainability, and item criticality number where computed for the twelve sub-units (air heater, riser, disengager, regenerator, stripper, spent catalyst plug valve, regenerator catalyst plug valve, flue gas slide valve, fresh catalyst drum, wash water pump, used catalyst drum, and fractionator primary condenser). The higher the criticality number (Cr) of a sub-unit, the more risk involve, the lower its reliability and the lower its time required for Turn Around Maintanance (TAM). Ten of the sub-units (air heater, riser, disengager, spent catalyst plug valve, regenerator catalyst plug valve, flue gas slide valve, fresh catalyst drum, wash water pump, used catalyst drum, and fractionator primary condenser) have their Cr > 0.002. while the remaining two sub-units (regenerator and stripper) have their Cr < 0.002.

Table 4: A Quantitative FMECA Sheet for Reactor-Regenerator Unit (Converter)

			QUANTITATIVE FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)					
			STUDY AREA: Area 3 (KRPC)					
			SYSTEM : Reactor-regeneration unit (Converter)					
			OBJECTIVE: To convert the higher molecular weight hydrocarbon into lighter and more valuable gases					
FUNCTIONAL ID	Operating time	Occurrence	Failure rate λ	Item failure rate	Failure probability β	Failure mode ratio α	Failure mode criticality number	Item criticality number
Regenerator	17280	1	5.78704E-08	2.89352E-07	1	0.2	0.0002	0.0014
	17280	2	1.15741E-07		1	0.4	0.0008	
	17280	1	5.78704E-08		1	0.2	0.0002	
	17280	1	5.78704E-08		1	0.2	0.0002	
Stripper	17280	2	1.15741E-07	1.73611E-07	1	0.67	0.00134	0.00167
	17280	1	5.78704E-08		1	0.33	0.00033	
Disengager	17280	5	2.89352E-07	4.05093E-07	1	0.71	0.00355	0.00413
	17280	2	1.15741E-07		1	0.29	0.00058	
Riser	17280	1	5.78704E-08	4.62963E-07	1	0.13	0.00013	0.00373
	17280	2	1.15741E-07		1	0.25	0.0005	
	17280	5	2.89352E-07		1	0.62	0.0031	
Fractionator primary condenser	17280	3	1.73611E-07	4.62963E-07	1	0.38	0.00114	0.00424
	17280	5	2.89352E-07		1	0.62	0.0031	
Air heater	17280	5	2.89352E-07	8.68056E-07	1	0.33	0.00165	0.00513
	17280	6	3.47222E-07		1	0.4	0.0024	
	17280	4	2.31481E-07		1	0.27	0.00108	
Spent catalyst plug valve	17280	8	4.62963E-07	7.52315E-07	1	0.62	0.00496	0.00686
	17280	5	2.89352E-07		1	0.38	0.0019	
Regenerated catalyst plug valve	17280	8	4.62963E-07	7.52315E-07	1	0.62	0.00496	0.00686
	17280	5	2.89352E-07		1	0.38	0.0019	
Flue gas slide valve	17280	8	4.62963E-07	7.52315E-07	1	0.62	0.00496	0.00686
	17280	5	2.89352E-07		1	0.38	0.0019	
Fresh catalyst storage drum	17280	3	1.73611E-07	4.05093E-07	1	0.43	0.00129	0.00357
	17280	4	2.31481E-07		1	0.57	0.00228	
Used catalyst storage drum	17280	3	1.73611E-07	4.05093E-07	1	0.43	0.00129	0.00357
	17280	4	2.31481E-07		1	0.57	0.00228	
Wash water pump	17280	6	3.47222E-07	7.52315E-07	1	0.46	0.00276	0.00469
	17280	3	1.73611E-07		1	0.23	0.00069	
	17280	4	2.31481E-07		1	0.31	0.00124	

Table 5 is the quantitative item ranking for the reactor-regenerator unit. Items were ranked according to their level of criticality number. Three sub-units (spent catalyst valve, regeneration catalyst valve and flue gas slide valve) have the highest criticality number of 0.00686 each, as such, they are listed first. While two of the sub-units (stripper and regenerator) have the least criticality number of 0.00167 and 0.0014 respectively. They are however, listed last. In terms of maintenance, or repair or replacement, sub-units with the highest criticality number would be considered first.

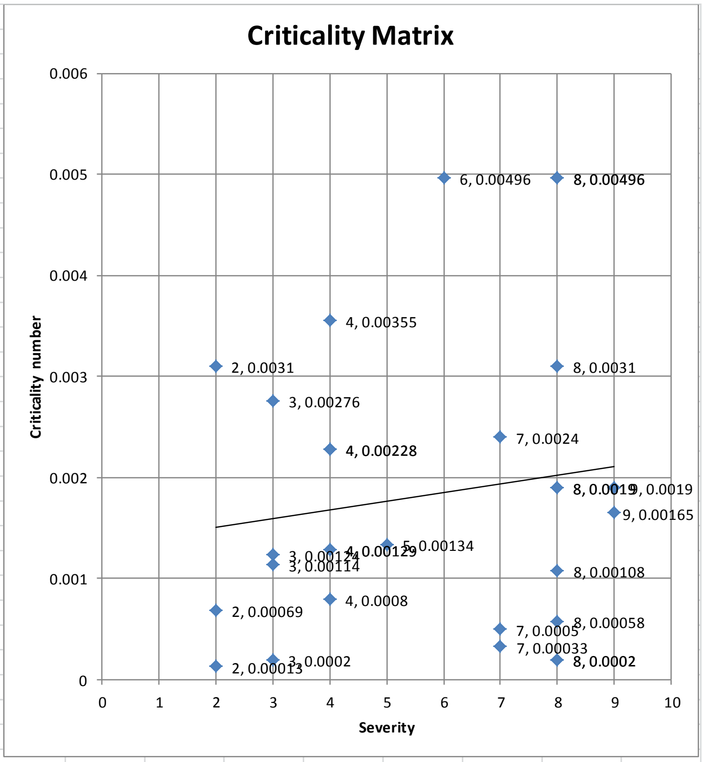
Table 5: A Quantitative FMECA Item Ranking for Converter

ITEM RANKING QUANTITATIVE (FMECA)				
STUDY AREA: Area 3 (KRPC)				
SYSTEM : Reactor-regeneration unit (Converter)				
Functional ID	**Operating time (hr)**	**failure rate λ**	**Failure effect probability β**	**Item criticality number Cr**
spent catalyst plug valve	17280	7.52315E-07	1	0.00686
regenerated catalyst plug valve	17280	7.52315E-07	1	0.00686
flue gas slide valve	17280	7.52315E-07	1	0.00686
Air heater	17280	8.68056E-07	1	0.00513
wash water pump	17280	7.52315E-07	1	0.00469
fractionator primary condenser	17280	4.62963E-07	1	0.00424
Disengager	17280	4.05093E-07	1	0.00413
Riser	17280	4.62963E-07	1	0.00373
fresh catalyst storage drum	17280	4.05093E-07	1	0.00357
used catalyst storage drum	17280	4.05093E-07	1	0.00357
Stripper	17280	1.73611E-07	1	0.00167
Regenerator	17280	2.89352E-07	1	0.0014

The criticality matrix for the reactor-regenerator unit is as shown in fig 1. From the figure,the plot of criticality number against severity was used to identify those critical failure modes related to the sub-units. There are twenty nine (29) failure modes associated to the twelve (12) sub-units. From the plot of Table 6, eight (8) values of the failure modes were above the criticality line, eight (8) values of the failure modes were closely below the criticality line and eight (8) 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 (Reactor-regenerator). However, it means that the reliability of those sub-units is low, therefore required immediate action(s). While those values below the line are less or moderate criticality with respect to the unit (reactor-regenerator).This means that the reliability of those sub-units is moderate.

Table 6: A criticality matrix for converter Figure 1: A criticality matrix for reactor-regenerator

Criticality Matrix for Reactor-regeneration unit		
Functional ID	**Severity**	**Criticality number**
Regenerator	3	0.0002
	4	0.0008
	8	0.0002
	8	0.0002
Stripper	5	0.00134
	7	0.00033
Disengager	4	0.00355
	8	0.00058
Riser	2	0.00013
	7	0.0005
	8	0.0031
Fractionator primary condenser	3	0.00114
	2	0.0031
Air heater	9	0.00165
	7	0.0024
	8	0.00108
Spent catalyst plug valve	8	0.00496
	9	0.0019
Regenerated catalyst plug valve	8	0.00496
	8	0.0019
Flue gas slide valve	6	0.00496
	8	0.0019
Fresh catalyst storage drum	4	0.00129
	4	0.00228
Used catalyst storage drum	4	0.00129
	4	0.00228
Wash water pump	3	0.00276
	2	0.00069
	3	0.00124



IV. CONCLUSION

FMECA as the reliability assessment tool was used to investigate the performance behavior of reactor-regenerator unit (converter) via its sub-units (air heater, riser, disengager, regenerator, stripper, spent catalyst plug valve, regenerator catalyst plug valve, flur gas slide valve, fresh catalyst drum, wash water pump, used catalyst drum, and fractionator primary condenser).

From both the qualitative and quantitative analysis used, the reliability of the reactor-regenerator unit (converter) was found to be low.This is because five sub-units (air heater, riser, spent catalyst valve, regenerated catalyst plug valve and flue gas slide valve)of the reactor-regenerator unit have their RPN greater than 300, these sub-units are critical and have low reliabilities. And also ten (10) sub-units (air heater, riser, disengager, spent catalyst plug valve, regenerator catalyst plug valve, flue gas slide valve, fresh catalyst drum, wash water pump, used catalyst drum, and fractionator primary condenser) of the reactor-regeneration unit have their have their Cr > 0.002.

From the analysis of the criticality matrix, most of the values of the failure modes were either above or very close to the criticality line, as such, it can be concluded that the reliability of the reactor-regeneration unit is low.

The use of FMECA to assess the reliability of reactor-rageneration unit,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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