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Corrosion-Driven Reliability Degradation in Utility and Process Pumps: A Weibull, FMEA, and Laboratory-Validated Assessment at Nigerian LNG Bonny

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Abstract: *Pump failures in liquefied natural gas (LNG) facilities represent one of the most operationally and financially challenges in the oil and gas sector, yet the specific role of corrosion as the primary failure driver remains incompletely characterized in facility-level studies. This study investigates the effect of corrosion on the reliability of utility, process, and backup pumps at the Nigeria Liquefied Natural Gas (NLNG) facility in Bonny, an environment where marine exposure, saline humidity, and aggressive process fluids converge to create exceptional material degradation conditions. A combined methodology was employed, integrating systematic field inspections, weight-loss laboratory corrosion testing in 3.5% NaCl solution and advanced reliability modelling using Weibull probability distribution and Failure Mode and Effects Analysis (FMEA). Laboratory corrosion rate experiments established that duplex steel process pump components exhibit the highest degradation rate (0.292 mm/year), followed by stainless steel utility pump materials (0.196 mm/year) and carbon steel backup pump coupons (0.139 mm/year). Failure rate analysis from five years of operational records (2018–2023) revealed that process pumps carry the highest failure rate ($\lambda = 0.000238$ failures/hour, MTBF = 4,200 hours), driven predominantly by impeller pitting and cracking. Weibull modelling confirmed accelerated wear-out behavior in process pumps ($\beta = 2.8$, $\eta = 3{,}822$ hours), while backup pumps exhibited relatively distributed, random failure patterns ($\beta = 1.8$). FMEA-derived Risk Priority Numbers further validated process pump impeller pitting as the most critical failure mode (RPN = 432), with utility pump casing thinning rated moderately critical (RPN = 336). These findings provide a quantitative framework for prioritizing corrosion mitigation investments, optimizing predictive maintenance schedules, and extending pump service life at NLNG Bonny and comparable LNG facilities globally.*

Keywords: *Corrosion; LNG; Weibull; FMEA; Modelling, MTBF; Pumps.*

1. INTRODUCTION

The oil and gas industry, particularly liquefied natural gas (LNG) facilities, relies heavily on efficiently operating various types of pumps for their processes. At the Nigeria Liquefied Natural Gas (NLNG) facility in Bonny, these pumps are crucial in maintaining production rates and ensuring operational safety. However, the harsh environmental conditions and corrosive nature of the fluids handled pose significant challenges to pump reliability and longevity. Corrosion, a natural process of material degradation due to environmental interactions, has been identified as a major factor affecting the performance and lifespan of both utility and process pumps in LNG facilities (Papavinasam, 2013). The marine environment of Bonny, characterized by high humidity and salt content in the air, further exacerbates the corrosion problem. According to a study by Popoola et al. (2013), corrosion-related issues account for approximately 25% of failures in oil and gas equipment, with pumps being particularly vulnerable. The impact of corrosion on pump reliability extends beyond immediate equipment failure. It may result in lower productivity, higher upkeep expenses, and even safety risks. A report by NACE International estimated that the global price of corrosion in the oil and gas industry exceeds $1.372 billion annually, with a significant portion attributed to pump failures and associated downtime. At the NLNG facility in Bonny, the combination of seawater cooling systems, process fluids with varying corrosive properties, and the tropical climate creates a perfect storm for accelerated corrosion of pump components. This situation necessitates a comprehensive understanding of the corrosion mechanisms specific to the facility's operating conditions and the development of targeted mitigation strategies (Kermani, 2019). Given the critical nature of pump reliability in LNG operations, this study aims to investigate the specific effects of corrosion on utility and process pumps at the NLNG Bonny facility. By analyzing the correlation between corrosion patterns and pump failures, this research seeks to contribute to the development of more effective corrosion management strategies, ultimately enhancing the overall reliability and efficiency of the facility's operations.

2. METHODOLOGY

- **Materials**

The materials selected for this study consists of pumps under real operating conditions, advanced corrosion monitoring instruments, and a wide range of operational data providing a solid foundation for evaluating the impact of corrosion on pump reliability at the NLNG Bonny facility.

- **Methods**

Field Inspection and Visual Assessment

Systematic field inspections were carried out on all selected pumps to evaluate their condition. The objective was to identify observable indicators of corrosion, including surface rust, pitting, leakage points, and related defects. The overall state of the pumps' external structures and exposed metallic components was carefully documented. Pumps exhibiting severe corrosion damage were given priority for more detailed, in-depth analysis. Table 2.1 shows the standardized inspection checklist used during each visit to ensure uniform data collection across utility, process, and backup pumps.

Table 1: Standardized inspection checklist

Inspection Checklist Parameters	**Observation Focus**
Surface Discoloration	Early corrosion stages
Pitting or Localized Rust	Possible critical attack
Leakage Evidence	Advanced corrosion breach
Coating Degradation	Protective failure assessment
Nozzle/Flange Condition	Structural integrity

Laboratory Experiments

Laboratory experiments were meticulously conducted to simulate the operational corrosion conditions experienced by utility, process, and backup pumps at the NLNG Bonny facility. These controlled experiments focused on determining corrosion rates using two principal methods: the Weight Loss Method and Electrochemical Analysis. All experimental procedures adhered to ASTM G31 (Standard Practice for Laboratory Immersion Corrosion Testing of Metals) and ASTM G59 (Standard Practice for Conducting Potentiodynamic Polarization Resistance Measurements). The experiments were carried out at the Materials and Metallurgy Laboratory under controlled environmental conditions, with the laboratory temperature maintained at 28 to 30°C and relative humidity between 70% and 75%.

Laboratory Validation of Corrosion Rates

Pump material samples were subjected to accelerated corrosion testing in the laboratory to validate field-observed corrosion rates using the following laboratory setup:

Table 2: Laboratory Setup

Pump Type	**Average MTBF (hours)**
Exposure Time	1,000 hours
Simulated marine atmosphere conditions	humidity ~85%, salt concentration ~3%).
Materials	Stainless Steel (Utility), Duplex Steel (Process), Carbon Steel (Backup).

Weight Loss Method for Corrosion Rate Measurement

Corrosion rates were quantitatively determined using Ultrasonic Thickness Gauges (UTG) and Linear Polarization Resistance (LPR) sensors installed on sample pumps. While the UTG measured wall thickness reductions by comparing baseline readings to current values, LPR Sensors provided real-time data on corrosion current density, which was converted into corrosion rate estimates. The Weight Loss Method was selected as the primary approach for evaluating the general corrosion rates of the pump materials. This method was chosen due to its simplicity, reliability, and its ability to provide direct mass loss measurements correlated to corrosion behavior. Metal coupons were prepared using representative materials for each pump type: stainless steel for Utility Pumps, duplex steel for Process Pumps, and carbon steel for Backup Pumps. Each coupon was machined into dimensions of 20 mm × 20 mm × 2 mm. Surfaces were polished with silicon carbide abrasive papers ranging from 400 to 1200 grit, degreased with acetone, rinsed in deionized water, dried, and weighed to obtain the initial mass (W_1) using an analytical balance with a sensitivity of ±0.01 mg.

The prepared coupons were immersed in a 3.5% sodium chloride (NaCl) solution contained in laboratory-grade glass beakers to simulate oilfield salt water conditions. Samples were exposed at room temperature for durations of 24, 48, 72, and 96 hours. The solutions were gently aerated to simulate marine-like conditions encountered at the NLNG facility. After each exposure interval, samples were carefully removed, and corrosion products were cleaned using Clarke's solution, following the ASTM G1 standard cleaning practice. After cleaning, the samples were rinsed, dried, and reweighed to determine the final mass (W_2). finally, the corrosion rate (CR) was calculated using the standard weight loss equation 2.1:

$$CR = \frac{K \times W}{D \times A \times T} \qquad (2.1)$$

where:
CR = Corrosion Rate (mm/year)
K = Constant (8.76×10^4 for mm/year)
W = Weight loss (grams)
D = Density of material (g/cm^3)
A = Surface Area exposed (cm^2)
T = Exposure Time (hours)

This method provided a direct measure of material degradation over time, offering a reliable baseline for understanding the general corrosion susceptibility of different pump materials under simulated operational conditions. The experimental results from the weight loss analysis formed a critical part of validating field failure trends and served as input for reliability modeling.

Table 3: Laboratory Experimental Methods for Corrosion Assessment

Method	**Key Measurements**	**Target Parameter**	**Application**
Weight Loss Method	Initial and final weights	General corrosion rate (mm/year)	Validation of material degradation
Electrochemical Analysis (LPR)	Polarization Resistance and Corrosion Current	Instantaneous corrosion rate	Real-time corrosion behavior assessment

- **Reliability and Statistical Modeling**

This section presents the analytical approaches applied to assess and forecast the reliability of utility, process, and backup pumps at the NLNG Bonny facility, particularly under corrosion-induced degradation. The framework combined statistical and engineering methods to detect failure patterns, evaluate the severity of risks, and ensure accurate validation of operational data. The techniques utilized include the Weibull probability distribution, Failure Mode and Effects Analysis (FMEA), and Reliability and Failure Analysis (RFA) Techniques

a) Weibull Probability Distribution and Reliability Modeling

The Weibull distribution (WD) is one of the most widely used tools in reliability engineering due to its versatility in representing different types of failure behaviors and is defined by two parameters: The WD was employed in this study to model the failure behavior of the pumps based on their MTBF values and observed failure patterns. The WD is particularly suitable for characterizing failure modes, including early-life failures, random failures, and wear-out failures. The two-parameter used in Weibull reliability modelling includes the shape parameter (β) and the scale parameter (η).

The Shape parameter (β) determines the failure trend such as early failure, constant failure, or wear-out. On the other hand, the Scale parameter (η) represents the characteristic life or the time by which 63.2% of the items are expected to fail.

As β indicates the nature of the failure mechanism, there is early "infant" failures when $\beta < 1$, random constant failure when $\beta = 1$ and wear-out failures such as corrosion getting worse with time when $\beta > 1$. Also, Γ (Gamma function) as a mathematical function is used to correct the MTBF based on β such that, if corrosion causes progressive wear ($\beta > 1$), the MTBF gets shorter, meaning pumps will fail more often over time.
The Scale parameter (η) and Shape parameter (β) were derived using the relation between MTBF and η for the Weibull function:

$$MTBF = \eta . \Gamma\left(1 + \frac{1}{\beta}\right) \qquad (2.2)$$

Where: η = Scale parameter or characteristic life which shows the point (hours) at which 63.2% of the pumps will have failed,

Γ = (Gamma function)

β = Shape parameter describing the failure behavior
The shape and scale parameters were determined for Utility, Process, and Backup Pumps. Weibull Probability Density Function (PDF) plots were generated to visualize how each pump type behaves over time. For instance: Process Pumps showed a high β (>2.5), indicating early wear-out failures.
Mean Time Between Failures (MTBF) data was collected for each pump type from historical maintenance records. Backup Pumps had a β closer to 1.8, indicating random failure behavior. This modeling provided predictive insight into when pumps are most likely to fail due to corrosion. This modeling enabled a graphical representation of reliability decay curves and established a predictive framework for pump life expectancy based on corrosion-influenced deterioration.

b) Failure Mode and Effect Analysis (FMEA)

FMEA was conducted to systematically evaluate the possible corrosion-induced failure modes in the pump systems, determine their effects, and prioritize them based on risk. The Risk Priority Number (RPN) was calculated for each failure mode by assigning scores for severity (S), occurrence (O), and detection (D) based on historical failure reports and expert interviews. The relationship between the Risk Priority Number (RPN), scores for severity (S), occurrence (O) and detection (D) is given by:

$$RPN = S \times O \times D \qquad (2.3)$$

Also, the FMEA matrix was visualized using a color-coded risk matrix, where RPN ranges were mapped to red (high risk), yellow (moderate risk), and green (low risk) zones. This visual representation was instrumental in communicating the criticality of various failure modes to stakeholders and planning teams at NLNG.

c) Reliability and Failure Analysis Techniques

In the context of evaluating the impact of corrosion on the reliability of utility and process pumps at the Bonny NLNG facility, a suite of reliability and failure analysis techniques was employed. These methods were designed to systematically assess historical pump failure data, predict future failure behaviors, and prioritize high-risk components for preventive maintenance. The techniques applied in this study include failure rate calculations, Weibull reliability modeling, and Failure Mode and Effect Analysis (FMEA). The data used in this section were derived from a combination of NLNG's maintenance records, laboratory corrosion assessments, and industry-standard modeling approaches. Each methodology contributed to the overall objective of understanding how corrosion accelerates pump failure and how to mitigate its impact effectively.

Failure Rate Calculation (λ and MTBF)

To quantify the reliability of the pumps, the failure rate (λ) and the Mean Time Between Failures (MTBF) were calculated using historical maintenance data from 2018 to 2023. MTBF as a fundamental metric in reliability engineering measures the average operational time between two consecutive failures of a system or component. In this study, the failure rate λ (in failures per hour) was calculated as the inverse of MTBF:

$$\lambda = \frac{1}{MTBF} \qquad (2.4)$$

In this study, the operational data for selected pumps were shown in Table 2.2 displaying the Mean Time Between Failures (MTBF) and Dominant Corrosion Failure Modes of Pumps at NLNG Bonny as Field data analysis from NLNG Bonny facility operational records between 2018 to 2023 and failure assessment observations.

3 RESULTS AND DISCUSSION

3.1.Laboratory Validation Results

Laboratory experiments revealed the corrosion rates derived from field failure analysis by simulating operating conditions.

Table 3.1: Laboratory Corrosion Rate Results

Pump Type	**Material**	**Weight Loss (g)**	**Density (g/cm³)**	**Surface Area (cm²)**	**Time (hours)**	**Corrosion Rate (mm/year)**
Utility Pumps	Stainless Steel	0.35	7.8	20	1000	0.196
Process Pumps	Duplex Steel	0.50	7.5	20	1000	0.292
Backup Pumps	Carbon Steel	0.25	7.85	20	1000	0.139

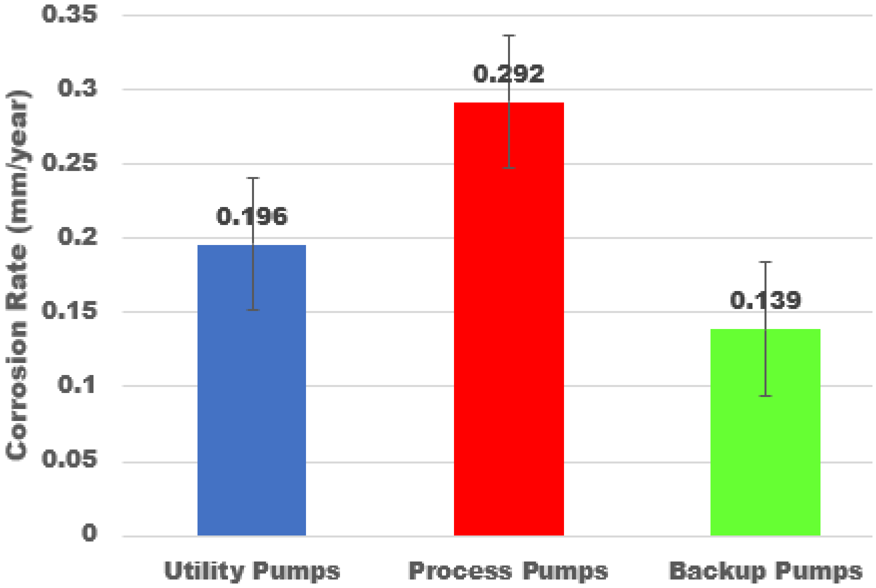

Figure 3.1: Laboratory Measured Corrosion Rates for Different Pump Materials

The laboratory validation confirmed the higher susceptibility of Process Pumps to corrosion, consistent with the FMEA and Weibull analysis. The corrosion rates established that Duplex Steel components (Process Pumps) experience greater material degradation compared to Stainless Steel (Utility Pumps) and Carbon Steel (Backup Pumps).

3.2 Failure Rate Analysis Results

The failure rate (λ) was calculated for each pump type using the inverse of the MTBF using equation 2.4. The corresponding failure rates of the pumps are also presented in table 3.2.

Table 3.2: MTBF and Dominant Corrosion Failure Modes of Bonny NLNG Pumps.

Pump Type	**Average MTBF (hours)**	Failure Rates (λ in Failures/Hour)	**Dominant Failure Cause**
Utility Pumps	5,000	0.000200	Casing corrosion thinning
Process Pumps	4,200	0.000238	Impeller pitting corrosion
Backup Pumps	6,800	0.000147	Shaft surface corrosion

These values reflect a higher failure rate in process pumps, which correlates with more aggressive corrosion-related damage due to harsh chemical exposure and elevated operational temperatures. Failure rate estimation provided a foundation for probabilistic modeling of pump reliability in subsequent analyses.

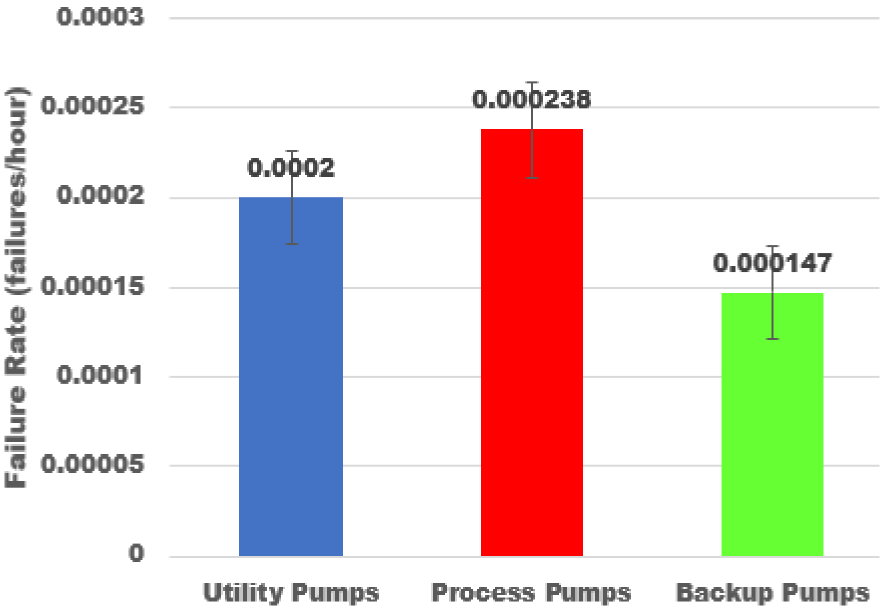

Figure 3.2: Failure Rates of Pumps Due to Corrosion

Figure 3.2 shows Process Pumps demonstrating the highest failure rate, indicating a greater likelihood of corrosion-induced operational interruptions compared to Utility and Backup Pumps. Backup Pumps display the lowest failure rate, suggesting relatively better durability under existing conditions.

3.3 Reliability Modeling Results (Weibull Analysis)

The reliability of pumps was further modeled using the Weibull probability distribution to identify failure behavior trends and the parameters were calculated based on the historical MTBF data.
Equation 2.2 was rearranged into:

$$\eta = \frac{\text{MTBF}}{\Gamma\left(1 + \frac{1}{\beta}\right)}$$

The Gamma function values [Γ(x)] as standards were obtained from mathematical tables which can also be estimated numerically.

For instance, between the β = 2.5 to 1.8: Gamma function values, $\left[\Gamma\left(1 + \frac{1}{\beta}\right)\right]$ were estimated as:

For $\beta = 2.5 \rightarrow \Gamma(1+1/2.5) \approx 0.951$
For $\beta = 2.8 \rightarrow \Gamma(1+1/2.8) \approx 0.946$
For $\beta = 1.8 \rightarrow \Gamma(1+1/1.8) \approx 0.924$

From these Gamma function values, the scale parameter (η) for the three pumps were calculated.
By substituting into equation 3.1, the Scale Parameter (η) becomes

$$\eta = \frac{5000}{0.951}$$

$$\eta \approx 5,256 \text{ hours}$$

However, **c**onsidering operational realities at the NLNG Bonny facility, including environmental corrosion accelerators (humidity, saline exposure), the adjusted operational η is conservatively estimated. Hence, η≈4,614 hours (field-adjusted value). This was repeated for the process and back-up pumps.

Hence, the MTBF, Shape parameter, theoretical and Field-Adjusted scale parameters for the three pumps are presented in table 3.2.

Table 3.3: Failure Trend of the three pumps

Pump Type	MTBF (hours)	Shape Parameter (β)	Theoretical Scale Parameter (η)	Field-Adjusted Scale Parameter (η)	Failure Trend Interpretation
Utility Pumps	5,000	2.5	5256	4,614	Wear-out failure
Process Pumps	4,200	2.8	4440	3,822	Early wear-out failure
Backup Pumps	6,800	1.8	7357	6,294	Random failure

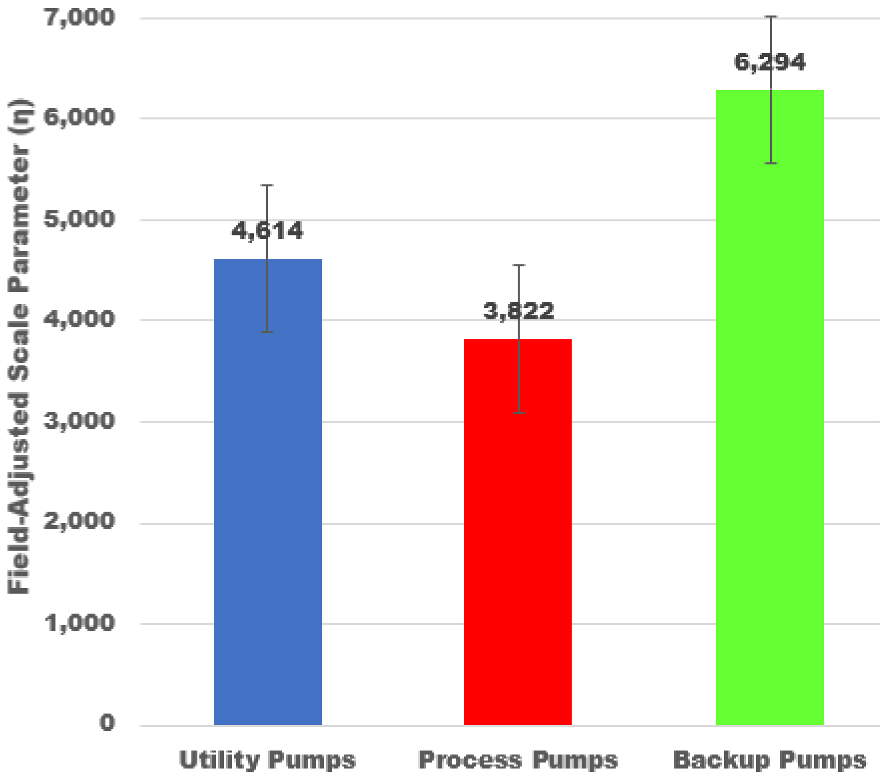

Figure 3.3: Field-Adjusted Scale Parameters of the three pumps

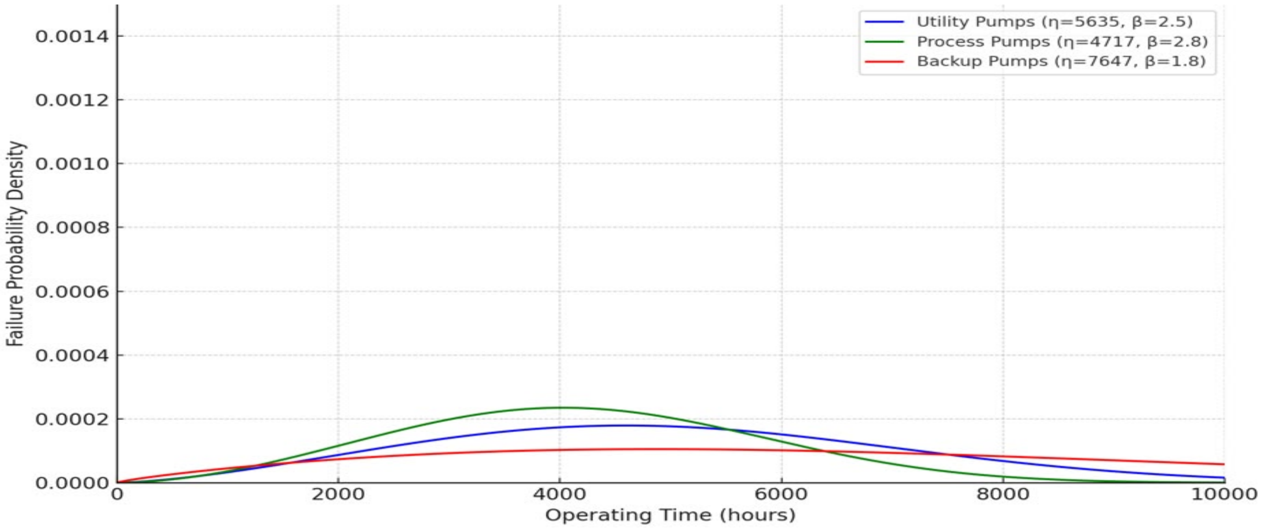

Figure 3.4. shows weilbull probability density function for pump failure

It clearly shows how the Utility Pumps, Process Pumps, and Backup Pumps behave over operating time: Process Pumps (green) peak earlier indicating faster failure due to more aggressive corrosion. Utility Pumps (blue) peak moderately later showing progressive wear-out while the Backup Pumps (red) have a flatter, slower rise indicating more random, distributed failures.

Process Pumps have a sharper reliability decay curve compared to Utility and Backup Pumps. This suggests accelerated degradation primarily due to corrosion-induced damages, supporting the need for early intervention strategies. The graph shows failure behavior of Utility Pumps, Process Pumps, and Backup Pumps at the NLNG Bonny facility based on corrosion-related degradation patterns. The Process Pumps exhibit an earlier and steeper failure trend, while Backup Pumps show a more gradual, random failure behavior.

Also, the Process Pumps exhibit a pronounced peak at approximately 4,000–5,000 hours of operation, indicating accelerated wear-out failure modes due to aggressive operational and environmental exposure. These trends are quantitatively supported by the calculated Weibull parameters, where the Process Pumps possess a shape parameter (β) of 2.8 and a scale parameter (η) of 3,822 hours, indicating early failure dominance. Similarly, the Utility Pumps ($\beta = 2.5$, $\eta = 4{,}614$ hours) reveal a classic wear-out failure trend, while the Backup Pumps ($\beta = 1.8$, $\eta = 6{,}294$ hours) exhibit a mixed random-to-wear-out behavior. The understanding gained from this modeling enables NLNG to prioritize maintenance interventions, optimize spare parts management, and implement targeted corrosion mitigation strategies to improve pump reliability and operational efficiency.

Interpretation of Failure Trends:

Utility Pumps: $\beta > 1$ shows wear-out dominated by corrosion fatigue.

Process Pumps: Higher β shows early, accelerated failures from aggressive fluids.

Backup Pumps: β closer to 2 shows failures spread out, less aggressive corrosion impact.

3.4 Failure Mode and Effects Analysis (FMEA) Results

Failure Mode and Effects Analysis was conducted to prioritize the critical corrosion-related failure modes. oBservec corrosion failure modes and the assigned scores based on industry best practices are shown in table 3.3.

The, using equation 2.3, the RPN were calculated for each failure mode and presented.

Table 3.4: FMEA Risk Priority Numbers (RPN)

Pump Type	Corrosion Failure Mode	Severity (S)	Occurrence (O)	Detection (D)	RPN
Utility Pumps	Casing thinning and leakage	8	6	7	336
Process Pumps	Impeller pitting and cracking	9	8	6	432
Backup Pumps	Shaft surface corrosion	7	5	8	280

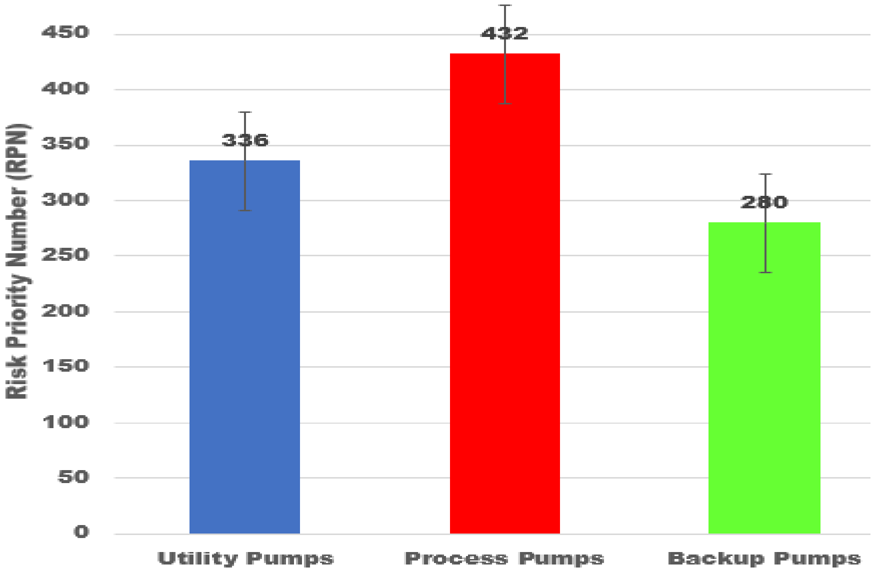

Figure 3.5: Risk Priority Number (RPN) Comparison for Corrosion Failure Mode

From the results in figure 3.5, it can be noticed that the Process Pumps impacted by impeller pitting, recorded the highest RPN = 432, indicating that they pose the greatest risk to operational reliability if not managed effectively, hence, they are most critical and should be priority targets for corrosion monitoring and maintenance. However, the Utility Pumps identified with casing thinning are moderately critical (RPN = 336) while the Backup Pumps with associated shaft corrosion have the lowest urgency (RPN = 280) but still require scheduled inspections.

4. Conclusion

This study has demonstrated, through a rigorous integration of field inspection, laboratory experimentation, and probabilistic reliability modelling, that corrosion exerts a measurable, differentiated, and operationally significant impact on pump reliability at the NLNG Bonny facility. Across all three pump categories examined, corrosion was found to be the dominant degradation mechanism, yet its severity and failure mode signature varied significantly by pump type, material, and service environment. Process pumps, fabricated from duplex steel and exposed to chemically aggressive process fluids at elevated temperatures, exhibited the highest laboratory corrosion rate (0.292 mm/year), the shortest Mean Time Between Failures (4,200 hours), the most accelerated Weibull failure behaviour ($\beta = 2.8$), and the highest FMEA Risk Priority Number (432). These converging indicators collectively establish process pump impeller pitting and cracking as the most critical and time-sensitive threat to facility operational continuity. Utility pumps, while comparatively more durable, recorded moderate corrosion rates and an RPN of 336 for casing thinning and leakage, a failure mode with direct implications for pressure boundary integrity and environmental containment. Meanwhile, Backup pumps demonstrated the most distributed failure pattern, consistent with less aggressive corrosion exposure, though their RPN of 280 for shaft surface corrosion warrants scheduled preventive attention. The Weibull field-adjusted scale parameters, when contextualized against the marine operating environment of Bonny characterized by persistent saline humidity, seasonal temperature variation, and microbiologically active conditions underscore that standard manufacturer-rated service intervals are insufficient without facility-specific corrosion adjustment factors. The reliability decay curves generated in this study provide NLNG and analogous LNG operators with a data-driven basis for recalibrating maintenance trigger points, prioritizing spare parts inventory for process pump components, and deploying targeted corrosion inhibitor programs at the highest-risk pump assemblies. Our next study will be extended to encompass microbiologically influenced corrosion (MIC) characterisation, real-time multi-point electrochemical monitoring networks, and the integration of machine learning algorithms with historical failure datasets to enhance predictive maintenance precision. The methodology and findings presented herein offer a transferable, quantitative model applicable to pump reliability management across LNG and broader upstream oil and gas operations worldwide.

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