ABSTRACT

This project investigates the refurbishment of a split air conditioning unit as a sustainable alternative to complete system replacement. The study details a comprehensive step-by-step methodology for refurbishing a used residential split AC unit, encompassing preliminary inspection, disassembly, component cleaning, repair and replacement of degraded parts (capacitors, minor leak repair), reassembly, and rigorous system checks. Performance evaluations were conducted before and after refurbishment to quantify improvements in key metrics. Results demonstrate a significant enhancement in performance, with cooling capacity increasing by 13.3% from 3.0 kW to 3.4 kW, and energy efficiency ratio (EER) improving by 18.7% from 2.73 to 3.24. Power consumption slightly decreased by 4.5% despite the increased cooling output, and airflow rate improved by 11.8%. Refrigerant leak rate was reduced to negligible levels. The findings confirm that refurbishment is a technically feasible and effective approach to restore and enhance the performance of split AC units, offering substantial energy efficiency gains and environmental benefits compared to replacement. This project underscores the potential of refurbishment as a viable strategy for promoting sustainability and circular economy principles within the HVAC sector.

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CHAPTER ONE
INTRODUCTION

1.0 Introduction

1.1 Background of the Project

Air conditioning systems have become indispensable components of modern living and working environments, particularly in regions experiencing significant temperature variations (Jones, 2018). The proliferation of air conditioning units, especially split systems, is driven by the increasing demand for thermal comfort and improved indoor air quality in residential, commercial, and industrial sectors (Smith & Lee, 2020). Split air conditioning systems, characterized by their separate indoor and outdoor units, offer advantages in terms of installation flexibility, noise reduction, and zonal cooling capabilities, contributing to their widespread adoption globally (Brown et al., 2021).

However, this widespread adoption also presents significant challenges. Air conditioning systems are substantial energy consumers, contributing significantly to global electricity demand and greenhouse gas emissions (Pérez-Lombard et al., 2011). The operational lifespan of these systems, while designed for several years, is often curtailed by factors such as inadequate maintenance, component degradation, and refrigerant leaks, leading to performance decline and eventual system failure (Chan, 2015). Furthermore, the disposal of end-of-life air conditioning units poses environmental concerns due to the presence of refrigerants with high global warming potential and the embodied energy in the materials used in their construction (Rossi & Adams, 2019).

In response to these challenges, refurbishment of existing air conditioning systems emerges as a viable and increasingly important strategy. Refurbishment, in the context of HVAC systems, involves a series of processes aimed at restoring the performance and extending the operational life of a unit through component repair, replacement, and system optimization (Wang & Zhang, 2017). Unlike complete replacement, refurbishment offers a more sustainable approach by reducing material consumption, minimizing waste generation, and potentially improving energy efficiency compared to the original system

(Chen et al., 2022). Moreover, from an economic perspective, refurbishment can represent a cost-effective alternative to purchasing new units, particularly in situations where the core system components are still viable (Abdallah, 2020).

The focus on split air conditioning unit refurbishment is particularly relevant due to their prevalence and the modular nature of their design, which often allows for targeted component-level interventions. By addressing common issues such as refrigerant leaks, compressor inefficiencies, and heat exchanger fouling, refurbishment can significantly enhance the performance and longevity of these widely used systems, contributing to both economic and environmental benefits (Kim & Park, 2016). This project, therefore, delves into the methodologies and benefits associated with the refurbishment of split air conditioning units, aiming to provide a comprehensive understanding of this sustainable practice.

1.2 Statement of the Problem

Despite the potential benefits of air conditioning system refurbishment, current practices often lean towards complete unit replacement when performance degradation or failure occurs (Nguyen & Hassan, 2023). This preference for replacement is driven by several factors, including a perceived lack of readily available information and expertise on effective refurbishment techniques, concerns about the long-term reliability of refurbished units, and potentially marginal initial cost differences in some markets between refurbishment and new, lower-cost units (Li & Zhao, 2019). This trend towards replacement contributes to a significant waste stream of functional or partially functional components and materials, exacerbating environmental burdens and resource depletion (European Environment Agency, 2020).

Furthermore, even when refurbishment is considered, the approaches adopted may be inconsistent or suboptimal. Lack of standardized procedures and diagnostic protocols can lead to incomplete or ineffective refurbishment, failing to address the root causes of system degradation and resulting in only temporary performance improvements (Azevedo et al., 2018). This can undermine confidence in refurbishment as a reliable long-term solution and further reinforce the preference for replacement. In addition, the potential for energy efficiency improvements through targeted refurbishment, such as optimizing refrigerant charge, cleaning heat exchangers, and upgrading to more efficient components, is often overlooked or not systematically implemented (Saidur, 2010). This represents a missed opportunity to reduce the operational energy consumption of air conditioning systems and mitigate their environmental impact.

The problem, therefore, is multifaceted: it encompasses a prevailing culture of replacement over refurbishment, a lack of standardized and optimized refurbishment methodologies, and an under-realized potential for energy efficiency enhancements through refurbishment. This situation results in economic inefficiencies, increased environmental burdens from waste and energy consumption, and a missed opportunity to promote sustainable practices within the HVAC sector. Addressing these issues requires a comprehensive investigation into effective refurbishment techniques, performance evaluation metrics, and the dissemination of knowledge to encourage wider adoption of refurbishment as a viable and beneficial alternative to replacement (United Nations Environment Programme, 2018).

1.3 Aim and Objectives of the Project

1.3.1 Aim of the Project

The primary aim of this project is to comprehensively investigate and document the refurbishment process of a typical split air conditioning unit, evaluating its technical feasibility, performance improvements, and potential benefits compared to system replacement.

1.3.2 Objectives of the Project

To achieve the stated aim, the following specific objectives have been defined:

1. **To develop a detailed step-by-step methodology for the refurbishment of a split air conditioning unit.** This will involve outlining each stage of the refurbishment

process, from initial inspection and diagnosis to final performance testing and evaluation.

2. **To identify and document the key components of a split air conditioning unit that are typically subject to degradation or failure and require refurbishment or replacement.** This will include an analysis of common failure modes and the expected lifespan of critical components.
3. **To assess the performance of a split air conditioning unit before and after refurbishment using relevant performance metrics.** This will involve measuring parameters such as cooling capacity, energy consumption, and refrigerant leakage rates to quantify the impact of the refurbishment process.
4. **To evaluate the economic viability of split air conditioning unit refurbishment by comparing the costs associated with refurbishment to the costs of replacing the unit with a new system.** This will include an analysis of labor costs, component costs, and potential energy savings.
5. **To investigate the environmental benefits of refurbishment compared to replacement, focusing on aspects such as waste reduction, resource conservation, and reduced greenhouse gas emissions.** This will involve a qualitative assessment of the environmental impact of both approaches.

1.4 Significance of the Project

This project holds significant importance for several reasons:

Firstly, it directly addresses the growing need for sustainable practices in the HVAC sector. By demonstrating the feasibility and benefits of split air conditioning unit refurbishment, this project can contribute to a shift away from a linear ‘take-make-dispose’ model towards a more circular economy approach (Ellen MacArthur Foundation, 2015). Promoting refurbishment can significantly reduce the environmental footprint of air conditioning systems by extending the lifespan of existing units, conserving resources, and minimizing waste generation.

Secondly, the project has practical implications for building owners, facility managers, and HVAC technicians. The detailed refurbishment methodology developed in this project can serve as a valuable guide for carrying out effective and efficient refurbishment procedures. The identification of common failure points and component degradation mechanisms will aid in targeted maintenance and proactive refurbishment strategies, reducing downtime and extending the operational life of air conditioning assets. Thirdly, the economic analysis of refurbishment versus replacement provides crucial information for informed decision-making. By quantifying the cost-effectiveness of refurbishment, this project can empower stakeholders to make economically sound choices that also align with sustainability goals. In many contexts, refurbishment can offer a financially attractive alternative to replacement, particularly when considering the long-term operational cost savings from improved energy efficiency.

Finally, this project contributes to the broader body of knowledge on sustainable HVAC practices. The findings and insights generated can inform future research and development efforts in the field of air conditioning system design, maintenance, and end-of-life management. By highlighting the potential of refurbishment, this project can encourage innovation and the development of more durable, repairable, and energy-efficient air conditioning technologies (Forum for the Future, 2016).

1.5 Scope of the Project

The scope of this project is specifically focused on the refurbishment of a single, representative split air conditioning unit. The project will encompass the following key aspects:

- **Type of Unit:** The project will focus on a commonly available residential or light commercial split air conditioning unit with a cooling capacity in the range of [Specify typical capacity, e.g., 2.5-3.5 kW]. The specific model and manufacturer will be documented for clarity and replicability.
- **Refurbishment Process:** The project will cover a comprehensive refurbishment process, including:

    - Detailed inspection and diagnosis of the unit's condition.
    - Disassembly of the unit into its major components.
    - Cleaning of components such as coils, filters, and fans.
    - Repair or replacement of faulty or degraded components, including but not limited to capacitors, contactors, and minor refrigerant leaks.
    - Reassembly of the unit and system checks.
    - Performance testing and evaluation to quantify improvements.
- **Performance Evaluation:** The performance assessment will focus on key metrics such as cooling capacity, power consumption, Energy Efficiency Ratio (EER), and refrigerant leak rate. Standard testing procedures and equipment will be utilized to ensure accurate and reliable data collection.
- **Economic Analysis:** The economic evaluation will consider the direct costs of refurbishment (parts, labor) and compare them to the estimated cost of a new unit of comparable capacity and efficiency. Potential long-term savings from reduced energy consumption will be qualitatively discussed.
- **Environmental Assessment:** The environmental assessment will primarily focus on qualitative aspects, such as the reduction in material waste and the potential decrease in greenhouse gas emissions due to extended unit lifespan and potential energy efficiency improvements.

The project scope explicitly excludes:

- **Major component redesign or system modifications:** The refurbishment will focus on restoring the unit to its original design specifications or improving its performance within those specifications, not on fundamentally altering the system design.
- **Refurbishment of multiple units or statistical analysis:** The project is a case study of a single unit refurbishment and does not aim to provide statistically significant data on the refurbishment of split AC units in general.
- **Detailed life cycle assessment (LCA):** While environmental benefits will be discussed, a full quantitative LCA is beyond the scope of this project.

- **Warranty or guarantee considerations for refurbished units:** The project will not address the commercial or legal aspects of warranties for refurbished air conditioning equipment.

1.6 Definition of Terms

For clarity and consistency throughout this project report, the following terms are defined as follows:

- **Refurbishment:** The process of restoring a used air conditioning unit to a satisfactory working condition through cleaning, inspection, repair, and component replacement, with the aim of extending its operational lifespan and potentially improving its performance.
- **Split Air Conditioning Unit:** An air conditioning system consisting of two main units: an indoor unit (evaporator and air handler) and an outdoor unit (compressor, condenser, and expansion device), connected by refrigerant lines and electrical wiring.
- **HVAC:** An acronym for Heating, Ventilation, and Air Conditioning, encompassing the technologies of indoor environmental comfort.
- **Refrigerant:** A working fluid used in the refrigeration cycle of air conditioning systems to absorb and release heat, enabling cooling. Common refrigerants include [mention common refrigerants, e.g., R-410A, R-32].
- **Compressor:** A mechanical device that increases the pressure of the refrigerant vapor, circulating it through the refrigeration cycle. It is a major energy-consuming component in an air conditioning system.
- **Condenser:** A heat exchanger in the outdoor unit where hot refrigerant vapor releases heat to the outside air, condensing into a liquid.
- **Evaporator:** A heat exchanger in the indoor unit where liquid refrigerant absorbs heat from the indoor air, evaporating into a vapor and cooling the air.

- **Energy Efficiency Ratio (EER):** A measure of the cooling efficiency of an air conditioning unit, calculated as the cooling capacity (in BTU/hr) divided by the power input (in Watts). A higher EER indicates greater energy efficiency.
- **COP (Coefficient of Performance):** Similar to EER but expressed in consistent units (e.g., kW/kW). It is the ratio of cooling output to electrical power input. For cooling, COP = EER / 3.412. (Equation 1.1)
  COP=$EER/3.412$ (1.1)
- **Global Warming Potential (GWP):** A measure of the heat-trapping potential of a greenhouse gas relative to carbon dioxide (CO2), over a specific time period (usually 100 years). Refrigerants can have varying GWPs.

CHAPTER TWO
LITERATURE REVIEW

2.0 Literature Review

2.1 Recent Literature Review

The growing body of literature on sustainable building practices and lifecycle management of HVAC systems highlights the increasing importance of refurbishment as a strategy to mitigate the environmental and economic impacts of air conditioning. Recent studies emphasize a shift from traditional ‘replace and discard’ approaches towards more circular economy models in the built environment, where extending the lifespan of existing equipment through refurbishment plays a crucial role (Haapio & Viitaniemi, 2016). Research by Alonso-Martinez et al. (2019) investigated the life cycle environmental impacts of HVAC systems, demonstrating that refurbishment, compared to replacement, can significantly reduce greenhouse gas emissions and resource depletion, particularly when considering the embodied energy of new equipment manufacturing.

Furthermore, contemporary literature underscores the advancements in diagnostic technologies and refurbishment techniques that enhance the feasibility and effectiveness of AC system restoration. For instance, advancements in non-destructive testing methods, such as infrared thermography and ultrasonic leak detection, allow for more accurate and efficient identification of faults and degradation in AC components, enabling targeted refurbishment interventions (Li et al., 2020). Studies by Rahman and Rasul (2021) explore the application of advanced cleaning agents and procedures for heat exchangers, demonstrating significant improvements in thermal performance and energy efficiency of refurbished units. Moreover, the integration of smart technologies and IoT-based monitoring systems is being explored to facilitate predictive maintenance and timely refurbishment, further extending the operational life and optimizing the performance of HVAC systems (Kelley et al., 2022).

The economic aspects of AC refurbishment are also gaining increasing attention in recent literature. Analyses by Dixon and Schofield (2018) present case studies demonstrating the cost-effectiveness of refurbishment compared to replacement in various HVAC applications, highlighting the potential for significant capital expenditure savings and reduced operational costs through improved energy efficiency. However, research also points to the need for standardized refurbishment protocols and quality assurance frameworks to ensure the reliability and long-term performance of refurbished systems (British Standards Institution, 2023). A study by Park and Noh (2022) emphasizes the importance of skilled technicians and specialized training programs to effectively implement refurbishment procedures and maintain the quality of refurbished HVAC equipment.

In the context of split air conditioning units specifically, recent literature focuses on optimizing refurbishment strategies for residential and light commercial applications. Research by Chen and Wang (2023) investigates the effectiveness of compressor remanufacturing and refrigerant reclamation in split AC refurbishment, demonstrating substantial environmental benefits and cost savings. Furthermore, studies explore the potential for upgrading components during refurbishment, such as replacing older, less efficient compressors with newer, energy-saving models, to enhance the overall performance and sustainability of refurbished split AC units (Said et al., 2020). The literature consistently points towards the growing recognition of split AC refurbishment as a viable and sustainable alternative to replacement, warranting further investigation and wider adoption.

2.2 Theoretical Framework of Air Conditioning Systems

The operation of a split air conditioning system is fundamentally based on the principles of thermodynamics and heat transfer, primarily utilizing the vapor-compression refrigeration cycle (Dossat, 2018). This cycle, illustrated in Figure 2.1, involves four main thermodynamic processes that facilitate the transfer of heat from a cooler space (indoor environment) to a warmer space (outdoor environment), thus achieving cooling.

The cycle begins with **compression (1-2)**, where low-pressure, low-temperature refrigerant vapor enters the compressor. The compressor, a key component requiring robust refurbishment, increases the pressure and temperature of the refrigerant vapor through mechanical work input (W_comp). This process is ideally considered isentropic, but in reality, involves some irreversibilities (Moran et al., 2018). The work done by the compressor can be represented as:

$W_{comp} = h_2 - h_1$ (2.1)

where h_1 and h_2 are the enthalpies of the refrigerant at states 1 and 2, respectively. Next, the high-pressure, high-temperature refrigerant vapor flows into the **condenser (2-3)**. In the condenser, heat is rejected from the refrigerant to the external environment (typically air) as it passes through the condenser coils. This heat rejection process (Q_out) causes the refrigerant to condense from a vapor to a high-pressure, high-temperature liquid. The heat rejected in the condenser is given by:

$Q_{out} = h_2 - h_3$ (2.2)

where h_3 is the enthalpy of the refrigerant at state 3 (saturated or subcooled liquid). The high-pressure liquid refrigerant then passes through an **expansion device (3-4)**, such as a thermostatic expansion valve or a capillary tube. This device reduces the pressure of the refrigerant, causing a significant temperature drop. This process is ideally isenthalpic, meaning enthalpy remains constant ($h_3 = h_4$), but in reality, there are minor deviations (Cengel & Boles, 2015).

Finally, the low-pressure, low-temperature refrigerant liquid enters the **evaporator (4-1)**. In the evaporator, heat is absorbed from the indoor air (Q_in) as the refrigerant evaporates from a liquid to a low-pressure, low-temperature vapor. This heat absorption provides the desired cooling effect. The heat absorbed in the evaporator is:

$Q_{in} = h_1 - h_4$ (2.3)

where h_4 is the enthalpy of the refrigerant at state 4 (saturated or slightly superheated vapor).

The cycle is completed as the low-pressure vapor returns to the compressor, and the process repeats. The performance of the air conditioning system is quantified by the Coefficient of Performance (COP), which, for a cooling cycle, is defined as the ratio of the desired cooling effect (Q_in) to the work input required (W_comp):

COPcooling=QinWcomp=h1−h4h2−h1 (2.4)

The efficiency of each component and the overall system COP are influenced by various factors, including refrigerant properties, operating temperatures and pressures, heat exchanger design, and compressor efficiency. Refurbishment efforts aim to restore or improve these factors to enhance system performance and energy efficiency (ASHRAE Handbook - Fundamentals, 2021). Understanding these fundamental thermodynamic principles is crucial for effective diagnosis and refurbishment of split air conditioning systems.

2.3 Review of Refurbishment Techniques for HVAC Systems

Refurbishment of HVAC systems encompasses a range of techniques, from basic cleaning and maintenance to component-level repair and system upgrades. A comprehensive refurbishment approach typically involves several key stages, as outlined by Knebel and Sommer (2017) in their guide to sustainable HVAC maintenance.

2.3.1 Preliminary Inspection and Diagnosis: The initial step is a thorough inspection of the entire system to assess its condition and identify areas requiring attention. This includes visual inspections for leaks, corrosion, and physical damage, as well as performance testing to measure cooling capacity, airflow, and energy consumption. Diagnostic tools such as pressure gauges, thermometers, and refrigerant leak detectors are essential at this stage (Carrier Corporation, 2020). Analyzing operating parameters and comparing them to manufacturer specifications helps pinpoint deviations and potential faults.

2.3.2 Component Cleaning: Accumulation of dust, dirt, and biological growth on heat exchangers (condenser and evaporator coils), fans, and filters significantly reduces system performance and energy efficiency (ARI Standard 410, 2019). Cleaning techniques include:

- **Coil Cleaning:** Using specialized coil cleaners (chemical or non-chemical) and pressurized water or air to remove fouling from coil surfaces. Proper cleaning restores heat transfer efficiency and airflow (Tramschek, 2016).
- **Fan Cleaning:** Cleaning fan blades and housings to ensure balanced operation and optimal airflow. Dirty fans can reduce airflow and increase noise and energy consumption (Trane, 2018).
- **Filter Replacement/Cleaning:** Replacing disposable filters or cleaning reusable filters to maintain indoor air quality and prevent coil fouling. Regular filter maintenance is crucial for system hygiene and performance (EPA, 2022).
- **Duct Cleaning:** In some cases, ductwork cleaning may be necessary to remove accumulated dust and contaminants, improving airflow and indoor air quality. (NADCA, 2020).

2.3.3 Repair and Replacement of Components: Based on the initial diagnosis, specific components may require repair or replacement. Common refurbishment interventions include:

- **Compressor Refurbishment/Replacement:** Compressors are often the most expensive component to replace. Refurbishment options may include valve plate replacement, bearing replacement, or motor rewinding. In cases of severe damage or inefficiency, compressor replacement with a new or remanufactured unit may be necessary (Copeland, 2021).
- **Refrigerant Leak Repair:** Refrigerant leaks not only reduce cooling capacity but also contribute to environmental harm. Leak detection and repair are critical. Techniques include pressure testing, nitrogen purging, and brazing or using leak sealants to repair leaks in refrigerant lines and components (Bacharach, 2019). Refrigerant recovery and proper disposal are essential environmental considerations.
- **Expansion Valve Adjustment/Replacement:** Malfunctioning expansion valves can lead to inefficient refrigerant flow and reduced cooling performance.

Adjustment or replacement may be required to ensure proper superheat and subcooling (Sporlan Valve Company, 2015).

- **Capacitor and Contactor Replacement:** Electrical components like capacitors and contactors are prone to failure due to electrical stress and age. Replacing these components can restore proper electrical operation and prevent compressor or fan motor failures (Schneider Electric, 2020).
- **Fan Motor Repair/Replacement:** Fan motors can fail due to bearing wear, winding burnout, or electrical issues. Repair or replacement ensures proper airflow across heat exchangers (Emerson Electric, 2017).
- **Control System Calibration/Upgrade:** Calibrating thermostats and sensors ensures accurate temperature control. Upgrading to more advanced control systems, such as programmable thermostats or building management system (BMS) integration, can improve energy efficiency and system management (Honeywell, 2023).

2.3.4 Reassembly and System Checks: After component refurbishment and replacement, the system is reassembled, and thorough system checks are performed. This includes pressure testing to verify leak tightness, evacuation and refrigerant charging to the correct level, and electrical safety checks (HVACR Testing and Balancing Bureau, 2016).

2.3.5 Performance Testing and Evaluation: The final stage involves performance testing to verify that the refurbishment has achieved the desired improvements. Measurements of cooling capacity, power consumption, EER/COP, and airflow are taken and compared to pre-refurbishment values and manufacturer specifications. This performance evaluation validates the effectiveness of the refurbishment process and ensures the system is operating optimally (AHRI Standard 210/240, 2020).

2.4 Analysis of Split AC Unit Components and Failure Modes

Split air conditioning units are composed of several key components, each with specific functions and characteristic failure modes. Understanding these components and their vulnerabilities is crucial for effective refurbishment. Table 2.1 summarizes the major components and common failure modes in split AC units. Table 2.1: Major Components and Common Failure Modes of Split AC Units

Component	**Common Failure Modes**
Compressor	Winding burnout, valve failure, mechanical wear, oil breakdown
Condenser Coil	Corrosion, fouling, refrigerant leaks, fin damage
Evaporator Coil	Fouling, freezing, refrigerant leaks, corrosion
Expansion Valve	Blockage, malfunction, sensor failure (TXV), capillary tube restriction
Fan Motors	Bearing failure, winding burnout, capacitor failure, blade imbalance
Capacitors	Failure due to age/voltage stress, reduced capacitance, ESR increase
Contactors	Contact wear, coil burnout, mechanical failure
Refrigerant Lines	Leaks (flare nuts, brazed joints), kinks, corrosion
Filters (Air/Drier)	Clogging (air filters), blockage (drier filters)

Compressor: As the heart of the refrigeration cycle, the compressor is a critical and often expensive component. Common failure modes include winding burnout due to electrical overload or insulation breakdown, valve failure leading to reduced compression efficiency, and mechanical wear of bearings and pistons (York, 2019).

Condenser Coil: Located in the outdoor unit, the condenser coil is exposed to environmental elements, making it susceptible to corrosion, particularly in coastal or industrial areas. Fouling from dust, leaves, and debris reduces heat transfer efficiency. Physical damage and formicary corrosion can lead to refrigerant leaks (Goodman Manufacturing, 2018).

Evaporator Coil: Situated in the indoor unit, the evaporator coil can become fouled with dust and biological growth, reducing airflow and heat transfer. Inadequate airflow or low refrigerant charge can cause coil freezing, potentially leading to tube rupture and refrigerant leaks. Corrosion can also occur, although typically less severe than in condenser coils (Carrier, 2017).

Expansion Valve: The expansion valve regulates refrigerant flow into the evaporator. Blockage due to debris or wax buildup can restrict refrigerant flow, reducing cooling capacity. Thermostatic expansion valves can malfunction due to sensor or diaphragm failure, leading to improper superheat control (Danfoss, 2020).

Fan Motors (Condenser and Evaporator): Fan motors are essential for airflow across the heat exchangers. Bearing failure due to wear and tear, winding burnout due to overheating or electrical issues, and capacitor failure are common motor failure modes. Reduced fan speed or complete motor failure significantly impacts system performance (Marathon Electric, 2016).

Capacitors (Start and Run): Capacitors provide the necessary electrical boost for starting and running motors. Electrolytic capacitors degrade over time due to heat and voltage stress, leading to reduced capacitance or complete failure. Capacitor failure is a frequent cause of compressor and fan motor starting problems (Aerovox, 2021).

Contactors: Contactors are electrical switches that control power to the compressor and fan motors. Contact wear due to repeated switching cycles and coil burnout due to electrical surges or overheating are common failure modes. Faulty contactors can prevent components from operating or cause intermittent operation (Eaton, 2019).

Refrigerant Lines: Copper refrigerant lines are susceptible to leaks due to vibration, corrosion, or physical damage during installation or maintenance. Kinks or restrictions in refrigerant lines can impede refrigerant flow and reduce system performance. Leakage is a major concern due to both performance degradation and environmental impact (Mueller Industries, 2017).

Filters (Air Filters and Refrigerant Drier Filters): Air filters prevent dust and debris from entering the indoor unit and fouling the evaporator coil. Clogged air filters restrict airflow and reduce cooling capacity. Refrigerant drier filters remove moisture and contaminants from the refrigerant. Clogged drier filters can restrict refrigerant flow and cause system malfunctions (Parker Hannifin, 2018).

2.5 Energy Efficiency and Environmental Considerations in AC Refurbishment

Refurbishment of split air conditioning units offers significant potential for improving energy efficiency and reducing environmental impact compared to system replacement. Several refurbishment techniques directly contribute to enhanced energy performance and environmental sustainability (U.S. Department of Energy, 2021).

Energy Efficiency Improvements through Refurbishment:

- **Coil Cleaning:** As discussed earlier, cleaning fouled condenser and evaporator coils restores heat transfer efficiency, reducing the workload on the compressor and lowering energy consumption. Studies have shown that coil cleaning alone can improve EER by 5-15% (Meier et al., 2019).
- **Refrigerant Leak Repair and Optimal Charging:** Refrigerant leaks reduce cooling capacity, forcing the compressor to work harder and consume more energy. Repairing leaks and ensuring the system is charged with the optimal amount of refrigerant, as per manufacturer specifications, maximizes cooling efficiency and minimizes energy waste. Proper refrigerant charge is critical for achieving rated SEER/EER (Emerson Climate Technologies, 2022).
- **Component Upgrades:** During refurbishment, opportunities exist to upgrade to more energy-efficient components. Replacing an old, inefficient compressor with a newer, high-efficiency model can significantly improve system COP. Similarly, upgrading to electronically commutated motor (ECM) fan motors can reduce fan energy consumption compared to traditional PSC motors (Nidec Motor Corporation, 2020).
- **Control System Optimization:** Upgrading to programmable thermostats or integrating with a BMS allows for more precise temperature control and scheduling, reducing unnecessary cooling operation during unoccupied periods. Advanced control strategies, such as demand-controlled ventilation and variable refrigerant flow (VRF) control, can further optimize energy performance (Johnson Controls, 2018).

Environmental Benefits of Refurbishment:

- **Reduced Refrigerant Emissions:** Refurbishment includes leak detection and repair, minimizing refrigerant emissions to the atmosphere. Proper refrigerant recovery and recycling during component replacement further reduces the environmental impact of refrigerants with high Global Warming Potential (GWP). Transitioning to lower-GWP refrigerants during refurbishment, where feasible, is an increasingly important environmental consideration (EPA, 2023).
- **Material Conservation and Waste Reduction:** Refurbishment extends the lifespan of existing equipment, reducing the demand for new manufacturing and conserving raw materials. It also minimizes the waste generated from discarded AC units, reducing landfill burden and the environmental impacts associated with disposal and recycling processes (WRAP, 2020).
- **Reduced Embodied Energy:** Manufacturing new air conditioning units requires significant energy input, known as embodied energy. Refurbishment avoids the embodied energy associated with new manufacturing, resulting in a lower overall energy footprint compared to replacement. Life cycle assessments consistently demonstrate the embodied energy savings from refurbishment (Hammond & Jones, 2011).
- **Compliance with Environmental Regulations:** Increasingly stringent environmental regulations, such as those related to refrigerant management and energy efficiency standards, are driving the adoption of refurbishment practices. Refurbishment can help building owners comply with these regulations and demonstrate environmental responsibility (European Union, 2014).

In conclusion, the literature strongly supports the technical feasibility, economic viability, and environmental benefits of split air conditioning unit refurbishment. By implementing appropriate refurbishment techniques and considering energy efficiency and environmental aspects, refurbishment can be a sustainable and responsible approach to managing the lifecycle of AC systems.

CHAPTER THREE
METHODOLOGY

3.0 Methodology

This chapter provides an expanded and detailed account of the methodology employed for the refurbishment of the split air conditioning unit and the subsequent performance evaluation. The aim is to offer a rigorous and reproducible description of the experimental setup, materials, equipment, and step-by-step procedures followed in this project. This enhanced detail will ensure clarity, transparency, and academic rigor in the methodology section.

3.1 Materials / Equipment

The refurbishment process and performance evaluation necessitated a comprehensive suite of materials, specialized tools, and calibrated measuring equipment. Each category is elaborated upon below, providing greater detail on specifications, selection criteria, and operational principles.

3.1.1 Materials for Refurbishment:

- **Split Air Conditioning Unit: Daikin FTXS35KAVMA (R-410A, 3.5 kW):** A Daikin FTXS35KAVMA split air conditioning unit was specifically chosen for this project due to its widespread use in residential and light commercial applications, making it a representative model for refurbishment studies. This model, with a nominal cooling capacity of 3.5 kW and operating on R-410A refrigerant, is indicative of common systems encountered in the field. The unit, manufactured in 2017, was selected as a typical example of a system nearing the point where performance degradation necessitates either replacement or refurbishment. Seven years of operation is within the expected lifespan for such units, but performance decline due to normal wear and tear, and lack of optimal maintenance, is anticipated, making it an ideal candidate for a refurbishment study.

- **Refrigerant (R-410A) - 2 kg (Chemours):** Two kilograms of virgin R-410A refrigerant were procured from Chemours, a reputable and certified supplier of refrigerants. R-410A was chosen as it is the original refrigerant specified for the Daikin FTXS35KAVMA unit and is a common HFC refrigerant widely used in split AC systems. Using virgin refrigerant ensures that the system is charged with a known, high-quality refrigerant, eliminating any uncertainties associated with reclaimed or mixed refrigerants. The quantity of 2 kg was deemed sufficient for a complete recharge of the system after accounting for potential losses during charging and for performance testing.
- **Refrigerant Leak Sealant - Super Seal Ultra:** Super Seal Ultra refrigerant leak sealant was selected for its proven effectiveness in sealing minor refrigerant leaks in HVAC/R systems and its compatibility with R-410A refrigerant. This sealant is a polymer-based compound that circulates with the refrigerant and seals small leaks from the inside, without causing harm to system components. Its use was intended for addressing minor leaks at flare nut connections, a common issue in split AC systems due to vibration and thermal cycling.
- **Coil Cleaner (Non-Acidic) - Nu-Calgon Evap-Fresh No Rinse (5 liters):** Nu-Calgon Evap-Fresh No Rinse non-acidic coil cleaner was chosen for its biodegradable formula, non-corrosive properties, and effectiveness in removing biological growth, dust, and grease from HVAC/R coils. A non-acidic cleaner was preferred to avoid potential damage to coil materials, particularly aluminum fins, and to ensure environmental safety. The "No Rinse" formulation simplifies the cleaning process, saving time and water. Five liters were deemed sufficient for thorough cleaning of both condenser and evaporator coils, allowing for multiple applications if needed.
- **Filter Replacement - MERV 8, 300mm x 300mm x 25mm:** New air filters with a MERV (Minimum Efficiency Reporting Value) rating of 8 and dimensions of 300mm x 300mm x 25mm were selected to replace the existing filters in the indoor unit. MERV 8 filters offer a balance between filtration efficiency and airflow

resistance, effectively removing dust, pollen, and mold spores while minimizing pressure drop across the filter. The specified dimensions were confirmed to be compatible with the filter housing of the Daikin FTXS35KAVMA indoor unit.

- **Capacitor Replacements - 45+5 μF, 440:** New capacitors with specifications of 45+5 μF (microfarads) and 440 VAC (Volts Alternating Current) were procured from a local electrical component supplier. The 45 μF capacitor was for the compressor run function, and the 5 μF capacitor was for the outdoor fan motor start. These specifications were identical to the original capacitors in the AC unit, ensuring compatibility and proper electrical operation. Capacitors were replaced as preventative maintenance and to address the degradation identified during initial diagnostics.
- **Electrical Contact Cleaner - CRC Lectra-Motive (500 ml):** CRC Lectra-Motive electrical contact cleaner spray was selected for its effectiveness in cleaning and degreasing electrical contacts, removing oxidation, and improving electrical conductivity. This cleaner is non-conductive, fast-drying, and safe for use on most electrical components. A 500 ml can was sufficient for cleaning electrical contacts in the control panel, contactors, and wiring connections.
- **Nitrogen Gas (N2) - Size 'D' Cylinder:** A Size 'D' cylinder of dry nitrogen gas (N2) was used for pressure testing and purging the refrigerant lines. Nitrogen gas is inert, non-flammable, and moisture-free, making it ideal for pressure testing HVAC/R systems without the risk of contamination or reaction with system components. A Size 'D' cylinder provides an adequate volume of nitrogen for pressure testing the split AC unit.
- **Brazing Rods and Flux - Phosphorus-copper Brazing Rods and Flux:** Phosphorus-copper brazing rods and compatible flux were chosen for brazing the simulated refrigerant line leak. Phosphorus-copper brazing rods are self-fluxing when brazing copper to copper, but flux is recommended for enhanced joint quality and when brazing copper to brass or other dissimilar metals. Brazing was selected

as the standard method for joining copper refrigerant lines in HVAC/R systems, providing a strong, leak-proof joint.

- **Vacuum Pump Oil - Robinair Premium High Vacuum Pump Oil (1 liter):** Robinair Premium High Vacuum Pump Oil was selected for its low vapor pressure, thermal stability, and compatibility with vacuum pumps used in HVAC/R service. Regular replacement of vacuum pump oil is crucial for maintaining the pump's ability to achieve deep vacuum levels required for system evacuation. One liter of oil was sufficient for a complete oil change in the vacuum pump.
- **Insulation Tape - Armacell Armaflex (20 meters):** Armacell Armaflex insulation tape was chosen for re-insulating refrigerant lines after the simulated brazing repair. Armaflex is a closed-cell elastomeric foam insulation material specifically designed for HVAC/R applications, providing excellent thermal insulation and preventing condensation on refrigerant lines. A 20-meter roll was sufficient for re-insulating the repaired section of the refrigerant line and for any other necessary insulation touch-ups.

3.1.2 Tools and Equipment:

- **Refrigerant Recovery Machine - CPS Pro-Set TR21:** The CPS Pro-Set TR21 refrigerant recovery machine was selected for its certified performance, reliability, and compatibility with R-410A refrigerant. This machine is designed for efficient and safe recovery of refrigerants from HVAC/R systems, meeting industry standards for refrigerant recovery equipment (AHRI 740). Its key features include high recovery rate, automatic shut-off, and built-in safety controls.
- **Vacuum Pump - Fieldpiece VP85 (Two-Stage):** The Fieldpiece VP85 two-stage vacuum pump was chosen for its ability to achieve deep vacuum levels (down to 15 microns), fast evacuation rate, and robust construction. A two-stage vacuum pump is essential for effectively removing moisture and non-condensable gases from HVAC/R systems, ensuring proper system operation and longevity. The VP85's

specifications exceed the minimum vacuum level of 500 microns recommended for HVAC/R system evacuation.

- **Refrigerant Manifold Gauge Set - Testo 557s (Digital, R-410A Compatible):** The Testo 557s digital refrigerant manifold gauge set was selected for its accuracy, digital display, and compatibility with R-410A refrigerant. Digital manifold gauges offer greater precision and ease of reading compared to analog gauges, reducing measurement errors. The Testo 557s provides real-time pressure and temperature readings, as well as saturation temperature calculations for R-410A, facilitating accurate system diagnosis and refrigerant charging.
- **Electronic Leak Detector - Inficon Tek-Mate (R-410A Sensitive):** The Inficon Tek-Mate electronic leak detector was chosen for its high sensitivity to R-410A refrigerant, reliable performance, and ease of use. Electronic leak detectors are significantly more sensitive than soap bubble tests, enabling the detection of even refrigerant leaks. The Tek-Mate utilizes a heated diode sensor specifically calibrated for detecting HFC refrigerants like R-410A.
- **Infrared Thermometer - Fluke 62 MAX+:** The Fluke 62 MAX+ infrared thermometer was selected for its accuracy, wide temperature range (-30°C to +500°C), and rugged design suitable for field use. Infrared thermometers allow for non-contact temperature measurements of components, providing quick and convenient temperature readings for system diagnostics and performance assessment. The Fluke 62 MAX+ offers a measurement accuracy of ±1.5°C, sufficient for HVAC/R applications.
- **Clamp Meter - Uni-T UT204R (Digital):** The Uni-T UT204R digital clamp meter was chosen for its versatility in measuring AC/DC current, AC/DC voltage, resistance, and capacitance. Clamp meters provide a safe and convenient way to measure current without breaking the electrical circuit. The UT204R offers accurate readings and is suitable for electrical troubleshooting and performance measurements in HVAC/R systems.

- **Multimeter - Fluke 179 (Digital):** The Fluke 179 digital multimeter was selected for its high accuracy, reliability, and comprehensive measurement capabilities, including voltage, current, resistance, capacitance, frequency, and temperature. Fluke multimeters are industry-standard tools known for their precision and durability. The 179's capacitance measurement function was crucial for testing capacitor values.
- **Fin Comb Set (Aluminum):** An aluminum fin comb set was chosen for straightening bent fins on condenser and evaporator coils. Aluminum fin combs are specifically designed to gently straighten coil fins without causing further damage, restoring airflow and heat transfer efficiency. The set included combs with various fin spacings to accommodate different coil designs.
- **Coil Cleaning Sprayer (Pump-up):** A pump-up sprayer was selected for applying coil cleaner to condenser and evaporator coils. Pump-up sprayers provide low-pressure, controlled application of cleaning solutions, preventing damage to delicate coil fins. The sprayer was equipped with an adjustable nozzle for different spray patterns.
- **Brazing Torch and Equipment (Oxy-acetylene):** An oxy-acetylene brazing torch set was used for brazing the simulated refrigerant line leak. Oxy-acetylene brazing provides high heat output and precise flame control, essential for achieving strong and reliable brazed joints in copper refrigerant lines. Necessary safety equipment, including welding gloves and goggles, were used during brazing operations.
- **Torque Wrench Set (5-50 Nm):** A torque wrench set with a range of 5-50 Nm (Newton-meters) was selected for tightening refrigerant line flare nut connections to manufacturer-specified torque values. Using a torque wrench ensures proper tightening of flare nuts, preventing both leaks from under-tightening and damage to fittings from over-tightening. The set included various socket sizes to accommodate different flare nut sizes.
- **Hand Tools (Standard Set):** A standard set of hand tools, including screwdrivers (Phillips and flat-head), wrenches (adjustable and open-end), pliers (slip-joint and

needle-nose), wire strippers, and cutters, were used for disassembly and reassembly of the AC unit. These tools are essential for general HVAC/R service and repair work.

- **Performance Testing Equipment:**
    - **Cooling Capacity Meter - AEMC Instruments CL800:** The AEMC Instruments CL800 cooling capacity meter was selected for its ability to directly measure the cooling capacity of air conditioning systems in real-time. This device measures airflow, temperature difference across the evaporator coil, and calculates cooling capacity in BTU/hr or kW. The CL800 is calibrated to industry standards and provides accurate measurements of cooling output. Calibration certificates for the CL800 were assumed to be valid and traceable to national standards.
    - **Power Meter - Yokogawa WT310 (Digital):** The Yokogawa WT310 digital power meter was chosen for its high accuracy (0.1% of reading), wide frequency range (DC to 100 kHz), and ability to measure various electrical parameters, including voltage, current, power, power factor, and energy consumption. The WT310 is a precision power meter suitable for laboratory-grade measurements and provides highly accurate readings of electrical power consumption of the AC unit. Calibration of the Yokogawa WT310 was assumed to be current and traceable.
    - **Anemometer - Testo 417 (Digital, Vane Anemometer):** The Testo 417 digital vane anemometer was selected for its accuracy in measuring air velocity and volume flow. Vane anemometers are suitable for measuring airflow at air outlets and ducts. The Testo 417 has a measurement range of 0.3 to 20 m/s and an accuracy of ±0.03 m/s + 1.5% of measured value. Airflow rate was calculated by multiplying the measured air velocity by the area of the indoor unit air outlet.
    - **Psychrometer - Vaisala HM70 (Digital, Handheld):** The Vaisala HM70 handheld digital psychrometer was chosen for its high accuracy and

reliability in measuring humidity, temperature, and dew point. The HM70 utilizes capacitive humidity sensors and platinum resistance thermometers, providing precise measurements of dry-bulb and wet-bulb temperatures required for psychrometric calculations. The accuracy for temperature measurement is ±0.2°C and for relative humidity is ±1% RH.

3.2 Method of Refurbishment

The refurbishment process was meticulously executed within a controlled workshop environment, adhering to a systematic and detailed step-by-step approach. Stringent safety precautions were observed throughout, including mandatory use of personal protective equipment (PPE) and strict compliance with refrigerant handling regulations and guidelines from organizations such as OSHA and EPA.

3.2.1 Preliminary Inspection and Diagnosis (Expanded):

1. **Initial Performance Assessment (30 minutes run time):** The split AC unit was operated in cooling mode for a minimum of 30 minutes to allow the system to stabilize and reach steady-state operating conditions. During this period, subjective assessments were made regarding cooling effectiveness (qualitative judgment of air temperature at the outlet), airflow (strength of air stream from the indoor unit), and noise levels (audible anomalies from both indoor and outdoor units). These initial observations provided a baseline for comparison after refurbishment.
2. **Electrical Safety Check (Power Disconnection, Multimeter):** Prior to any physical inspection or disassembly, electrical power to the AC unit was completely disconnected at the main power supply to ensure technician safety. A Fluke 179 multimeter was used to verify the absence of voltage at the unit's electrical terminals. Grounding continuity was tested to confirm proper grounding of all metallic parts of both indoor and outdoor units, ensuring protection against electrical shock. Wiring insulation was inspected visually for any signs of damage, cracking, or fraying. Terminal connections were checked for tightness and corrosion. These

checks were performed in accordance with IEC 60335-2-40 safety standards for household and similar electrical appliances.

3. **Visual Inspection (Indoor and Outdoor Units, Photographic Documentation):** A detailed visual inspection was conducted on both the indoor and outdoor units, both externally and internally after removing access panels. Specific attention was paid to:
    - **Physical Damage:** Inspection for dents, cracks, or deformation of unit casings, coil fins, fan blades, and refrigerant lines.
    - **Corrosion:** Examination for rust or corrosion on coils, cabinets, and structural components, particularly on the outdoor unit exposed to weather elements.
    - **Refrigerant Leaks (Oil Stains):** Careful observation for oil stains around refrigerant line connections, valves, and components, which are indicative of refrigerant leaks as refrigerant oil often escapes with the refrigerant.
    - **Coil Fouling:** Assessment of dust and debris accumulation on condenser and evaporator coils, visually estimating the degree of fouling.
    - **Filter Condition:** Inspection of air filters for dirt loading, discoloration, and physical integrity.
    - **Wiring Condition:** Detailed inspection of wiring insulation, terminal connections, and overall wiring harness condition. All visual observations were meticulously documented with photographs using a digital camera to create a visual record of the unit's pre-refurbishment condition.
4. **Refrigerant Pressure Measurement (Manifold Gauge Set, R-410A):** Using the Testo 557s digital manifold gauge set, suction (low-side) and discharge (high-side) pressures were measured while the AC unit was operating in cooling mode and had reached a stable operating condition (after approximately 15-20 minutes of operation). These pressure readings were recorded and compared to the manufacturer's specifications (if available) or typical operating pressure ranges for R-410A systems under the given ambient conditions. Deviations from expected

pressures can indicate refrigerant charge issues (undercharge or overcharge), compressor inefficiency, or restrictions in the refrigerant circuit.

5. **Temperature Measurements (Infrared Thermometer, Component Surface Temperatures):** Surface temperatures of key components were measured using the Fluke 62 MAX+ infrared thermometer to identify abnormal temperature profiles. Measurements included:
   - **Compressor Housing Temperature:** Elevated compressor temperature can indicate overheating, inefficiency, or motor issues.
   - **Condenser Coil Inlet and Outlet Temperatures:** Temperature difference across the condenser coil indicates heat rejection efficiency.
   - **Evaporator Coil Inlet and Outlet Temperatures:** Temperature difference across the evaporator coil indicates heat absorption and cooling effectiveness.
   - **Refrigerant Line Temperatures (Suction and Liquid Lines):** Abnormal line temperatures can indicate refrigerant charge issues or restrictions. These temperature readings provided further diagnostic information about component performance and system operation.
6. **Electrical Component Testing (Multimeter, Capacitance Measurement, Contactor Inspection):** Electrical components, particularly capacitors and contactors, were tested for proper function using the Fluke 179 multimeter and visual inspection:
   - **Capacitor Testing:** Capacitance values of the compressor run capacitor and fan motor start capacitor were measured using the multimeter's capacitance measurement function. Measured values were compared to the nominal capacitance values printed on the capacitors. Significant deviations (typically >10% below nominal) indicate capacitor degradation and the need for replacement. ESR (Equivalent Series Resistance) was qualitatively assessed; high ESR also indicates capacitor degradation.

- **Contactor Inspection:** Contactors were visually inspected for contact wear, pitting, or corrosion on the electrical contacts. Contactor coil continuity was tested using the multimeter's continuity function to check for coil burnout. Mechanical operation of the contactor was checked for smooth movement and proper contact closure.
- **Fan Motor Testing:** Fan motors (condenser and evaporator fan motors) were checked for winding continuity using the multimeter to rule out winding burnout. Fan bearings were manually checked for excessive play or roughness, indicating bearing wear. Unusual noise during manual fan blade rotation was also noted.

7. **Leak Detection (Electronic Leak Detector, R-410A Sensitivity):** An Inficon Tek-Mate electronic leak detector, specifically sensitive to R-410A refrigerant, was used to systematically scan all refrigerant line connections (flare nuts, brazed joints), valves, and component housings (compressor, condenser, evaporator) for refrigerant leaks. The leak detector's probe was moved slowly along each potential leak point, and the detector's audible and visual alarms were monitored for leak indication. Any detected leaks were clearly marked with tape for subsequent repair.
8. **Filter Inspection (Visual Assessment of Dirt Loading):** Air filters in the indoor unit were visually inspected to assess the level of dirt and dust accumulation. Filters were removed from their housings for closer examination. Heavily soiled filters, exhibiting significant dust loading and discoloration, were deemed in need of replacement. Filter type and dimensions were noted for procuring replacement filters.

3.2.2 Disassembly and Component Cleaning (Expanded):

1. **Refrigerant Recovery (Recovery Machine, AHRI Guideline K):** Using the CPS Pro-Set TR21 refrigerant recovery machine, the remaining R-410A refrigerant in the split AC system was carefully recovered. Recovery procedures strictly adhered

to AHRI Guideline K for refrigerant recovery, recycling, and reclamation. The recovery process involved:

- Connecting the recovery machine to the high-side and low-side service ports of the AC unit using appropriate hoses.
- Setting the recovery machine to the R-410A refrigerant setting.
- Initiating the recovery process, allowing the machine to draw refrigerant from both sides of the system.
- Monitoring the system pressure using the manifold gauge set to ensure that the system pressure was reduced to a deep vacuum (typically below 5 inches of mercury vacuum).
- Continuing the recovery process until the recovery machine indicated that recovery was complete and the system was under vacuum.
- Weighing the recovered refrigerant using a calibrated refrigerant scale to quantify the amount of recovered refrigerant (recorded as 1.8 kg).
- Storing the recovered refrigerant in a dedicated, properly labeled recovery cylinder.
- Documenting the refrigerant recovery process, including date, refrigerant type, recovered quantity, and machine used.

2. **Unit Disassembly (Systematic Approach, Photographic Documentation, Component Labeling):** Disassembly of the indoor and outdoor units was performed in a systematic and organized manner to facilitate efficient reassembly. The disassembly process involved:
    - **Outdoor Unit Disassembly:**
        - Removing the outer casing panels of the outdoor unit, carefully unscrewing and setting aside fasteners.
        - Disconnecting electrical wiring to the fan motor, compressor, and other electrical components, labeling each wire and terminal connection with tape and marker for correct re-wiring.

        - Removing the condenser fan assembly (fan blade and motor) after disconnecting wiring and unbolting mounting brackets.
        - Disconnecting refrigerant lines from the compressor and condenser coil, capping open line ends to prevent contamination.
        - Removing the compressor from its mounting base after disconnecting electrical connections and refrigerant lines.
        - Separating the condenser coil assembly from the outdoor unit chassis.
        - Removing the control box containing electrical components (capacitors, contactors, terminal blocks).
    - **Indoor Unit Disassembly:**
        - Removing the front grille and air discharge louvers of the indoor unit.
        - Removing the air filters and setting them aside for replacement.
        - Removing the indoor unit casing panels, exposing internal components.
        - Disconnecting electrical wiring to the fan motor, thermistors, and other sensors, labeling wires and terminals.
        - Removing the evaporator fan assembly (blower wheel and motor).
        - Disconnecting refrigerant lines from the expansion valve and evaporator coil, capping open line ends.
        - Separating the evaporator coil assembly from the indoor unit chassis.
        - Removing the expansion valve and distributor assembly.
        - Removing the control board and wiring harness. Throughout the disassembly process, photographs were taken at each stage to document component locations and wiring configurations, aiding in accurate reassembly. Removed components were labeled with numbered tags or markers to ensure correct placement during reassembly. Fasteners were organized and stored in labeled containers to prevent loss.

3. **Coil Cleaning (Condenser and Evaporator, Non-Acidic Cleaner, Low-Pressure Sprayer, Fin Combs):** Condenser and evaporator coils were thoroughly cleaned to remove accumulated fouling and restore heat transfer efficiency. The cleaning process involved:
    - **Preparation:** Positioning the coils in a well-ventilated area and protecting surrounding surfaces from overspray.
    - **Cleaner Application:** Applying Nu-Calgon Evap-Fresh No Rinse non-acidic coil cleaner to both sides of the condenser and evaporator coils using a pump-up sprayer. The cleaner was sprayed evenly, ensuring complete coverage of all coil surfaces.
    - **Dwell Time:** Allowing the coil cleaner to dwell on the coils for approximately 15 minutes, as per manufacturer's instructions, to allow the cleaner to penetrate and loosen fouling.
    - **Rinsing (Optional, Minimal Water):** While Evap-Fresh is a "No Rinse" cleaner, a light rinse with clean water using the low-pressure sprayer was performed to remove loosened debris and cleaner residue, ensuring optimal coil cleanliness. Water usage was minimized to prevent excessive moisture.
    - **Fin Straightening:** After cleaning and rinsing, fin combs were used to carefully straighten any bent or damaged fins on both condenser and evaporator coils. Straightening fins restores airflow and maximizes heat transfer surface area. Different fin combs from the set were used to match the fin spacing of each coil.
    - **Drying:** Allowing the cleaned coils to air dry completely before reassembly to prevent moisture entrapment.
4. **Fan Cleaning (Indoor and Outdoor, Mild Detergent, Water Solution):** Fan blades and fan housings of both indoor and outdoor units were cleaned to remove dust and debris, ensuring balanced fan operation and optimal airflow. The cleaning process involved:

- **Removal:** Removing fan blades from fan motors (typically secured with screws or set screws).
- **Cleaning Solution:** Preparing a mild detergent and water solution.
- **Washing:** Washing fan blades and fan housings with the detergent solution using a soft brush or cloth to remove dust, dirt, and grease.
- **Rinsing:** Rinsing fan blades and housings thoroughly with clean water to remove detergent residue.
- **Drying:** Allowing fan blades and housings to air dry completely before reassembly.

5. **Filter Housing Cleaning (Indoor Unit, Dust and Mold Removal):** The air filter housing in the indoor unit was cleaned to remove accumulated dust and potential mold growth, ensuring hygienic operation. The cleaning process involved:
    - **Vacuuming:** Vacuuming the filter housing interior to remove loose dust and debris.
    - **Wiping:** Wiping down the interior surfaces of the filter housing with a damp cloth and mild detergent solution to remove any remaining dust or mold. For mold removal, a mild bleach solution (diluted bleach in water) can be used cautiously, followed by thorough rinsing with clean water and drying.
    - **Drying:** Ensuring the filter housing is completely dry before installing new air filters.
6. **Component Inspection Post-Cleaning (Visual Inspection for Corrosion, Damage):** After cleaning all components, a detailed visual inspection was performed again to identify any remaining corrosion, damage, or defects that may have been obscured by dirt prior to cleaning. This post-cleaning inspection included:
    - **Coil Inspection:** Close examination of condenser and evaporator coils for any signs of corrosion, leaks (oil stains), or physical damage to tubes or headers.
    - **Component Housing Inspection:** Inspection of fan housings, compressor housing, and control box for cracks, corrosion, or damage.

- **Wiring Inspection:** Re-inspection of wiring harnesses for any damage to insulation, loose connections, or corrosion at terminals.
- **Fastener Inspection:** Checking fasteners (screws, bolts) for corrosion or damage, replacing any damaged fasteners as needed. Any identified issues during this post-cleaning inspection were addressed during the repair and replacement phase.

3.2.3 Repair and Replacement of Components:

1. **Capacitor Replacement (Compressor Run and Fan Motor Start, Identical Specifications):** Based on the initial diagnostic testing, the compressor run capacitor (45 µF) and the outdoor fan motor start capacitor (5 µF) were identified as degraded (capacitance values below specification). These capacitors were replaced with new capacitors of identical specifications (45+5 µF, 440 VAC) procured. The replacement process involved:
    - **Discharging Capacitors:** Before handling, capacitors were safely discharged using a capacitor discharge tool or by shorting the terminals with an insulated screwdriver to prevent electrical shock.
    - **Disconnecting Wiring:** Disconnecting electrical wires from the terminals of the old capacitors, noting wire positions for correct re-wiring.
    - **Removing Old Capacitors:** Removing the old capacitors from their mounting brackets or clips.
    - **Installing New Capacitors:** Installing the new capacitors in the same mounting locations.
    - **Reconnecting Wiring:** Reconnecting electrical wires to the terminals of the new capacitors, ensuring correct wire positions based on notes taken during disassembly.
    - **Securing Connections:** Ensuring all electrical connections were clean and securely tightened.

2. **Refrigerant Leak Repair (Flare Nut Tightening, Leak Sealant, Brazing Simulated Leak, Nitrogen Purging):** Refrigerant leaks were addressed using a combination of techniques:
    - **Flare Nut Tightening and Leak Sealant:** Minor refrigerant leaks detected at flare nut connections were initially addressed by tightening the flare nuts using a torque wrench to the manufacturer-recommended torque specifications. After tightening, Super Seal Ultra refrigerant leak sealant was applied to the flare nut connections as an additional measure to seal any remaining leaks.
    - **Simulated Brazing Repair (Refrigerant Line):** For demonstration purposes, a hypothetical minor leak on a refrigerant line was simulated by creating a small pinhole using a pin vise. This simulated leak was then repaired by brazing, following standard brazing procedures:
        - **Preparation:** Cleaning the area around the simulated leak on the refrigerant line using emery cloth to remove paint and oxidation, ensuring clean metal for brazing.
        - **Nitrogen Purging:** Initiating a low-flow nitrogen purge through the refrigerant line to prevent oxidation inside the pipe during brazing. Nitrogen was flowed continuously throughout the brazing process.
        - **Heating and Brazing:** Heating the joint area with an oxy-acetylene brazing torch to the appropriate brazing temperature (reddish glow of the copper pipe). Applying phosphorus-copper brazing rod and flux to the heated joint, allowing the brazing alloy to flow and fill the pinhole and create a sealed joint.
        - **Cooling:** Allowing the brazed joint to air cool naturally while continuing the nitrogen purge for a short period.
        - **Leak Testing Brazed Joint:** After cooling, the brazed joint was leak tested using an electronic leak detector to verify the integrity of the repair.

        - **Insulation:** Re-insulating the brazed section of the refrigerant line with Armacell Armaflex insulation tape to restore thermal insulation.
3. **Filter Replacement (Air Filters, MERV 8):** Used air filters were replaced with new MERV 8 filters of the correct dimensions (300mm x 300mm x 25mm). The replacement process involved:
    - **Removing Used Filters:** Carefully removing the used air filters from the filter housing, noting their orientation for correct installation of new filters.
    - **Installing New Filters:** Inserting the new MERV 8 filters into the filter housing, ensuring correct orientation and proper seating within the housing.
4. **Wiring Inspection and Repair (Damaged Wiring Replacement, Connection Cleaning):** Wiring within both indoor and outdoor units was thoroughly inspected for any signs of damage, fraying, or loose connections. The inspection and repair process involved:
    - **Visual Inspection:** Detailed visual inspection of all wiring harnesses, individual wires, and terminal connections for damage to insulation (cracks, cuts, abrasions), fraying of wire strands, and loose or corroded terminal connections.
    - **Wiring Replacement:** Any wires with damaged insulation or frayed strands were replaced with new wires of the same gauge, type (stranded copper), and insulation rating. Wire replacements were made by cutting out the damaged section and splicing in a new wire section using crimp connectors or soldering and heat shrink tubing, ensuring secure and insulated connections.
    - **Connection Cleaning:** All electrical terminal connections were cleaned using electrical contact cleaner spray (CRC Lectra-Motive) to remove any oxidation or corrosion. Terminal connections were then tightened to ensure good electrical contact.
5. **Component Lubrication (Fan Motor Bearings, Suitable Lubricant):** Accessible moving parts, specifically fan motor bearings (both condenser and evaporator fan motors, if equipped with grease fittings or accessible bearings), were lubricated to

reduce friction and noise and extend bearing lifespan. Lubrication was performed using a suitable electric motor bearing grease or light machine oil, applying a small amount of lubricant to each bearing point. Over-lubrication was avoided. If fan motors were sealed units without grease fittings, lubrication was not performed.

3.2.4 Reassembly and System Checks:

1. **Unit Reassembly (Reverse Disassembly Order, Torque Wrenches, Component Securing):** Reassembly of the split AC unit was performed systematically, following the reverse order of disassembly and utilizing the photographic documentation and component labels created during disassembly. Key aspects of reassembly included:
    - **Component Placement:** Carefully positioning and securing each component in its original location, ensuring proper alignment and orientation.
    - **Wiring Reconnection:** Reconnecting all electrical wiring according to the labels and photographs taken during disassembly, ensuring correct wire routing and secure terminal connections.
    - **Fastener Tightening:** Tightening all screws, bolts, and fasteners securely, but avoiding over-tightening to prevent damage to components or housings.
    - **Refrigerant Line Connection (Flare Nuts, Torque Specifications):** Reconnecting refrigerant lines at flare nut connections, ensuring clean flare surfaces and proper alignment. Flare nuts were tightened using a torque wrench to the manufacturer-recommended torque specifications for the flare nut size to ensure leak-tight seals without damaging flare fittings. Torque specifications were typically obtained from manufacturer's service manuals or industry standard torque charts for flare fittings.
2. **Pressure Testing (Nitrogen, 300 psi, 24-hour Monitoring):** After reassembly of the refrigerant circuit, a nitrogen pressure test was performed to verify the leak

tightness of the entire system before refrigerant charging. The pressure testing procedure involved:

- **Pressurizing System:** Pressurizing the entire refrigerant circuit with dry nitrogen gas to a pressure of 300 psi (pounds per square inch) using a nitrogen regulator. Pressure was introduced slowly and gradually to avoid pressure shocks.
- **Pressure Stabilization:** Allowing the system pressure to stabilize for approximately 30 minutes to account for temperature equalization.
- **Leak Check (Soap Bubbles, Electronic Leak Detector):** Checking all refrigerant line connections, brazed joints, and component housings for leaks using soap bubble solution and an electronic leak detector. Soap bubbles were applied to all connections, and any bubble formation indicated a leak. The electronic leak detector was used to confirm and pinpoint any suspected leaks. Any leaks detected were addressed by further tightening connections or re-brazing joints as needed, and the pressure test was repeated after repairs.
- **Pressure Monitoring (24 hours):** After confirming no initial leaks, the system pressure was monitored for a period of 24 hours using the manifold gauge set. Pressure readings were recorded at the beginning and end of the 24-hour period. A pressure drop of more than a few psi (e.g., >5 psi) over 24 hours would indicate a leak, requiring further investigation and repair. In this project, no pressure drop was observed after 24 hours, confirming the leak tightness of the system.

3. **Evacuation (Vacuum Pump, 500 Microns, 2-hour Hold, Vacuum Monitoring):** Following successful pressure testing, the refrigerant circuit was evacuated using the Fieldpiece VP85 two-stage vacuum pump to remove moisture, air, and other non-condensable gases from the system. The evacuation process involved:
    - **Connecting Vacuum Pump:** Connecting the vacuum pump to the system service ports using vacuum-rated hoses.

- **Initiating Evacuation:** Starting the vacuum pump and opening service valves to evacuate the entire refrigerant circuit.
- **Vacuum Level Monitoring (Digital Manifold Gauge):** Continuously monitoring the vacuum level using the digital manifold gauge set. Evacuation was continued until the vacuum level reached 500 microns (0.5 Torr) or lower.
- **Vacuum Hold Test (2 hours):** Once the target vacuum level was achieved, the vacuum pump was isolated from the system by closing manifold valves, and the vacuum level was monitored for a period of 2 hours. A rise in vacuum pressure during the hold test (e.g., >100 microns increase) would indicate the presence of leaks or residual moisture in the system, requiring further evacuation or leak investigation. In this project, the vacuum level remained stable below 600 microns during the 2-hour hold test, indicating successful evacuation.

4. **Refrigerant Charging (Recovered Refrigerant, Virgin R-410A, Manufacturer Specifications, Liquid Charging, Fine-Tuning):** After successful evacuation, the AC system was charged with refrigerant. The charging process involved:
    - **Recovered Refrigerant Charging (1.8 kg):** Initially, the recovered refrigerant (1.8 kg), which was hypothetically assumed to be clean and of acceptable quality, was charged back into the system. The recovery cylinder containing the recovered refrigerant was connected to the high-side service port of the AC unit. Refrigerant was charged in the liquid phase by inverting the refrigerant cylinder and slowly opening the cylinder valve, allowing liquid refrigerant to flow into the system under vacuum. Refrigerant charging was monitored using a calibrated refrigerant scale to ensure accurate charging quantity.
    - **Virgin Refrigerant Supplement (0.2 kg):** To reach the manufacturer-recommended total refrigerant charge of 2.0 kg, virgin R-410A refrigerant was supplemented. A new cylinder of virgin R-410A was connected, and an

additional 0.2 kg of refrigerant was charged into the system, again in the liquid phase and monitored using the refrigerant scale.

    - **Fine-Tuning Charge (Operating in Cooling Mode):** After initial charging, the AC unit was operated in cooling mode, and the refrigerant charge was fine-tuned based on system performance and operating parameters. Subcooling and superheat measurements were ideally used to optimize the refrigerant charge, although for this project, charging was primarily based on weight. Suction and discharge pressures were monitored during operation to ensure they were within normal operating ranges. Refrigerant charging was adjusted if needed, to optimize cooling performance and energy efficiency.

5. **Electrical Checks Post-Reassembly (Safety Checks, Wiring Verification):** After reassembly and refrigerant charging, final electrical safety checks were repeated to ensure proper wiring and grounding and to verify that no electrical hazards were introduced during the refurbishment process. These checks included:
    - **Grounding Continuity Test:** Re-verifying grounding continuity of all metallic parts of both indoor and outdoor units using a multimeter.
    - **Wiring Insulation Check:** Re-inspecting all wiring connections and wiring runs to ensure no wires were pinched, damaged, or in contact with sharp edges during reassembly.
    - **Terminal Connection Tightness:** Re-checking tightness of all electrical terminal connections to ensure secure and reliable electrical contacts.
    - **Voltage and Current Measurements (Initial Start-up):** Upon initial start-up of the refurbished unit, voltage and current readings were measured using the clamp meter and multimeter to verify proper electrical operation of the compressor, fan motors, and other electrical components, and to check for any abnormal electrical conditions (e.g., overcurrent, undervoltage).

3.2.5 Performance Testing and Evaluation:

1. **Post-Refurbishment Performance Assessment (1-hour Stabilization, Controlled Ambient Conditions):** After refurbishment and refrigerant charging, the split AC unit was operated in cooling mode for at least 1 hour to allow the system to stabilize and reach steady-state operating conditions before performance measurements were taken. Performance testing was conducted under controlled ambient conditions of 27°C Dry Bulb temperature and 50% Relative Humidity, maintained within a climate-controlled laboratory or test chamber. These controlled conditions ensured consistent and repeatable performance measurements. Ambient conditions were monitored using the Vaisala HM70 psychrometer and maintained throughout the testing period.
2. **Cooling Capacity Measurement (Cooling Capacity Meter, ISO 5151):** Cooling capacity was measured using the calibrated AEMC Instruments CL800 cooling capacity meter, following the manufacturer's instructions and adhering to standard testing procedures outlined in ISO 5151 (Air conditioners and heat pumps - Testing and rating for performance). The measurement process involved:
    - **Sensor Placement:** Positioning the CL800's airflow sensor at the indoor unit air outlet to measure airflow rate. Positioning temperature sensors at the air inlet and outlet of the indoor unit to measure the temperature difference across the evaporator coil.
    - **Data Logging:** Activating the CL800's data logging function to record airflow rate and temperature difference measurements over a period of at least 15-20 minutes of steady-state operation. Data logging frequency was set to 1-minute intervals.
    - **Cooling Capacity Calculation (CL800):** The CL800 automatically calculated the cooling capacity in BTU/hr or kW based on the measured airflow rate and temperature difference, using pre-programmed psychrometric algorithms and air property data. The average cooling capacity over the data logging period was recorded.

    - **Calibration Verification:** While direct calibration of the CL800 was not performed in this project, it was assumed that the instrument was recently calibrated and its calibration was traceable to national standards, as is typical for calibrated measuring instruments. Manufacturer's stated accuracy specifications for the CL800 were considered for assessing measurement uncertainty.

3. **Power Consumption Measurement (Digital Power Meter, Steady-State Operation):** Electrical power consumption of the AC unit was measured using the Yokogawa WT310 digital power meter during steady-state cooling operation. The measurement process involved:
    - **Power Meter Connection:** Connecting the Yokogawa WT310 power meter in-line with the power supply to the outdoor unit, measuring the total power consumed by both indoor and outdoor units. Voltage and current probes were connected according to the power meter's instructions.
    - **Data Logging:** Activating the power meter's data logging function to record power consumption (in Watts or kW), voltage (Volts), and current (Amps) over a period of at least 15-20 minutes of steady-state operation, synchronized with the cooling capacity measurements. Data logging frequency was set to 1-minute intervals.
    - **Average Power Consumption Calculation (WT310):** The average power consumption over the data logging period was calculated from the recorded data.
    - **Calibration Verification:** Calibration of the Yokogawa WT310 was assumed to be current and traceable, based on typical calibration practices for precision power meters. Manufacturer's stated accuracy specifications for the WT310 were considered for assessing measurement uncertainty.

4. **Airflow Measurement (Anemometer, Outlet Grille, Averaging):** Air velocity at the indoor unit air outlet was measured using the Testo 417 digital vane anemometer to estimate airflow rate. The measurement process involved:

- **Outlet Grille Area Measurement:** Measuring the dimensions of the indoor unit air outlet grille to calculate the outlet area.
- **Velocity Traverse:** Performing a velocity traverse across the outlet grille by dividing the grille area into a grid of equal sections (e.g., 3x3 grid) and measuring air velocity at the center of each section using the anemometer. The anemometer vane was held perpendicular to the airflow direction for each measurement.
- **Average Velocity Calculation:** Calculating the average air velocity by averaging the velocity readings from all grid sections.
- **Airflow Rate Estimation:** Estimating the airflow rate (in m^3/hr or CFM) by multiplying the average air velocity by the outlet grille area. Airflow rate = Average Velocity x Outlet Area. Units were converted as needed (m/s to m/min, m^2 to m^2, min to hr).

5. **Temperature and Humidity Measurements (Psychrometer, Inlet and Outlet):** Dry-bulb and wet-bulb temperatures of the air entering and leaving the indoor unit were measured using the Vaisala HM70 digital psychrometer to determine air conditions and calculate indoor relative humidity. Measurements were taken at:
    - **Indoor Unit Air Inlet:** Positioning the psychrometer sensor at the air inlet of the indoor unit to measure the temperature and humidity of the air entering the evaporator coil.
    - **Indoor Unit Air Outlet:** Positioning the psychrometer sensor at the air outlet of the indoor unit to measure the temperature and humidity of the cooled air leaving the evaporator coil.
    - **Data Recording:** Recording dry-bulb and wet-bulb temperature readings at both inlet and outlet locations after allowing the psychrometer readings to stabilize.

- **Relative Humidity Calculation:** Calculating relative humidity at both inlet and outlet conditions using psychrometric charts or online psychrometric calculators, based on the measured dry-bulb and wet-bulb temperatures.

6. **EER/COP Calculation (Equations 3.1 and 3.2):** Energy Efficiency Ratio (EER) and Coefficient of Performance (COP) were calculated using the measured cooling capacity and power consumption data, using Equations 3.1 and 3.2 as presented in Chapter Three:

   EER=Cooling Capacity (BTU/hr)Power Consumption (Watts) (3.1)

   COP=Cooling Capacity (kW)Power Consumption (kW) (3.2)

   Cooling capacity was converted to BTU/hr for EER calculation and used in kW for COP calculation. Power consumption was used in Watts for EER and converted to kW for COP. Calculations were performed using spreadsheet software to ensure accuracy.

7. **Performance Data Comparison (Pre- and Post-Refurbishment, Percentage Improvements):** Post-refurbishment performance data (cooling capacity, power consumption, EER/COP, airflow rate, refrigerant leak rate) were systematically compared to the pre-refurbishment performance data obtained during the initial diagnostic phase. Percentage improvements for each performance metric were calculated using the following formula:

   Percentage Improvement=(Post−Refurbishment Value−Pre−Refurbishment Value) Pre−Refurbishment Value×100% (3.3)

   Calculated percentage improvements were presented in Chapter Four: Results and Discussion to quantify the effectiveness of the refurbishment process. Where available, post-refurbishment performance data were also qualitatively compared to manufacturer's specifications for a new unit of the same model or similar models to assess the degree of performance restoration achieved through refurbishment.

3.3 Expected Results and Performance Metrics

As previously stated in Section 3.3 of the original Chapter Three, it was anticipated that the refurbishment process would yield measurable improvements in the split air conditioning unit's performance. The key performance metrics used to evaluate the success of the refurbishment, and their expected trends, are reiterated below for clarity:

- **Cooling Capacity (kW or BTU/hr):** Expected to increase significantly after refurbishment due to enhanced heat transfer from coil cleaning, resolution of refrigerant leaks, and restoration of optimal refrigerant charge.
- **Power Consumption (kW):** Expected to decrease or remain stable after refurbishment, despite the anticipated increase in cooling capacity, indicating improved energy efficiency.
- **Energy Efficiency Ratio (EER) / Coefficient of Performance (COP):** Expected to exhibit a substantial increase after refurbishment, reflecting the combined positive effects of improved cooling capacity and reduced or stable power consumption.
- **Refrigerant Leak Rate (g/year):** Expected to be reduced to negligible levels (near zero) after leak repair and rigorous pressure testing of the refrigerant circuit.
- **Airflow Rate (m^3/hr or CFM):** Expected to improve after cleaning of fan blades and housings and replacement of clogged air filters, leading to enhanced air distribution and improved cooling effectiveness within the conditioned space.

These performance metrics, quantitatively measured and analyzed, formed the basis for evaluating the effectiveness of the refurbishment methodology and are presented and discussed in detail in Chapter Four: Results and Discussion.

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