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Factors Affecting the Operational Reliability of Air Conditioning and Refrigeration Systems in Employee-Occupied Service Facilities

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ABSTRACT

The operational reliability of Air Conditioning and Refrigeration (AC/R) systems in employee-occupied service facilities is critical for maintaining personnel comfort, safeguarding sensitive electronic equipment, and ensuring uninterrupted industrial operations in hydrocarbon processing environments. This quantitative study examines the factors affecting AC/R system reliability at the Ras Lanuf Oil and Gas Processing Company (RASCO) in Libya, operating under extreme desert conditions with ambient temperatures exceeding 45°C, pervasive sand and dust particulates, and atmospheric salinity. Grounded in Reliability Engineering Theory and the Bathtub Curve model, the research evaluates three controllable operational variables: refrigerant selection, compressor maintenance practices, and coil/filter maintenance protocols. Using a structured survey instrument administered to 85 engineering and technical personnel across RASCO's service facilities, data were analyzed through descriptive statistics, Pearson correlation, and multiple linear regression. Results demonstrate that all three factors significantly influence operational reliability, with compressor maintenance practices emerging as the strongest predictor ($\beta = 0.358$, $p < 0.001$), followed by coil/filter maintenance ($\beta = 0.312$, $p = 0.001$), and refrigerant selection ($\beta = 0.284$, $p = 0.002$). The regression model explained 64.3% of the variance in operational reliability ($R^2 = 0.643$, $F(3,81) = 48.62$, $p < 0.001$). These findings provide empirical validation for transitioning from reactive maintenance to condition-based predictive strategies, implementing adaptive weather-responsive cleaning schedules, and establishing standardized refrigerant management protocols. The study contributes to bridging the research gap between HVAC engineering and industrial reliability theory in extreme climate contexts, offering actionable insights for facility managers to optimize system uptime, reduce lifecycle costs, enhance energy efficiency, and maintain safe working conditions in desert industrial environments.

Keywords: Operational reliability, air conditioning systems, refrigeration systems, predictive maintenance, desert environment, compressor reliability, heat exchanger fouling

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1. Introduction

The reliable functioning of Air Conditioning and Refrigeration (AC/R) systems is an essential but often unpursued aspect in evaluating the overall safety, employee comfort, and operational productivity of large-scale industrial complexes. This research is carried out within the operational context of the Ras Lanuf Oil and Gas Processing Company (RASCO), a major hydrocarbon processing entity operating in Libya. In addition to its primary processing and refining units, RASCO maintains a wide network of critical support facilities that are essential to sustain 24/7 industrial operations. These support facilities include central control rooms, administrative wings, analytical laboratories, and technical workshops. Within these environments, AC/R systems serve a dual function: providing thermal comfort and indoor air quality for site personnel, while simultaneously safeguarding sensitive digital control electronics, instrumentation, and laboratory processes from the severe climate of the Libyan desert (Shalin Designs Team, 2025). The dependability of these environmental control systems directly impacts the continuity of operations, occupational health and safety standards, and overall facility operating expenditure. However, operating AC/R units in arid coastal desert environments presents extreme engineering challenges, characterized by ambient temperatures frequently exceeding 45°C, pervasive airborne sand and dust particulates, atmospheric salinity, and the operational mandate for continuous, non-stop performance identical to primary industrial process machinery (Nazarichev et al., 2025). While significant engineering focus and resource allocation are traditionally directed toward primary process equipment reliability, support systems such as Heating, Ventilation, and Air Conditioning (HVAC) in employee-occupied facilities have historically received less empirical investigation. Comparative research in adjacent industrial sectors, such as gas-fired power generation and offshore platform hydraulic systems, underscores the profound financial and safety ramifications of secondary support system failures (Elmetwalli & Muzaiel, 2025; Reliability Analysis of Gas Power Plant, 2025). This study focuses on three primary operational factors under the direct control of facility management at RASCO: refrigerant selection, compressor maintenance practices, and coil/filter maintenance protocols.

Despite the vital necessity of climate control, RASCO continuously faces operational challenges in optimizing system performance and preventing unscheduled downtime across its employee-occupied service facilities. Unexpected breakdowns of AC/R equipment induce severe thermal discomfort for personnel, increase the risk of overheating in mission-critical process control hardware, and trigger costly emergency repairs. A primary operational deficit is the lack of an empirically validated, data-driven reliability model tailored to RASCO's unique environmental and operational conditions. Presently, maintenance decisions regarding refrigerant management, compressor servicing, and heat exchanger cleaning rely largely on generic manufacturer specifications or reactive run-to-failure approaches rather than empirical evaluations of environmental stressors. This situation mirrors broader industrial maintenance trends, where the transition from traditional reactive servicing to proactive, data-driven predictive maintenance remains incomplete (Rahman, 2025; Park & Lee, 2025). Although advanced predictive methodologies exist for process heat exchangers—such as Machine Learning-enhanced Extended Kalman Filters (Paruthipulli & Subbaiah, 2024)—these tools are rarely deployed for environmental comfort and electronic cooling systems in oil and gas complexes. Consequently, resource allocation for HVAC maintenance remains sub-optimal, accelerating equipment degradation under harsh desert conditions where severe sandstorms rapidly induce physical fouling (Ishiyama et al., 2021; Gomez Suarez et al., 2023). This study addresses this research gap by establishing an empirical model linking controllable operational variables with AC/R system reliability, grounding facility management at RASCO in modern Prognostics and Health Management (PHM) principles (Soualhi et al., 2021). The overarching aim of this research is to analyze and model the key factors affecting the operational reliability of AC/R systems in employee-occupied service facilities at RASCO. Specifically, the study formulates three research objectives: (1) to evaluate the relationship between Refrigerant Selection and the operational reliability of AC/R units at RASCO; (2) to assess the impact of Compressor Maintenance Practices on operational reliability; and (3) to examine the influence of Coil/Filter Maintenance protocols on operational reliability. Correspondingly, three research questions guide the investigation: RQ1 asks what relationship exists between refrigerant selection and operational reliability; RQ2 inquires into the influence of compressor maintenance practices on operational reliability; and RQ3 examines the effect of coil/filter maintenance on operational reliability. To address these questions, three main hypotheses are posited: H1 states that there is a significant positive relationship between proper Refrigerant Selection and Operational Reliability; H2 states that there is a significant positive relationship between proactive Compressor Maintenance Practices and Operational Reliability; and H3 states that there is a significant positive relationship between rigorous Coil/Filter Maintenance and Operational Reliability.

The practical and academic significance of this research is substantial. Practically, the findings offer an empirical foundation for RASCO's facility management team to optimize HVAC maintenance schedules, validate predictive technologies like vibration analysis (Othman et al., 2025; Zavyalov & Zhuchkov, 2023), and adjust heat exchanger cleaning frequencies to mitigate desert fouling. This directly contributes to reducing unscheduled downtime, lowering lifecycle operating costs, conserving energy, and maintaining safer working conditions. Academically, the study provides a valuable case study bridging general HVAC engineering with industrial reliability theory (Ebeling, 2019) in an extreme desert climate, serving as a benchmark for hydrocarbon facilities operating under similar environmental conditions. For the scope of this research, operational reliability is operationally defined as the probability that an AC/R system continuously maintains specified temperature and humidity thresholds without unscheduled failure over a given timeframe, quantified through indicators such as availability and failure frequency (Ebeling, 2019; Wang et al., 2024). Refrigerant selection refers to the strategic evaluation and application of working fluids based on thermal performance, ambient temperature stability, oil compatibility, and local supply chain availability (D'Alessandro et al., 2025). Compressor maintenance practices encapsulate both scheduled preventive tasks (e.g., oil level checks, motor insulation testing) and condition-based predictive monitoring techniques like vibration analysis (Othman et al., 2025). Coil and filter maintenance denotes the systematic cleaning of condenser/evaporator coils and replacement of air filters to combat dust accumulation and thermal performance degradation (Müller-Steinhagen, 2011; Paruthipulli & Subbaiah, 2024).

2. Literature Review

Operational reliability within heavy industrial complexes represents a critical strategic imperative directly governing workplace safety, operational continuity, and economic efficiency. In reliability engineering, system reliability is defined as the probability that a unit will perform its intended function under specified operating conditions for a designated period (Ebeling, 2019). In hydrocarbon processing environments like RASCO, AC/R reliability translates into the uninterrupted delivery of conditioned air to preserve human health and protect process automation hardware. Recent scholarship on Integrated Energy Systems (IES) demonstrates that failure in secondary environmental control units can trigger cascading disruptions across primary operational networks (Wang et al., 2024). In high-risk operations, system adequacy is quantitatively benchmarked using metrics such as Loss of Load Probability (LOLP) and Forced Outage Rate (FOR) (Reliability Analysis of Gas Power Plant, 2025), while advancements in offshore hydraulic systems prove that proactive maintenance innovation prevents catastrophic shutdowns (Elmetwalli & Muzaiel, 2025). The paradigm shift from reactive to proactive maintenance frameworks—exemplified by Reliability-Centered Maintenance (RCM), Predictive Maintenance (PdM), and Digital Twin health management (Park & Lee, 2025)—highlights the necessity of elevating HVAC support infrastructure to the same rigorous reliability standards applied to core process machinery.

The strategic selection of refrigerants directly impacts the thermal efficiency, environmental compliance, and long-term mechanical longevity of vapor-compression refrigeration systems. Global environmental regulations, notably the Kigali Amendment to the Montreal Protocol, mandate the phasedown of high-Global Warming Potential (GWP) Hydrofluorocarbons (HFCs), compelling industrial operators to adopt low-GWP alternatives. Studies on high-temperature heat pumps underscore that working fluid selection must rigorously balance temperature glide, discharge temperature, and lubricant solubility (D'Alessandro et al., 2025). In extreme ambient environments like the Libyan desert, operating with an improper or degraded refrigerant mixture alters system pressure ratios, elevates compressor discharge temperatures, causes chemical breakdown of lubricating oils, accelerates mechanical wear, and increases leak risks. Furthermore, managing refrigerant transitions in aging industrial complexes introduces supply chain logistics, handling procedures for flammable alternatives (e.g., A2L or A3 refrigerants like R-290), and inventory control challenges, establishing refrigerant choice as a foundational factor in overall system dependability.

As the mechanical heart of the vapor-compression cycle, the compressor's operational state dictates the overall reliability of the AC/R system. Maintenance strategies for rotating machinery have progressed from reactive run-to-failure approaches to calendar-based preventive maintenance and advanced condition-based predictive techniques. While preventive servicing reduces catastrophic failures, it may induce unnecessary maintenance interventions and fail to detect incipient mechanical flaws. Conversely, predictive maintenance utilizes real-time condition monitoring tools—such as vibration spectrum analysis, thermography, motor current signature analysis, and oil tribology—to identify mechanical anomalies prior to operational breakdown. Empirical research on automotive air conditioning compressors demonstrates that 3D vibration Z-chart analytics effectively diagnose lubricating oil deficiencies before mechanical seizure occurs (Othman et al., 2025). Similarly, vibration parameter monitoring in industrial gas compression units confirms a direct relationship between operating vibration profiles and component reliability (Zavyalov & Zhuchkov, 2023). Deploying predictive monitoring on critical HVAC compressors allows facility engineers at RASCO to identify bearing wear, rotor imbalance, and electrical degradation early, extending useful component life.

Particulate fouling on heat transfer surfaces and air filtration media presents a ubiquitous threat to AC/R performance, particularly in arid, coastal desert locations like Ras Lanuf. Dust, fine sand, and saline aerosol accumulation on condenser and evaporator coils creates an insulating thermal barrier that severely reduces heat transfer efficiency. Consequently, the system operates at elevated head pressures and extended duty cycles, increasing compressor energy consumption by over 30% and inducing premature thermal overload failures (Müller-Steinhagen, 2011). Advanced research in industrial heat exchanger management employs sophisticated mathematical modeling, such as Machine Learning-enhanced Dual Extended Kalman Filtering (DEKF), yielding a 38.49% improvement in fouling resistance prediction accuracy (Paruthipulli & Subbaiah, 2024). Major refinery operators utilize specialized software suites (e.g., HTRI SmartPMTM) to monitor heat transfer resistance, optimize cleaning intervals, and minimize thermal losses (Ishiyama et al., 2021; Gomez Suarez et al., 2023). Grounding cleaning schedules in health indicator analytics rather than fixed calendar dates establishes a condition-based maintenance framework vital for combating severe desert sandstorm fouling (Soualhi et al., 2021).

A synthesis of existing scholarship reveals a rich body of literature covering industrial heat exchanger fouling models (Paruthipulli & Subbaiah, 2024; Ishiyama et al., 2021), data-driven prognostic health management (Soualhi et al., 2021; Park & Lee, 2025), primary process equipment reliability (Wang et al., 2024; Elmetwalli & Muzaiel, 2025), compressor vibration monitoring (Othman et al., 2025), and thermodynamic refrigerant optimization (D'Alessandro et al., 2025). However, a distinct research gap exists: there is a lack of comprehensive, empirical studies examining the combined influence of refrigerant selection, compressor maintenance practices, and coil/filter maintenance on the operational reliability of HVAC support systems in employee-occupied service facilities operating within severe desert industrial environments. Existing studies predominantly isolate process equipment fouling or general commercial building HVAC, ignoring the critical intersection of harsh environmental stressors, technical support facilities, and employee safety in oil and gas processing complexes. Table 2.1 synthesizes key academic literature, mapping specific findings and research gaps to the RASCO context.

Table 2.1: Synthesis of Key Literature and Research Gap

Literature Focus	**Key Insights from Provided Articles**	**Relevance to RASCO AC/R Study**	**Identified Research Gap**
Fouling Prediction & Management	ML-enhanced DEKF improves fouling resistance estimation by 38.49% (Paruthipulli & Subbaiah, 2024). HTRI SmartPM enables optimized cleaning schedules in refineries (Ishiyama et al., 2021; Gomez Suarez et al., 2023).	Highlights the critical impact of heat exchanger fouling on thermal performance and validates condition-based cleaning schedules for desert environments.	Advanced predictive models focus almost exclusively on primary process heat exchangers rather than comfort/equipment cooling AC/R coils in industrial service buildings.
Prognostics & Data Analytics	Methodology to construct prognostic indicators for heat exchanger fouling (Soualhi et al., 2021). Digital-twin PHM for RTOs improves operational	Demonstrates the paradigm shift toward data-driven, predictive health monitoring for critical asset management.	PHM and digital-twin methodologies are rarely applied to secondary support systems like administrative and control room HVAC units.

Literature Focus	Key Insights from Provided Articles	Relevance to RASCO AC/R Study	Identified Research Gap
	availability (Park & Lee, 2025).		
Compressor Reliability	3D Z-freq vibration analysis detects compressor oil insufficiency (Othman et al., 2025). Vibration analysis is critical for gas compressor reliability (Zavyalov & Zhuchkov, 2023).	Validates predictive vibration analysis as an effective tool for monitoring rotating compressor health and preventing mechanical failure.	Lack of empirical studies evaluating the practical implementation and reliability returns of compressor PdM specifically in desert industrial sites.
System Reliability Engineering	IES reliability requires balancing multi-subsystem interdependencies (Wang et al., 2024). Enhanced HPU design prevents costly offshore plant shutdowns (Elmetwalli & Muzaiel, 2025).	Underscores that reliability is a actively managed output of maintenance design, applicable to support utilities like control room HVAC.	Primary research emphasizes core hydrocarbon process units or power generation, marginalizing environmental control support infrastructure.
Refrigerant & Working Fluids	Refrigerant selection is vital for thermal efficiency and component longevity in high-temp heat pumps (D'Alessandro et al., 2025).	Guides the evaluation of refrigerant thermodynamic stability and lubricant compatibility under extreme ambient temperatures.	Minimal empirical literature examining how refrigerant choice and supply chain management directly influence long-term failure rates in desert industrial facilities.

This study is theoretically anchored in Reliability Engineering Theory, specifically incorporating the classic "Bathtub Curve" model which describes component failure rates across time through three distinct phases: early infant mortality, constant random useful life, and wear-out degradation (Ebeling, 2019). The three independent variables represent primary managerial levers designed to optimize system lifespan within this theoretical framework. Refrigerant Selection (IV1) dictates fundamental thermodynamic stress and material compatibility, where improper fluid choice accelerates wear-out degradation. Compressor Maintenance Practices (IV2) serve as direct condition-monitoring interventions that extend the constant failure-rate useful life phase and delay wear-out onset. Coil and Filter Maintenance (IV3) directly mitigates environmental fouling stressors that elevate system operating pressures, effectively flattening operating stress during useful life. Grounded in this framework, three core hypotheses are formulated: H1 positing a positive relationship between Refrigerant Selection and Operational Reliability; H2 positing a positive relationship between Compressor Maintenance Practices and Operational Reliability; and H3 positing a positive relationship between Coil/Filter Maintenance and Operational Reliability.

3. Method

This chapter presents the quantitative research methodology utilized to empirically examine the relationships between refrigerant selection, compressor maintenance, coil/filter maintenance, and operational reliability at RASCO. Grounded in a positivist research philosophy, this study assumes an objective reality that can be measured, quantified, and systematically analyzed through deductive hypothesis testing (Creswell & Creswell, 2018). The positivist framework is well-suited for reliability research, facilitating the measurement of technical parameters and maintenance practices to establish statistically valid relationships (Sekaran & Bougie, 2016). The operational design employs a descriptive-correlational, cross-sectional survey framework within a single-case study setting at the Ras Lanuf Oil and Gas Processing Company. The descriptive dimension characterizes current maintenance protocols and environmental impact, while the correlational dimension evaluates the strength and direction of associations between variables (Fraenkel et al., 2019). The cross-sectional design captures data across facility technical staff at a single point in time, enabling multivariate regression analysis to assess independent variable contributions to system reliability (Lavrakas, 2008).

The target population comprises all engineering and technical personnel at RASCO possessing direct operational responsibility for AC/R systems in employee-occupied service facilities, including control rooms, administrative buildings, laboratories, and workshops. The defined population includes Maintenance Engineers, HVAC Technicians, HVAC Supervisors, and Facility Operations Managers. A census sampling strategy was adopted due to the bounded and specialized nature of the target group within the RASCO complex, estimated at 70 to 90 qualified personnel. Targeting the total accessible population eliminates sampling bias and enhances internal validity. A statistical power analysis for multiple regression analysis confirmed that for a medium effect size ($f^2 = 0.15$), statistical power of 0.80, and alpha level of 0.05 across three predictor variables, a minimum sample size of 77 respondents is required (Cohen, 1992). The final collected sample of 85 usable responses successfully satisfies and exceeds this statistical power threshold (Baruch & Holtom, 2008). Table 3.1 details the methodological specifications and sampling justifications.

Table 3.1: Methodology and Sampling Specifications

Methodological Aspect	**Specification**	**Justification & Source**
Research Philosophy	Positivism (Deductive)	Facilitates objective measurement of operational variables and statistical hypothesis testing (Creswell & Creswell, 2018).
Research Design	Descriptive-Correlational, Cross-Sectional	Enables quantitative analysis of variable associations and multiple regression modeling at a single time point (Sekaran & Bougie, 2016).
Case Study Setting	Ras Lanuf Oil & Gas Processing Co. (RASCO)	Provides an authentic industrial environment operating in an extreme desert climate in Libya.
Target Population	HVAC/Maintenance Engineers, Technicians, Managers	Captures direct experiential and technical knowledge from personnel managing facilities daily.
Sampling Technique	Census Approach (Near-Total Population)	Maximizes data completeness across all technical job roles in a bounded facility (Baruch & Holtom, 2008).
Sample Size & Power	N = 85 Responses (Exceeds G*Power N=77)	Ensures sufficient statistical power (>0.80) for stable multivariate regression parameters (Cohen, 1992).

Data collection utilized a structured, self-administered questionnaire mapped directly to the research variables. Designed following scale development best practices (DeVellis, 2017), the instrument was originally drafted in English based on established literature—such as heat exchanger health metrics (Soualhi et al., 2021), compressor vibration analytics (Othman et al., 2025), and refrigerant selection protocols (D'Alessandro et al., 2025)—and translated into Arabic using double-blind back-translation (Brislin, 1970). Content validity was evaluated by an expert panel of reliability academics, senior industrial HVAC engineers, and survey methodologists. The Content Validity Index (CVI) was computed, retaining only items achieving a scale-level CVI ≥ 0.80 (Polit & Beck, 2006). A pilot study conducted with 25 technical staff from a comparable non-participating facility established scale reliability, yielding Cronbach's alpha values exceeding the 0.70 threshold (Nunnally & Bernstein, 1994). Exploratory Factor Analysis (EFA) using Principal Axis Factoring with Promax rotation confirmed construct validity, demonstrating clean factor loadings > 0.50 on intended constructs without cross-loadings > 0.30 (Fornell & Larcker, 1981). Table 3.2 outlines the final instrument structure.

Table 3.2: Research Instrument Structure and Construct Measurement

Section	Construct / Variable	Items	Measurement Scale & Example Item	Theoretical Source
Section A	Demographic & Facility Context	4	Categorical (Job Role, Experience, Education, Facility Type).	Demographic screening.
Section B	Refrigerant Selection (IV1)	5	5-point Likert (1=Strongly Disagree to 5=Strongly Agree). "Refrigerant used is appropriate for high ambient temperatures."	D'Alessandro et al. (2025)
Section C	Compressor Maintenance (IV2)	5	5-point Likert (1=Strongly Disagree to 5=Strongly Agree). "Vibration analysis is utilized to detect bearing wear or misalignment."	Othman et al. (2025); Zavyalov & Zhuchkov (2023)
Section D	Coil & Filter Maintenance (IV3)	5	5-point Likert (1=Strongly Disagree to 5=Strongly Agree). "Cleaning schedules are adjusted during sandstorm/high dust periods."	Paruthipulli & Subbaiah (2024); Soualhi et al. (2021)
Section E	Operational Reliability (DV)	5	5-point Likert (1=Strongly Disagree to 5=Strongly Agree). "AC/R systems maintain required temperature and humidity (>95% uptime)."	Ebeling (2019); Wang et al. (2024)

Quantitative analysis was executed using IBM SPSS Statistics (Version 28). Data screening verified dataset completeness, while univariate outliers (z-scores > ±3.29) and multivariate outliers (Mahalanobis distance at $p < 0.001$) were evaluated and ruled out. Internal consistency reliability was confirmed via Cronbach's alpha (target $\alpha \geq 0.70$). Bivariate Pearson correlation analysis (r) evaluated preliminary relationships between each IV and the DV. Hypothesis testing utilized Standard Multiple Linear Regression (MLR), regressing Operational Reliability simultaneously on Refrigerant Selection, Compressor Maintenance, and Coil/Filter Maintenance. Regression diagnostics confirmed parametric assumptions, including residual normality (Q-Q plots), linearity, homoscedasticity, error independence (Durbin-Watson test), and absence of multicollinearity (Variance Inflation Factor [VIF] < 10, Tolerance > 0.10) (Field, 2018; Keith, 2019). Ethical protocols strictly adhered to institutional guidelines: informed consent was prefaced on the questionnaire, complete anonymity was preserved without collecting personal identifiers, data were aggregated securely on encrypted storage, and formal organizational approval was granted by RASCO management prior to survey administration (Resnik, 2020).

4. Data Analysis

A total of 85 completed questionnaires were returned through the digital survey distribution at RASCO. Data screening confirmed 100% data usability with zero missing values across critical items. Univariate outlier checks confirmed that all standardized z-scores remained within the ±3.29 threshold, while Mahalanobis distance values did not exceed critical chi-square parameters ($p < 0.001$), establishing dataset cleanliness for parametric evaluation. An analysis of the demographic profile of the 85 respondents reveals a highly qualified, experienced technical sample. In terms of job categories, Maintenance Engineers represent the largest group (n = 36, 42.4%), followed by Facility Operations Managers (n = 20, 23.5%), HVAC Supervisors (n = 19, 22.4%), and HVAC Technicians (n = 10, 11.8%). Table 4.1 details the distribution by job role.

Table 4.1: Distribution of Respondents by Job Category

Job Category	**Frequency (n)**	**Percentage (%)**
Maintenance Engineer	36	42.4
HVAC Technician	10	11.8
HVAC Supervisor	19	22.4
Facility Operations Manager	20	23.5
Total	85	100.0

Work experience at RASCO demonstrates a mature workforce: 35.3% (n = 30) possess 2–5 years of experience, 30.6% (n = 26) have 6–10 years, 25.9% (n = 22) have 11–15 years, while only 8.2% (n = 7) have less than 2 years of service. Table 4.2 outlines experience levels. Educational qualifications show high academic attainment: 49.4% (n = 42) hold a Bachelor's degree, 23.5% (n = 20) hold a Master's degree, 18.8% (n = 16) hold a Technical Diploma, 4.7% (n = 4) possess a Vocational Certificate, and 3.5% (n = 3) hold a PhD. Table 4.3 outlines educational distribution. Regarding primary facility assignments, 31.8% (n = 27) operate in the Main Control Building, 23.5% (n = 20) in Technical Workshops, 22.4% (n = 19) in Laboratories, 11.8% (n = 10) in the Administration Wing, and 10.6% (n = 9) oversee multiple facilities. Table 4.4 outlines facility distribution.

Table 4.2: Distribution of Respondents by Years of Experience at RASCO

Years of Experience	**Frequency (n)**	**Percentage (%)**
< 2 years	7	8.2
2–5 years	30	35.3
6–10 years	26	30.6
11–15 years	22	25.9
Total	85	100.0

Table 4.3: Distribution of Respondents by Highest Educational Qualification

Educational Qualification	**Frequency (n)**	**Percentage (%)**
Diploma	16	18.8
Bachelor's Degree	42	49.4
Master's Degree	20	23.5

Educational Qualification	Frequency (n)	Percentage (%)
PhD	3	3.5
Vocational Certificate	4	4.7
Total	85	100.0

Table 4.4: Distribution of Respondents by Primary Work Facility Type

Primary Work Facility Type	Frequency (n)	Percentage (%)
Main Control Building	27	31.8
Administration Wing	10	11.8
Laboratory	19	22.4
Technical Workshop	20	23.5
Multiple Facilities	9	10.6
Total	85	100.0

Descriptive statistics were computed for all items across the study variables using a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). For Refrigerant Selection (IV1), mean scores ranged from 3.38 to 3.60. Prompt leak detection received the highest mean (M = 3.60, SD = 1.649), followed by local supply chain availability (M = 3.55, SD = 1.452) and ambient temperature appropriateness (M = 3.53, SD = 1.790), while refrigerant charge monitoring recorded the lowest mean (M = 3.38, SD = 1.520). Table 4.5 summarizes IV1 descriptive metrics.

Table 4.5: Descriptive Statistics for Refrigerant Selection (IV1)

Item Statement	Min	Max	Mean	Std. Dev.
Refrigerant is appropriate for high desert ambient temperatures	1	5	3.53	1.790
Refrigerant availability in supply chain avoids delays	1	5	3.55	1.452
Refrigerant leaks are promptly detected and repaired	1	5	3.60	1.649
Refrigerant charge level is regularly monitored	1	5	3.38	1.520
Improper refrigerant type/mixture has caused past failures	1	5	3.45	1.577

For Compressor Maintenance Practices (IV2), items ranged from 3.44 to 3.96. Topping up lubricating oil recorded the highest agreement (M = 3.96, SD = 1.085), motor electrical testing scored M = 3.68 (SD = 1.441), vibration analysis scored M = 3.61 (SD = 1.544), and routine visual inspection scored M = 3.55 (SD = 1.666), while predictive/condition-based maintenance usage scored lowest (M = 3.44, SD = 1.636). Table 4.6 presents IV2 metrics. For Coil/Filter Maintenance (IV3), item means ranged from 3.46 to 3.95. Adjusting schedules for sandstorms recorded the highest mean (M = 3.95, SD = 1.379), coil cleaning effectiveness scored M = 3.81 (SD = 1.435), and regular coil cleaning scored M = 3.76 (SD = 1.477), while condition-based cleaning indicators scored lowest (M = 3.46, SD = 1.468). Table 4.7 presents IV3 metrics. For Operational Reliability (DV), item means ranged from 3.47 to 3.71, led by temperature/humidity maintenance (M = 3.71, SD = 1.487) and general reliability satisfaction (M = 3.49, SD = 1.652), with system availability (>95% uptime) scoring M = 3.47 (SD = 1.516). Table 4.8 presents DV metrics.

Table 4.6: Descriptive Statistics for Compressor Maintenance Practices (IV2)

Item Statement	Min	Max	Mean	Std. Dev.
Routine visual inspection of compressor for leaks/sounds	1	5	3.55	1.666
Checking and topping up compressor lubricating oil	1	5	3.96	1.085

Item Statement	Min	Max	Mean	Std. Dev.
Vibration analysis to detect wear, imbalance, misalignment	1	5	3.61	1.544
Electrical testing of compressor motor (current, insulation)	1	5	3.68	1.441
Use of condition-based/predictive maintenance techniques	1	5	3.44	1.636

Table 4.7: Descriptive Statistics for Coil/Filter Maintenance (IV3)

Item Statement	Min	Max	Mean	Std. Dev.
Air filters are cleaned/replaced on a regular schedule	1	5	3.59	1.621
Condenser coils are cleaned on a regular schedule	1	5	3.76	1.477
Schedules adjusted during sandstorms/high dust periods	1	5	3.95	1.379
Coil cleaning effectively removes accumulated sand/dust	1	5	3.81	1.435
Condition indicators (pressure/temp) used for cleaning decisions	1	5	3.46	1.468

Table 4.8: Descriptive Statistics for Operational Reliability (DV)

Item Statement	Min	Max	Mean	Std. Dev.
AC/R systems are available & operational (>95% uptime)	1	5	3.47	1.516

Item Statement	**Min**	**Max**	**Mean**	**Std. Dev.**
Unscheduled breakdowns occur frequently in facility	1	5	3.59	1.466
Time to repair after breakdown is generally short	1	5	3.54	1.555
Systems consistently maintain required temp & humidity	1	5	3.71	1.487
Overall operational reliability of AC/R systems is satisfactory	1	5	3.49	1.652

Scale internal consistency was evaluated using Cronbach's alpha coefficient. All four constructs demonstrated high reliability exceeding the 0.70 benchmark: Operational Reliability (DV) achieved $\alpha = 0.847$, Compressor Maintenance (IV2) achieved $\alpha = 0.835$, Refrigerant Selection (IV1) achieved $\alpha = 0.812$, and Coil/Filter Maintenance (IV3) achieved $\alpha = 0.801$. Table 4.9 presents the reliability analysis. Bivariate Pearson correlation analysis examined relationships among variables. Operational Reliability (DV) exhibited strong, positive, statistically significant correlations with all three predictors: Compressor Maintenance Practices ($r = 0.702$, $p < 0.01$), Coil/Filter Maintenance ($r = 0.689$, $p < 0.01$), and Refrigerant Selection ($r = 0.671$, $p < 0.01$). Inter-variable correlations among predictors ranged from $r = 0.584$ to $r = 0.653$, indicating distinct constructs free from extreme multicollinearity. Table 4.10 presents the correlation matrix.

Table 4.9: Reliability Analysis (Cronbach's Alpha)

Construct / Variable	**Number of Items**	**Cronbach's Alpha (α)**
Refrigerant Selection (IV1)	5	0.812
Compressor Maintenance Practices (IV2)	5	0.835
Coil/Filter Maintenance (IV3)	5	0.801
Operational Reliability (DV)	5	0.847

Table 4.10: Pearson Correlation Matrix

Variables	**1. IV1**	**2. IV2**	**3. IV3**	**4. DV**
1. Refrigerant Selection (IV1)	1.000			
2. Compressor Maintenance Practices (IV2)	0.612**	1.000		
3. Coil/Filter Maintenance (IV3)	0.584**	0.653**	1.000	
4. Operational Reliability (DV)	0.671**	0.702**	0.689**	1.000

*** Correlation is significant at the 0.01 level (2-tailed).*

Multiple regression analysis evaluated the combined predictive power of the independent variables on Operational Reliability. The overall model was statistically significant ($F(3, 81) = 48.62$, $p < 0.001$), explaining 64.3% of the variance in operational reliability ($R^2 = 0.643$, Adjusted $R^2 = 0.630$). All three predictors contributed significantly to the model: Compressor Maintenance Practices exerted the largest positive effect ($\beta = 0.358$, $t = 3.842$, $p < 0.001$), followed by Coil/Filter Maintenance ($\beta = 0.312$, $t = 3.315$, $p = 0.001$), and Refrigerant Selection ($\beta = 0.284$, $t = 3.108$, $p = 0.002$). VIF values ranged from 1.68 to 1.92, confirming the absence of multicollinearity. Hypothesis testing confirmed empirical support for all three hypotheses (H1, H2, H3). Table 4.11 summarizes hypothesis testing outcomes.

Table 4.11: Summary of Hypotheses Testing

Hypothesis	**Hypothesized Relationship**	**Path Beta (β)**	**t-Value**	**p-Value**	**Empirical Decision**
H1	Refrigerant Selection (IV1) → Operational Reliability (DV)	0.284	3.108	0.002	Supported
H2	Compressor Maintenance (IV2) → Operational	0.358	3.842	0.000	Supported

Hypothesis	Hypothesized Relationship	Path Beta (β)	t-Value	p-Value	Empirical Decision
	Reliability (DV)				
H3	Coil/Filter Maintenance (IV3) → Operational Reliability (DV)	0.312	3.315	0.001	Supported

5. Discussion and Implications

This chapter interprets the empirical findings in relation to the study's research objectives, existing literature, and underlying theoretical frameworks. The results demonstrate that all three independent variables—refrigerant selection, compressor maintenance practices, and coil/filter maintenance—exert a statistically significant positive influence on the operational reliability of AC/R systems in RASCO's employee-occupied service facilities. Addressing RO1, the finding that proper refrigerant selection significantly enhances reliability ($\beta = 0.284$, $p = 0.002$) corroborates studies emphasizing thermodynamic compatibility and oil solubility under extreme operating temperatures (D'Alessandro et al., 2025; Gokhale et al., 2025). Selecting thermal-grade refrigerants prevents fluid breakdown and maintains compressor lubrication, proving vital for desert industrial environments. Addressing RO2, compressor maintenance emerged as the most potent predictor of system reliability ($\beta = 0.358$, $p < 0.001$). This aligns with literature identifying the compressor as the primary failure point in vapor-compression equipment and validating predictive monitoring—such as vibration analytics—as an essential tool to prevent unscheduled shutdowns (Othman et al., 2025; Tejani, 2024). Addressing RO3, coil and filter maintenance exhibited a strong positive impact ($\beta = 0.312$, $p = 0.001$), reinforcing findings that severe desert dust accumulation degrades heat transfer and elevates operating pressure (Müller-Steinhagen, 2011; Paruthipulli & Subbaiah, 2024; Gomez Suarez et al., 2023).

From a theoretical perspective, this study advances Reliability Engineering by providing empirical validation for operational and maintenance levers within the "Bathtub Curve" framework (Ebeling, 2019). It demonstrates that proactive maintenance interventions and proper working fluid selection directly flatten failure rates during the useful life phase and delay wear-out degradation. Furthermore, this research expands HVAC literature into extreme industrial settings, demonstrating how secondary support systems (comfort and equipment cooling) in oil and gas facilities can be effectively managed using Reliability-Centered Maintenance (RCM) and Prognostics and Health Management (PHM) principles (Soualhi et al., 2021; Park & Lee, 2025).

Practically, the findings offer actionable insights for RASCO management and facility operators. First, maintenance teams must accelerate the transition from calendar-based servicing to condition-based predictive maintenance, adopting vibration analysis, oil sampling, and infrared thermography for compressors (Othman et al., 2025). Second, heat exchanger maintenance must incorporate adaptive, weather-responsive cleaning schedules that automatically intensify during sandstorm seasons, utilizing pressure-drop sensors to trigger condition-based cleaning (Falcunitin et al., 2024). Third, facility managers should institute standardized refrigerant management protocols, including regular charge monitoring, advanced leak detection, and audited procurement to prevent thermal breakdown (D'Alessandro et al., 2025). Organizational policy should support these technical interventions by investing in technical training programs, Computerized Maintenance Management Systems (CMMS), and standardized operating procedures across all service facilities.

6. Limitations and Future Research Study

Several methodological limitations should be considered when interpreting the conclusions of this study. First, the research relied on a single-case study design focused exclusively on the Ras Lanuf Oil and Gas Processing Company (RASCO) in Libya. While this provided an in-depth context, findings may not be directly generalizable to industrial facilities operating under different climatic or organizational conditions. Second, the study utilized a cross-sectional survey design, measuring technical perceptions at a single point in time, which inherently limits the ability to establish definitive longitudinal causal trajectories. Third, operational reliability was evaluated primarily through structured technical survey instruments and quasi-objective estimations rather than direct automated sensor logs or multi-year CMMS historical failure records. Fourth, the conceptual model focused on three core operational variables, excluding other potential influences such as initial equipment design quality, power quality variations, and age distribution of machinery.

To build upon these findings, future research should adopt multi-site comparative designs across various hydrocarbon processing facilities in the Middle East and North Africa (MENA) region to enhance external generalizability. Longitudinal studies tracking system performance pre- and post-implementation of predictive maintenance technologies are strongly recommended to measure long-term reliability gains. Furthermore, future investigations should integrate objective CMMS failure metrics, real-time IoT vibration/pressure sensor logs, and financial cost-benefit modeling. Expanding the research framework to evaluate environmental parameters (e.g., ambient temperature fluctuations, ambient salinity) and human factors (e.g., technician certification levels) will provide a more comprehensive, multi-dimensional model for industrial HVAC reliability management.

In conclusion, this study empirically demonstrates that the operational reliability of AC/R systems in desert industrial service facilities depends on an integrated maintenance strategy encompassing thermodynamic refrigerant optimization, predictive compressor monitoring, and adaptive heat exchanger fouling control. Implementing these evidence-based practices at RASCO will optimize system uptime, protect critical control infrastructure, reduce energy consumption, and ensure workplace safety in extreme environments.

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