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Comparative Analysis of Gas-Turbine Engine Diagnostics through Compressor Wash Wastewater Parameter Monitoring for Geregu Gas-Turbine Power Plant

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***Abstract**: This paper focuses on finding a lasting solution to the reason why offline compressor washing of unit 13 at Geregu Power plc in Ajaokuta does not restore power output lost due to fouling back to the rated output, as is the case for the other two (2) units in the plant and for several reported cases published in the literature. Monitoring of parameters closely related to the power output was carried out to find out the root causes for the low output recovery after offline compressor wash and came up with a successful diagnosis by interrelating GT13 wash effluent test results of parameters like conductivity, turbidity, and heavy metal concentration with parameters of two (2) other turbines in the plant. Using statistical tools like the mean and Pearson correlation coefficient for the four-year period, the mean comparative result indicates that the conductivity of GT13 was higher than that of GT11 and GT12 by 50% and 79%, respectively. The turbidity of GT13 was 570% and 700% higher than that of GT11 and GT12. The Pearson correlation coefficients of GT13 effluent conductivity, turbidity, and silica content relative to the power output recovery after wash were (-89.2%), (-64.4%), and (-77.3%), respectively, and the covariance of each of the three parameters relative to one another was high. Effluent Ph as a factor was discarded based on its 0% linear correlation coefficient with the output. The conclusion reached is that the co-linear relationship between conductivity, silica content, and effluent turbidity is responsible for GT13's low output recovery after the wash.*

***Keywords:** Compressor Wash Effluent, Gas Turbine Engines, Geregu Power, Gas Path Parameters, Diagnosis, Monitoring*

1. INTRODUCTION

According to Original equipment manufacturers (OEM) such as Siemens and General Electric (GE), gas turbines have an average productive life span of between 25 and 30 years, depending on the environment and maintenance culture. Despite having numerous advantages such as quick startup and shutdown and wide applicability in numerous sectors (energy, rail, ships, cars, planes, etc.), gasturbine performance is generally limited by factors like high ambient temperature, fouling and other conditions. Brun and Kurz [1] said that a negative performance from a gasturbine component could result in the other components not performing optimally which could lead to a decline in the overall output of the turbine.

Researchers like Kurz [2], Brun and Kurz [1], and Homji [3] reported that plant practices like compressor wash (online and offline) aid in recovering salvageable output. Kurz [4], kurz and Brun [5], Brun and Kurz [1] and Boyce [6] stated that non-recoverable output is fixed through the replacement of faulty component or through other corrective measures. Generally, the negative effects of the recoverable and non-recoverable degradation are interwoven. For example, Brun and Kurz [1] stated that both airfoil fouling and airfoil clearance increment could lead to a declining pressure ratio and thus efficiency. Homji [3] narrowed the major sources of gasturbine compressor fouling to be cement, fly ash, sand, oil, salt, water droplets and insects. Brun and Kurz [1] classed the major sources of gasturbine fouling to be salts, heavy hydrocarbons (oil, wax), carbon dirt and other sources. Brun and Kurz [1] stated that heavy fouling of the compressor could reduce power output by as much as 10%. Boyce [6] reported that a 2% fouling rate could increase the heat rate by 0.65% and reduce power output by 2%. Zuniga [7] stated that Hoeft etal. (1993) reported a 13% decrease in power output and a 6% increase in the heat rate when fouling led to a 5% decrease in the compressor inlet air mass flow rate. Zuniga [7] equally stated that Caguiat etal. (2003) reported a 3% increase in gasturbine fuel consumption and a 7% drop in the pressure ratio due to fouling of the compressor blade by 30g of salt. Gbanaibolu [8], after integrating gas path and rotor dynamic response model of the compressor to monitor the effect of fouling on the rotor, concluded that as compressor fouling increased, the rotor vibration amplitude also increased. kurz and Brun [5], Serverud [9], Ogbonanya [10], and Igie

[11] all reported that Output lost due to degradation agents like ash, dust or salts can easily be recovered through compressor offline or detergent wash. Researchers such as Abbas [12], Agbadede and Kanaiga [13], Kurz etal. [4], Boyce [6], kurz and Brun [5], and Maiwada [14] have all reported output restoration very close to rated values after offline wash.

Report on use of compressor wash effluent for gasturbine condition monitoring/fault diagnosis as a technique is quite scanty in open literature. In fact, researchers like Tahan [15], Loboda [16] and Mevissien [17] stated that much of interest has been in the area of using sensors, vibration, acoustic and other yardsticks to do condition monitoring. Gas turbine component deterioration monitoring through compressor wash effluent has not really been researched, so investing time and resource into this area could yield extremely positive feedback Researchers like Sachdeva [18] mentioned that chemical specie results of a gas turbine component using effluent characterization can be used as a reference for a second component there by saving time and cost .So technically, engine health monitoring through compressor wash water discharge could be a fast and cheap way to prevent catastrophic failures in the long run. Because, compared to most non-destructive techniques, long term shutdown of unit is not required and compared to online sensor monitoring techniques which most times are restricted to a particular parameter and are highly sensitive only when a sharp deviation in reading is encountered. The wash effluent for condition monitoring can potentially diagnose for multiple faults, ranging from fouling, component wearing, oxidation, sulphation and even mechanical degradation. Researchers such as Sachdeva [18] reported that effluent characteristics could be used to determine if degradation is oxidation, corrosion or erosion based. Sachdeva [18] looked at factors like trace metal levels in the effluent but they never mentioned the link between the concentration of the metals to gasturbine output.

Kurz [2], Fronapel [19], and Homji [3] looked at the relationships between compressor wash efficacy and wastewater parameters like effluent conductivity and metal concentrates. Homji [3] and Kurz [4] tried to correlate some aspects of wash parameters to the effectiveness of the wash itself but much attention was given to the required physiochemistry of the water for the offline and online compressor washes with very little detail given on the interrelationship between the output recovery after the wash with the compressor wash wastewater. Similarly, Fronapel [19] and Prickle [20] had more interest in the toxic composition of the compressor effluent and its effect on the environment than interrelating it to the gasturbine power output recovery rate. So literarily, there is a key gap in literature which needs to be researched and as such the aim of the paper will be to delve into use of compressor wash effluent parameters such as effluent wear metals, conductivity, and turbidity to resolve issue of turbine output recovery shortfall after offline compressor wash. This parameters were selected on the premise of the research by the likes of Kurz [4],Homji [3] and General electric(GE). Similarly in other related field, researchers like Ma [21], Sathya [22], Schutte [23], Trygar [24] and Doyle [25] also gave significance to PH, Conductivity, turbidity, and trace metals as factors which determine effluent quality. So due the strength placed on theses parameters by the above-mentioned researchers, this project will concentrate on the aforementioned wash effluent parameters for gasturbine fault diagnosis. Thus, the main objective of the present work is to use compressor wash effluent characterization to resolve the reason why output recovery after compressor offline wash of a particular unit at Geregu power plant is less than those of other units in the plant and values reported for similar plants in literature.

2. METHODOLOGY

2.1 Case Study: (GT13 gasturbine Power Output after Offline Compressor Wash at Geregu Power Plant, Nigeria)

Plant location and layout: The Geregu plant is located at Longitude 6.65^{o}E and Latitude 7.469 ^{o}N, adjacent to Ajaokuta Steel Company Limited. The turbine equipment consists of three Siemens V94.2 configurations with a total net rating of 435 MW at ISO. (145MW/unit). GT13 is at the left-hand side of GT"s 12 and GT11. The units are also encircled on the left by five other industrial setups. Two (2) tile making plants (BN ceramics (commissioned 2013) and West African ceramics (Commissioned 2006) and Three (3) other gasturbine plants belonging to Geregu phase 2 (All commissioned in 2013). The plant layout is shown in Figures 1 and 2. The plant is an open cycle power plant built by Siemens energy, with an extension to accommodate future conversion to combined- cycle gas turbine (CCGT) configuration.

So as earlier stated, this research is aimed at investigating the reason why, after offline compressor wash of unit 13, power output is not restored to rated value as is the case for other units in the plant and also of several similarly rated turbines cited in literature using compressor wastewater parameter characterization technique. So, it is of paramount importance to look at unit 13 compressor system.

The Compressor system is responsible for providing the turbine with all the air it needs in an efficient manner. In the Siemens V94.2 manual (2006), it is indicated that the compressor is a 16-stage axial flow type with a 2-stage inlet guide vane to regulate air flow from the air intake system into the compressor. It is further stated in the manual that the pressure ratio across the compressor stage is 11.2 bar. Authors like Homji [3], Maiwada [14] and Kurz [4] all reported that fouling of the compressor leads to a reduction in this pressure ratio and thus compressor efficiency which directly impacts on the gasturbine output. The aforementioned authors equally stated that light fouling of the compressors can be taken care of by online compressor wash while heavy fouling due to agents like oil deposition, salt contamination, and even corrosion can be reversed through offline wash. In Conclusion, the authors surmised that, provided output loss is not due to mechanical degradation or other irreversible causes, output lost due to the above-named sources can be regained through offline washing. To use offline wash effluent to resolve a case study, offline wash methodology background has to be looked at. Offline compressor wash; Maiwada [14], Agebeda and Kanaiga[13], Stalder [26] and Abbas [12] reported that the offline wash of the compressor generally involves a compressor soaking period, followed by the rinsing of the compressor with a quantity of fresh water .In this research, about 400 liters of demineralized water were used for the rinsing phase and 100 liters of Zok 27 detergent were used for the soaking. The waste effluent through the compressor was then discharged through the drains, as seen in Figure 5.

Figures 3 and 4 and 5 show the nozzle locations for the offline compressor wash and wash effluent flow path through the drains respectively.

Figure1: Front view of Geregu gas turbines with flue exhaust from Geregu phase 2 plants and the tile companies

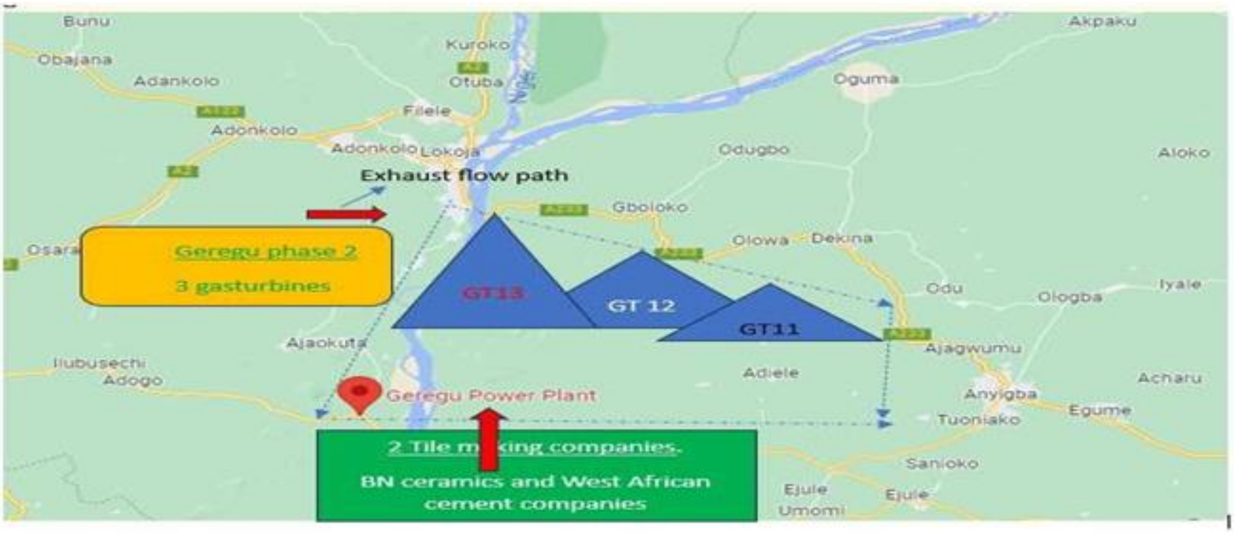

Figure 2: Modified google map view of Geregu gas turbines with flue exhaust from Geregu phase 2 plants and the tile companies.

Figure 3: Offline wash procedure with jet nozzles prominent

Figure 4: Wash nozzle locations for offline compressor wash [3]

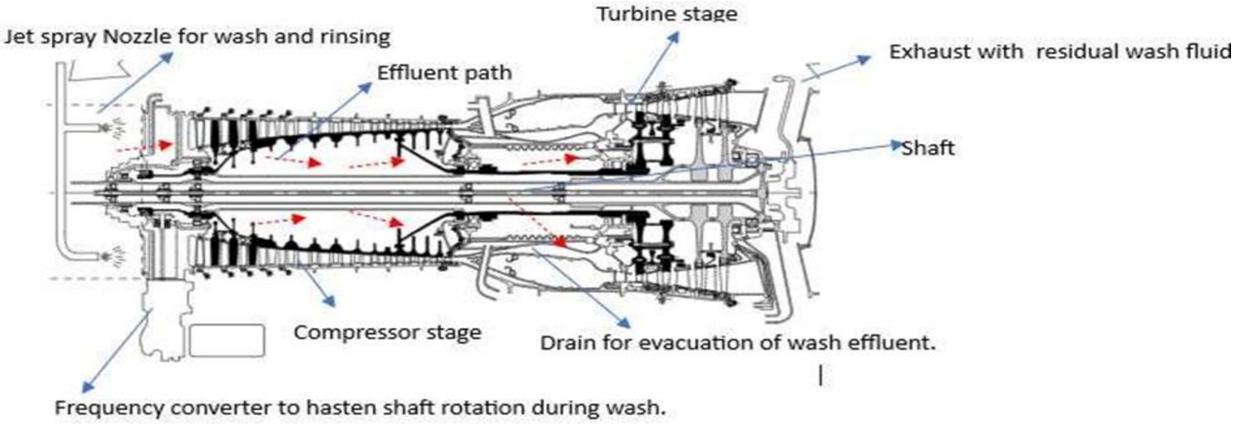

Figure 5: Schematic of offline wash procedure with jet nozzles prominent [27]

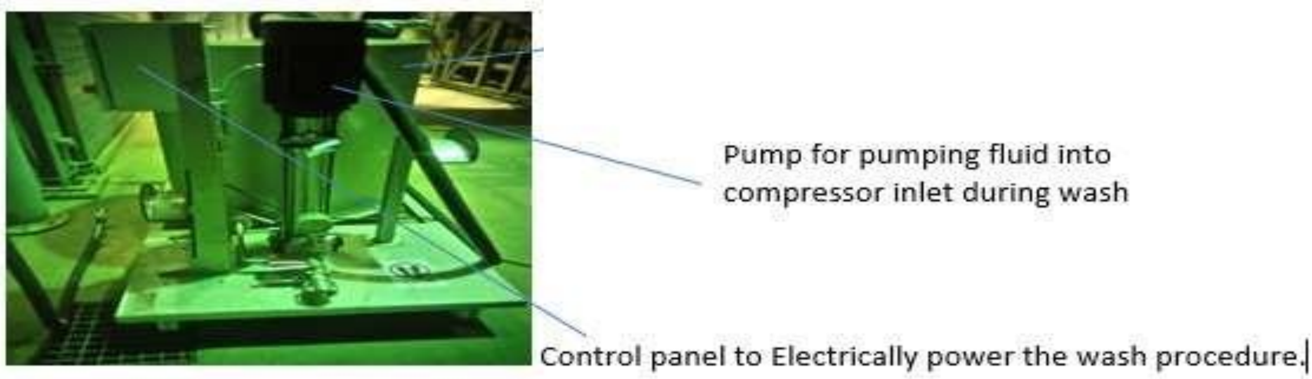

Figure 6: Compressor wash skid for online and offline washes (Present work)

2.2 Materials: The materials used for the experiments are: (i) The compressor turbine system of GT13 Gas Turbine at Geregu Power Plant in Ajaokuta, Nigeria. (ii)The Compressor offline wash skid, as seen in Figure 6 (has an integrated pump/tank arrangement for pumping diluted wash fluid into the compressor system and for storing water and wash fluid mixture respectively). (iii) Demineralized Water: About 500 liters used for each of washing and rinsing cycles (with a specification for Ph of between 6.5 and 7.5 and Alkali metal limit of about 25ppm for the water). (iv) Zok 27 compressor wash fluid: About 100 liters is used for the wash with wash fluid having specifications of 7.3 and specific gravity of 1.1, respectively. (v) Compressor offline wash wastewater; (vi) Offline effluent Test Equipment.

2.3 Effluent Test Equipment: Three basic test equipment were used for the tests, namely;

1. Multipurpose effluent parameter measurement meter for measuring the effluent conductivity, Ph and total suspended solids. According to [28], the multipurpose meter has an accuracy range of 0.5% reading, ±1 digit (conductivity), and ± 0.02 relative accuracy for the Ph. The meter has a Temperature range of -5 to 105°C.
2. The Turbidity meter: For measuring the effluent turbidity. The turbidity meter is an EPA Compliant Benchtop Meter. The version used in this work is the HI88703 type; it has a high accuracy measurement. (±2% of reading plus 0.02 NTU). The HI88703 meter readings meet and exceed the requirements of EPA Method 180.1 and Standard Methods for the Examination of Water and Wastewater for turbidity measurements.
3. The absorption Emission Spectrophotometer: used to measure the concentration of a known substance (mostly metals) in a solution, by passing light through the substance and measuring the light intensity as a function of wavelength. The model is the ICE AA 3000 series version 1.3, with a Focal Length of 270 mm and a linear dispersion: 1.5 – 2 mm. It has a Correction of Less than 2% and a temperature range of ambient to 1000^0C in steps of 1^oC.

2.4 Key Effluent Parameters for Gas Turbine Engine Monitoring

1. Ph: According to Ma [21], PH, or potential hydrogen refers to its H^+activity and it is given as the log of the reciprocal of H+ activity at a given temperature. Chikwe and Onojake [29] stated that the PH is a numeric scale used to specify the acidity or basicity of an aqueous solution. Chikwe and Onojake [29] further reported that Aina etal. (92) suggested that industrial discharge violations of PH will increase maintenance requirements of pumps. Ma [21] equally stated that the tolerance limit of PH varies from 6 to 9 for wastewater. Likewise, Chikwe and Onojake [29] concurred with the values given by Ma [21] for industrial effluents. Sathya [22] reported that Ravindra etal. (2018) said that for an electric power

plant effluent, the PH limit should be between 5.5 and 9.5. Trygar [24] and Drisu [30] reported that a very low PH measurement of an industrial effluent could be indicative of high concentration of metals like Zinc, Aluminium and copper or due to traces of fuel contaminants like Sulphur and Nitrogen oxides. Doyle [25] said that high acidity or low PH levels from power plant effluents could be as a result of contaminants from the lubrication oil or seal oils into the effluents.

2. Conductivity: Ma [21] stated that electrical conductivity of water is the measure of water capacity to convey electrical current and that the electrical conductivity of water is directly proportional to its dissolved mineral matter content. He further stated that the source of conductivity may be due to abundance of dissolved salts and that the conductivity of water is a useful indicator of its salinity or total salt content. Ma [21] also stated that the world health organization (WHO) guideline constrained the maximum conductivity values for discharge of wastewater from hotels into sewages to 1000Us/cm. Chikwe and Onojake [29] said that WHO stipulated that wastewater effluent conductivity limits should be less than or equal to 500Uscm^{-1}. Orion enterprises [28], a major supplier of effluent test equipment, in their manual specified that APHA (92) standard set industrial effluent values to be as high as 10000 Us/cm. Ekwere [31] reported that the Nigerian Federal environmental protection agency (FEPA) limits for industrial effluent is about 1000Us/cm and that the effluent conductivity is determined by the presence and level of concentration of sodium, Magnesium and calcium ions. Chikwe and Onojake [29] said that Hendrick and David in 2007, classified conductivity as an indicator of water quality correlating directly to the amount of dissolved salt. Chikwe and Onojake [29] further stated that Nordstrom etal. (99) said that if effluent conductivity is too high, it could result in the corrosion of pipes. Kurz [2], and Homji [3] concluded that high conductivity in power plant compressor wash effluent could be as a result of high salt content in the effluent originating from compressor blades fouled from salt contaminants in the air. Thus, Kurz [2], Homji [3], and General electric in their 2010 manual concluded that effluent conductivity level can be used for gasturbine engine health monitoring.

3. Total Alkalinity: According to Ma [21], low alkalinity causes pipe corrosion and increases the chance for the release of heavy metals. Ma [21] further stated that alkalinity and PH are the main factors in determining the amenability of wastewater for treatment. Hanson [32] said that the US Environmental Protection Agency's (EPA) alkalinity limit is about 200(Mg/L) and that alkalinity is a measure of water needed to neutralize a strong acid. Naaz [33] stated that the Alkalinity limits for beureau of Indian standards is between 200 and 600 (Mg/L).

4. Heavy Metals: Chikwe and Onojake [29] reported that the EPA 2009 specification for metals in industrial effluent is as follows: 2 mg/L for iron, 2.0 mg/L for Zinc, 0.5 mg/L for copper, 0.1 mg/L for Nickel, 0.01 mg/L for Cadmium, 200 mg/L for sodium, 0.05 mg/L for chromium and 0.05 mg/L for lead. Ma [21] stated that the WHO pronounced that iron levels above 0.3 mg/L in effluents might be harmful and that zinc concentration above 15mg/L might be toxic to human health. Ma [21], concluded that physio chemical effluent levels of PH, turbidity and metal concentration were highest when the conductivity and alkalinity were high. Orhon & Tilche [34] said that the limits for various trace metals in the effluents of textile and leather industries were between 0.05 and 0.5 for chromium, between (2.0 and 3.0) for copper, (0.2) for lead, between (0.1 and 0.2) for Nickel and between (0.5and 2) for zinc. Sathya [22] reported that Ravindra etal. (2018) said that for an electric power plant effluent, the Zinc content limit should be about 15 mg/L (Maximum). Prickle [20] and Sachdeva [18] reported that high trace metal content like Nickel, and chromium in power plant wash effluents could be as a result of corrosion and pitting originating from compressor and turbine blades and the above named researchers believe that the degree of trace metals in effluents can be used for gas turbine engine health.

5. Turbidity: Hanson [32] reported that increased turbidity in water reduces light penetration in the water. Shell petroleum development company (SPDC) Nigeria in their report in 2018, stated that turbidity,color, and total suspended solids are related parameters and that they usually vary in response to similar factors. Likewise, Schutte [23], in his text, reported that turbidity gives an indication of the concentration of colloidal particles in the effluent. Schutte [23] further stated that turbidity is expressed in nephelometric turbidity units (NTU) and that the turbidity is determined by comparing the intensity of light scattered by the water sample to the intensity of light scattered by a standard reference in the turbidity meter. Naaz [33] reported that the Indian standard limit of allowable industrial effluent turbidity is about 510NTU. Homji [3] in his report noted that turbidity levels in power plant effluents could be as a result of compressor fouling intensity. He further stated that the compressor rinsing cycle is inversely related to the effluent turbidity. Zuniga [7] concluded that high turbidity in power plant compressor wash effluent could be as a result of high silica and dust content in the effluent originating from compressor blades fouled from the contaminants in the air. Characteristic limits for the various parameters are shown in Table 1-3.

Table 1: Characteristics limits of physiochemical parameters for water effluent in industries.[29]

Characteristics	**Limits**
Ph	6.0 to 9.0
Conductivity (Us\cm)	Less than or equal to 1000
Total dissolved solids (TDS)(Mg\L)	Less than or equal to 500(For natural gas industries) and less than or equal to 2000 for other Industries

Characteristics	Limits
Total suspended solids (TSS)(Mg\L)	Less than or equal to 350
Chlorides (Cl-)(Mg\L)	Less than or equal to 100
Sulphates (Mg\L)	300 to 600

Table2: Trace metal limits for water effluent in industries [29]

Trace metals (ppm)	Limits
Iron (Mg\L)	Less than or equal to2
Zinc	Less than or equal to 2
Copper	Less than or equal to 0.5
Nickel	Less than or equal to 0.1
Cadmium	Less than or equal to 0.01
Sodium	Less than or equal to 200
Chromium	Less than or equal to 0.2
Lead	Less than or equal to 0.05
Magnesium	Less than or equal to 100

Table 3: Indian standard limits for industrial effluents [33]

Parameters	Limits
Turbidity (NTU)	Less than or equal 510
Alkalinity	Less than or equal to 600

2.5 Experimental Procedure and Test Methods

1. Sampling: Approximately about 2 liters of wash effluent for (GT11, GT12 and GT13) was captured into the sampling bottle and sealed. Emphasis was placed on the waste from the rinse cycle at the first drain. (Since wastewater at this juncture is mostly from the compressor and IGV. During effluent evacuation from the first drain into the sampling bottle, the effluent was continuously stirred to ensure homogeneity of effluent. The samples were collected quickly and sent to the lab for test. The effluent tests performed include wear metal, PH, Conductivity and turbidity tests. Table 4 presents Standards methods for gas turbine effluent tests undertaken.

Table 4: Standard methods used for gas turbine discharge effluent Tests

Tests\Limits	Equipment/Specifications	Methods	Sources
Conductivity	About 50ml effluent into 100ml Beaker. Filter paper for effluent filtering. Calibrated conductivity meter (430 pH/cond. Meter JENWAY) used. About 30ml effluent in 100ml Beaker	APHA 2510	[35,29]
Ph	The pH meter (pH-8414 Ph/mV/^{o}C) was calibrated using three buffers pH4, pH7 and pH9.	EPA 150.2	[35]
Turbidity	HI88703 -Turbidimeter. About 30ml of the compressor wash effluent sample was poured into a glass tube	EPA (2012) & EPA 180.2	[29]
Wear metals and additives	Absorption optical emission spectro-phometer, 100 ml of the effluent sample & 20ml of concentrated HNO_3	EPA 200.7	[18,19]

To gauge the strength of each independent variable relative to the dependent variable (Power output recovery after wash), statistical tools like covariance and correlation coefficients was used in rating the variables

2.6 Statistical Tools

1. **Correlation coefficient:** Correlation coefficient is the level of linear association between the dependent and independent variables. The Pearson correlation coefficient is measured on a scale that varies from -1 to +1. Thus, 100% correlation between the two variables is either +1(positive) when one increases as the other increases or 1 (negative)

when one increases or the other decreases. Also, two variables which have small or no linear correlation could have a strong nonlinear correlation. Thus, finding out the linear correlation before fitting a model is a useful tool in identifying the kind of relationships between dependent and independent variables. The correlation coefficient between the input and the output is expressed below as shown in Equation 1 [36].

$$r = \frac{n(\sum XY)-(\sum X)(\sum Y)}{\sqrt{[n\sum X^2-(\sum X)^2([n\sum Y^2-(\sum Y)^2}} \tag{1}$$

Where r is the correlation coefficient, n is the number of observations and X and F are the variables.

2. **Variable covariance:** According to Thakur [37], Covariance determines the directional relationship between two independent variables. A positive covariance between two variables means they behave exactly the same. As such, when one increases the other also increases while a negative covariance is denoted by an inverse relationship between the two independent variables. The equation used for computation of independent variables covariance is shown in Equation 2.

$$\mathrm{Cov}\,(\mathrm{x},\mathrm{y}) = \sum\left(\frac{(X_i-\bar{X})*(Y_i-\bar{Y})}{(N-1)}\right) \tag{2}$$

Where $\mathrm{X_i}$ is a **d**ata variable of x, $\mathrm{F_i}$ is a data variable of F, X is the mean value of x data, $\bar{\mathrm{F}}$ is the mean value of y data and N is the number of data set variables.

3. TEST CASE RESULTS AND DISCUSSIONS

3.1 Composition and Property Variation of Wash Effluent Parameters

Prior to confining research technique to use of wash effluent characters for fault tracking to years 2020-2023, factors like the compressor pressure ratio, Compressor outlet temperature, turbine inlet and outlet temperatures which affect turbine outputs based on thermodynamical relationships were trended from year 2017 with historical data obtained from the HMI in the control room. The aforementioned parameters for GT13 after offline compressor wash were compared to values prior to wash, and the % improvement of critical parameters like pressure ratio was gauged against % gains for units 11 and 12(after wash). The GT13 gain was found to be relatively in consonance with the other two units (At same ambient temperature and frequency). But from around 2020 (as seen in Figure 7), it was discovered that even at same reference temperature and speed, GT13 pressure ratio and thus power output recovery after offline wash started declining till gains became just marginal in 2022.This led to the classification of critical period as being between 2020 and 2022.

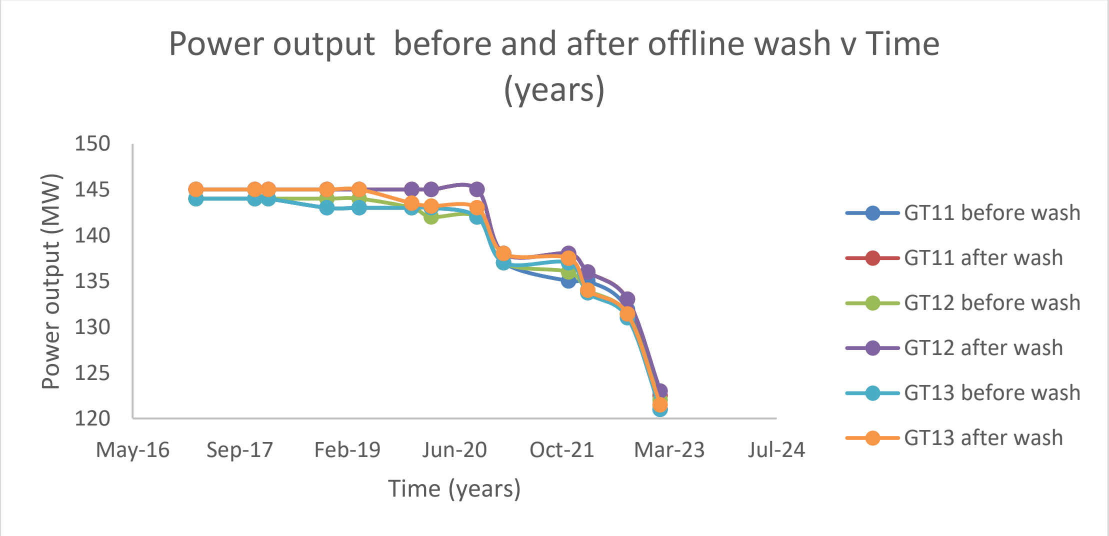

Figure 7: Power output values prior to and post offline compressor wash through the test period.

The concentration of major heavy metals, conductivity, pH, Turbidity, and silica content in GT11, GT12 and GT13 effluents monitored from 2020 to 2023 are presented in Table 5,6, and 7

1. **Wear Metal analysis:** Using the four (4) year period as a gauge, it can be seen from Tables 5, 6 and 7, that on the average, Zinc, magnesium, Cadmium, Lead, chromium and Copper concentration in the effluents for all the units were below the hazard limits set by ESEPA (as seen in Table 2). The iron content of GT11 effluent was relatively high in comparison to GT12 and GT13 effluents. The high iron content of GT11 effluent is probably as a result of wearing from the bearings, as was reported by Langfield [38], Magaroni [39] and Evans [40] or due to rust and pitting from the compressor and turbine blades.

Table 5: Compressor wash effluent test results for unit 13 at Geregu power plc (2020-2023)

Year	**Ph**	**Conductivity**	**Turbidity**	**Copper**	**Chromium**	**Lead**	**Magnesium**	**Iron**	**Cadmium**	**Silica**
2023	6.3	2215	3050	0.21	0.05	0.18	0.5	1.3	0.31	1.65
2022	6.12	2050	3034	0.037	0.051	0.15	0.96	0.074	0.267	1.58
2021	6.88	2400	3386	0.03	0.04	0.08	0.89	0.05	0.21	1.94
2020	7.06	1900	3000	0.24	0.07	0.11	0.55	1.12	0.24	1.24

Table 6: Compressor wash effluent test results for unit 12 at Geregu power plc (2020-2023)

Year	**Ph**	**Conductivity**	**Turbidity**	**Copper**	**Chromium**	**Lead**	**Magnesium**	**Iron**	**Cadmium**	**Silica**
2023	7.22	1510	880	0.11	1.1	0.17	0.2	2.5	0.18	0.45
2022	7.19	1189	547	0.09	0.08	0.22	0.88	0.057	0.25	0.23
2021	7.23	1063	229	0.06	0.044	0.18	0.53	0.028	0.183	0.17
2020	7.11	1003	123	0.04	0.11	0.2	0.40	0.08	0.31	0.24

Table 7: Compressor wash effluent test results for unit 11 at Geregu power plc (2020-2023)

Year	**Ph**	**Conductivity**	**Turbidity**	**Copper**	**Chromium**	**Lead**	**Magnesium**	**Iron**	**Cadmium**	**Silica**
2023	7.94	1692	1166	0.02	1.39	0.38	0.72	9.8	0.11	0.27
2022	7.5	1200	103	0.044	0.07	0.19	0.46	3.36	0.36	0.11
2021	7.05	1310	229	0.025	0.03	0.13	0.48	2.11	0.28	0.13
2020	7.4	1520	678	0.05	0.04	0.22	0.53	1.97	0.44	0.16

2. **Ph:** As viewed in Figure 8, it is observed that the PH level of GT13 effluent was quite low compared to the PH levels of GT12 and GT11.This is probably due to the presence of carbon or fuel trace contaminants like Hydrogen sulphide, as reported by Trygar [24] or Nitrogen dioxide/Sulphur dioxide as suggested by Drisu [30]. The most likely sources of the aforementioned contaminants are constituents from the exhaust flue gas of the three (3) gasturbine plants owned by Geregu phase 2 company close to Geregu phase 1 vicinity (as shown in Figures 1 and 2). The GT13 air intake system is just about 2km from the exhaust of the aforementioned plants. Gas turbine exhaust flue is generally known as a major source of Sulphur dioxide and Sulphur trioxide which are water- soluble and are relatively acidic in nature. Figure 8 indicates the Ph behavior of the three (GT11,12 and 13) effluents.

3. **Effluent Conductivity and Turbidity:** From Tables 5,6 and 7, it is observed that the two (2) most likely sources of low output recovery of GT13 after the offline wash compared to GT11 and GT12 can be traced to the very high conductivity and turbidity of its effluent relative to the other units effluent as is seen in Figures 9 and 10.

4. **Correlation:** Likewise, from table 8, it can be seen that the correlation coefficients of Conductivity, turbidity and silica content with GT13 low output recovery post compressor wash is strong while the correlation of the low output recovery with ph and other trace metals is relatively weak. Also, from the covariance graph of the independent variables in Figure 11, it is noticed that the covariance between the effluent conductivity, turbidity, and effluent silica content is strong while the covariance between the aforementioned variables with the other independent variables is weak. So, the preliminary results indicate that factors which affect conductivity also impact on the turbidity and silica content in like pattern. Based on the consistently high silica, turbidity and conductivity values of GT13 effluent, it is suspected that at any point in time GT13 fouling is usually heavier than those of GT11 and GT12 because GT13 is the closest unit at Geregu power plc to the earlier mentioned three (3) turbines and the two (2) additional tile manufacturing plants (As viewed in Figure 1 and 2). The tile companies are well known sources of contaminants like

feldspar and Quartz.

“ Results indicate that the aforementioned foulants lead to simultaneous increase in the effluent conductivity, turbidity and silica content because as earlier stated, tile making materials like feldspar, Quartz and clay are key sources of alkali oxides (sodium, potassium, calcium),silicon oxides and dust respectively .The alkali oxides are dispatched in the air as atmospheric salts and according to Homji [3],high concentration of atmospheric salts manifest in effluents through high electrical conductivity values .Likewise, high concentration of atmospheric dust also manifest in effluents through high turbidity values as effluent clarity is diminished. Similarly, high atmospheric silicon dioxide in turn gives rise to high silica content in effluents. Therefore, provided tile making process is ongoing, due to the raw materials (Feldspar, Quartz, clay, sand) used during tile production, there will be concurrent increment in salt concentration, silicon dioxides and other dust particles in the atmosphere and any setups close to these tile production sites will experience heavy fouling and this is most probably the source of the high concentration of silica, conductivity and turbidity values of GT13 effluent relative to GT11 and GT12.

Also, since the raw materials responsible for high atmospheric salt, silica and dust constituents are simultaneously being used during tile production process; this explains the co-variant nature of the aforementioned effluent parameters (Conductivity, turbidity and silica content). Equally, the traditional practice at Geregu power plant of only rinsing the compressor once during the offline wash procedure despite heavy fouling of GT13 turbine as reflected by its effluent characters is reason for its relative lower output recovery compared to the other turbines that are further away from the pollutant sources (The tiling plant). Though both GT11 and GT12 are similarly subjected to a single rinse cycle, their power output recovery is more due to less likelihood of fouling (due to Siting). The Introduction of extra rinsing cycles will reduce effluent conductivity and Turbidity as suggested by the likes of Homji [3] and Sachdeva [18] and this in turn will improve GT13 output recovery as both salt and dust particles on compressor blades are contaminants/foulants and according to Howarth of Rochem Fyre wash [41], salts, minerals and silicon dioxide can adhere to blades leading to reduced performance.’’ In summary, the major sources of the relatively low PH and high conductivity and turbidity figures of GT13 effluent compared to GT11 and GT12 effluent are mostly industrial pollutants emanating from other gas turbines and tile making plants some distance away from Geregu power plant but proximally closest to GT13 compared to GT11 and GT12. Coefficient correlation result also indicates that the low ph level of the effluent has no linear connection with the low rate of output recovery on GT13.

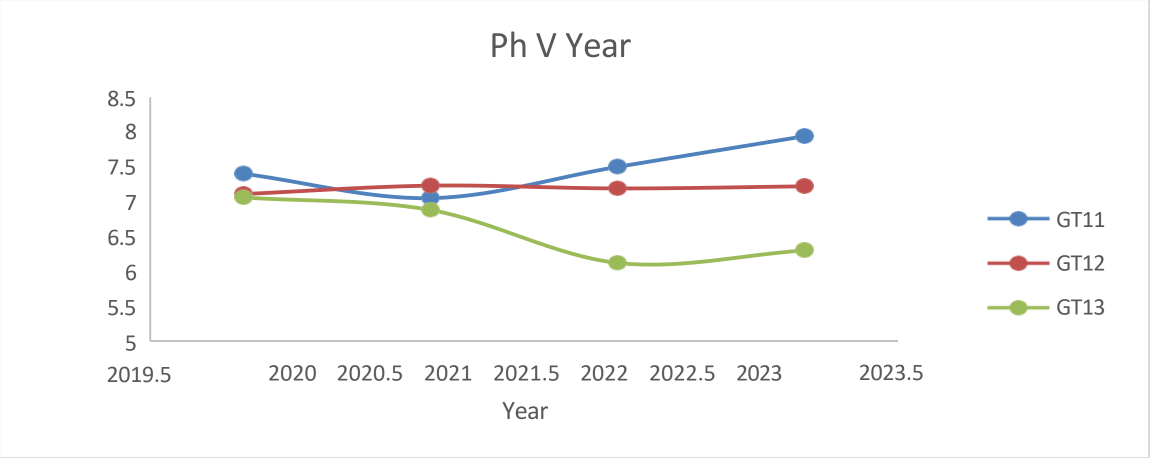

Figure 8: Ph values for the three units effluent from 2020-2023

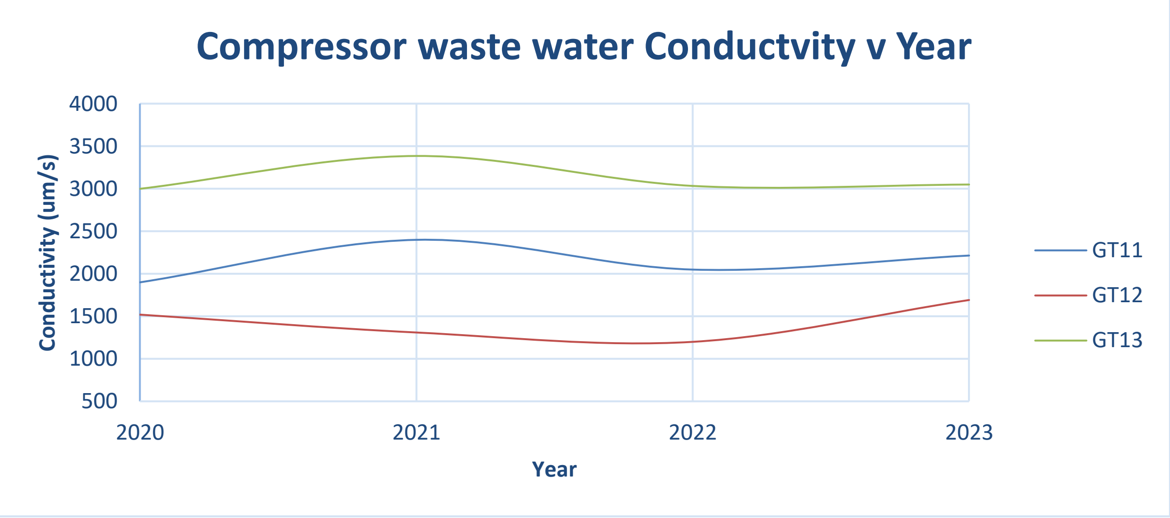

Figure 9: Effluent conductivity values for the three units’ effluent from 2020-2023

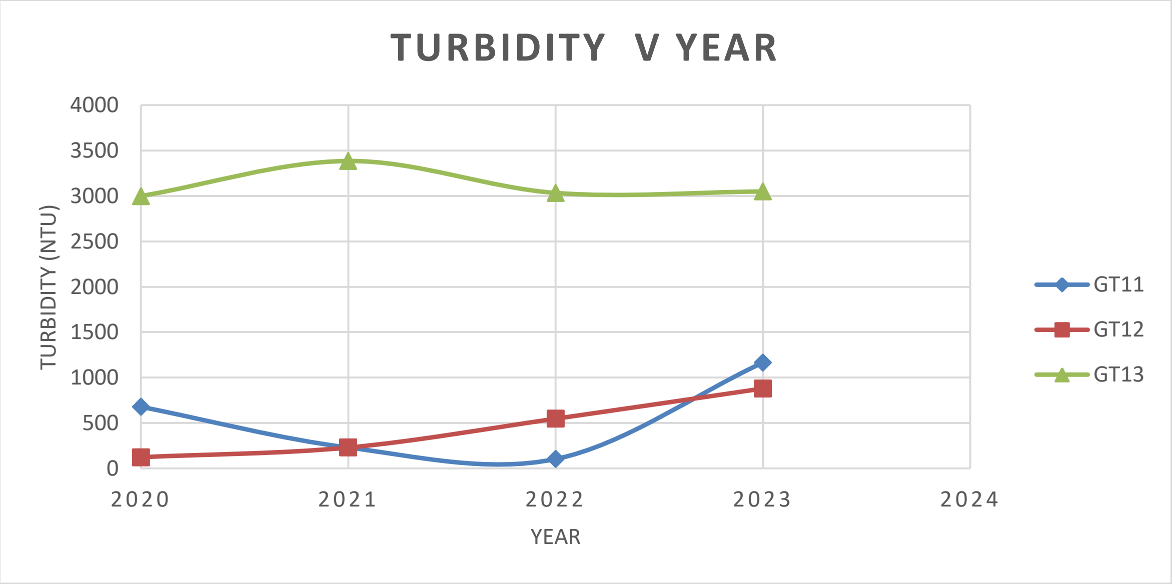

Figure 10: Turbidity values for the three units' effluent from 2020-2023

Table 8 and Figure 11 below were principally obtained from Equations 1 and 2 respectively.

Table 8: Correlation coefficient of the variables relative to the power output recovery after offline wash

S/N	Parameters	Correlation coefficient Method	Value
1	Conductivity	Linear correlation	-0.89
2	Turbidity	Linear correlation	-0.64
3	Ph	Linear correlation	0.0
4	Silica content	Linear correlation	-0.773
5	Iron	Linear correlation	-0.07
6	Cadmium content	Linear correlation	-0.084
7	Magnesium Content	Linear correlation	0.154
8	Lead Content	Linear correlation	0.009
9	Chromium Content	Linear correlation	0.071

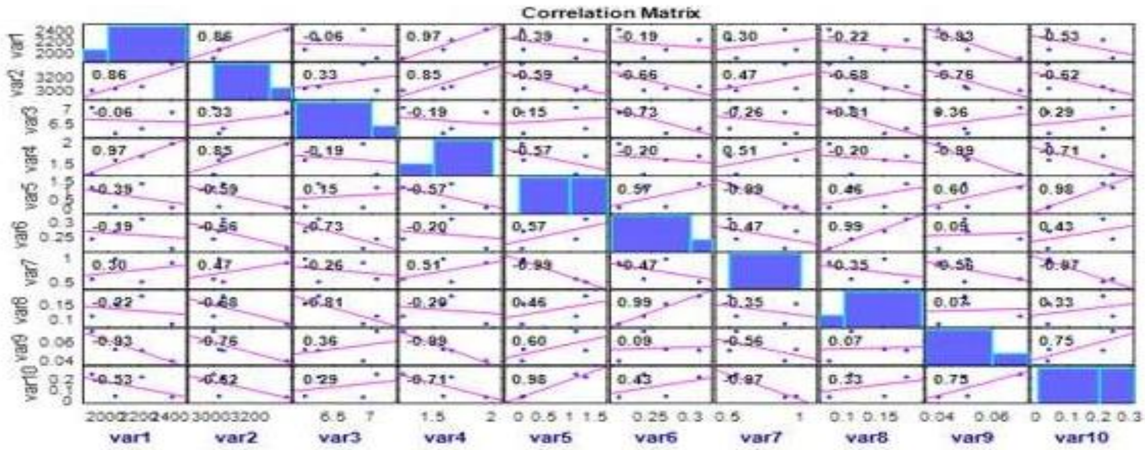

Figure 11: Effluent parameter covariance plot where: Variable 1: Conductivity.2: Turbidity.3: Ph.4:Silica content.5:Iron content.6:Cadmium.7:Magnesium.8:Lead.9:Chromium.10:Copper

4. CONCLUSION

This paper looked into the use of compressor wash effluent to ascertain reason why the power recovery of unit 13 at Geregu power plc after offline wash is low compared to the output recovery of the other two (2) units in the plant and values published in literature. The research utilized historical values of the effluent parameters like PH, wear metal, conductivity, and turbidity values to resolve the problem. Findings drawn were that, relative to GT11 and GT12, the PH level of GT13 effluent tended towards acidic (low), while the conductivity and turbidity values were high. In fact, taking the mean conductivity and turbidity values of each unit for the four-year period and evaluating GT11 and GT12 values as a fraction of GT13 conductivity and turbidity figures, it was discovered that the conductivity of GT13 was more than that of GT11 and GT12 by 50% and 79% respectively. The turbidity of GT13 likewise was 570% and 700% higher than those of GT11 and GT12. The wear metal concentration of GT13 effluent compared to other units was fairly similar. After undertaking input parameters-output parameter correlation coefficient test and input parameters covariance assessment, Conclusion reached is that the correlation coefficients of the effluent conductivity (-89.2%), turbidity (-64.4%), and silica content (-77.3%) with the low output recovery of the gasturbine are high (Negative) i.e. (The relationship of the parameters with output recovery is inverse, which means if pattern continues, output recovery in future will be negative).Likewise, the covariance of the three parameters amongst themselves is strong. This strong relationship between the variables reveals why their dynamism in the effluent follows same sequence which leads to the conclusion that the parameters serial link is responsible for the turbine low output recovery after wash. The low PH level of GT13 effluent is ascertained not to be responsible for the turbines low output recovery based on its Zero linear correlation coefficient with the output recovery rate.

The high degree of fouling of GT13 relative to the other two units is probably traced to its higher exposure to contaminants like the oxides of silica and salts like potassium, sodium and calcium as a result of its closer proximity to the aforementioned industrial set ups. Robb of power engineering [42] reported that the degree of fouling of a gas turbine depended on wind direction, closeness to other industrial set ups and the weather condition. The likes of Homji [3], Sachdeva [18], and Kurz [4] all reported that degree of fouling of a turbine is strongly influenced by its proximity to other industrial sites. Therefore, this salt constituents, together with the silica elementals emanating from the tile-making companies are most likely responsible for the higher conductivity, turbidity, and silica content values manifested in its effluent relative to the other turbine effluents. This makes sense since GT13 air intake system is closest to this tile making companies as can be seen in Figs1 and 2 compared to the other two turbines.

In summary, the main objective of using compressor wash effluent for condition monitoring was achieved. Additionally, it was confirmed that the use of wash effluent for diagnosis has the potential to diagnose multiple problems at once as was reported by Sachdeva [18]. Since through this work, metal wearing (GT11), fouling (GT13) corrosion/sulphation (GT13) were all discovered using one effluent test sample. Likewise, through effluent monitoring, concentration of wear metals was ascertained and the toxicity of the effluent to people and environment was gauged.

5. RECOMENDATION

From findings: The recommendation is to modify the offline washing of GT13 and subsequently of the two other units. (Because with increasing generation as a result of more gas availability to the Geregu phase 2 turbines and with massive expansion of capacity by the tile companies, the two farthest units from this pollutant sources will eventually equally experience the problem of heavy fouling GT13 is currently being subjected to base on the trend from 2013 (when phase 2 and BN ceramics were commissioned) to 2020 (When impact of fouling became apparent on GT13). Modification of the offline wash could be by either increasing the number of wash cycles per offline wash procedure as suggested by Kurz [2] and Homji [3] or by changing the wash detergent as recommended by Sachdeva [18], Homji [3] and Kurz [4]. Conversely, the number of rinsing cycles could be increased per wash procedure till turbidity and conductivity reduces drastically as recommended by General Electric (GE,2010), Homji [3], and Kurz [4].

REFERENCES

[1] Brun, K. & Kurz, R (2019).Introduction to Gasturbine theory 3nd edition, Solar Turbines Incorporated e-book, San Diego, California. USA

[2] Kurz, R., Homji, C.M. Brun, K. Moore, J. & Gonzalez, F. (2013**).** Gasturbine performance and maintenance, in *Proceeding of. 42nd Turbomachinery symposium Houston, Texas.October1-3*

[3] Homji, C.M., Bromley, A.F. & Stalder, J.P. (2013). Gas turbine deterioration and compressor fouling, in Proceeding of 2nd Middle East turbomachinery symposium, Doha, Qatar March 17-20.

[4] Kurz, H., C. & Brun, K. (2014). Gas turbine degradation, in Proceeding of 43rd Turbomachinery & 30th Pump Users Symposia (Pump & Turbo 2014). September 23-25, 2014 Houston, Texas.

[5] Kurz, R. & Brun, K. (2007). Gas turbine tutorial-maintenance and operating practices effects on degradation and life in Proceeding of 36th Turbomachinery Symposia 2007 .

[6] Boyce, M. (2002). Gasturbine engineering handbook.2nd edition ,Gulf professional publishing company.an imprint of Butterworth-Heinemann Oxford, United Kingdom.

[7] Zuniga, M.O. (2008**).** Analysis of gas turbine compressor fouling and washing online. “PhD Thesis, Cranfield University, United Kingdom.

[8] Gbanaibolou, J., Sampath, S. & Gray, I. (2017). Diagnostics of gasturbine system using gas path and rotordynamic

response approach in *Proceedings of 23rd symposium on air breathing engines, Manchester, United Kingdom.*
[9] Syverud, E., Bakken, L. Bjornas, F. & Langnes, K. (2003). Gasturbine operation offshore and online compressor wash at peak load in Proceedings of ASME turbo expo on "power for land, sea and air June 16-19 Atlanta, Georgia.
[10] Ogbonanya, E.A. (2011). Gas turbine performance optimization using compressor online washing technique Scientific Research Engineering, 3(1), 500-507.
[11] Igie, U. (2017). Gasturbine compressor fouling and washing in Power, Aerospace and propulsion on gasturbine performance. ASME journal of Engineering for gasturbines and power. 139 (12).
[12] Abbas, O.K. (2014). Techno economic analysis of gasturbine compressor washing to combat fouling. MSc thesis, Cranfield university, United Kingdom.
[13] Agbadede, R. & Kainga, B. (2020) Investigation of wash fluid pre-heating on effectiveness of online compressor washing in industrial gasturbines. Research square, : https://doi.org/10.21203/rs.3.rs-41657/v1.
[14] Maiwada, B., Muazu, N.M., Ibrahim, S. & Musa, S.M. (2016). Impact of compressor wash on gasturbine performance. Indian journal of Engineering sciences and computing ,6 (3)
[15] Tahan, M., Tstoutsanis, E., Mohammed, M. & Abdulkarim, Z.A. (2017).Performance-based health monitoring, diagnostics and prognostics for condition-based maintenance of gas turbines. Journal of Applied energy, 198(1), 122-144.
[16] Loboda, I. (2010**)**. Gasturbine condition monitoring and diagnostics. *Gurrapa Injeti(Ed.)*, 120-145.
[17] Mevissen, F. & Meo, M. (2019). A review of Nondestructive test/structural health monitoring techniques .National Institute of health(.gov).https://pubmed.ncbi.nlm.nih.gov.
[18] Schadeeva, D., Shanmukh, S., Rajagoplan, V., Kaushik, A., Parayalil, C. & Reddy, R.(2018). Methods for effluent based condition assessment. International application published under patent cooperation treaty (PCT).IPN number:WO2018/004873A1.
[19] Fronapel, J.P. (1995). C-130 Engine compressor wash study. Defense Technical Information center. https://apps.dtic.mil/sti/citations/ADA299862
[20] Pirkle, P. S. (1995). Cadmium in Engine compressor wash water effluent. Defense Technical Information center.Lynn Holden 501-388-007, (DSN731)
[21] Ma, J., Wu, S., Ravi, S., Biswas, S. & Sahu, A.K. (2020). Determination of Physicochemical Parameters and Levels of Heavy Metals in Food Wastewater with Environmental Effects. Hindawi Bio-inorganic chemistry and applications journal, 8886093, 9.
[22] Sathya, K.., Nagarajan, K., Malar, G., Rajalakshmi, S. & Raja, L. P. (2022). A comprehensive review on comparison among efuent treatment methods and modern methods of treatment of industrial wastewater efuent from diferent sources .Applied Water Science Journal, 12(70), 3201-022.
[23] Schutte, F. (2006). Handbook for operation of water treatment works. Printed in the Republic of South Africa by Rietvlei Water Treatment Works Water Research Commission .Private Bag X03 Gezina 0031.
[24] Trygar, R (2013). What exactly is Ph? https://www.tpomag.com>2013/12-tpomag.com .
[25] Doyle, D. (2017). Turbine oil analysis. eSource https://www.alsglobal.com/en/News-and-publications/2022/06/esource-102-turbine-oil-analysis
[26] Stalder, J.P. (1998). Gasturbine compressor washing state of the art field experiences. American Solar turbines incorporated. American society of engineering (ASME). 123(2), 363-370.
[27] Safety Institute. (2023). Graz University of Technology.
[28] Orion Thermo Scientific™ A326 pH/Dissolved Oxygen Portable Multiparameter Meter. cohttps://www.fishersci.se/shop/products/orion-star-a326-ph-dissolved-oxygen-portable-multiparameter-meter/11601489
[29] Chikwe, T.N. & Onojake, M.C. (2016**)**. An appraisal of Physicochemical Parameters and some Trace metals at the Disposal Points of Five Industrial Effluents in Trans-Amadi Industrial Area of Port Harcourt, Nigeria. Journal of applied Science environment and Management. 4 (20), 31-37
[30] Drisu, C.G. Mafianna, M,O., Dirisu, G.B. & Amodu, R. (2016). Level of Ph in drinking water of an oil and gas producing community and perceived biological and health implications. European journal of basic and applied sciences. 3(3), 2059-3058
[31] Ewere, E.E., Omoigerale, M.O., Bamawo,O.E.R. & Erhunmwunse, N.O. (2014). Physio-Chemical Analysis of Industrial Effluents in parts of Edo States Nigeria. Journal of applied Science environment and Management. 18(2), 267- 272
[32] Hanson, R., Twumasi, A.K. & Boi-D (2019). Analysis of Industrial Effluent from some factories in Tema. European Journal of Earth and Environment .6(1).
[33] Naaz, A., Swaroopa, S. & Choudry, A.K. (2017). Physico-chemical and microbial analysis of steel industry effluent. International Journal of Scientific and Research Publications, 3(7), 2250- 3153.
[34] Orhon, D. & Tilche, A. (2002). Appropriate basis of effluent standards for industrial wastewaters. Article in Water Science & Technology Journal. 45(12), 1-11, Doi:10.2166/wst.2002.0404.
[35] Estefan, G, Sommer, R. & Ryan, J. (2013). Methods of soil,plant and water analysis:A manual for the West/Asia and North Africa region. 3rd edition, International centre for agricultural research in dry areas. (ICARDA).Bierut,84- 105.
[36] Srivastava, H.S. & Patel, P. (2022). Radar remote sensing of soil moisture .Radar Remote sensing Applications and

challenges earth observation, 405-44, Science Direct.https://doi.org/10.1016/B978-0-12
[37] Thakur, M. (2023). Covariance Formulae. https://www.educba.com/covariance-formula/
[38] Langfill, Q. & Haselbach, L. (2016). Assessment of Lube Oil Management and Self Cleaning Oil Filter Feasibility in WSF Vessels-Final Report. (Washington State Department of Transport). 29-68.
[39] Magaroni, D. (2002). The Role of Lubricant Condition Monitoring in Maintenance Programmes. Lube -Tech 024. http://www.safety.odpm.gov.uk/fire/firesafetyindex.htm or https://www.lube -media.com., 4.
[40] Evans, J.S. (2010). Where does all that metal come from. www.wearcheck.co.za. 42, 1-6.
[41] Howarth, M. (2020). {Rochem Fyre wash) engineerlive.com/content/essentials-gas turbine-cleaning#(2020) online edition
[42] Robb, D. (2008). Power engineering int.com. https://www.gtefficiency.com power engineering.com