RESEARCH ON THE DESIGN AND PRODUCTION OF TYPE IV COMPOSITE LPG CYLINDERS AND HOW THEY CAN BE IMPROVED

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CERTIFICATION

This is to certify that this project, Research on the Design and Production of Type IV Composite LPG cylinders and how they can be improved, was carried out by Nosakhare Ephraim AGHAHOWA ENG2002415, Osejiele Promise OKOYO ENG2002495, Uyiosa Abraham OSAKUE ENG2002505, Rasaki Osamende JIMOH ENG2002466, in the department of Mechanical Engineering, Faculty of Engineering, University of Benin.

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DEDICATION

This project is dedicated to God Almighty, whose guidance, wisdom, and grace made this work possible.
We also dedicate it to our parents and families, for their unwavering love, encouragement, and support throughout our academic journey.
Finally, this work is dedicated to all engineers and researchers striving to advance technology for a safer and more sustainable future.

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ABSTRACT

This study investigates the technology employed in the production of Type 4 Liquefied Petroleum Gas (LPG) composite cylinders and explores potential improvements to enhance their performance, safety, and cost-effectiveness. Type 4 cylinders, composed of a polymer liner fully wrapped with fiber-reinforced composites, represent the most advanced generation of LPG storage vessels due to their lightweight structure, corrosion resistance, and superior burst strength.

Data for the research were obtained through field observations at Don Mac Limited, review of standard operating procedures (SOPs), and engineering simulations. The study analyzed each stage of the production process—from liner molding and surface preparation to filament winding, curing, testing, and inspection—based on **ISO 11119-3** and **EN 12245** standards. Simulation results revealed that substituting high-density polyethylene (HDPE) liners with **polyamide (PA11)** and E-glass fibers with **hybrid carbon–glass reinforcements** increased burst pressure from 50 bar to 70 bar while maintaining a high factor of safety.

Identified challenges include high material costs, liner gas permeability, and limited local production capacity. To address these, the research proposes the adoption of **nano-filled epoxy resins**, **automated filament winding systems**, and **locally sourced high-performance polymers** to optimize strength and reduce cost. These improvements will advance the development of composite cylinder manufacturing in Nigeria, enabling safer, lighter, and more sustainable LPG storage solutions.

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CHAPTER ONE

INTRODUCTION

Liquefied Petroleum Gas (LPG) has become one of the most important sources of clean energy worldwide, providing fuel for domestic cooking, heating, automotive applications, and various industrial processes (World LPG Association, 2021). With the growing global emphasis on energy efficiency, safety, and environmental protection, the storage and transportation of LPG demand innovative and reliable containment solutions. Traditionally, steel cylinders have been used for this purpose, but their disadvantages, such as heavy weight, susceptibility to corrosion, and relatively high maintenance requirements, have created the need for more advanced technologies (Mertiny & Gold, 2018).

The introduction of composite cylinders represents a significant technological advancement in pressure vessel design. Among these, Type 4 LPG composite cylinders have emerged as the most advanced, owing to their lightweight nature, corrosion resistance, high fatigue life, and improved safety profile (Peters, 2018). Type 4 cylinders are fully composite pressure vessels with a polymer liner, usually polyethylene or polyamide, that is completely wrapped in fiber-reinforced polymer such as carbon fiber or glass fiber with epoxy resin. This unique combination of materials results in cylinders that are up to 70% lighter than steel, easier to handle, and more resistant to environmental degradation (Messager et al., 2016).

However, despite their advantages, the technology faces challenges that limit widespread adoption, especially in developing countries. High production costs, limited local manufacturing capacity, liner permeability concerns, and recycling difficulties remain key barriers (Kumar & Bhatnagar, 2020). This study, therefore, seeks to investigate the technology used to produce Type 4 LPG composite cylinders and examine how these challenges can be mitigated through improved design, manufacturing techniques, and material selection.

1.1 Background Of The Study

The evolution of LPG cylinders can be broadly classified into four types (Mertiny & Gold, 2018). Type 1 cylinders are fully metallic, traditionally manufactured from steel or aluminum, and although reliable, they are heavy and prone to corrosion. Type 2 cylinders consist of metal cylinders reinforced with hoop-wrapped fiber composites, which reduce weight but retain much of the mass of the metallic core. Type 3 cylinders introduced fully composite overwraps with metallic liners, resulting in further weight reduction but still retaining metallic elements that may corrode. Finally, Type 4 cylinders, which represent the state-of-the-art in LPG containment technology, are manufactured with polymer liners fully wrapped with fiber composites, making them the lightest and most corrosion-resistant option (Peters, 2018).

The technology behind Type 4 cylinders involves advanced manufacturing processes such as filament winding, resin transfer molding, and precise curing methods (Cohen, 2017). The choice of materials is also critical: carbon fiber provides superior strength-to-weight ratio, while glass fiber offers cost advantages. The polymer liner ensures impermeability to LPG while maintaining flexibility and resistance to fatigue stresses (Messager et al., 2016).

In Nigeria, the demand for LPG has grown significantly due to government efforts to reduce reliance on firewood, kerosene, and other environmentally harmful energy sources (Emodi & Yusuf, 2021). However, the country remains heavily reliant on imported LPG cylinders, particularly advanced composite cylinders, due to limited local production. Companies such as Donmac Ltd. have begun initiatives to address this gap, yet there remains limited research and development into the optimization of Type 4 cylinders under local economic and climatic conditions. This study is therefore timely and necessary to address the gaps in technology adoption and improvement.

1.2 Statement Of The Problem

Although Type 4 LPG composite cylinders offer numerous advantages, their adoption remains limited due to several pressing challenges. Firstly, the cost of raw materials such as carbon fiber and epoxy resin, as well as the high level of technical expertise required for manufacturing, makes these cylinders expensive compared to traditional steel options (Kumar & Bhatnagar, 2020). Secondly, local production capacity is limited in many regions, including Nigeria, leading to dependency on imports that are not always economically sustainable (Emodi & Yusuf, 2021). Thirdly, there are concerns about the permeability of polymer liners and their compatibility with LPG under different climatic conditions, which may affect long-term safety (Messager et al., 2016). Fourthly, end-of-life disposal and recycling of composite materials remain unresolved, presenting an environmental concern (Witik et al., 2013).

Without significant improvements in production processes, material efficiency, and cost reduction, the widespread use of Type 4 LPG composite cylinders will remain constrained. It is therefore necessary to study the technology behind their production and explore avenues for innovation and improvement.

1.3 Aim And Objectives

The aim of this study is to critically examine the technology used in producing Type 4 LPG composite cylinders and to propose improvements that can enhance their performance, safety, and economic viability.

The objectives of the study are as follows:

1.To review the existing technological processes employed in the production of Type 4 LPG composite cylinders.

2.To identify the strengths and weaknesses of current materials and manufacturing techniques.
3.To investigate the challenges associated with cost, liner permeability, recycling, and local production capacity.
4.To propose improvements in materials, design, and production methods that can optimize performance and reduce costs.
5.To design and carry out engineering simulations that demonstrate potential improvements in cylinder design and production processes.
6.To recommend strategies for encouraging large-scale adoption in Nigeria and other developing countries.

1.4 Significance Of The Study

This study holds significance for multiple stakeholders. For the mechanical engineering field, it contributes to the knowledge of advanced composite pressure vessels and their engineering design considerations (Mertiny & Gold, 2018). For manufacturers, it provides insights into optimizing production processes and material selection in order to reduce costs while maintaining high safety standards (Cohen, 2017). For consumers, the findings encourage the adoption of safer, lighter, and more user-friendly cylinders that improve overall handling and safety (World LPG Association, 2021). Policymakers and energy regulators will also benefit from the study, as it provides evidence to support policies that promote local manufacturing, safety regulations, and sustainable energy practices (Emodi & Yusuf, 2021).

1.5 Scope Of The Study

The focus of this study is on Type 4 LPG composite cylinders, specifically their design, materials, and manufacturing technologies. The study examines their advantages over conventional steel and earlier composite types, while also addressing the challenges associated with their production and usage. Although comparisons will be made with Type 1, Type 2, and Type 3 cylinders for contextual understanding (Mertiny & Gold, 2018), the emphasis remains on the improvement of Type 4 cylinders. Other LPG storage systems, such as bulk tanks, pipelines, or non-pressurized containers, are outside the scope of this research.

1.6 Research Methodology

This research adopts a descriptive, analytical, and simulation-based methodology. Firstly, a comprehensive review of existing literature, including academic journals, technical reports, and manufacturer specifications, was conducted to establish a theoretical understanding of Type 4 cylinder production technology (Peters, 2018; Messager et al., 2016). Secondly, a comparative analysis between Type 4 cylinders and earlier generations was undertaken, with particular emphasis on material performance, manufacturing costs, and safety records (Mertiny & Gold, 2018).

Thirdly, a case study approach was employed through a visit to Donmac Ltd., a cylinder manufacturing company in Nigeria. This industrial exposure provided practical insights into the production processes, challenges faced in local manufacturing, and strategies currently being employed to overcome these limitations.

Fourthly, engineering simulations will be developed to model the mechanical performance of Type 4 LPG composite cylinders and to demonstrate how improvements in material selection, filament winding patterns, or liner design could enhance structural integrity, weight reduction, and gas retention. These simulations, often utilizing Finite Element Analysis (FEA), are a recognized method for optimizing composite pressure vessel design (Cohen, 2017).

Finally, expert consultations and informal interviews with engineers and industry practitioners were carried out to validate findings and provide recommendations for improvement.

1.7 Outline Of The Research Study

The research is structured into five chapters. Chapter One introduces the study by presenting the background, problem statement, aim and objectives, significance, scope, methodology, and outline of the report. Chapter Two presents a comprehensive literature review on LPG storage technologies, composite materials, and advanced manufacturing methods relevant to Type 4 cylinders. Chapter Three discusses the research methodology in detail, including data collection, case studies, and analytical approaches. Chapter Four presents the results, analysis, and discussion of findings, including proposed improvements to current technologies. Finally, Chapter Five concludes the study with a summary of findings, recommendations, and suggestions for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Liquefied Petroleum Gas (LPG) as an Energy Source

Liquefied Petroleum Gas (LPG) is a versatile energy carrier derived primarily as a by-product of crude oil refining and natural gas processing (IEA, 2022). Chemically, it consists mainly of propane (C_3H_8) and butane (C_4H_{10}), either individually or as a mixture in varying proportions depending on regional climatic conditions and usage requirements (WLPGA, 2021). At ambient temperature and moderate pressure, LPG exists in a liquid state, which allows large quantities of energy to be stored and transported in relatively small volumes. This property makes LPG particularly suitable for domestic, commercial, and industrial applications where portability, efficiency, and energy density are critical.

Globally, LPG has gained recognition as a transition fuel in the move towards cleaner energy systems (IEA, 2022). Unlike solid fuels such as coal and firewood, LPG burns with minimal soot, low particulate matter, and reduced greenhouse gas emissions. Its higher calorific value per unit mass compared to kerosene or firewood makes it not only environmentally preferable but also economically efficient in the long term (Rosenthal et al., 2018). For developing economies, the adoption of LPG has been directly linked to improvements in public health, as it reduces indoor air pollution caused by the combustion of traditional biomass fuels (Bruce et al., 2018).

In Nigeria and other African countries, LPG has emerged as a strategic fuel to bridge the gap between energy demand and environmental sustainability (Emodi & Yusuf, 2021). Government programs have increasingly encouraged households to switch from kerosene and firewood to LPG for cooking and heating, thereby addressing issues of deforestation, indoor smoke-related illnesses, and inefficient energy consumption. Despite this progress, the widespread adoption of LPG is still constrained by limited distribution infrastructure and the cost of safe and reliable storage cylinders (Emodi & Yusuf, 2021).

From a technical perspective, LPG possesses several properties that necessitate stringent storage and handling requirements. It is stored under moderate pressure, typically between 7 to 15 bar depending on temperature, which means that storage vessels must be designed to withstand repeated pressurization cycles without failure (Mertiny & Gold, 2018). Furthermore, LPG is highly flammable, and leaks can result in dangerous vapor clouds that may ignite explosively when mixed with air. This underscores the importance of robust and safe containment technologies (Peters, 2018).

Conventional steel cylinders have historically been the most common means of LPG storage and transportation. They are durable and relatively cheap to manufacture but are heavy, prone to corrosion, and difficult to handle (Kumar & Bhatnagar, 2020). These limitations often discourage households, especially in rural and low-income areas, from adopting LPG as a primary energy source. The introduction of composite LPG cylinders, particularly the advanced Type 4 designs, represents a major technological leap forward. By reducing weight, improving corrosion resistance, and enhancing safety performance, Type 4 cylinders have the potential to accelerate LPG adoption rates and expand its role as a sustainable energy source (Messager et al., 2016).

It is therefore evident that LPG, while already critical in the global and Nigerian energy mix, requires continued innovation in storage technology to fully realize its potential. The development and improvement of Type 4 LPG composite cylinders directly address the central challenge of safe, efficient, and user-friendly LPG storage, making them highly relevant to the future of energy systems (Peters, 2018).

2.2 Classification of LPG Cylinders

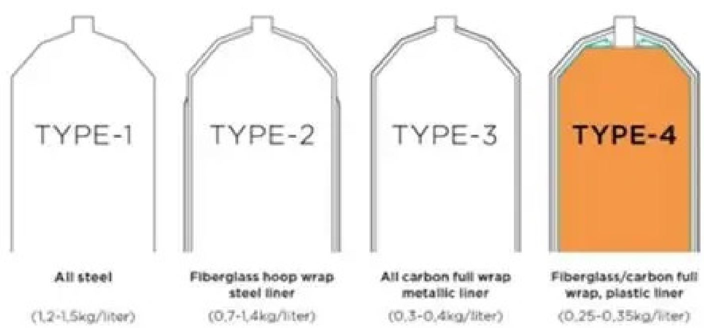

Figure 2.1: Classification of Gas Cylinders

The development of LPG cylinder technology reflects the progressive demand for safer, lighter, and more efficient storage solutions. Over time, innovations in materials science and pressure vessel design have led to four major categories of LPG cylinders, each representing a significant step forward from its predecessor (Mertiny & Gold, 2018). These classifications—Type 1 through Type 4—are widely recognized by international standards such as ISO 11119 and provide the framework for evaluating current and future technologies.

Figure 2.2: Type 1 Gas Cylinder

1. Type 1 Cylinders: Fully Metallic Cylinders

Type 1 cylinders are the earliest and most traditional form of LPG storage vessels. They are manufactured entirely from metals such as steel or aluminum, typically through processes such as hot rolling, deep drawing, forging, and welding (Peters, 2018). Steel Type 1 cylinders dominate the global market due to their durability, high strength, and relatively low production costs.

However, these cylinders have notable disadvantages. Their heavy weight makes them difficult to transport and handle, particularly for domestic users such as households and small businesses (Kumar & Bhatnagar, 2020). They are also prone to corrosion, especially in humid or coastal environments, which not only shortens their lifespan but also increases maintenance requirements (Mertiny & Gold, 2018). Furthermore, the need for periodic requalification, repainting, and valve replacement raises long-term ownership costs.

Despite these limitations, Type 1 cylinders remain in use worldwide, especially in developing regions, due to their low upfront cost and simple manufacturing process (WLPGA, 2021).

2. Type 2 Cylinders: Hoop-Wrapped Composite Cylinders

Figure 2.3: Type 2 Gas Cylinders

The second stage in the evolution of LPG storage introduced the Type 2 cylinder. In this design, the main body of the cylinder is a metallic liner, usually steel or aluminum, reinforced with composite fibers wrapped in the hoop (circumferential) direction (Mertiny & Gold, 2018). The composite overwrap, typically made from glass or carbon fibers embedded in resin, reduces weight by partially replacing the metallic structure.

Type 2 cylinders represent a compromise between traditional steel vessels and advanced composite designs. They offer moderate weight reduction compared to Type 1 while retaining much of the strength of a metallic base (Peters, 2018). However, since the metallic liner is still exposed in some regions, particularly at the domes, issues of corrosion remain unresolved. Additionally, the partial composite wrapping adds complexity to manufacturing while only modestly improving performance, limiting their long-term competitiveness (Cohen, 2017).

3. Type 3 Cylinders: Fully Wrapped Cylinders with Metallic Liners

Figure 2.4: Type 3 Gas Cylinder

Further innovation led to the development of Type 3 cylinders. These vessels consist of a metallic liner—usually aluminum—completely overwrapped with continuous composite fibers and resin (Mertiny & Gold, 2018). Unlike Type 2 cylinders, the reinforcement covers the entire surface of the liner, greatly improving structural performance.

Type 3 cylinders are significantly lighter than Type 1 and Type 2 counterparts and have much higher fatigue resistance, making them more durable under repeated pressurization cycles (Messager et al., 2016). They are also better suited for automotive and industrial applications where weight reduction is critical.

Nonetheless, Type 3 cylinders retain a metallic core, which continues to present challenges of corrosion and cost (Kumar & Bhatnagar, 2020). Aluminum liners, while lighter than steel, are considerably more expensive to manufacture. This cost factor, combined with relatively complex production processes, limits their adoption in domestic LPG storage, although they remain popular in applications such as compressed natural gas (CNG) storage for vehicles (Peters, 2018).

4. Type 4 Cylinders: Fully Composite Cylinders with Polymer Liners

Figure 2.5: Type 4 Gas Cylinder

Type 4 cylinders represent the most advanced generation of LPG storage vessels (Messager et al., 2016). In this design, the metallic liner is eliminated and replaced with a lightweight polymer liner, usually high-density polyethylene (HDPE) or polyamide (PA). The liner provides impermeability to gas, while the structural strength is entirely derived from continuous fiber reinforcement—most commonly glass fiber, carbon fiber, or a hybrid combination—impregnated with epoxy or similar resins (Peters, 2018).

The advantages of Type 4 cylinders are substantial. They are up to 70 percent lighter than conventional steel cylinders, which dramatically reduces handling and transportation challenges (Kumar & Bhatnagar, 2020). Their non-metallic composition eliminates the risk of corrosion, extending service life and reducing maintenance (Mertiny & Gold, 2018). In terms of safety, Type 4 cylinders have demonstrated superior burst pressure and fatigue resistance. Furthermore, in extreme failure scenarios, they tend to rupture in a controlled, non-explosive manner, reducing risks to users (Messager et al., 2016).

Despite their promise, Type 4 cylinders face challenges related to high production costs, due largely to the expense of carbon fibers and advanced resin systems (Kumar & Bhatnagar, 2020). Additionally, polymer liners can exhibit permeability to LPG molecules over long service periods, raising concerns about long-term safety and efficiency (Rousseau et al., 2019). Recycling and end-of-life disposal also remain unresolved due to the difficulty of separating fiber, resin, and liner materials (Witik et al., 2013).

Nevertheless, Type 4 technology is increasingly being adopted worldwide, particularly in high-value applications such as automotive fuel storage, aerospace, and advanced domestic LPG solutions (Cohen, 2017). For developing countries like Nigeria, they offer a transformative opportunity if manufacturing costs can be reduced and localized production is established (Emodi & Yusuf, 2021).

5. Comparative Summary

In summary, the four types of LPG cylinders can be viewed as a progression in engineering innovation (Mertiny & Gold, 2018):

1. **Type 1:** Strong and cheap, but heavy and prone to corrosion.
2. **Type 2:** Offers modest weight savings with partial composite reinforcement, but corrosion remains a problem.
3. **Type 3:** Fully composite-wrapped metallic liner cylinders, lighter and more durable, but costly.
4. **Type 4:** Fully composite with polymer liners, lightest and safest, but expensive and technically demanding to manufacture.

This evolution highlights the trade-offs between cost, weight, safety, and manufacturability. The challenge for engineers today is to optimize Type 4 technology such that its advantages can be realized at lower cost, particularly for mass domestic adoption in emerging economies (Kumar & Bhatnagar, 2020).

2.3 Materials Used in Type 4 Cylinders

The success of Type 4 composite LPG cylinders lies primarily in the advanced materials used for their construction. Unlike earlier designs that rely heavily on metals, Type 4 cylinders utilize a combination of lightweight polymers, high-strength fibers, and robust resin systems (Peters, 2018). Each material contributes to specific performance attributes such as impermeability, structural strength, durability, and safety. The synergy of these materials results in a cylinder that is lighter, safer, and more resistant to environmental degradation than conventional steel alternatives (Messager et al., 2016).

1. Polymer Liners

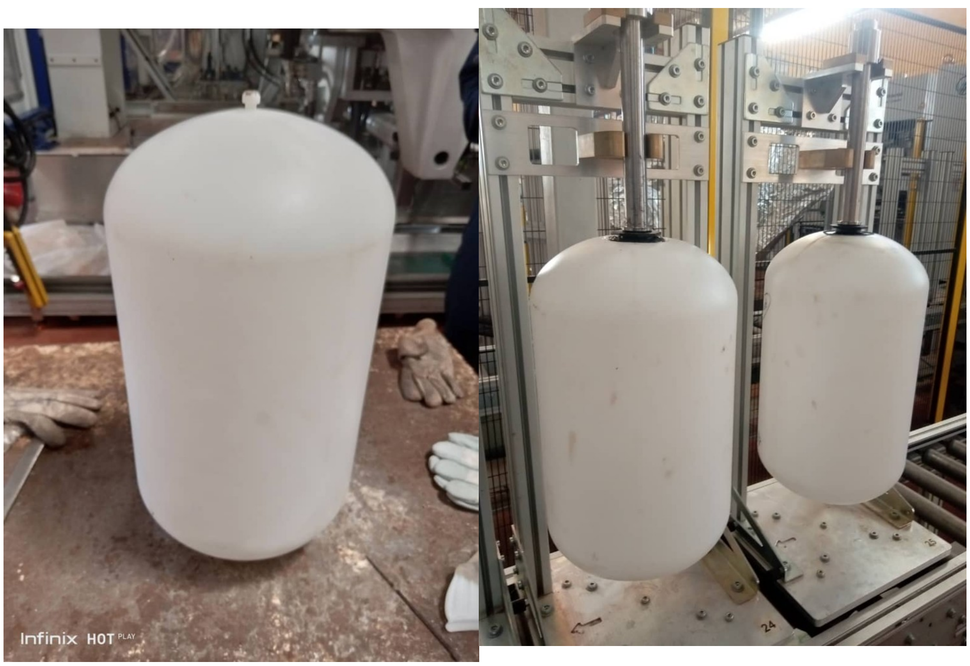

Figure 2.6: Polymer Liners

At the core of a Type 4 cylinder lies a polymer liner, which serves as the gas containment barrier. Unlike metallic liners in previous designs, polymer liners are non-corrosive and significantly lighter, making them more practical for handling and transportation (Rousseau et al., 2019). High-density polyethylene (HDPE) is the most widely used material due to its excellent chemical resistance, ease of processing, and cost-effectiveness (Peters, 2018). In some advanced applications, polyamide (PA) is employed because it offers superior mechanical strength and lower gas permeability compared to HDPE (Messager et al., 2016). The polymer liner does not bear structural loads but is essential for ensuring that the gas remains sealed within the vessel. A critical challenge associated with polymer liners is the gradual diffusion of small hydrocarbon molecules over long storage periods, a phenomenon known as gas permeation (Rousseau et al., 2019). This remains a subject of ongoing research aimed at improving liner formulations or integrating barrier layers to enhance impermeability.

2. Fiber Reinforcements

Figure 2.7: Glass Fiber

The primary structural strength of Type 4 cylinders is derived from continuous fiber reinforcements wound around the liner (Mertiny & Gold, 2018). The most commonly employed fibers are glass fibers and carbon fibers, each offering distinct advantages. Glass fibers are widely used because they are cost-effective, possess high tensile strength, and provide good resistance to impact loading (Peters, 2018). Carbon fibers, while considerably more expensive, deliver superior stiffness-to-weight ratios and fatigue resistance, making them highly desirable for cylinders subjected to high operating pressures and long service lives (Messager et al., 2016). In some cases, hybrid systems combining glass and carbon fibers are employed to balance cost and performance (Kumar & Bhatnagar, 2020). The orientation and winding pattern of the fibers—whether hoop winding, helical winding, or a combination—determine the cylinder's ability to resist circumferential and longitudinal stresses. The precision of this winding process is therefore critical to ensuring structural reliability under cyclic pressurization (Cohen, 2017).

3. Resin Systems

To bond the fiber reinforcements together and transfer loads effectively, resin systems are used as the matrix material. Epoxy resins are the most prevalent choice because they provide excellent adhesion to fibers, high thermal stability, and superior resistance to chemical attack (Peters, 2018). Polyester and vinyl ester resins may also be used in cost-sensitive applications, but they generally offer lower mechanical performance compared to epoxy (Mertiny & Gold, 2018). The resin not only holds the fibers in place but also distributes stresses uniformly, thereby preventing localized failure. Additionally, the resin matrix protects the fibers from environmental degradation, moisture ingress, and mechanical abrasion (Messager et al., 2016). Advances in resin chemistry, such as the development of toughened epoxies and nano-enhanced systems, continue to improve the overall durability and safety of composite cylinders (Kumar & Bhatnagar, 2020).

4. Material Synergy and Performance

The performance of Type 4 cylinders is not solely dependent on individual materials but on the interaction between the liner, fibers, and resin system (Peters, 2018). The liner ensures impermeability, the fibers provide structural strength, and the resin maintains cohesion and durability. Together, these materials produce a cylinder that can withstand high internal pressures, repeated loading cycles, and harsh environmental conditions, all while being lightweight and user-friendly (Messager et al., 2016). The challenge for engineers lies in optimizing these material systems to balance cost, performance, and manufacturability (Kumar & Bhatnagar, 2020).

2.4 Manufacturing Processes of Type 4 Cylinders

The production of Type 4 LPG composite cylinders requires advanced manufacturing techniques that combine polymer processing, composite filament winding, resin curing, and stringent quality control measures (Cohen, 2017). Unlike traditional metallic cylinders that rely heavily on forging and welding, Type 4 cylinders are fabricated using methods drawn from polymer technology and aerospace-grade composite engineering. The process must be carefully controlled to ensure that the final product meets international safety standards for pressure vessels, such as ISO 11119 (Peters, 2018).

1. Fabrication of the Polymer Liner

The manufacturing sequence begins with the formation of the polymer liner, which serves as the inner gas-retaining shell. High-density polyethylene (HDPE) or polyamide (PA) pellets are typically processed using blow molding, rotational molding, or injection molding techniques (Rousseau et al., 2019). Blow molding is the most common approach, in which melted polymer is extruded into a mold and expanded with compressed air to achieve the desired shape and wall thickness. The liner must be uniform in thickness to minimize weak points that may contribute to long-term gas permeation. The molded liner is then trimmed, machined if necessary, and fitted with a metallic boss or insert at the neck region to enable valve attachment (Messager et al., 2016). This stage is crucial, as defects in the liner may compromise the impermeability of the cylinder.

2. Surface Preparation of the Liner

Before reinforcement, the surface of the polymer liner undergoes preparation to enhance adhesion with the composite layers. Techniques such as flame treatment, plasma treatment, or chemical priming are employed to improve bonding between the inert polymer surface and the resin-impregnated fibers (Peters, 2018). Proper adhesion ensures structural integration between the liner and the overwrap, preventing delamination during pressurization cycles (Mertiny & Gold, 2018).

3. Filament Winding of Fiber Reinforcements

The most critical step in the process is filament winding, in which continuous fibers, impregnated with epoxy resin, are wound onto the polymer liner in controlled patterns (Cohen, 2017). Advanced winding machines apply fibers under tension in hoop, helical, or polar winding orientations to withstand circumferential and longitudinal stresses. Hoop winding primarily resists radial expansion, while helical winding provides axial strength (Mertiny & Gold, 2018). The combination of both orientations creates a balanced laminate structure capable of withstanding high internal pressures and fatigue loads. The winding process must be highly precise, as deviations in fiber placement or tension can significantly reduce the cylinder’s performance (Messager et al., 2016).

4. Resin Curing and Consolidation

Once the fiber reinforcement is applied, the cylinder undergoes a curing process to solidify the resin matrix. Thermosetting epoxy resins are commonly cured using heat in ovens or autoclaves, although some manufacturers use ultraviolet curing or microwave-assisted curing methods (Peters, 2018). The curing process crosslinks the resin, transforming it into a rigid, three-dimensional network that binds the fibers together. During curing, parameters such as temperature, pressure, and time must be carefully monitored to prevent voids, incomplete polymerization, or residual stresses (Cohen, 2017). The result is a robust composite shell that provides the primary structural strength of the cylinder (Mertiny & Gold, 2018).

5. Machining and Assembly

The metallic boss at the neck is secured, and valves or regulators may be attached depending on the intended application (Peters, 2018). External protective layers, such as UV-resistant coatings or aesthetic casings, may also be added to shield the cylinder from environmental degradation and enhance user appeal (Messager et al., 2016).

6. Testing and Quality Assurance

The final stage in the manufacturing process involves rigorous testing to ensure compliance with international safety standards such as ISO 11119, EN 12245, and other relevant regulatory frameworks (Peters, 2018). Cylinders are subjected to hydrostatic burst testing to determine their maximum pressure capacity, cyclic fatigue testing to simulate repeated filling and emptying cycles, and permeation testing to assess gas retention performance (Messager et al., 2016). Fire resistance and drop impact tests are also carried out to evaluate performance under accidental conditions. Non-destructive evaluation methods, including ultrasonic inspection and X-ray scanning, may be used to detect hidden defects within the composite structure (Mertiny & Gold, 2018). Only cylinders that pass these stringent quality checks are approved for commercial distribution.

7. Integration of Automation and Simulation Tools

Modern manufacturers increasingly employ computer-aided design (CAD) and simulation software to optimize the filament winding patterns, stress distribution, and thermal curing cycles (Cohen, 2017). Finite element analysis (FEA) allows engineers to predict failure modes and refine material placement for maximum efficiency (Mertiny & Gold, 2018). Automation of winding machines and curing systems not only improves precision but also reduces production variability, thereby enhancing safety and cost-effectiveness (Kumar & Bhatnagar, 2020).

The combination of these processes ensures that Type 4 LPG composite cylinders achieve the necessary balance of lightweight construction, high safety margins, and long service life. However, the complexity of the manufacturing process, reliance on specialized equipment, and high cost of raw materials continue to limit large-scale adoption, particularly in developing countries (Emodi & Yusuf, 2021).

2.5 Advantages and Limitations of Type 4 Cylinders

The introduction of Type 4 composite cylinders marks a significant advancement in LPG storage technology. By replacing heavy metallic structures with lightweight polymers and fiber-reinforced composites, engineers have developed vessels that are both safer and more user-friendly (Messager et al., 2016). However, despite their numerous advantages, certain technical and economic limitations continue to restrict their widespread adoption (Kumar & Bhatnagar, 2020). A comprehensive understanding of these strengths and weaknesses is essential for identifying areas of improvement and guiding future research.

1. Advantages of Type 4 Cylinders

The first major advantage of Type 4 cylinders is their exceptional weight reduction compared to conventional steel cylinders. A Type 4 cylinder can be up to seventy percent lighter than its steel counterpart, which greatly enhances portability and ease of use (Peters, 2018). This reduction in weight is particularly beneficial for domestic consumers, distribution companies, and industries where frequent handling and transportation are required (WLPGA, 2021).

The second advantage lies in corrosion resistance. Since Type 4 cylinders contain no metallic components in their main body, they are entirely immune to rusting (Mertiny & Gold, 2018). This eliminates one of the greatest weaknesses of steel cylinders, especially in humid, coastal, or tropical environments such as Nigeria. The absence of corrosion also extends the cylinder's service life and reduces the need for maintenance or repainting (Kumar & Bhatnagar, 2020).

The third advantage is improved safety performance. Type 4 cylinders exhibit higher burst pressure capabilities than steel cylinders of equivalent size, and their failure mode is typically less catastrophic (Messager et al., 2016). Instead of fragmenting explosively, they tend to rupture in a controlled manner that reduces the risk of injury or property damage. In addition, their resistance to fatigue under repeated filling and emptying cycles is significantly better than that of metallic designs (Mertiny & Gold, 2018).

A fourth advantage is the aesthetic and ergonomic flexibility of the design. Composite materials allow manufacturers to produce cylinders in various colors, shapes, and surface finishes, often incorporating transparent sections that allow users to visually monitor the gas level (Peters, 2018). This feature enhances convenience for domestic users and adds commercial value for manufacturers (WLPGA, 2021).

2. Limitations of Type 4 Cylinders

Despite these advantages, Type 4 cylinders also face several limitations that hinder large-scale adoption. The most critical limitation is their high production cost (Kumar & Bhatnagar, 2020). The use of advanced materials such as carbon fibers, high-grade resins, and precision filament winding machines significantly increases manufacturing expenses compared to steel cylinders. As a result, their affordability in developing countries remains a major challenge (Emodi & Yusuf, 2021).

The second limitation is related to polymer liner permeability. Although polymers such as HDPE and polyamide are effective barriers, they are not completely impermeable to small hydrocarbon molecules (Rousseau et al., 2019). Over extended service periods, gradual permeation of LPG through the liner can occur, raising concerns about efficiency and safety. Research into multi-layered liners or barrier coatings is ongoing to mitigate this issue.

A third limitation involves recycling and end-of-life management. Unlike metallic cylinders, which can be easily melted down and reused, Type 4 cylinders are difficult to recycle because of the inseparability of fibers, resins, and liners (Witik et al., 2013). This creates environmental concerns and complicates disposal once the cylinder has reached the end of its operational life.

A fourth limitation is technical complexity in manufacturing. The precision required in filament winding, curing, and quality control means that production facilities must be highly specialized and capital intensive (Cohen, 2017). In regions with limited industrial infrastructure, such as parts of Africa, establishing such facilities poses a significant barrier to localization and cost reduction (Emodi & Yusuf, 2021).

3. Balanced Perspective

From an engineering standpoint, the advantages of Type 4 cylinders—lightweight design, corrosion resistance, enhanced safety, and durability—position them as the ideal storage solution for the future of LPG distribution (Messager et al., 2016). However, the limitations of cost, liner permeability, recycling challenges, and manufacturing complexity must be addressed before they can be adopted on a mass scale, particularly in developing economies (Kumar & Bhatnagar, 2020). These challenges form the basis for continued research into alternative materials, optimized manufacturing techniques, and innovative design solutions.

2.6 Current Research Trends and Improvements in Type 4 Cylinders

The continuous evolution of Type 4 LPG composite cylinders is driven by the dual goals of enhancing safety and performance while reducing costs and environmental impact (Kumar & Bhatnagar, 2020). As demand for LPG expands globally, particularly in developing regions, researchers and manufacturers are pursuing innovations that address the limitations of existing designs. Current research focuses on materials engineering, manufacturing optimization, sustainability, and digital simulation, all of which aim to make Type 4 cylinders more practical and affordable for widespread adoption (Peters, 2018).

1. Advances in Polymer Liner Technology

One of the most active areas of research is the development of improved polymer liners. Traditional liners made of high-density polyethylene, while cost-effective, suffer from gradual gas permeation over long service lifetimes (Rousseau et al., 2019). To address this, researchers are exploring advanced materials such as polyamide (PA), polyethylene terephthalate (PET), and multilayered hybrid liners. These new liners exhibit lower gas permeability, higher thermal stability, and better mechanical integrity (Messager et al., 2016). Barrier coatings and nanocomposites reinforced with clay, silica, or graphene nanoparticles are also being investigated to further enhance impermeability while maintaining low weight (Kumar & Bhatnagar, 2020).

2. Development of Cost-Effective Fiber Reinforcements

The high cost of carbon fibers remains a major challenge for Type 4 cylinders. To reduce dependence on expensive fibers, hybrid systems that combine carbon and glass fibers are gaining attention (Mertiny & Gold, 2018). Such systems aim to balance performance with affordability, providing sufficient structural strength while lowering raw material costs (Kumar & Bhatnagar, 2020). Research into next-generation fibers, including basalt fibers and natural fiber composites, is also emerging as a potential pathway for sustainable and lower-cost alternatives (Peters, 2018).

3. Improvements in Resin Systems

The resin matrix plays a central role in the structural performance of Type 4 cylinders. Current research seeks to enhance toughness, fatigue resistance, and chemical stability through the use of advanced epoxy formulations, thermoplastic resins, and nano-modified systems (Mertiny & Gold, 2018). Self-healing resins capable of repairing micro-cracks are under development, which could significantly extend cylinder service life and reliability (Kumar & Bhatnagar, 2020). Furthermore, low-temperature curing and fast-curing resin systems are being explored to reduce energy consumption and accelerate production cycles (Cohen, 2017).

4. Manufacturing Innovations

Automated filament winding processes are being refined with the aid of robotics and computer-controlled systems to achieve higher precision and repeatability (Cohen, 2017). Simulation tools integrated into the winding process allow optimization of fiber placement for maximum strength-to-weight efficiency (Mertiny & Gold, 2018). Additive manufacturing techniques are also being tested for producing complex liner geometries and hybrid composite structures (Peters, 2018). These innovations aim not only to enhance cylinder performance but also to reduce production costs and minimize defects (Kumar & Bhatnagar, 2020).

5. Sustainability and Recycling Solutions

The difficulty of recycling Type 4 cylinders is prompting significant research into sustainable disposal and reuse methods (Witik et al., 2013). One approach involves designing cylinders with thermoplastic composites instead of thermosetting resins, allowing for re-melting and reshaping at the end of life (Peters, 2018). Chemical recycling processes that separate fibers from resin matrices are also being studied, although they remain costly at present (Kumar & Bhatnagar, 2020). Researchers are further exploring the use of bio-based resins and recyclable fibers as part of a circular economy model for LPG storage systems.

6. Digital Simulations and Structural Optimization

The use of computational tools is rapidly transforming cylinder design and testing. Finite element analysis (FEA) is widely applied to simulate stress distributions, failure modes, and fatigue behavior under different loading conditions (Mertiny & Gold, 2018). Computational fluid dynamics (CFD) is also being used to study gas flow, thermal effects, and pressure variations within cylinders (Messager et al., 2016). These simulations reduce the need for extensive physical prototyping, saving time and cost while enabling the exploration of innovative geometries and material combinations (Cohen, 2017). In line with this trend, our study plans to employ simulation-based approaches to demonstrate potential improvements in both the cylinder structure and the manufacturing process.

7. Regional Adaptations and Policy-Driven Improvements

In addition to technical research, policy and regional adaptation play a key role in the adoption of Type 4 cylinders. In developing countries, the high upfront cost is a barrier to widespread use (Emodi & Yusuf, 2021). Researchers and manufacturers are therefore exploring modular designs and localized production models to lower costs. Governments are also introducing standards and subsidy programs to encourage adoption of safer and lighter cylinders (WLPGA, 2021). This integration of research, manufacturing, and policy reflects the broader ecosystem required for technological improvements to succeed.

8. Outlook for Future Improvements

The trajectory of current research suggests that Type 4 cylinders will continue to evolve toward lighter, stronger, more affordable, and environmentally sustainable designs (Kumar & Bhatnagar, 2020). Breakthroughs in polymer nanocomposites, fiber technology, and recyclable resins are expected to address many of the existing challenges (Peters, 2018). Coupled with advanced simulation tools and automated production, these improvements will make Type 4 cylinders increasingly competitive with traditional steel designs (Cohen, 2017). The integration of our proposed simulations into this research landscape aligns with global trends and provides a practical pathway for demonstrating improvements tailored to the Nigerian context (Emodi & Yusuf, 2021).

2.7 Previous Studies and Improvements

The rapid development of Type 4 composite cylinders has attracted significant attention from both academic researchers and industrial practitioners, leading to a growing body of studies aimed at improving material performance, safety, and cost efficiency (Peters, 2018). These studies provide valuable insights into the challenges of composite cylinder production and offer a foundation for further innovation.

One notable area of research has focused on material optimization. Several studies have investigated the effectiveness of different polymer liners in reducing gas permeability. For instance, polyamide liners have been shown to provide lower hydrocarbon permeation compared to high-density polyethylene, thereby improving safety and efficiency (Rousseau et al., 2019). Researchers have also explored multilayered liner designs and the use of nanocomposite barrier layers reinforced with clay or graphene, with positive results in extending service life and minimizing gas loss (Kumar & Bhatnagar, 2020).

Another stream of research has concentrated on fiber reinforcement systems. Investigations into hybrid configurations of glass and carbon fibers have demonstrated that such combinations can significantly reduce production costs without compromising structural strength (Mertiny & Gold, 2018). Experimental results have shown that optimized fiber winding angles and thickness distributions can enhance burst pressure capacity while minimizing material consumption (Cohen, 2017).

Advances have also been made in resin systems. Epoxy resins remain the most common choice; however, studies into thermoplastic matrices and nano-modified resins have reported improvements in toughness, fatigue resistance, and impact tolerance (Kumar & Bhatnagar, 2020). Some researchers have experimented with self-healing resin systems, which have the potential to repair micro-cracks during service, thereby extending the operational lifespan of cylinders (Peters, 2018).

In terms of manufacturing improvements, the use of automation and robotics in filament winding has been widely reported (Cohen, 2017). Studies employing finite element analysis to simulate winding patterns and stress distributions have shown that computer-assisted optimization can substantially improve structural efficiency while reducing production errors (Mertiny & Gold, 2018). Research into alternative curing methods, such as microwave and ultraviolet curing, has further suggested potential for faster production cycles and reduced energy costs (Messager et al., 2016).

Safety testing has been another critical area of study. Previous experimental investigations have demonstrated that Type 4 cylinders exhibit safer failure modes compared to steel cylinders when subjected to fire, impact, and over-pressurization (Messager et al., 2016). Researchers have also explored the incorporation of smart sensors to monitor pressure, temperature, and structural integrity in real time, opening new avenues for intelligent LPG storage systems (Kumar & Bhatnagar, 2020).

Finally, in the domain of sustainability, studies have highlighted the challenges of recycling composite cylinders at end-of-life (Witik et al., 2013). Proposed solutions include the development of thermoplastic composites that can be remelted, as well as chemical recycling methods to recover fibers from cured resins (Peters, 2018). While these approaches are still at early stages of commercialization, they offer potential long-term solutions to the environmental concerns associated with composite cylinder disposal (Kumar & Bhatnagar, 2020).

In summary, previous studies and industrial improvements have collectively advanced the performance and reliability of Type 4 cylinders. However, the recurring challenges of cost reduction, polymer liner permeability, recycling, and large-scale manufacturability remain unresolved (Emodi & Yusuf, 2021). These knowledge gaps provide the motivation for this study, which aims to evaluate existing technologies and propose practical improvements through both field analysis and simulation-based demonstrations.

2.8 Summary of Literature Review

This chapter has examined the fundamental aspects of Liquefied Petroleum Gas (LPG) as an energy source, its growing relevance in global and Nigerian contexts, and the evolution of storage technologies from Type 1 to Type 4 cylinders (WLPGA, 2021; Emodi & Yusuf, 2021). The review highlighted the limitations of conventional steel cylinders, including their heavy weight, susceptibility to corrosion, and maintenance demands, which restrict their appeal for widespread domestic adoption (Kumar & Bhatnagar, 2020). The introduction of composite technology, culminating in Type 4 cylinders, represents a significant breakthrough by combining polymer liners with fiber-reinforced composite overwraps to achieve lightweight, corrosion-resistant, and safer alternatives (Messager et al., 2016).

The discussion on materials demonstrated the importance of polymer liners for gas containment, fibers for structural reinforcement, and resin systems for cohesion and durability (Peters, 2018). Advances in these materials have been shown to directly influence cylinder performance, service life, and safety (Mertiny & Gold, 2018). The review of manufacturing processes underscored the precision required in polymer molding, filament winding, resin curing, and testing to ensure compliance with international standards (Cohen, 2017).

The analysis of advantages and limitations revealed that while Type 4 cylinders offer superior weight reduction, corrosion resistance, and safety, challenges remain in terms of high production cost, polymer liner permeability, recycling difficulties, and technical complexity in manufacturing (Kumar & Bhatnagar, 2020; Witik et al., 2013). These limitations form the basis of ongoing research, which is directed toward cost-effective materials, improved liners, advanced resin systems, automation of production, and sustainable end-of-life solutions (Peters, 2018).

Finally, the section on current research trends showed that digital simulations, hybrid material systems, and recycling innovations are shaping the future of Type 4 cylinders (Mertiny & Gold, 2018; Cohen, 2017). Importantly, the global push toward cleaner, safer, and more efficient energy storage technologies is in alignment with Nigeria's growing need for reliable LPG infrastructure (Emodi & Yusuf, 2021). However, a gap still exists in adapting these technologies to the Nigerian context through localized manufacturing, cost optimization, and demonstration of process improvements.

In conclusion, the literature confirms the potential of Type 4 cylinders to transform LPG storage but emphasizes the need for further research into material optimization, manufacturing efficiency, and contextual adaptation (Kumar & Bhatnagar, 2020). These identified gaps justify the present study, which seeks not only to analyze the existing technology but also to propose improvements using practical insights from Donmac Ltd and computer-based simulations.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Overview

This Chapter Presents The Materials, Equipment, And Methodology Employed In The Study Of The Technology Used To Produce Type 4 Lpg Composite Cylinders. The Approach Adopted Integrates *Field Observation*, *Review Of Standard Operating Procedures (Sops)* From Don Mac Limited, And *Simulation-Based Analysis* To Understand And Evaluate Each Stage Of The Manufacturing Process. The Methodology Was Designed To Trace The Full Production Flow—From Raw-Material Preparation To Final Quality Testing—Highlighting Critical Process Parameters, Inspection Stages, And Areas Where Technological Improvements Can Be Made.

The Production Of A Type 4 Lpg Composite Cylinder Involves A Sequence Of Interrelated Operations That Transform Polymer Pellets And Composite Fibers Into A Fully Functional Pressure Vessel Capable Of Withstanding High Internal Pressures. At Don Mac Limited, The Established Process Follows The Lpg Composite Cylinder Production Process Flow Chart (Document No. Dml-Prd_2-Cat-9011, 2024), Which Outlines The Major Stages: *Liner Blow-Molding, Cooling And Weighting, Surface Flaming, Boss-Part Molding And Welding, Air Filling, Filament Winding, Curing, Casing Assembly, Proof And Leak Testing, Marking, And Final Inspection*. Each Operation Is Governed By Documented Sops And In-Process Inspection Procedures To Ensure Product Uniformity, Mechanical Reliability, And Compliance With International Standards Such As Iso 11119-3 And En 12245.

In This Study, The Methodological Framework Was Organized To Reflect Both The *Technical Sequence Of Production* And The *Engineering Principles Underlying Each Step*. Data Were Collected Through Direct Observation At Don Mac Limited’s Composite Cylinder Manufacturing Plant, Review Of Internal Process Documentation, And Consultation With Production Engineers. Supplementary Data From Literature And International Design Codes Were Used To Validate Process Specifications And To Support The Analytical And Simulation Components Of The Work.

The Subsequent Sections Of This Chapter Detail The Materials Utilized In Cylinder Fabrication, The Equipment And Machines Employed In Each Process Stage, And The Corresponding Manufacturing And Quality-Control Procedures. Together, These Elements Form The Experimental And Analytical Basis For The Evaluation And Improvement Of Type 4 Lpg Composite Cylinder Technology Discussed In Later Chapters.

3.2 Materials

The Materials Used In The Production Of Type 4 Lpg Composite Cylinders Determine The Overall Structural Integrity, Weight Efficiency, And Service Life Of The Product. Each Material Is Carefully Selected To Fulfil Specific Mechanical, Chemical, And Safety Requirements While Maintaining Compatibility With The Manufacturing Processes Documented In The Don Mac Ltd. Standard Operating Procedures (Sops) And In-Process Inspection Guidelines That Accompany This Report.

At Don Mac Ltd., The Main Material Components Involved In The Composite Cylinder Production Line Are The Polymer Liner, Fiber Reinforcement, Resin Matrix, Metallic Boss Part, And Outer Protective Casing. The Characteristics And Functions Of These Materials Are Described Below.

3.2.1 Polymer Liner

Figure 3.1: High Density PolyEthelene(HDPE) Polymer Liner

The Liner Forms The Innermost Layer Of The Cylinder And Serves As The Gas-Retaining Barrier. It Is Typically Produced From High-Density Polyethylene (Hdpe) Or Polyamide (Pa-6) Pellets Through The Blow-Molding Process (See *Sop For Injection Moulding For Cylinder Casing*). Hdpe Offers Excellent Chemical Resistance, Low Cost, And Ease Of Processing, Whereas Pa-6 Provides Superior Mechanical Strength And Lower Gas Permeability. The Choice Of Polymer Depends On Design Requirements Such As Working Pressure, Permeability Tolerance, And Cost Considerations.

The Liner Material Must Also Exhibit Good Adhesion Characteristics With The Composite Overwrap. To Achieve This, The Liner Surface Undergoes A Flaming Or Plasma-Treatment Process (*Importance Of Flaming* Document) That Modifies Its Surface Energy, Ensuring Effective Bonding With The Resin-Impregnated Fibers During Filament Winding.

Importance Of Flaming

Figure 3.2: KLN flaming and air filling section

Flaming Of The Liner In A Composite Cylinder Manufacturing Company Is A Surface Treatment Process Typically Applied To Thermoplastic Liners (E.G., Hdpe, Pa) Before The

Winding Of Fiber (Glass Or Carbon) Begins. This Process Involves Exposing The Liner's Surface Briefly To An Open Flame Or Controlled Plasma Flame.

Purpose Of Flaming The Liner:

Table 3.1: Purpose Of Flaming The Liner

Function	Explanation
1. Surface Activation	Flaming Oxidizes The Surface, Creating Polar Functional Groups That Enhance Adhesion.
2. Improved Resin Bonding	Ensures Strong Adhesion Between The Liner Surface And Epoxy Resin/Fiber Composite Layer.
3. Removal Of Contaminants	Burns Off Surface Oils, Mold Release Agents, Or Dust That Would Interfere With Bonding.
4. Increased Surface Energy	Makes The Surface More Receptive To Wetting By Resin, Improving Impregnation And Bonding.
5. Prevents Delamination	Reduces Risk Of Separation Between Liner And Composite During High-Pressure Service.

Without Proper Flaming, Potential Issues Include:

- Poor Adhesion Leading To **Debonding** Between Liner And Composite.
- Increased Chance Of **Gas Migration** Or **Liner Deformation**.
- Higher Rate Of **Burst Failures** At Liner-Composite Interfaces During Testing.

3.2.2 Fiber Reinforcement

Figure 3.3: Fiber Glass

The Structural Strength Of The Cylinder Is Provided By Continuous Fiber Reinforcements Wound Around The Liner. Don Mac Ltd. Utilizes Either E-Glass Fiber Or Carbon Fiber, Depending On The Cylinder's Rated Pressure And Target Weight.

- *Glass Fiber* Is Preferred For Standard Domestic Cylinders Because Of Its Lower Cost And Good Tensile Strength (~2.4 Gpa).
- *Carbon Fiber* Offers A Higher Strength-To-Weight Ratio (Up To 4.5 Gpa) And Greater Fatigue Resistance, Suitable For High-Pressure Or Automotive Applications.

The Winding Process (Refer To *Sop For Fiber Winding Machine Section*) Ensures Precise Placement Of The Fibers At Controlled Tension And Orientation To Resist Both Hoop And Longitudinal Stresses.

3.2.3 Resin Matrix

The Fibers Are Impregnated With A Thermosetting Epoxy Resin That Acts As The Load-Transfer Medium And Environmental Shield. The Epoxy System Used Conforms To Iso 11119-3 Standards For Composite Pressure Vessels. Alternative Resins Such As Vinyl Ester Or Polyester May Be Used For Specific Performance Or Cost Requirements. The Curing Of This Resin Is Achieved In A Controlled Thermal Environment Using An Oven Or Autoclave, As Defined In The *Sop For Curing Oven Section* And Its Corresponding *In-Process Inspection Checklist*. Proper Resin Crosslinking Ensures Dimensional Stability And High Fatigue Life.

3.2.4 Metallic Boss Part

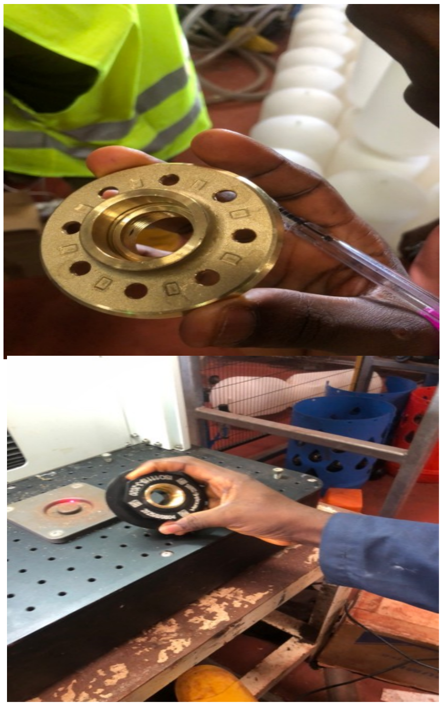

Figure 3.4: Boss Part

The Boss Part Provides The Interface For The Valve Connection And Is Typically Manufactured From Aluminum 6061-T6 Or Stainless Steel 304, Owing To Their Corrosion Resistance And High Tensile Strength. The Boss Is Welded Or Bonded To The Liner Neck During The *Liner-To-Boss Part Welding* Stage (See Related Sops And Inspection Records). Accurate Alignment And Bonding Are Crucial To Prevent Leakage And Ensure Structural Continuity Between The Liner And Composite Shell.

3.2.5 Outer Protective Casing

Figure 3.5: Plastic Outer Casing

For Improved Handling And Environmental Protection, Each Cylinder Is Enclosed In A Polymer Outer Casing, Molded From Polypropylene (Pp) Or Glass-Fiber-Reinforced Plastic (Gfrp). This Casing Shields The Composite Shell From Ultraviolet Radiation, Mechanical Abrasion, And Impact Damage During Use And Transportation. The *Outer Casing Molding And Assembly* Sop Governs Material Specifications, Molding Temperature, And Dimensional Tolerances.

3.2.6 Auxiliary Materials And Consumables

Additional Materials Include:

- Adhesive Bonding Agents Used During Boss Insertion.
- Labeling Inks And Laser-Marking Additives For Product Identification.
- Pressurized Air And Deionized Water Used In The Air-Filling And Proof-Testing Stages.

These Consumables, Though Minor, Are Critical For Maintaining Consistent Production Quality And Traceability.

3.2.7 Material Specification And Compliance

All Materials Used In Don Mac Ltd.'S Composite Cylinder Production Comply With Relevant International Standards Such As Iso 11119-3:2022 (*Gas Cylinders, Composite Construction, Specification And Testing Of Fully Wrapped Composite Cylinders With A Non-Metallic Liner*). Each Material Batch Is Accompanied By Supplier Certificates Verifying Chemical Composition, Tensile Strength, Modulus, And Thermal Stability.

In Addition, In-Process Inspections Documented In The Attached Sops Verify Conformity Between Incoming Material Properties And Design Specifications Before Use In Production.

3.2.8 Summary

In Summary, The Material System Of A Type 4 Composite Lpg Cylinder Consists Of A Gas-Tight Polymer Liner, High-Strength Fiber Reinforcement, Epoxy Resin Matrix, Metallic Boss, And Protective Casing—Each Fulfilling A Unique Mechanical Or Functional Role. The Integration Of These Materials, Guided By Don Mac Ltd.'S Documented Procedures, Ensures That Every Cylinder Achieves The Required Balance Of Lightweight Design, Mechanical Integrity, And Long-Term Safety.

3.3 Methods

3.3.1 Project Flow Test And Assembly

1. The Worker Takes The Winded Cylinder From The Conveyor System (Position 01) And Places It In Shaft Unscrewing Station Position 02.

2. After Shaft Unscrewing The Worker Hangs The Shaft Back To Pallet On Conveyor Position 01 And The Cylinder Will Be Placed In The Proof Test Station (Position 03).

3. After Successful Proof Test The Worker Takes The Cylinder Out Of Position 3 And Bring It On The Buffer Station (Position 04) For Temporary Storage.

4. The Worker Takes Cylinder From Buffer Station (Position 04) And Bring It To Position 05 For Valve Assembly.

5. After Valve Assembly In Position 05 The Worker Brings The Cylinder For Air Filling In Position 06.

6. After Air Filling In Position 06 The Cylinder Will Be Placed In Buffer Station 07 For Storage.

7. The Air-Filled Cylinders Will Be Taken From The Storage In Position 07 And Brought To The Leak Test Stations (Position 08).

8. After Successful Leak Test The Cylinders The Worker Brings The Cylinders From Leak Test To Air Release Station (Position 09). In Position 09 Is The Air Released And Cylinders Will Be Dried.

9. Next, The Worker Takes A Lower Casing From Conveyor Belt Position 12 And Places It In Assembly Station Position 10.

10. Then He Takes A Cylinder From Position 9 And Places It In The Assembly Station (Position 10).

11. Then He Takes An Upper Casing From Conveyor Belt Position 11 And Place It As Well In Assembly Station (Position 10).

12. In Assembly Station (Position 10) All Three Parts (Lower Casing, Cylinder, Upper Casing) Will Be Assembled.

13. Last The Assembled Cylinder Casing Goes To Packing Area Position 13.

14. From Packing Area (Position 13) The Packed Cylinders Go To The Warehouse.

<u>Stations</u>

Position 1: Conveyor System

Position 2: Shaft Unscrewing Unit

Position 3: Prooftest Station
Position 4: Buffer Station

Position 5: Valve Installation
Position 6: Airfilling

Position 7: Buffer Station

Position 8: Leak Test

Position 9: Air Release + Drying

Position 10: Casing Assembly Station

Position 11: Conveyor Upper Casing

Position 12: Conveyor Lower Casing

Position 13: Packing Area

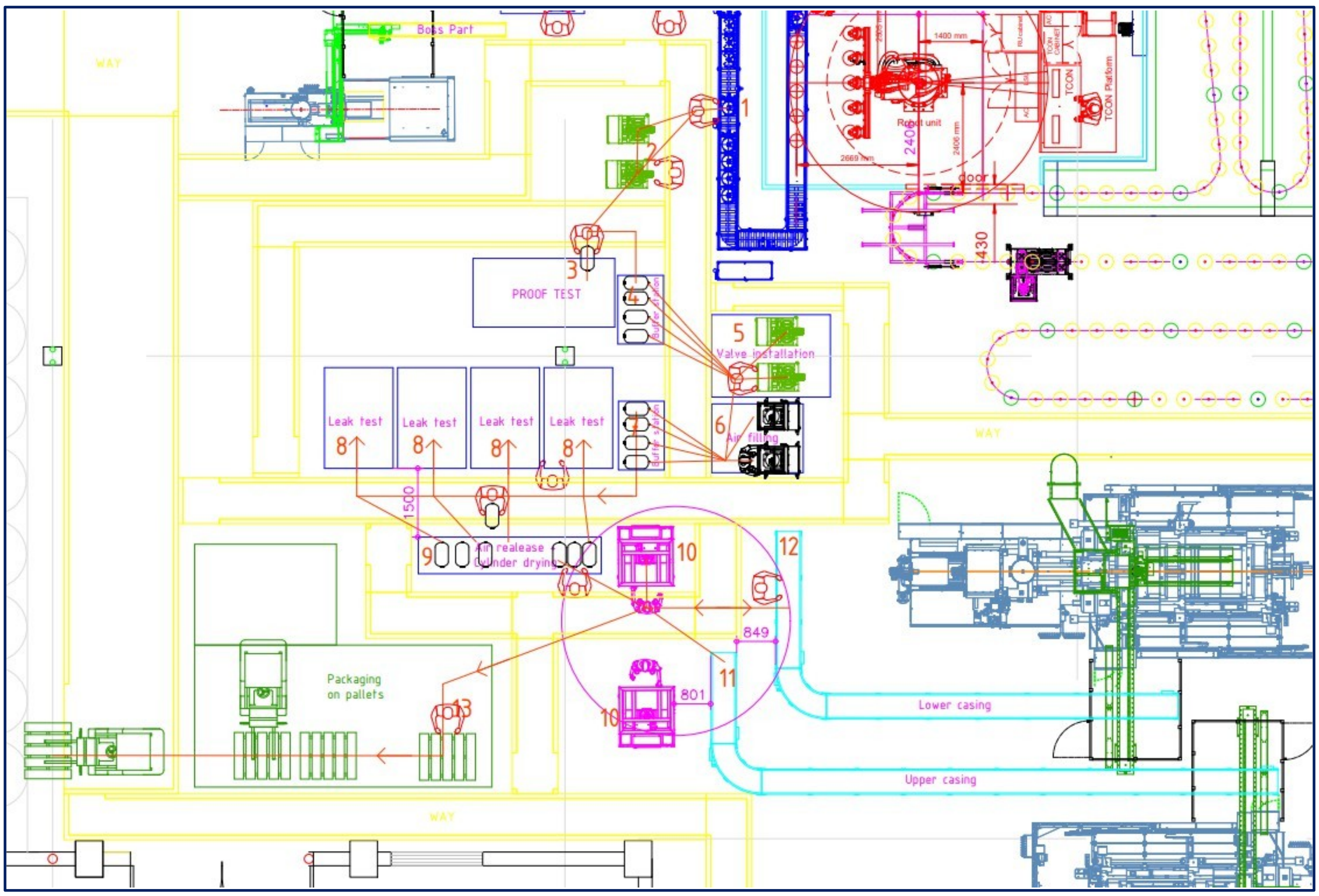

Figure 3.6: Process Flow Plan

Example For Packaging In Position 13

Figure 3.7: Example for packaging in position 13

3.3.2 Process Flowchart

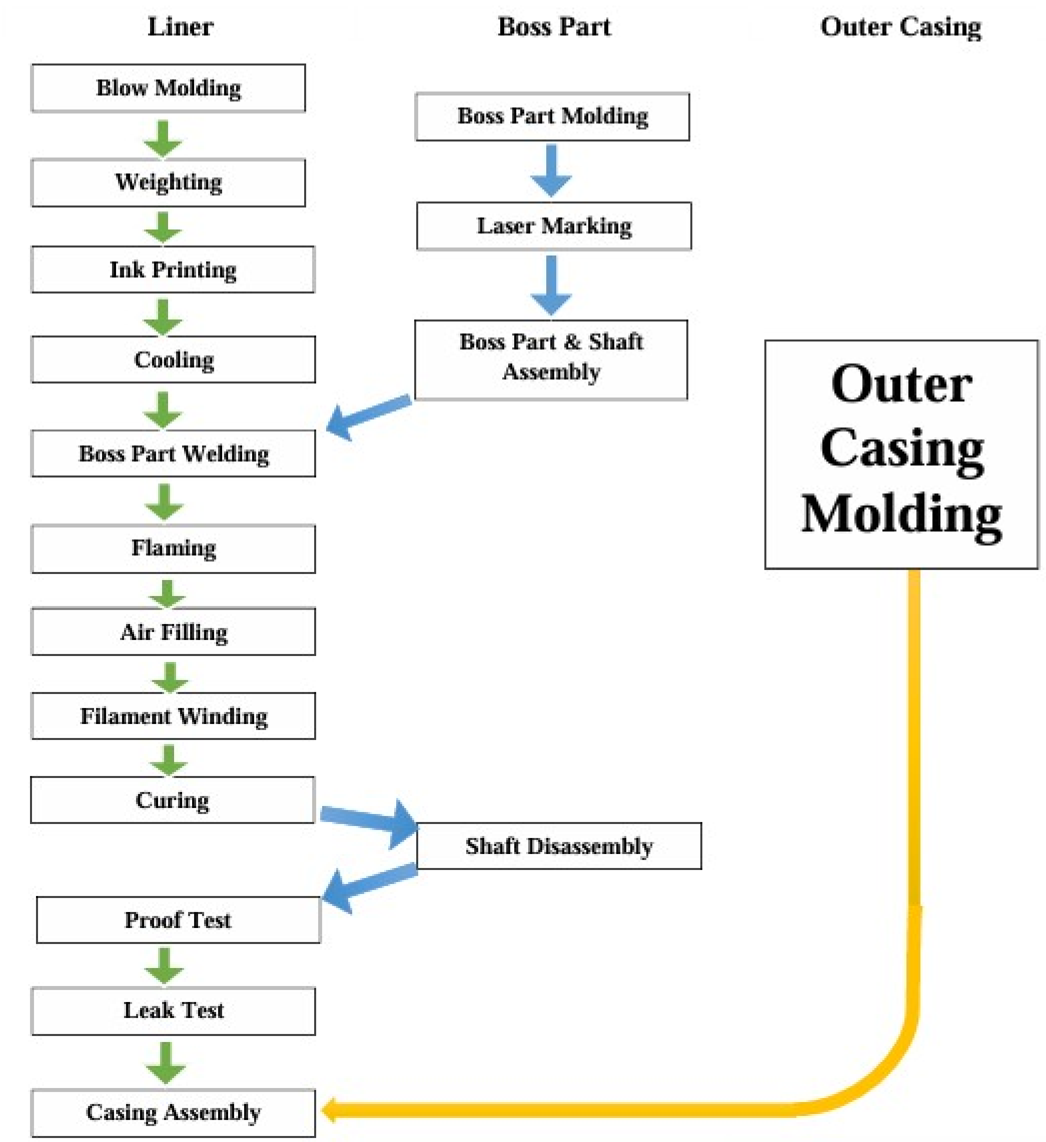

Figure 3.8: Process Flowchart

3.3.3 Process Operations (Production Sops)

Injection Moulding Machine Operation For Composite Cylinder Casing Production

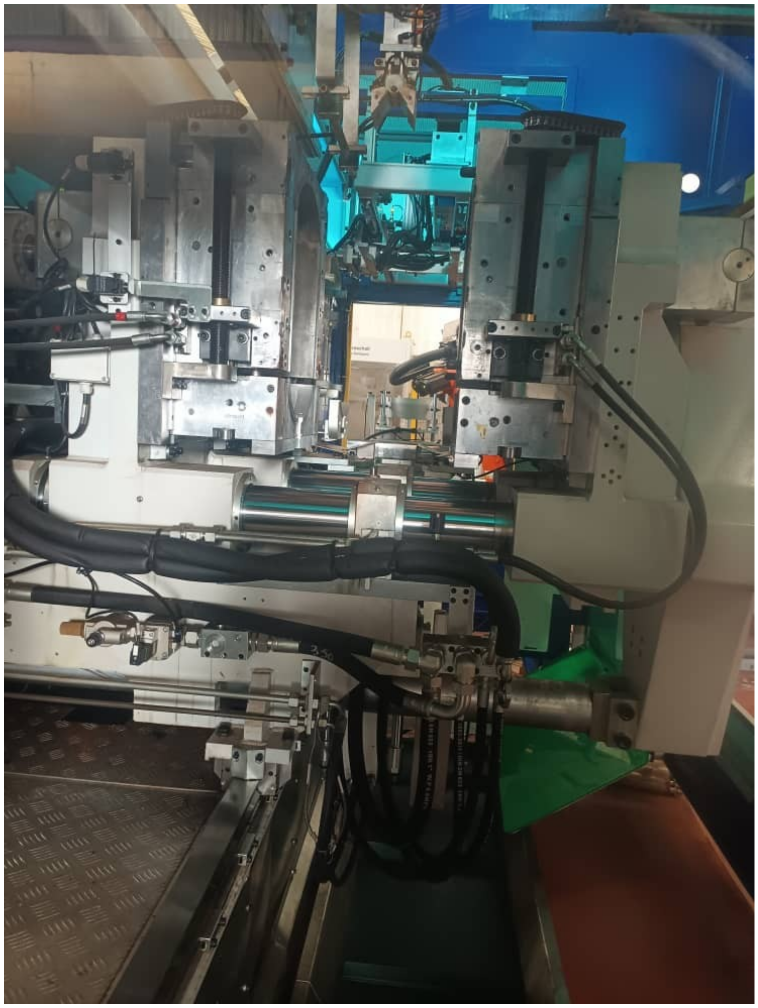

Figure 3.9: Blow Molding Machine

Figure 3.10: Blow Molding Machine

Figure 3.11: Blow Molding Machine

1. Purpose

To Define The Correct And Safe Operating Procedures For Using The Injection Moulding Machine To Manufacture Casing Components For Composite Cylinders In Accordance With Iso 11119-3 Requirements.

2. Scope

This Sop Covers The Setup, Operation, And Quality Inspection During The Injection Moulding Process Of Plastic Casings (E.G. Valve Guards, Base Caps, Etc.) For Type Iv Composite Cylinders.

3. Responsibility

Operators – To Follow This Sop And Report Any Deviation Or Machine Fault.

Production Supervisor – To Monitor Compliance And Ensure Operator Training.

Quality Control (Qc) – To Inspect And Approve Parts For Use.

4. Equipment & Materials

- Injection Moulding Machine (E.G., Arburg, Engel, Haitian)
- Mould Tools (For Caps, Valve Guards, Etc.)
- Thermoplastic Resin (E.G., Polypropylene, Polyamide)
- Chiller Or Mould Cooling Unit
- Mould Release Agent (If Needed)
- Ppe (Gloves, Safety Glasses, Apron)

5. Procedure

5.1 Pre-Start Checks

Table 3.2: Pre-Start Checks

Step

	Action	Responsibility
1	Ensure The Area Is Clean And Free Of Obstructions	Operator
2	Verify Mould Tool Is Correctly Mounted And Clamped	Operator/Supervisor
3	Check Water Cooling Lines And Chiller Connection	Operator
4	Confirm Resin Material Is Dry And Properly Loaded	Operator
5	Wear All Necessary Ppe	Operator

5.2 Machine Settings

Table 3.3: Machine Settings

Parameter	Typical Range	Note
Injection Pressure	80 – 120 Mpa	Depends On Part Geometry And Material
Barrel Temperature	200°C – 250°C	Adjust Based On Resin
Mould Temperature	30°C – 60°C	Use Chiller For Control

Parameter	Typical Range	Note
Holding Pressure	40 – 60 Mpa	To Avoid Shrink Marks
Injection Speed	Moderate To Fast	To Ensure Complete Fill

5.3 Operation

- Start Machine And Warm Up To Operating Temperature.
- Prime The Machine By Purging The Barrel.
- Start Production Cycle.
- Monitor First Part Output And Inspect Visually And Dimensionally.
- Continue Automatic Cycle After Qc Approval.

5.4 In-Process Inspection

Table 3.4: In-Process Inspection

Check	Frequency	Tool Used
Dimensional Check	Every 50 Parts	Vernier Calliper, Go/No-Go Gauge
Visual Inspection	Every Batch	Visual With Good Lighting
Surface Finish	Random	Operator Judgment, Qc Audit
Weight	1 In 100	Precision Scale

6. Common Defects And Troubleshooting

Table 3.5: Common Defects And Troubleshooting

Defect	Possible Cause	Corrective Action
Short Shot	Low Pressure/Temperature	Increase Temp Or Injection Pressure
Flashing	Excessive Pressure	Lower Injection Pressure Or Check Clamp Force
Burn Marks	Overheating	Reduce Melt Temp Or Improve Venting
Warping	Improper Cooling	Optimize Mould Temp Or Cycle Time

7. Shutdown Procedure

- Stop Machine After Final Cycle.
- Purge Remaining Material.
- Switch Off Heaters.
- Turn Off Hydraulic/Pneumatic Power.
- Clean Machine And Surrounding Area.

8. Health And Safety

- Always Use Ppe.
- Avoid Contact With Hot Surfaces.

- Ensure Emergency Stop Is Functional.
- Never Reach Into Mould Area During Operation.

9. Records To Maintain

- Daily Machine Log Sheet
- In-Process Inspection Records
- Maintenance Logs
- Non-Conformance Reports (If Any)

This Sop Aligns With **Iso 11119-3:2020** For Injection Mould For Composite Cylinders Casings.

HDPE Liner To Boss Part Welding

Figure 3.12: KLN welding section

Figure 3.13: KLN welding machine

In Accordance With Iso 11119-3:2020– Gas Cylinders — Refillable Composite Gas Cylinders And Tubes — Design, Construction And Testing — Part 3: Fully Wrapped Fibre Reinforced Composite Gas Cylinders With Non-Load Sharing Metallic Or Non-Metallic Liners

1. Purpose

To Define The Standard Procedure For Welding High-Density Polyethylene (Hdpe) Liners To Metallic Or Polymeric Boss Parts In The Production Of Type Iv Composite Pressure Vessels, Ensuring Leak-Free, Structurally Sound Joints In Compliance With Iso 11119-3.

2. Scope

Applies To All Hdpe Liner And Boss Assemblies Manufactured For Type Iv Fully Wrapped Composite Gas Cylinders Within The Production Facility.

3. Equipment And Materials

- Hot Plate Welding Machine (With Temperature And Pressure Control)
- Calibrated Clamping Fixtures
- Temperature Sensors (Thermocouples)
- Stopwatch Or Timer
- Clean Boss Parts (Aluminum, Stainless Steel, Or Other Compatible Material)
- Hdpe Liners (Post-Machining And Pre-Cleaning)
- Isopropyl Alcohol Or Equivalent Cleaning Agent
- Lint-Free Cloths

4. Safety Precautions

- Wear Heat-Resistant Gloves, Safety Goggles, And Antistatic Clothing.
- Ensure Ventilation Near Welding Zone To Avoid Fume Accumulation.
- Keep Flammable Materials Away From The Heating Area.
- Confirm Machine Emergency Stop Functionality Before Operation.

5. Procedure

5.1. Pre-Welding Preparation

- Verify Liner And Boss Part Match Drawing Specifications.
- Clean Welding Surfaces (Liner Neck And Boss Base) With Isopropyl Alcohol.
- Inspect For Contamination, Scratches, Or Deformation. Reject If Defects Found.
- Record Liner And Boss Batch Numbers For Traceability.

5.2. Machine Setup

- Set Hot Plate Temperature: 220°C To 240°C (Adjust Per Hdpe Grade).
- Set Clamp Pressure: Typically 0.2–0.5 Mpa (Check Process Qualification Record).
- Set Heating And Joining Time:
  Heating Time: 15–30 Seconds
  Joining Pressure Time: 20–40 Seconds
- Cooling Under Pressure: Minimum 30 Seconds

5.3. Welding Operation

- Mount The Hdpe Liner In The Lower Clamp And The Boss Part In The Upper Clamp.
- Move The Heated Plate Into Position Between The Two Parts.
- Bring Both Parts Into Light Contact With The Hot Plate (No Excessive Force).
- After Dwell Time, Retract Both Parts From The Plate.
- Quickly Align And Press The Parts Together Under Specified Joining Pressure.
- Maintain Pressure During Cooling Cycle.
- Release Clamps After Cooling, And Remove Welded Assembly.

6. Post-Weld Inspection

- Visual Check For Flash, Misalignment, Burn Marks, Voids, Or Cracks.
- Dimensional Check For Weld Bead Height, Neck Height, Boss Position.

- Leak Test (E.G., Helium Or Air Under Pressure) To Ensure Seal Integrity.
- Ensure Proper Flaming So As To Oxidizes The Surface, Creating Polar Functional Groups That Enhance Adhesion.
- Tensile Or Torque Test (Sample-Based, If Required By Qa).
- Clean Liner With Isopropyl Alcohol With A Lint Fee Cloths And Allow To Dry In Atmospheric Air.

7. Acceptance Criteria

- No Visible Cracks Or Incomplete Welds.
- Weld Flash Should Be Uniform And Within Specified Height Limits.
- Boss Must Be Concentric With Liner Axis Within Defined Tolerance.
- Joint Must Pass Leak And Pull Test According To Internal Qc Plan And Iso 11119-3.

8. Records And Documentation

- Record Batch Number, Machine Id, Welding Parameters, Operator Id, And Results Of Visual And Functional Inspection.
- Maintain Traceability To Liner And Boss Part Manufacturing Records.

9. References

- Iso 11119-3

This Sop Aligns With **Iso 11119-3** And Includes **Pneumatic Testing** For Detecting Leaks In Composite Cylinders.

Fiber Winding Section – Type Iv Composite Cylinder

Figure 3.14: Filament winding section

Figure 3.15: Filament winding section

Figure 3.16: Filament winding section

1. Purpose

To Establish A Standard And Controlled Method For The **Fiber Winding** Process In The Manufacturing Of **Type Iv Composite Cylinders**, Ensuring Safety, Consistency, And Compliance With Iso 11119-3:2020.

2. Scope

Applicable To All Operators And Technicians Engaged In Fiber Winding Of Composite Cylinders Using Continuous Fiber-Reinforced Materials And Epoxy/Anhydride Resin Systems.

3. Responsibilities

Role	Responsibility
Winding Operator	Execute Fiber Winding Per Set Parameters And Report Abnormalities.

Role	Responsibility
Quality Inspector	Monitor And Verify Parameters And Winding Quality.
Production Supervisor	Approve Setup, Monitor Productivity, And Ensure Safety Compliance.

4. Materials & Equipment

Materials

- Continuous Glass/Carbon Fiber (E.G., Jushi E6dr17-1200-300)
- Epoxy Resin (E.G., Litestone® 2130e)
- Hardener (E.G., Litestone® 2142h)
- Type Iv Polymer Liner
- Release Agent (If Required)

Equipment

- Cnc Filament Winding Machine
- Resin Bath With Controlled Viscosity & Temperature
- Fiber Tensioning & Guiding System
- Resin Mixing System
- Digital Scale For Resin Ratio
- Cure Oven (If Post-Winding Curing Is Required)

5. Safety Precautions

- Wear **Ppe**: Gloves, Goggles, Safety Boots, Apron.
- Ensure **Fiber Under Tension** Is Never Touched.

- Keep Emergency Stop Buttons Accessible.
- Resin And Hardener Must Be Handled With **Proper Ventilation**.

6. Procedure

6.1 Pre-Winding Checks

Table 3.6: Pre-Winding Checks

Check Item	Criteria
Liner	Clean, Dry, Dimensionally Verified, Visually Defect-Free
Fiber Material	Verified By Batch Number And Certificate Of Conformity
Resin System	Mixed In Correct Ratio (E.G., 100:85 By Weight) With Pot Life Monitored
Machine	Calibrated And Winding Pattern Verified (Hoop, Helical, Polar)
Environment	Temperature: 20–30 °C, Humidity: ≤ 75%, Dust-Free Area

6.2 Resin Mixing

1. Weigh Resin And Hardener Using Calibrated Scale.
2. Mix Thoroughly Using Mechanical Stirrer For 10–15 Min.
3. Measure Viscosity (Target: 600–1200 Cp).
4. Pour Into Resin Bath (With Temperature Control Between 25–35 °C).
5. Record Batch Number, Mix Ratio, Time, And Operator.

6.3 Fiber Winding Process

Figure 3.17: Type 4 composite cylinder with epoxy resin and hardener before curing

Figure 3.18: Composite cylinder with epoxy resin and hardener before curing

Table 3.7: Fiber Winding Process

Step	Description
1	Load The Liner Onto The Mandrel And Lock It.
2	Set Up The Winding Parameters In The Cnc System (Angle, Layer Count, Speed).
3	Thread The Fiber Through Tensioners, Resin Bath, And Onto The Liner.
4	Start Winding According To The Program: Hoop (90°) And Helical (E.G., ±15°

Step	Description
	To ±85°)
5	Monitor Tension (E.G., 30–60 N For Glass, Higher For Carbon).
6	Ensure Resin Impregnation Is Consistent (Wet-Out Visual Check).
7	Apply Layers As Per Design Thickness (Measure Intermittently Using Caliper Or Laser Micrometer).
8	Final Layer Should Be Visually Defect-Free With Fiber Ends Secured.
9	Stop Winding, Remove Liner, And Mark With Job Id And Time.

6.4 Cure Process (If Applicable)

Figure 3.19: Composite cylinder with epoxy resin and hardener after curing

- Move Wound Cylinder To Curing Area Or Oven.
- Curing Cycle (Example): 80 °C For 4 Hours (As Per Resin Tds).
- Allow Cooling To Room Temperature.
- Record Cure Cycle Parameters.

7. Quality Control Checks

Table 3.8: Quality Control Checks

Checkpoint	Method	Frequency	Tolerance
Fiber Tension	Tension Gauge	Continuous	As Per Sop
Winding Angle	Machine Log & Visual	Every Cylinder	±2°
Wall Thickness	Micrometer/Laser	Every 5 Pcs	As Per Design

Checkpoint	Method	Frequency	Tolerance
Resin Impregnation	Visual	Continuous	Uniform Wetting
Void/Bubble Check	Visual & Tap Test	Every Unit	No Dry Spots
Cure Verification	Hardness Test	Every Batch	Shore D/Barco Per Spec

8. Documentation & Traceability

- Winding Batch Report
- Resin Mixing Record
- Operator Log Sheet
- Cure Cycle Record
- Qc In-Process Checklist
- Cylinder Id And Traceability Log

9. Non-Conformance & Rework

- Any Defects (Dry Spots, Misalignment, Loose Ends) Must Be Reported.
- Minor Defects: Repair As Per Repair Sop (If Allowed).
- Major Defects: Reject And Record Under Ncr (Non-Conformance Report).

10. References

- Iso 11119-3:2020 – Gas Cylinders — Refillable Composite Gas Cylinders And Tubes — Part 3
- Internal Quality Manual

- Resin & Fiber Tds (Technical Data Sheets)

This Sop Aligns With **Iso 11119-3:2020** For Fiber Winding In Composite Cylinders Manufacturing Company.

Curing Oven – Type Iv Composite Cylinder

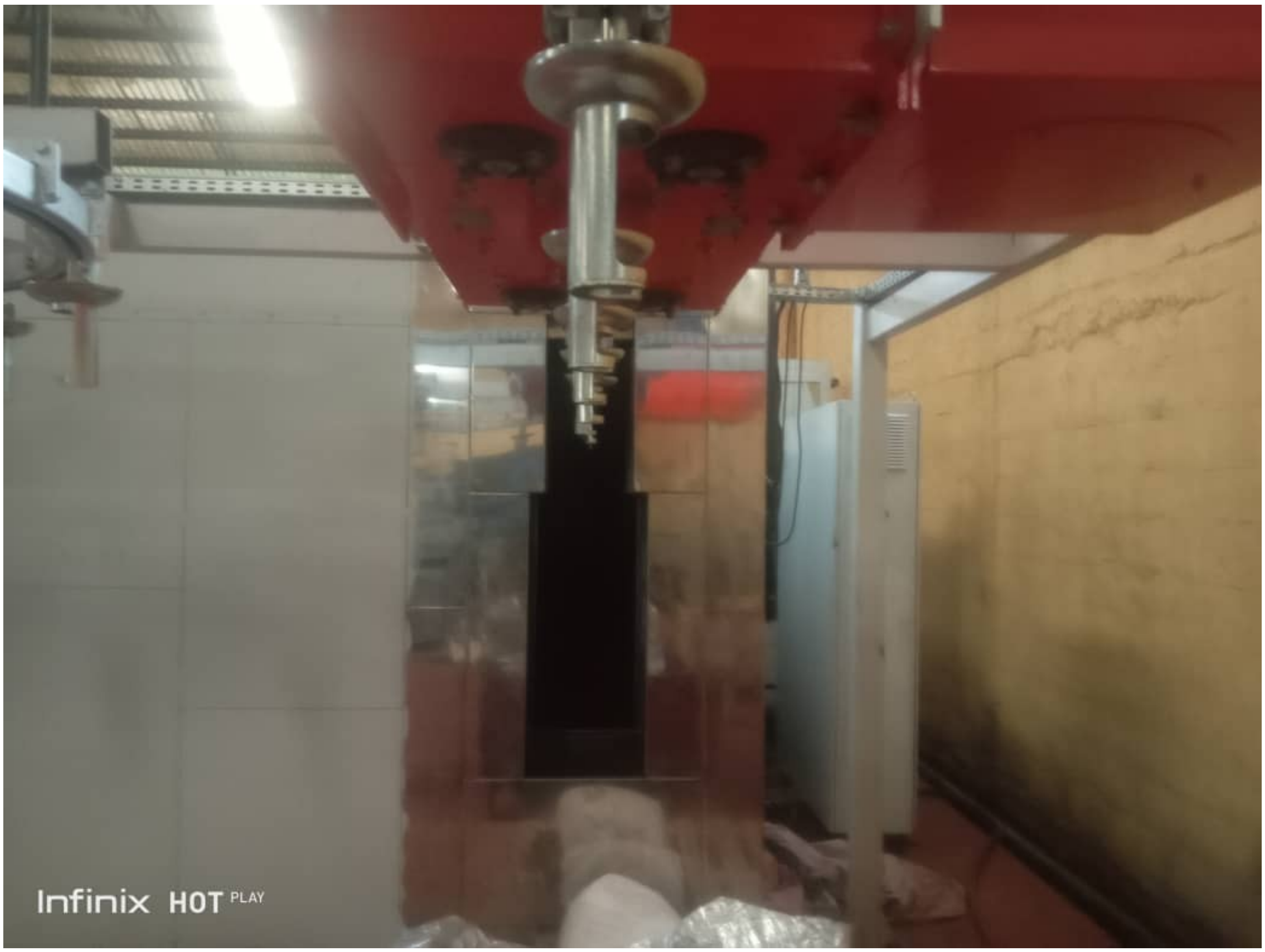

Figure 3.20: Curing oven

1. Purpose

To Define The Standard Method For Curing Composite Cylinders Post-Fiber Winding Using An Industrial Curing Oven, Ensuring The Proper Polymerization Of Resin Matrix In Line With Iso 11119-3:2020.

2. Scope

This Sop Applies To All Post-Winding Curing Operations For Type Iv Cylinders That Require Thermal Curing Of Wet Filament Wound Parts Using Epoxy/Anhydride Resin Systems.

3. Responsibilities

Table 3.9: Responsibilities

Role	Responsibility
Oven Operator	Load/Unload Parts, Monitor Oven Settings And Curing Cycle.
Process Engineer	Define And Validate Curing Parameters.
Quality Inspector	Verify Curing Cycle And Perform Post-Cure Inspections.
Maintenance Technician	Maintain Oven Calibration And Ensure Safety Systems Are Functional.

4. Equipment And Materials

Curing Equipment

- Industrial Convection Oven With Pid Controller
- Data Logger/Recorder With At Least 3 Thermocouple Channels
- Rack Or Mandrel For Holding Cylinders
- Heat-Resistant Gloves And Ppe

Materials

- Wound Type Iv Composite Cylinders
- Identification Tags Or Markers
- Oven Loading Sheet And Curing Log

5. Safety Precautions

- Use **Heat-Resistant Gloves**, Apron, And Safety Glasses.
- Ensure **Proper Ventilation** In The Oven Room.
- Confirm All **Emergency Stops** And Interlocks Are Functional.
- Do Not Open The Oven During The Heating Cycle.
- Ensure Cylinders Are Stable To Prevent Falling.

6. Procedure

6.1 Pre-Curing Checks

Table 3.10: Pre-Curing Checks

Check	Requirement
Oven Temperature Calibration	Must Be Certified/Calibrated Within The Last 12 Months
Cylinder Id Verification	Confirm Traceability And Winding Batch
Resin Gel Time Check	Must Still Be Within Pot Life Range
Oven Environment	Free Of Flammable Materials, Clean Interior

6.2 Loading The Oven

- Place The Cylinders **Horizontally Or Vertically** As Per Fixture Design.
- Ensure **Even Spacing** For Airflow And Temperature Distribution.
- Avoid Contact Between Cylinders And Oven Walls.
- Place **Thermocouples** In At Least 3 Zones: Top, Middle, And Near A Cylinder Surface.
- Record **Cylinder Id, Batch Number, Operator Name, And Time Of Loading**.

6.3 Setting The Curing Cycle

Set The Oven As Per The Resin Manufacturer's Tds Or Validated Process, For Example:

- **Ramp Up**: From Ambient To 90°C At 1–2 °C/Min For Chamber One And 100-120°C For Chamber Two
- **Hold**: At 90°C For Chamber One And 100-120°C ± 2 °C For **3 Hours** For Chamber Two With A Four Minutes Per Movement Of The Fixture Line.
- **Cool Down**: To ≤40 °C Before Removal From The Fixture Line, Allow To Cool Under Atmospheric Air.

6.4 Monitoring During Curing

- Monitor Oven Display And Ensure **Temperature Uniformity**.
- Record Temperature Data (Auto-Logging Preferred).
- If **Temperature Deviation > ±2 °C**, Pause And Alert Process Engineer.
- Do Not Open The Oven During Soak Time.

6.5 Post-Curing

1. Allow Oven To Cool To ≤40 °C Before Opening.
2. Use Gloves To Unload Cylinders Carefully.
3. Inspect Each Unit Visually For Any Defects (Resin Sag, Discoloration, Deformation).

7. Quality Control Checks

Table 3.11: Quality Control Checks

Parameter	Method	Frequency	Acceptance Criteria
Oven Temperature Uniformity	Thermocouple Log	Every Cycle	±2 °C
Cure Time	Timer/Log	Every Cycle	As Per Tds
Visual Inspection	Manual	Every Unit	No Defects
Resin Cure Status	Shore /Barcol Hardness	1 Per Batch	Per Tds Spec

8. Documentation

- **Curing Log Sheet**: Records Temperature, Time, Batch Info, Operator
- **Cylinder Id Log**: Ensures Traceability
- **Maintenance Log**: For Calibration And Oven Checks
- **Non-Conformance Report (If Any)**

9. Non-Conformance Handling

If A Cylinder Fails Post-Cure Inspection:

- Quarantine The Item And Tag It As **"Suspect"**
- Notify Quality Assurance
- Re-Cure Or Scrap Based On Assessment

- Document Findings In Ncr

10. References

- Iso 11119-3:2020
- Resin Manufacturer's Tds
- Internal Quality & Traceability Procedures
- Maintenance & Calibration Procedures

This Sop Aligns With **Iso 11119-3:2020** For Fiber Winding In Composite Cylinders Manufacturing Company.

Recycling Of Rejected/Bad Polymer Liners

1. Purpose

To Define The Procedure For Managing And Recycling Defective, Damaged, Or Non-Conforming Polymer Liners Used In Type Iv Composite Cylinder Production In A Controlled, Traceable, And Environmentally Compliant Manner.

2. Scope

This Sop Applies To All Polymer Liners (E.G., Hdpe, Pa, Pet) That Are Rejected Before Or After The Moulding Process But **Before Composite Winding** Begins.

3. Responsibilities

Table 3.12: Responsibilities

Role	Responsibility
Operator/Qc Inspector	Identify And Tag Defective Liners

Role	Responsibility
Production Supervisor	Approve Removal Of Defective Liners
Recycling Technician	Operate Shredding, Grinding Or Reclaiming Units
Ehs Officer	Ensure Recycling Complies With Local Environmental Regulations

4. Equipment And Materials

Equipment

- Plastic Shredder Or Granulator
- Grinder With Mesh Screen
- Collection Bins (Labelled)
- Weighing Scale
- Barcode/Tag Printer (For Traceability)

Materials

- Defective Liners (Scrap)
- Logbooks Or Digital Recycling Logs

5. Safety Precautions

- Use Appropriate **Ppe**: Gloves, Earplugs, Goggles, Safety Boots.
- Ensure Shredding Equipment Has Safety Interlocks And Emergency Stop.
- Do Not Recycle Contaminated Or Composite-Wrapped Liners.

- Keep Scrap Bins Clearly Labelled And Segregated By Material Type.

6. Procedure

6.1 Identification Of Bad Liners

Table 3.13: Identification Of Bad Liners

Condition	Examples
Visual Defects	Cracks, Dents, Irregular Geometry, Color Mismatch
Dimensional Out-Of-Tolerance	Neck Od/Id, Wall Thickness Variation
Failed Leak/Pressure Tests	Blow Molding Or Post-Mold Testing
Contaminated Surfaces	Grease, Oil, Embedded Dirt

1. Tag Defective Liner With **“Rejected” Label**.
2. Move To The **“Scrap Holding Area”** Under Qc Supervision.

6.2 Segregation And Storage

- Store Defective Liners By Material Type (E.G., Pet, Hdpe, Pa).
- Maintain Traceability To Batch Number And Rejection Reason.
- Store Indoors To Prevent Uv Degradation Or Contamination.

6.3 Recycling Process

1. Inspect Liner To Ensure No Composite Winding Or Foreign Matter Is Attached.
2. Weigh The Liner And Record Data.

3. Shred/Grind Into Flakes Or Pellets (As Applicable).
4. Collect In Labelled Bins With Liner Type And Date.
5. Store Recycled Material In A Clean, Dry, Designated Area.
6. Blended With Virgin Resin.(Max. 30% Recycled Content,When There Is A Need For Reuse In Type Iv Production Of Liner)

6.4 Utilization Of Recycled Material

- Recycled Liner Material May Only Be Used For:
    - In-House Trial Moulding (Not For Pressure Vessels Unless Qualified).
    - Non-Critical Components Or Packaging Applications.
- Reuse In Type Iv Production Only If Requalified Via Testing (Density, Flow Index, Strength).

6.5 Documentation

Table 3.14: Documentation

Document	Purpose
Liner Rejection Log	Records Reason And Batch Info Of Rejected Liners
Recycling Log	Tracks Weight, Process Date, And Operator Name
Material Traceability Sheet	Links Recycled Material Back To Source
Monthly Recycling Summary	For Review By Ehs And Qa Departments

7. Non-Conforming Situations

If Contaminated, Mixed-Material, Or Post-Wound Liners Are Found:

- Tag As "Non-Recyclable"
- Dispose Of Via Approved Waste Handler
- Record Disposal Details In Scrap Disposal Log

8. Environmental Compliance

- Follow National & Local Ehs Regulations (E.G., Nesrea In Nigeria)
- Ensure No Air, Water, Or Soil Contamination During Shredding/Storage
- Maintain Audit-Ready Records Of Waste Handling And Recycling

9. References

- Iso 11119-3:2020 – Composite Cylinders
- Company Waste Management Policy
- Polymer Material Safety Data Sheets (Msds)
- Local Environmental Regulations

Recycling Of Type Iv Composite Cylinders

Reference Standard: Iso 11119-3:2020
Department: Production / Quality / Waste Management
Process Area: Post-Use Cylinder Decommissioning & Material Recovery

1. Purpose

To Outline The Standardized Method For Identifying, Decommissioning, And Recycling Type Iv Composite Pressure Cylinders That Have Failed Inspection, Reached End-Of-Life, Or Were Rejected During Production, In Compliance With Iso 11119-3:2020 And Environmental Regulations.

2. Scope

This Sop Applies To All Type Iv (Plastic Liner With Full Composite Overwrap) Cylinders That Are:

- Rejected During Or After Hydrostatic Burst Testing Or Visual Inspection
- Expired Based On Certified Service Life
- Returned From Service For Safe Disposal
- Failed Post-Curing Ndt Or Leak Tests

3. Responsibilities

Table 3.15: Responsibilities

Role	Responsibility
Qa Inspector	Identifies And Approves Cylinders For Decommissioning
Production Supervisor	Oversees Physical Cylinder Destruction
Recycling Operator	Operates Shredding/Cutting/Grinding Equipment
Ehs Officer	Ensures Environmental And Safety Compliance

4. Materials & Equipment

- High-Speed **Composite Cutting Saws**
- **Shredder Or Granulator** (For Polymer Liners)
- **Steel Shears** (If Applicable For End Fittings)
- **Ppe**: Cut-Resistant Gloves, Goggles, Boots, Hearing Protection
- **Tagging System**: For Rejected/Expired Cylinders
- Cylinder Log Sheets And Rejection Forms

5. Safety Precautions

- All Cylinders Must Be Vented And Depressurized Before Cutting.
- Use Explosion-Proof Tools Where Applicable.
- Maintain A Safe Work Perimeter During Cutting Or Shredding.
- Ensure Fire Extinguishers And First Aid Kits Are Available.

6. **Procedure**

6.1 Cylinder Identification & Quarantine

- Identify Defective Or Expired Cylinder Based On:
    a. Hydrostatic Failure
    b. Visual/Internal Delamination
    c. Expired Serial Number
- Tag The Cylinder With **"For Destruction"** Label.
- Update The **Cylinder Rejection/Disposal Log** (Id, Batch, Reason).

6.2 Cylinder Depressurization & Decontamination

- Confirm That The Cylinder Is Completely Depressurized (Zero Gauge Pressure).
- If Applicable, Rinse And Dry Internal Volume To Remove Any Gas Residues Or Oil.
- Remove Valve And Fittings For Separate Disposal (If Reusable, Send For Recertification).

6.3 Physical Destruction

- Secure Cylinder On Cutting Cradle.
- Use Composite Saw To Make 2–3 Longitudinal Cuts To Ensure Cylinder Cannot Be Reused.
- If Possible, Separate Polymer Liner From Composite Shell.
- Collect Composite And Liner Waste Separately.

6.4 Material Sorting & Recycling

Table 3.15: Material Sorting & Recycling

Material	Action
Composite Fibers (E.G., Carbon/Glass/Epoxy)	Sent To Approved Composite Recycler Or Ground For Filler
Plastic Liner (E.G., Hdpe, Pa, Pet)	Shredded And Reused Internally (If Qualified) Or Sold As Industrial Scrap
Metallic End Fittings	Sent To Metal Recycling Plant

6.5 Record Keeping

- Update Recycling Logbook: Cylinder Id, Date, Reason, Process Method, Operator Signature.
- Maintain Certificate Of Destruction (Cod) If Required By Customer Or Regulatory Body.
- Submit Monthly Summary To Qa And Ehs Departments.

7. Environmental Compliance

- Segregate Waste To Prevent Contamination.
- Comply With **Local Waste Regulations** (E.G., Nesrea In Nigeria).
- Keep All Records For **At Least 5 Years**.
- Audit Recycling Vendors For Proper Disposal Practices.

8. References

1. Iso 11119-3:2020 – Gas Cylinders – Refillable Composite Gas Cylinders
2. Company Environmental Policy

3. Msds Of Epoxy, Polymer Liner, And Composite Materials

4. Nesrea Waste Guidelines (Nigeria)

3.3.4 In-Process Inspection & Quality-Control

In-Process Inspection Liner Production

In Accordance With Iso 11119-3:2020 – Gas Cylinders — Refillable Composite Gas Cylinders And Tubes — Design, Construction And Testing — Part 3: Fully Wrapped Fibre Reinforced Composite Gas Cylinders With Non-Load Sharing Metallic Or Non-Metallic Liners

1. Purpose

This In-Process Inspection Requirements For The Production Of Liners Used In Type Iv Composite Gas Cylinders To Ensure Compliance With Iso 11119-3 Standards.

2. Scope

Applies To All Manufacturing Stages Of Thermoplastic (Hdpe) Liners Prior To Composite Overwrapping.

3. Responsibilities

- Operators: Perform Self-Checks And Record Results.
- Qc Inspectors: Conduct Dimensional, Visual, And Functional Checks.
- Supervisors: Monitor Compliance And Approve Continuation Of Production.
- Maintenance: Ensure Equipment Calibration And Functionality.

4. In-Process Inspection Points

Table 3.16: In-Process Inspection Points

Checkpoint	Method	Frequency	Pass/Fail	Remarks
Liner Dimensions Within Tolerance	Calipers / Ultrasonic Gauge	Every 10th Part		

Visual Defects Absent	Visual Inspection	Inline / Sampling		
Liner Weight Acceptable	Digital Scale	Hourly		
Neck/Mouth Geometry Correct	Thread/Plug Gauge	Every 10th Liner		
Part Warpage/Concentricity	Jig/Fixture Test	Hourly		

Raw Material Check

- Verify Supplier Certificate Of Analysis (Coa).
- Ensure Correct Resin Type And Batch Number.
- Check Storage Conditions Of Raw Hdpe Resin.

Moulding Or Extrusion

- Check Equipment Parameters (Temperature, Pressure, Time).
- Inspect Liner For Voids, Discoloration, And Contamination.
- Verify Parison Wall Thickness (If Blow Molding).

Cooling And De-Moulding

- Inspect Liner Shape For Deformation Or Warpage.
- Ensure Uniform Wall Thickness Using Ultrasonic Or Caliper Methods.

Trimming And Machining

- Verify Neck Profile, Threads, And Chamfers Per Drawing.

- Use Go/No-Go Gauges And Calipers For Threads And Neck Dimensions.

Dimensional Checks

- Measure Overall Length, Inner Diameter, Outer Diameter, And Wall Thickness.
- Frequency: Every 10th Liner Or As Per Control Plan.

Weight Check

- Ensure Weight Is Within ±2% Of Target Value.
- Frequency: Every 20th Liner.

Visual Inspection

- Check For Surface Defects: Scratches, Bubbles, Black Specks, Incomplete Fill.
- Confirm Cleanliness Of Inner And Outer Surfaces.

5. Tools And Equipment

- Vernier Calipers
- Micrometer
- Ultrasonic Wall Thickness Gauge
- Weighing Scale (Digital)
- Thread Gauges
- Inspection Lights And Magnifiers

6. Documentation And Records

- Maintain Inspection Logs With Lot Numbers.
- Record Non-Conformances And Corrective Actions.
- Use Approved Forms And Checklists.
- Ensure Traceability To Raw Materials And Process Parameters.

7. Acceptance Criteria

- All Dimensions Within Specified Tolerance.
- No Critical Visual Defects (E.G. Cracks, Inclusions, Contamination).
- Weight And Wall Thickness Conform To Specifications.
- Thread Fit And Neck Geometry Compliant With Cylinder Design.

8. References

- Iso 11119-3:2020

In-Process Inspection For Hdpe Liner To Boss-Part Welding

1. **Purpose**

To Establish A Systematic Method For Conducting In-Process Inspection During The Welding Of Hdpe Liners To Boss-Parts To Ensure Consistent Quality And Compliance With Iso 11119-3 Requirements For Type Iv Composite Pressure Cylinders.

2. Scope

This Procedure Applies To All Hdpe Liner And Boss-Part Welding Operations Performed During The Manufacturing Of Type Iv Composite Gas Cylinders.

3. **Responsibilities**

- **Quality Control (Qc) Inspector**: Conduct Inspections, Record Findings, And Reject/Approve Parts.
- **Welding Operator**: Ensure Welding Process Is Correctly Followed And Inform Qc Of Anomalies.
- **Production Supervisor**: Oversee Process Adherence And Support Corrective Actions If Needed.

4. Inspection Equipment

- Vernier Calliper Or Digital Micrometre
- Thermocouple Reader Or Pyrometer
- Stopwatch Or Timer
- Visual Inspection Light And Magnifier (If Needed)
- Leak Testing Setup (Dry Air Or Helium Under Pressure)
- Torque/Tensile Test Setup (Sample Basis)

5. Inspection Stages And Parameters

5.1. Pre-Welding Inspection

Table 3.17: Pre-Welding Inspection

Check Item	Criteria	Frequency	Action If Rejected
Liner Surface	Clean, No Oil, Scratches, Or Deformities	100%	Re-Clean Or Reject
Boss Fit	Should Align Correctly With Liner Neck	100%	Rework Or Reject
Part Identity	Batch Number Traceability	100%	Correct Documentation Required

5.2. In-Welding Inspection

Table 3.18: In-Welding Inspection

Check Item	Criteria	Frequency	Action If Out Of Spec
Plate Temperature	220°C – 240°C (As Per Wps/Pqr)	Per Batch	Adjust Before Next Operation
Heating Time	15 – 30 Seconds	Per Weld	Correct And Repeat If Early/Late
Joining Pressure	0.2 – 0.5 Mpa	Per Weld	Adjust Clamps
Alignment	Axial And Radial Alignment Within ±0.5 Mm	100%	Stop Process And Correct Setup

5.3. Post-Welding Inspection (In-Process)

Table 3.19: Post-Welding Inspection (In-Process)

Check Item	Criteria	Frequency	Action If Defective
Weld Bead Appearance	Uniform, Smooth Flash, No Burns Or Voids	100%	Reject
Boss Concentricity	Within ±0.3 Mm From Liner Center	100%	Rework Or Reject
Visual Defects	No Cracks, Deformations, Or Contamination	100%	Reject

Check Item	Criteria	Frequency	Action If Defective
Leak Test (Sample)	No Leak Under Specified Pressure (E.G., 10 Bar)	Every 10 Units Or Per Sop	Reject & Investigate Batch

6. Documentation

- Record All Inspection Data Including:
    - Operator Id
    - Welding Parameters (Time, Temp, Pressure)
    - Visual Inspection Outcome
    - Non-Conformance Reports (If Any)
- Maintain Traceability To Part Batch And Process Stage Per Iso 11119-3.

7. Acceptance Criteria

- Weld Must Meet Visual And Dimensional Standards.
- Welded Joint Must Pass Leak And Mechanical Tests.
- No Misalignment, Deformation, Or Material Damage Allowed.

8. References

- Iso 11119-3:2020
- Quality Management Manual

3.3.5 Common Quality Problems In Composite Cylinder Manufacturing

Table 3.20: Common Quality Problems In Composite Cylinder Manufacturing

Quality Problem	**Visual Illustration Description**	**Cause**	**Symptoms & Implications**	**Solution & Prevention**
1. Delamination (Separation Of Composite Layers)	**Imagine:** A Cross-Section Of The Cylinder Wall Where The Layers, Which Should Be A Single Solid Unit, Are Visibly Peeling Apart Or Separated, Much Like The Pages Of A Damp, Swollen Book. Edges Might Look Frayed Or Lifted.	- **Improper Interlaminar Bonding:** Weak Adhesion Between Plies Due To Insufficient Chemical Bonding Or Mechanical Interlocking. **Insufficient Resin Wetting:** Resin Fails To Fully Penetrate And Encapsulate Fibres Between Layers, Creating Dry Spots That Act As Initiation Points For Separation. **Contamination:** Presence Of Foreign Materials (Oils, Grease, Dust, Release Agent Residue) On Ply	- **Visible Layer Separation:** Obvious Gaps Or Splits Between Layers, Often Starting At Edges, Cutouts, Or Impacttes. **Surface Blistering/Bubbling:** Raised, Dome-Like Areas On The Cylinder Surface Indicating Localized Delamination Beneath. **Reduced Structural Integrity:** Significant Decrease In Stiffness, Load-Bearing Capacity (Tensile, Compressive, Flexural Strength), And	- **Thorough Surface Preparation:** Implement Stringent Cleaning Protocols (E.G., Solvent Wiping, Abrasion) And Consider Surface Treatments (E.G., Plasma, Corona, Chemical Etching) To Enhance Surface Energy And Promote Adhesion. **Optimize Resin System & Application:** Ensure Correct Resin Viscosity (E.G., By Controlling Temperature, Using Appropriate Diluents As Per Datasheet) For Thorough Fiber Wetting. Calibrate Resin Application Equipment. **Maintain Cleanliness:** Enforce Cleanroom Or Controlled Environment

		Surfaces, Acting As A Barrier To Adhesion. **Incorrect Curing Cycle:** Deviations From Specified Cure Temperature (Too Low Prevents Full Cross-Linking, Too High Can Cause Thermal Stresses) Or Pressure (Insufficient Pressure Fails To Consolidate Layers And Expel Trapped Air/Volatiles). **Trapped Moisture/Solvents:** Volatilization Of Trapped Moisture Or Solvents During Cure Can Create Internal Pressure, Pushing Layers Apart.	Resistance To Fatigue. The Cylinder May Feel "Soft" Or Overly Flexible In Affected Areas. **Characteristic "Hollow" Sound:** Tapping The Affected Area With A Coin Or Tap Hammer Produces A Dull, Hollow, Or "Dead" Sound Compared To The Crisp, Sharp Sound From A Well-Bonded Area, Indicating A Discontinuity. **Premature Failure:** Can Lead To Catastrophic Failure Under Operational Loads, Well Below Design Limits.	Standards. Regularly Clean Molds, Tools, And Equipment. Ensure Raw Materials Are Stored Properly And Are Free From Contaminants. **Precise Curing Control:** Accurately Monitor And Control All Cure Cycle Parameters (Temperature Ramps, Dwell Times, Pressure, Vacuum) Using Calibrated Equipment. Ensure Uniform Heat Distribution In Ovens/Autoclaves. **Material Control:** Ensure Proper Storage And Handling Of Prepregs To Prevent Moisture Absorption. Implement Out-Gassing Steps If Necessary. **Non-Destructive Testing (Ndt):** Routinely Use Ndt Methods Like Ultrasonic Testing (C-Scan), Tap Testing, Or Acoustic Emission To Detect And Characterize Internal

				Delaminations.
2. Voids / Porosity (Trapped Air/Gas Bubbles)	**Imagine:** A Magnified Slice Of The Composite Material Looking Like A Dark Sponge, With Numerous Tiny, Empty Pockets (Black Dots Or Irregular Cavities) Peppered Throughout The Resin Matrix Between The Fibers.	- **Trapped Air/Volatiles:** Air Entrapped During Layup, Filament Winding, Or Resin Mixing. Volatiles (E.G., Moisture, Solvents) In The Resin Or On Fibers Vaporize During Cure If Not Removed. **Insufficient Resin Flow:** Resin Viscosity Too High, Or Cure Time Too Short, Preventing Resin From Flowing Into And Filling All Interstitial Spaces Between Fibers. **Inadequate Consolidation:** Insufficient Pressure Or Vacuum Applied During Curing, Failing To Squeeze Out Trapped Air And Compact The Laminate.	- **Surface Pits/Pinholes:** Small, Visible Depressions Or Tiny Holes On The Cured Cylinder Surface. **Reduced Density & Mechanical Properties:** Lower Overall Density. Significant Reduction In Interlaminar Shear Strength, Compressive Strength, And Fatigue Life. Voids Act As Stress Concentrators. **Increased Environmental Susceptibility:** Voids Can Create Pathways For Moisture, Chemicals, Or Gases To Ingress Into The Composite, Leading To Degradation Of The Matrix And	- **Resin Degassing:** Implement Vacuum Degassing Of Mixed Resin Systems Prior To Impregnation To Remove Dissolved Air And Volatiles. **Optimized Impregnation:** Ensure Thorough Fiber Wetting During Impregnation. For Filament Winding, Control Resin Bath Temperature And Winding Speed. **Controlled Layup/Winding:** Use Techniques That Minimize Air Entrapment (E.G., Proper Squeegeeing, Appropriate Winding Tension). **Adequate Consolidation:** Apply Specified Vacuum Bagging Techniques And Autoclave Pressures. Ensure Bag Integrity. **Optimized Cure Cycle:** Use Recommended Ramp Rates And Dwell Times To Allow Volatiles To Escape

		Resin Shrinkage: Some Resins Shrink Significantly During Curing, And If Not Adequately Fed By Excess Resin, Can Lead To Shrinkage Voids. **Too Rapid Curing:** Fast Temperature Ramp-Up Can Cause Volatiles To Expand Rapidly Before The Resin Has Properly Flowed Or Gelled, Trapping Them.	Fibers Over Time. **Reduced Dielectric Strength:** In Applications Requiring Electrical Insulation, Voids Can Lower The Breakdown Voltage. **Cloudy/Opaque Appearance:** High Void Content Can Sometimes Make A Translucent Laminate Appear More Opaque Or Cloudy.	And Resin To Flow Before Gelation. Consider A Staged Cure. **Material Selection:** Choose Low-Volatility Resins Or Prepregs With Controlled Volatile Content. **Process Monitoring & Ndt:** Monitor Vacuum Levels And Temperatures During Cure. Use Ultrasonic Inspection Or X-Ray Radiography To Quantify Void Content.
3. Resin-Rich Areas (Excess Resin Concentration)	**Imagine:** Patches On The Cylinder Surface, Or Zones Within A Cross-Section, That Are Exceptionally Glossy, Smooth, And	- **Incorrect Fiber-To-Resin Ratio:** Dispensing Or Applying Significantly More Resin Than Required By The Design Specifications. **Resin Drainage/Pooling:** Gravity Causing Liquid Resin To Flow	- **Localized Glossy, Thick Resin Areas:** Visibly Thicker Layers Of Resin, Often Appearing Darker Or More Translucent. **Reduced Fiber Volume Fraction (Fvf):** Lower Proportion Of Load-Bearing	- **Precise Resin Metering & Control:** Calibrate And Accurately Control Resin Mixing And Dispensing Equipment To Achieve The Target Fiber-To-Resin Ratio. **Optimized Process Parameters:** Control Resin Viscosity (E.G., Via Temperature),

	Transluce nt, Where Fibers Are Sparse Or Deeply Submerge d Under A Thick Layer Of Resin.	And Accumulate In Certain Areas (E.G., Lower Sections Of A Vertically Cured Part) Before Or During Gelation. **Poor Fiber Compaction:** Insufficient Pressure Or Fiber Tension During Processing, Leading To Fibers Not Being Tightly Packed, Leaving Larger Gaps Filled By Resin. **Inadequate Bleed-Out Control:** If A Bleeder System Is Used, It May Not Be Functioning Correctly To Remove Excess Resin.	Fibers In These Areas. **Increased Brittleness & Reduced Toughness:** Neat Resin Is Generally More Brittle Than The Composite. Excess Resin Reduces Impact Resistance And Toughness. **Potential For Cracking:** Due To The Brittleness And Different Thermal Expansion Coefficients, Resin-Rich Areas Are More Prone To Micro-Cracking Under Thermal Or Mechanical Stress. **Increased Weight:** Contributes To Unnecessary Weight In The Component. **Obscuring Underlying Defects:** Thick Resin Can Mask Other Defects	Application Speed, And Fiber Tension To Ensure Even Distribution. **Tooling Design & Orientation:** Design Molds And Supports To Minimize Resin Pooling. Consider Part Orientation During Cure. **Effective Bleeder/Breather Design:** If Using Bleed-Out, Ensure The Bleeder Material And Bagging Scheme Are Correctly Designed And Applied To Absorb Only The Excess Resin. **Regular Process Audits:** Monitor Material Usage And Part Weights To Detect Trends Towards Resin-Rich Conditions. **Visual Inspection & Ndt:** Careful Visual Inspection. Techniques Like Thermography Can Sometimes Highlight Areas With Different Thermal Mass Due To Resin Variation.

			Like Voids Or Fiber Misalignment.	
4. Resin-Starved Areas (Insufficient Resin)	**Imagine:** Areas On The Cylinder Surface Or Within A Cross-Section That Appear Dull, Dry, And Rough, With Fibers Clearly Visible And Not Fully Encapsulated By Resin. Fibers Might Look Fuzzy Or Easily Disturbed.	- **Incorrect Fiber-To-Resin Ratio:** Dispensing Or Applying Too Little Resin Relative To The Fiber Content. **Excessive Resin Bleed-Out:** Too Much Resin Being Squeezed Out During Consolidation Or Cure Due To Overly Aggressive Vacuum, High Pressure, Or An Overly Effective Bleeder System. **High Fiber Tension:** In Filament Winding, Excessive Fiber Tension Can Squeeze Out Too Much Resin From The Tow Before It Reaches The Mandrel. **Poor Resin Impregnation:**	- **Dry, Exposed, Or Fuzzy Fibers:** Fibers Are Not Fully Wetted And Encapsulated By The Resin, Appearing Loose On The Surface. **Dull, Matte Surface Appearance:** Lack Of A Glossy Resin Film On The Surface. **Reduced Interlaminar Shear Strength (Ilss):** Insufficient Resin Leads To Poor Bonding Between Fibers And Layers, Drastically Reducing Shear Strength. **Increased Susceptibility To Damage:** Exposed Fibers Are Prone To Abrasion, Moisture Ingress, And	- **Accurate Resin Control:** Ensure Precise Metering And Application Of The Correct Amount Of Resin. **Controlled Bleed-Out:** Optimize Bleeder/Breather Materials And Vacuum/Pressure Application To Remove Only The Necessary Amount Of Excess Resin And Volatiles, Not Essential Resin. **Optimize Winding/Layup Parameters:** Adjust Fiber Tension, Resin Bath Levels, And Application Speed To Ensure Proper Impregnation Without Excessive Squeeze-Out. **Resin Viscosity Management:** Control Resin Temperature To Maintain Optimal Viscosity For Wetting. If Viscosity Is Inherently Too High, Evaluate

		Resin Failing To Fully Saturate The Fiber Bundles During The Wetting Process. **High Resin Viscosity:** Resin Being Too Thick To Flow And Penetrate The Fiber Bundles Adequately.	Chemical Attack. **Reduced Compressive & Flexural Strength:** The Matrix Supports Fibers Against Buckling Under Compression; Insufficient Matrix Compromises This. **Porous Structure:** Can Lead To Higher Permeability And Susceptibility To Environmental Degradation.	Alternative Resin Systems Or Approved Modifiers. **Thorough Impregnation Techniques:** Ensure Sufficient Dwell Time In Resin Baths Or Use Impregnation Rollers/Methods That Force Resin Into Fiber Bundles. **Quality Checks:** Implement In-Process Checks For Proper Wet-Out.
5. Wrinkles / Fiber Misalignment ~~ (Distorted Fiber Paths)	**Imagine:** The Reinforcing Fibers, Which Should Lie Smooth, Straight, And Parallel (Or In A Defined Pattern), Instead Appear Buckled, Wavy,	- **Improper Layup/Winding Technique:** Incorrect Placement, Insufficient Tension, Or Slippage Of Plies/Tows During Manual Layup Or Automated Filament Winding. **Ply/Material Handling Issues:** Prepreg Or Dry Fiber	- **Visible Waviness Or Distortion:** Obvious Deviations In The Fiber Pattern From The Intended Straight Or Curved Paths. **Reduced Strength & Stiffness:** Significant Knockdown In Mechanical Properties, Especially	- **Improved Layup/Winding Procedures:** Implement Standardized, Validated Techniques. For Manual Layup, Use Templates And Ensure Careful Smoothing And Debulking. For Filament Winding, Optimize Payout Eye Guidance, Band Width Control, And Winding Trajectory. **Proper Material**

	Folded Over, Or Significantly Deviated From Their Intended Orientation.	Movement Or Distortion During Cutting, Transportation To The Mold, Or Draping Over Complex Contours. **Insufficient Fiber Tension (Filament Winding):** Leading To Loose Fibers That Can Buckle Or Shift. **Excessive Fiber Tension (Filament Winding):** Can Cause Underlying Layers To Shift Or Buckle, Particularly On Non-Cylindrical Mandrels. **Tooling/Mandrel Issues:** Complex Tool Geometry, Insufficient Tack Of The Material To The Tool, Or Thermal Expansion Mismatch Between Tool And Composite. **Bridging:**	Compressive Strength, As Misaligned Fibers Cannot Carry Load Efficiently And May Buckle Prematurely. Tensile Strength Can Also Be Affected If Angles Are Incorrect. **Stress Concentrations:** Wrinkles Act As Geometric Discontinuities, Creating Points Of High Stress That Can Initiate Failure. **Dimensional Inaccuracy:** Can Lead To Parts Not Meeting Geometric Tolerances. **Resin-Rich Pockets:** Often Associated With Wrinkles, Where Resin Accumulates In The Troughs Of The Waves.	**Handling:** Minimize Distortion Of Prepregs; Use Backing Films; Store And Transport Materials Carefully. **Optimized Fiber Tension:** Maintain Consistent And Appropriate Tension During Filament Winding Using Calibrated Tensioners. **Tooling Design & Preparation:** Ensure Tools Are Clean And Properly Prepared (E.G., Appropriate Release Agent, Tackifiers If Needed). Design Tools To Facilitate Material Conformance. Use Female Molding Where Out-Of-Plane Wrinkles Are Critical. **Debulking/Consolidation:** Perform Intermediate Debulking Steps During Layup Of Thick Laminates To Remove Trapped Air And Ensure Plies Conform To The Tool. **Operator Training:** Ensure Operators Are Well-

		Material Stretching Over Concave Radii Instead Of Conforming To The Tool Surface, Leading To A Void Beneath And Fiber Misalignment.		Trained In Handling Composite Materials And Executing Layup/Winding Procedures Correctly. **Automated Fiber Placement (Afp) / Automated Tape Laying (Atl):** For Complex Parts, These Automated Methods Offer Better Control Over Fiber Placement And Orientation.
6. Liner Defects (If Applicable For Type Iii/Iv/V Cylinders) (Flaws In Or With The Inner Liner)	**Imagine:** For A Cylinder With A Metallic Or Polymeric Liner: A Visible Bulge Where The Liner Has Detached From The Composit e Overwrap, A Crack In The Liner Itself, Or A Visible Fold/Crea	- **Liner Damage Pre-Overwrap:** Scratches, Gouges, Dents, Or Cracks In The Liner Occurring During Manufacturing, Handling, Or Storage Before Composite Application. **Poor Liner-Composite Adhesion:** Insufficient Bonding Between The Liner Material And The First Layer Of Composite Due	- **Leakage (Critical For Gas Containment):** Failure Of The Liner To Act As An Impermeable Barrier, Leading To Gas Or Fluid Leakage Through The Cylinder Wall. **Reduced Burst Pressure/Structural Integrity:** If The Liner Is Designed To Share Load Or Prevent Direct Gas Impingement On The Composite, Its Failure	- **Rigorous Liner Inspection:** Implement 100% Inspection Of Liners (Visual, Dimensional, Ndt Like Eddy Current For Metallic, Or Leak Testing For Polymeric) Before Overwrapping. **Optimized Liner Surface Preparation:** Develop And Strictly Follow Procedures For Cleaning And Treating Liner Surfaces (E.G., Chemical Etching, Grit Blasting, Plasma Treatment, Primer Application) To Maximize Adhesion.

	se In A Polymeric Liner.	To Contamination, Improper Surface Treatment Of The Liner, Or Incompatible Materials. **Manufacturing Flaws In Liner:** Porosity, Inclusions, Inconsistent Wall Thickness, Or Weld Defects (For Metallic Liners); Or Pinholes, Thin Spots, Or Material Degradation (For Polymeric Liners). **Thermal Expansion Mismatch:** Significant Differences In Thermal Expansion Coefficients Between Liner And Composite Can Induce Stresses During Curing Or Thermal Cycling, Leading To Debonding Or	Compromises The Cylinder's Performance. **Blisters/Bulges:** Localized Debonding Between Liner And Composite Can Manifest As Raised Areas On The Cylinder Surface If Internal Pressure Pushes The Liner Outward Into The Void. **Cracks/Buckling In Liner:** Visible Damage To The Liner, Which Can Propagate Or Lead To Leakage. **Premature Composite Failure:** Gas Permeating Through A Failed Liner Can Pressurize Voids Or Delaminations Within The Composite, Accelerating Damage.	**Material Compatibility & Selection:** Ensure The Liner Material, Composite Resin, And Any Adhesives/Primers Are Chemically And Mechanically Compatible Across The Operational Temperature Range. **Controlled Overwrapping Process:** Ensure The First Composite Layers Are Applied With Appropriate Tension And Wet-Out To Promote Good Bonding Without Damaging A Thin Liner. **Cure Cycle Optimization:** Design Cure Cycles To Minimize Thermal Stresses Arising From Cte Mismatch. **Proof Testing & Leak Detection:** Conduct Hydraulic Or Pneumatic Proof Tests And Sensitive Leak Detection (E.G., Helium Mass Spectrometry) On Finished Cylinders.

		Liner Buckling. **Chemical Incompatibility:** Resin System Reacting Adversely With The Liner Material.		
7. Inconsistent Wall Thickness (Variation In Composite Wall Dimensions)	**Imagine:** A Diagram Showing A Cutaway Of The Cylinder Where The Thickness Of The Composite Wall Noticeably Varies From One Side To The Other, Or Along Its Length, Instead Of Being Uniformly Thick.	- **Uneven Resin Distribution:** More Resin Accumulating In Some Areas Than Others During Wet Winding Or Layup. **Non-Uniform Fiber Placement:** Inconsistent Band Width, Excessive Overlap, Or Gaps Between Fiber Bands During Filament Winding. Incorrect Number Of Plies In Certain Areas During Layup. **Inconsistent Winding Tension:** Fluctuations In Fiber Tension Can Lead To Variations In	- **Weight & Balance Issues:** Significant Variation In Cylinder Weight From Nominal; Can Cause Imbalance In Rotating Applications. **Localized Stress Concentrations:** Thinner Sections Will Experience Higher Stress Under Pressure And May Yield Or Fail Prematurely. Thicker Sections Might Not Contribute Efficiently To Strength And Add Unnecessary Weight. **Non-Uniform**	- **Precise Process Control:** Ensure Accurate Control Of Resin Content, Fiber Placement (E.G., Band Width Control, Consistent Overlap), And Winding Angles. Use Cnc Filament Winders With Precise Motion Control. **Consistent Fiber Tension:** Employ And Regularly Calibrate Fiber Tensioning Systems. **Mandrel/Tooling Maintenance & Inspection:** Regularly Inspect Mandrels And Molds For Wear, Damage, And Dimensional Accuracy. **Machine Calibration:** Implement A Regular Calibration Schedule For All Critical Parameters Of The Filament Winding

		Fiber Packing Density And Resin Content Per Unit Volume. **Mandrel/Tooling Irregularities:** An Out-Of-Tolerance Mandrel (E.G., Eccentric, Tapered Incorrectly) Will Translate Into Wall Thickness Variations. **Machine Miscalibration:** Issues With The Filament Winding Machine's Carriage Speed, Spindle Rotation, Or Payout Eye Movement.	**Performance:** Variability In Burst Pressure, Stiffness, And Fatigue Life Across Different Units Or Within A Single Unit. **Fitment Problems:** May Not Fit Correctly With Mating Parts Or In Assemblies If Outer Dimensions Are Affected. **Difficulty In Ndt Interpretation:** Can Complicate The Interpretation Of Ultrasonic Thickness Measurements Or Other Ndt Results.	Machine Or Layup Equipment. **In-Process Monitoring:** Use Laser Micrometers Or Other Sensors During Winding To Monitor Build-Up, Or Use Ultrasonic Thickness Gauging After Cure. **Statistical Process Control (Spc):** Track Wall Thickness Measurements To Identify Trends And Sources Of Variation.
8. Curing Defects (Under-Cure / Over-Cure) (Improper Polymerization)	**Imagine:** A Micrograph Where An Under-Cured Resin Looks Poorly Fused And Grainy,	- **Incorrect Cure Parameters:** Deviations From The Resin Manufacturer's Specified Temperature (Too Low/High), Time (Too Short/Long), Or Ramp Rates.	- **Under-Cure Symptoms:** Soft, Tacky, Or Rubbery Surface. Low Glass Transition Temperature (T_G). Significantly Reduced Mechanical Properties	- **Strict Adherence To Cure Schedules:** Precisely Follow Resin Manufacturer's Recommendations For Mix Ratio, Cure Temperature, Ramp Rates, Dwell Times, And Pressure/Vacuum. **Equipment**

	Perhaps With Unreacted Components. An Over-Cured Resin Might Show Signs Of Thermal Degradation, Like Discoloration Or Micro-Cracks In The Matrix.	**Malfunctioning Curing Equipment:** Faulty Thermocouples, Uneven Heating In Ovens/Autoclaves, Inaccurate Pressure Controllers. **Improper Resin/Hardener Mixing:** Incorrect Ratio, Insufficient Mixing Leading To Unreacted Components (Under-Cure) Or Localized Exothermic Reactions (Can Contribute To Over-Cure Or Thermal Stress). **Material Age/Storage:** Using Resin Systems That Are Past Their Shelf Life Or Have Been Improperly Stored Can Affect Reactivity. **Thermal Mass Effects:** Very	(Strength, Stiffness, Hardness). Poor Chemical And Solvent Resistance. Higher Volatile Content Remaining. **Over-Cure Symptoms:** Brittle Material, Reduced Toughness And Impact Strength. Discoloration (E.G., Darkening, Yellowing) Of The Resin. Potential For Micro-Cracking Due To Excessive Shrinkage Or Thermal Degradation. Sometimes An Overly High T_G But With Compromised Mechanicals.	**Calibration & Maintenance:** Regularly Calibrate Thermocouples, Pressure Gauges, And Controllers On Curing Ovens, Presses, And Autoclaves. Ensure Uniform Heating. **Accurate Material Handling & Mixing:** Use Calibrated Scales For Mixing Resin And Hardener. Employ Thorough Mixing Techniques (Manual Or Mechanical) To Ensure Homogeneity. **Monitor Material Shelf Life & Storage:** Implement A "First-In, First-Out" (Fifo) Inventory System. Store Resins And Hardeners Under Recommended Conditions. **Thermal Management:** For Thick Parts, Model Or Experimentally Determine Appropriate Cure Cycles To Manage Exotherm And Ensure Uniform Cure. Use Multiple

		Thick Parts May Experience Different Cure States Internally Versus Externally If The Cure Cycle Doesn't Account For Exotherm And Heat Transfer.		Thermocouples To Monitor Part Temperature. **Post-Cure Adjustments (Limited):** Slight Under-Cure Might Sometimes Be Rectifiable With An Additional Post-Cure Cycle, But This Is Not Always Effective Or Recommended. Over-Cure Is Generally Irreversible. **Quality Control Testing:** Perform Hardness Tests (E.G., Barcol, Shore D), Differential Scanning Calorimetry (Dsc) To Verify T_G And Degree Of Cure, And Mechanical Tests On Witness Coupons.
9. Contamination (Foreign Objects/Inclusions) (Embedded Unwanted Material)	**Imagine:** A Clear Or Translucent Composite Sample Where You Can See An Embedded Piece Of Dirt, A Stray Fiber Of A	- **Unclean Manufacturing Environment:** Dust, Dirt, Hair, Insects, Or Airborne Particles Settling On Materials Or Tooling. **Contaminated Raw Materials:** Fibers, Resins, Or Prepregs	- **Localized Stress Concentrations:** Inclusions Act As Stress Risers, Significantly Reducing Fatigue Life And Potentially Initiating Cracks Or Delamination Under Load. **Reduced**	- **Cleanroom Environment/Controlled Areas:** Implement And Maintain Appropriate Levels Of Cleanliness For Different Manufacturing Stages (E.G., Positive Pressure, Air Filtration, Sticky Mats, Designated Clean Zones).

	Different Color, A Piece Of Backing Film, An Air Bubble That Has Debris In It, Or Even A Small Insect.	Contaminated At The Supplier Or During Storage And Handling (E.G., Debris In Resin Drum, Backing Paper Particles). **Debris From Tooling/Equipment:** Flakes Of Old Resin, Metal Shavings From Tools, Release Agent Build-Up, Or Pieces Of Consumables (E.G., Bagging Film, Tape). **Operator Error:** Dropping Tools, Personal Items (E.G., Pen Caps), Or Improper Handling Leading To Transfer Of Contaminants.	**Mechanical Properties:** The Inclusion Itself Typically Has No Structural Integrity And Creates A Discontinuity In The Load Path. **Pathway For Environmental Attack:** Can Create A Route For Moisture Or Chemicals To Penetrate The Composite. **Cosmetic Defect:** Visible Inclusions Are Often Unacceptable For Aesthetic Reasons, Especially On Exposed Surfaces. **Electrical Short Circuit Risk:** Conductive Contaminants (E.G., Metal Filings) Can Compromise Electrical Insulation Properties.	**Incoming Material Inspection:** Inspect Raw Materials For Visible Contamination Upon Receipt. **Tooling & Equipment Cleaning:** Establish Rigorous Cleaning Schedules For Molds, Mandrels, Mixing Equipment, And Application Tools. **Operator Practices & Attire:** Enforce Use Of Appropriate Lint-Free Garments, Gloves, And Hairnets. Train Operators On Clean Handling Procedures. Prohibit Food, Drink, And Smoking In Production Areas. **Protection Of Materials:** Keep Prepregs, Fibers, And Resins Covered When Not In Use. Use Peel Plies To Protect Layups. **In-Process Inspection:** Visually Inspect Layups Before Curing. **Foreign Object Debris (Fod) Prevention**

				Program: Implement A Formal Fod Program.
10. Impact Damage / Handling Damage (Mechanical Damage Post-Cure)	**Imagine:** A Finished Cylinder Surface With A Clear Mark Of Impact – A Star-Shaped Crack Pattern, A Localized Dent Or Crushed Area, Or A Visible Chip. Subsurface Damage Might Not Be Immediately Obvious But Could Be Extensive.	- **Accidental Dropping:** Cylinders Being Dropped During Movement, Assembly, Or Inspection. **Collisions:** Impacting Other Objects, Equipment, Or Facility Structures During Transport Or Handling. **Improper Tool Use:** Using Unsuitable Tools For Assembly, Or Tools Slipping And Striking The Composite Surface (E.G., Wrench, Screwdriver). **Inadequate Support/Fixturing:** Improperly Designed Or Used Fixtures For Holding, Transporting, Or Testing Cylinders,	- **Visible Surface Damage:** Dents, Gouges, Scratches, Chips, Or Cracks On The Cylinder Surface. **Subsurface Damage (Often Invisible):** Extensive Internal Delamination, Fiber Breakage, And Matrix Cracking That May Not Be Visible On The Surface (Barely Visible Impact Damage - Bvid). This Is A Major Concern For Composites. **Significantly Reduced Structural Integrity:** Compromises Tensile, Compressive, And Burst Strength, Particularly If	- **Careful Handling Protocols & Training:** Implement Strict Procedures For Lifting, Moving, And Storing Cylinders. Train All Personnel On Proper Handling Techniques For Composite Parts. **Use Of Protective Fixtures & Packaging:** Employ Padded Supports, Protective Sleeves, And Custom-Designed Crates Or Containers For Transport And Storage. **Controlled Access & Work Areas:** Designate Specific Pathways And Work Zones To Minimize Collision Risks. **Appropriate Tool Selection & Use:** Ensure Correct Tools Are Used For Any Assembly Or Interfacing Operations, And That Operators Are Trained In Their Cautious Use

		Leading To Concentrated Loads Or Abrasion. **Environmental Exposure (Extreme Cases):** Hail, Flying Debris In Service (Though Usually A Design Consideration For Specific Applications).	Fibers Are Broken Or Delamination Is Widespread. Impact Damage Can Reduce Residual Strength By More Than 50%. **Reduced Fatigue Life:** Damage Sites Act As Initiation Points For Fatigue Crack Growth. **Potential For Catastrophic Failure:** Undetected Or Unaddressed Impact Damage Can Lead To Sudden And Unexpected Failure Under Operating Pressure Or Load.	Around Composites. **Regular Inspection (Pre & Post Handling):** Visually Inspect Cylinders For Any Signs Of Damage Before And After Each Handling Operation, Transport, Or Assembly Step. **Ndt For Suspected Impact:** If An Impact Is Known Or Suspected, Use Ndt Methods Like Ultrasonic Inspection (C-Scan), Thermography, Or Shearography To Assess The Extent Of Subsurface Damage. **"Tap Test" For Quick Checks:** While Not As Reliable For Bvid, A Change In Sound During A Tap Test Can Indicate Significant Delamination From An Impact.

3.3.6 Test Procedures / Validation Reports

Standard Operating Procedure

For Leak Test

Figure 3.21: Leak test section

1. Purpose

To Establish A Standardized Method For Conducting Leak Tests On Composite Cylinders To Ensure Their Structural Integrity, Safety, And Compliance With Iso 11119-3.

2. Scope

This Sop Applies To All Composite Gas Cylinders Manufactured And Tested For Leak-Proof Performance Before Final Approval.

3. Responsibilities

- Quality Control (Qc) Team: Inspect And Supervised Leak Tests And Records Results.
- Production Team: Ensures Cylinders Meet Design Specifications Before Testing.

- Maintenance Team: Ensures Testing Equipment Is Calibrated And In Good Working Condition.

4. Materials And Equipment

- Pressurized Air
- Pressure Regulator
- Submersion Tank
- Pressure Gauge (Calibrated)
- Timer

Visual Inspection Tools (Cameras, Borescope, Etc.)

- Ppe (Gloves, Safety Goggles, Protective Clothing)

5. Procedure

5.1 Pre-Test Inspection

- Ensure The Cylinder Surface Is Free Of Visible Defects, Cracks, Or Damages.
- Verify That The Valve And Cylinder Connections Are Properly Sealed.
- Confirm That Testing Equipment Is Calibrated And Functioning Correctly.

5.2 Pressurization For Leak Testing

- Connect The Cylinder To The Pressurized Air Using A Pressure Regulator.
- Slowly Pressurize The Cylinder To Its Working Pressure (20 Bar).
- Maintain Pressure For At Least 60 Seconds To Stabilize.

5.3 Leak Detection Methods

A. Soap Bubble Test (Preferred For Valve & Joint Leaks)

- Apply Soap Bubble Solution Around The Valve, Boss, And Weld Joints.

- Observe For The Formation Of Bubbles, Indicating A Leak.
- If Bubbles Appear, Report The Cylinder As Non-Conforming And Retest After Reworking.

B. Submersion Test

- Fully Submerge The Pressurized Cylinder In A Water Tank.

- Allow For A Soak Time For The Cylinder Off Up To 60 Seconds(1min).

- Observe Keenly For Bubbles For At Least 180 Seconds (3mins) .
- Observe For Air Bubbles Escaping, Indicating A Leak.
- Mark And Report Any Leaking Cylinders.

5.4 Depressurization & Post-Test Inspection

- Slowly Depressurize The Cylinder In A Controlled Manner.
- Dry The Cylinder Using Atmospheric Drying Or Compressed Air
- .Perform A Final Inspection To Ensure No Physical Damage Occurred During Testing.

6. Acceptance Criteria

- No Visible Bubbles Forming In The Soap Bubble Test.
- No Continuous Air Leakage Detected In The Submersion Test.
- Cylinder Maintains Working Pressure With No Drop Beyond The Allowable Limits

(Iso 11119-3).

7. Safety Precautions

- Always Wear Ppe (Gloves, Safety Goggles, And Protective Clothing).
- Use Only Dry, Clean Air Or Nitrogen To Prevent Contamination.
- Do Not Exceed Working Pressure To Avoid Overloading The Cylinder.
- Ensure All Connections Are Secure Before Pressurization.

8. Record Keeping

- Test Results Log (Pressure Readings, Test Duration, Observations).
- Cylinder Serial Number & Operator’s Signature.
- Non-Conformance Report (If Applicable).

This Sop Aligns With **Iso 11119-3** And Includes **Soap Bubble And Submersion Tests** For Detecting Leaks In Composite Cylinders.

Pneumatic (Proof) Pressure Test For Type 4 Composite Cylinders

Figure 3.22: Proof test machine

1. Objective

To Verify The Structural Integrity And Leak Tightness Of Type 4 Fully-Wrapped Composite Cylinders Using A Pneumatic Proof Pressure Test As Per Iso 11119-3.

2. Scope

This Procedure Applies To Type 4 Composite Cylinders Manufactured With A Non-Metallic Liner And Fully Overwrapped With Fiber-Reinforced Resin (Glass Fiber), Intended For The Storage Of Compressed Gases.

3. Equipment & Materials

- High-Pressure Test Rig With Certified Pressure Gauges (Accuracy Class ≤ 1.0)
- Incompressible Or Inert Test Gas (Typically Dry Air Or Nitrogen)

- Test Enclosure (Blast-Proof Chamber Or Protective Barrier)
- Soap Solution Or Electronic Leak Detector (If Leak Test Is Combined)
- Personal Protective Equipment (Ppe): Face Shield, Gloves, Safety Boots, Etc.
- Calibration Certificates For Pressure Gauges And Transducers

4. Safety Precautions

- Ensure Test Area Is Properly Barricaded And Marked.
- Only Authorized Personnel Are Allowed During Testing.
- Use Remote Pressurization And Monitoring System If Available.
- Vent Cylinder Gas Safely After Testing Using A Regulator Or Bleed Valve.

5. Cylinder Preparation

- Visually Inspect The Cylinder For Damage Or Defects.
- Verify Cylinder Identity And Traceability (Serial Number, Manufacturing Date).
- Ensure All Fittings And Plugs Are Securely Installed.
- Place The Cylinder Inside The Protective Test Chamber.
- Connect Pressure Line And Pressure Transducer To The Cylinder.

6. Test Procedure

6.1. Leak Tightness Pre-Check (Optional)

- Apply Low Pressure (~10 Bar).
- Check For Leaks Using A Soap Solution Or Electronic Detector.
- Proceed Only If No Leaks Are Found.

6.2. Pneumatic Proof Test

- Gradually Pressurize The Cylinder To Proof Pressure:
- As Per Iso 11119-3, The Proof Pressure Is Typically 1.5 × Service Pressure.
- The Proof Pressure In This Case Is 30bar While Our Service Pressure 20bar.
- Hold The Pressure At Proof Level For At Least 60 Seconds (Or Per Design Specification).
- Monitor The Pressure Gauge For:
- Pressure Loss (Indicating A Leak)
- Abnormal Deformation Or Sound (Indicating Potential Failure)
- After The Hold Time, Gradually Depressurize The Cylinder.

7. Acceptance Criteria

- No Leakage Or Pressure Drop During Hold Period.
- No Visible Deformation, Cracks, Or Abnormal Noise.
- Cylinder Returns To Original Dimensions After Depressurization (Within Tolerance).

8. Post-Test Activities

- Remove Cylinder From Test Rig.
- Document Test Results: Cylinder Id, Date, Operator, Pressure Values, And Observations.
- Mark The Cylinder Appropriately (E.G., Stamped Or Tagged As "Tested").

Record Keeping

- **Test Results Log** (Pressure Readings, Test Duration, Observations).
- **Cylinder Serial Number & Operator’s Signature**.
- **Non-Conformance Report** (If Applicable)

This Sop Aligns With **Iso 11119-3** And Includes **Pneumatic Testing** For Detecting Leaks In Composite Cylinders.

Standard Operating Procedure For Valve Mounting And Testing

1. Purpose

This Document Defines The **Step-By-Step** Process For **Mounting The Valve And Testing** On The Composite Cylinders As Per **Iso 11119-3**.

2. Scope

Applicable To All Composite Cylinders With **Brass Valves** Designed For A **Working Pressure Of 26.5 Bar** Before Final Product Approval.

3. Responsibilities

Production Team: Ensures Proper Valve Fitting.

Quality Control (Qc) Team: Inspect And Supervise Hydrostatic Tests And Records Results.

Maintenance Team: Ensures Testing Equipment Is Calibrated.

4. Materials And Equipment

- Torque Wrench (Calibrated)
- Approved **Brass Gas Cylinder Valve**
- Thread Sealant (As Per Specifications)
- Soap Bubble Solution For Leak Testing

5. Procedure

5.1 Valve Mounting

Step 1: Pre-Inspection

- Verify That The **Brass Valve And Cylinder Neck** Are Clean And Debris-Free.
- Verify That The **Brass Valve Is Working And The Seal Inside Is Intact**.

- Confirm That The **Valve Thread Matches The Cylinder Neck**

(Iso 228, Bspp, Or Specified Type).

Step 2: Applying Sealant

- Apply **Approved Thread Sealant** Or Teflon Tape **As Specified**.
- Ensure Uniform Coverage Without Excess Material.

Step 3: Valve Installation

- Secure The Valve Into The Cylinder **By Hand** Until It Seats Properly.
- Use A **Torque Wrench** To Tighten The Valve To The **Specified Torque (100-150 Nm)**.
- **Do Not Overtighten**, As This May Damage The Threads Or Seal.

Step 4: Leak Check (Preliminary)

- Apply The Soap Bubble Solution On The Boss Part To The Liner And Valve To The Boss Part Before Applying Air Pressure At 10-20bar.
- If Bubbles Form On The Valve To Boss Part, Reapply The Sealant And Retighten If Necessary. If Bubbles Form Again After Reapplying Sealant And Retightening, Remove And Dispose Of Such Valves As Non-Conformity.
- Observe For The Formation Of **Bubbles On The Boss Part To Liner Joint**, Indicating A Leak.
- If Bubbles Appear, Report The Cylinder As **Non-Conforming**.
- Any Cylinder With A Turning Boss Part Shall Be Set Aside.

6. Acceptance Criteria

- No **Visible Leaks** At The Valve, Boss Part Or Cylinder Body.
- No **Permanent Deformation** After Pressure Release.

7. Safety Precautions

- Always Wear **Ppe** (Gloves, Safety Goggles, And Protective Clothing).
- Ensure **Valves And Test Equipment** Are Certified And Calibrated.
- Do Not Exceed The **Maximum Test Pressure** To Avoid Damage.

This Sop Aligns With **Iso 11119-3** And Includes **Soap Bubble** For Detecting Leaks In Composite Cylinders.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and discussion of the study on the technology used to produce Type 4 LPG composite cylinders. The findings address the six objectives outlined in Chapter One, covering the evaluation of existing manufacturing processes, materials, cost challenges, and proposed improvements. Additionally, the results of finite element simulations conducted on different material configurations are analyzed to demonstrate the structural performance and pressure resistance of the improved designs.

4.2 Review of Existing Technological Processes

Don Mac Limited currently employs a structured process for the production of Type 4 LPG composite cylinders in accordance with ISO 11119-3:2022. The major stages, as indicated in the company's Process Flow Chart, include:

1. **Liner Formation (HDPE or PA Molding):** The polymer liner is blow-molded or injection-molded to form the gas-retaining core.

2. **Surface Flaming and Boss Attachment:** The liner surface is flame-treated for adhesion, and the metallic boss is welded to the neck.

3. **Filament Winding:** Resin-impregnated glass or carbon fibers are wound around the liner at controlled angles to provide structural strength.

4. **Curing and Cooling:** The composite is heat-cured to solidify the resin matrix and bond the fibers to the liner.

5. **Testing:** Hydrostatic proof testing (1.5× working pressure) and burst testing (≥2.35× working pressure) verify the integrity of the final product.

This process sequence successfully produces Type 4 cylinders with a **working pressure of 20 bar**, **proof pressure of 30 bar**, and **minimum burst pressure of 47 bar**. However, it remains semi-automated, with manual operations during winding, curing, and inspection—introducing variability in product quality and increasing cycle time.

4.3 Strengths and Weaknesses of Existing Materials and Methods

The current production process uses HDPE liners, E-glass fiber reinforcement, and epoxy resin matrices. The system's main strengths include:

- Lightweight construction (about 60% lighter than steel cylinders).
- Resistance to corrosion and chemical attack.
- Compliance with ISO and EN composite pressure vessel standards.

However, several weaknesses were identified:

- HDPE liners have relatively high gas permeability, leading to gradual LPG loss during storage.
- E-glass fiber has limited tensile strength compared to carbon fiber, reducing burst capacity.
- Manual filament winding and curing can result in fiber misalignment and resin-rich zones.
- Thermoset epoxy is difficult to recycle, creating sustainability challenges.

These limitations provided the basis for exploring improved material combinations and processing techniques.

4.4 Cost, Permeability, and Local Production Challenges

The study found that local production costs are heavily influenced by imported raw materials, which account for nearly 60% of total expenses. The cost of carbon fiber and high-performance polyamides remains high in Nigeria, posing economic barriers to large-scale adoption.

Permeability issues with HDPE liners were confirmed as a major factor limiting long-term pressure retention. Tests and literature review indicate that PA11 liners possess up to 10 times lower gas permeability and superior temperature resistance.

Additionally, recycling and end-of-life management of composite waste present environmental and operational challenges due to the cross-linked nature of epoxy resin. While Don Mac Ltd. possesses the basic machinery for blow molding, curing, and hydrostatic testing, limited automation and expertise continue to restrict productivity.

4.5 Simulation Analysis of Improved Cylinder Designs

To evaluate the performance of improved material combinations, a finite element analysis (FEA) was conducted using SolidWorks Simulation. Two configurations were modeled under an internal pressure load of 20 bar to assess stress, strain, displacement, and burst capacity.

4.5.1 Simulation Cases

Table 4.1: Simulation Cases

Case	Liner Material	Fiber Reinforcement	Matrix Resin	Remarks
Case 1	High-Density Polyethylene (HDPE)	E-Glass Fiber	Epoxy	Current Don Mac configuration
Case 2	Polyamide 11 (PA11)	Carbon Fiber	Epoxy	Proposed improved configuration

4.5.2 Burst Pressure Comparison

Table 4.2: Burst Pressure Comparison

Configuration	Simulated Burst Pressure (bar)	Improvement (%)
HDPE + Glass Fiber	50	—
PA11 + Carbon Fiber	70	+40%

The simulation results revealed that the **PA11 + Carbon Fiber** combination achieved a burst pressure of approximately **70 bar**, significantly higher than the 50 bar obtained with the **HDPE + Glass Fiber** configuration.
This improvement is attributed to carbon fiber's higher tensile strength (≈4900 MPa) and lower strain-to-failure, as well as PA11's enhanced stiffness and liner–fiber adhesion properties.

4.5.3 Factor of Safety (FoS) Analysis

Table 4.3: Factor of Safety (FoS) Analysis

Configuration	Factor of Safety (FoS)
HDPE + Glass Fiber	12.0
PA11 + Carbon Fiber	4.4

While the PA11–carbon fiber design achieved higher strength, its lower FoS indicates that it operates closer to material limits. Conversely, the HDPE–glass fiber cylinder, though less strong, provides a greater safety margin against pressure surges and material defects.

This trade-off reflects an important design decision: high performance vs. high reliability. For domestic LPG applications, an FoS between 3.0–4.5 is considered sufficient, meaning both configurations are acceptable, but the improved version provides greater pressure efficiency.

4.5.4 Stress, Strain, and Displacement Behavior

- **Stress Distribution:** The PA11–carbon fiber cylinder exhibited higher localized stress (due to higher stiffness), leading to greater resistance to deformation.
- **Strain Response:** The HDPE–glass fiber design displayed higher strain and ductility, absorbing more energy before yielding.
- **Displacement:** Maximum radial displacement of **1.0 mm** was observed in the HDPE–glass fiber model, compared to a smaller deflection in the PA11–carbon fiber case.

These patterns confirm that the stiffer PA11–carbon fiber system provides superior load resistance but less deformation capability, while the HDPE–glass fiber system offers better energy absorption and damage tolerance.

4.5.5 Simulation Interpretation

From the simulations, it can be concluded that:

- Both configurations comfortably withstand the nominal working pressure of 20 bar.
- The PA11 + Carbon Fiber design achieves higher burst strength (70 bar), exceeding the ISO 11119-3 minimum requirement of 47 bar.
- The HDPE + Glass Fiber design has a higher FoS, making it more forgiving under fluctuating pressure conditions.
- The results validate the potential of using hybrid material systems (e.g., Carbon/Glass combinations) to balance weight, strength, and safety.

4.6 Proposed Material and Process Improvements

Based on the combined process review and simulation results, the following improvements are proposed:

Table 4.4: Proposed Material and Process Improvements

Area	Current Practice	Proposed Improvement	Expected Benefit
Liner Material	HDPE	Polyamide 11 (PA11) or multilayer PA/EVOH	Reduced gas permeability
Fiber Reinforcement	E-Glass	Hybrid Carbon–Glass Fiber	Increased burst pressure and weight reduction
Resin System	Standard Epoxy	Toughened Epoxy / Vinyl Ester	Improved impact resistance
Surface Treatment	Flaming	Plasma or Corona Discharge	Better liner–fiber bonding
Winding Method	Manual	Automated Filament Winding	Improved precision and reduced defects
Curing	Oven Batch	Controlled Temperature Ramp	Shorter cycle time, higher quality

Implementing these improvements can increase pressure capacity, reduce cylinder mass, and enhance production efficiency.

4.7 Strategies for Large-Scale Adoption

For widespread use of Type 4 LPG cylinders in Nigeria:

1. **Government Support:** Offer tax incentives for composite manufacturing and import duty relief on raw materials.
2. **Local Material Development:** Encourage petrochemical industries (e.g., Indorama Eleme) to develop PA-based liners and resin precursors.
3. **Technical Training:** Partner with universities to train engineers in composite fabrication and quality testing.
4. **Standardization:** Enforce ISO 11119-3 and EN 12245 compliance for all locally made cylinders.
5. **Public Awareness:** Promote composite LPG cylinders as lightweight, corrosion-resistant, and safer alternatives to steel.

4.8 Summary of Findings

- Don Mac Ltd.'s current technology meets global safety requirements but can be improved through automation and material upgrades.
- HDPE–glass fiber cylinders perform safely at 50 bar but have limited burst strength.
- PA11–carbon fiber cylinders show a 40% higher burst capacity (70 bar) with improved stiffness and durability.
- Process automation, hybrid reinforcement, and improved liner materials can significantly optimize performance and cost.
- Both configurations are safe for domestic LPG use, but the PA11–carbon fiber design offers a superior strength-to-weight ratio for advanced applications.

4.9 Conclusion of Chapter

This chapter demonstrated that material and process improvements can substantially enhance the performance of Type 4 LPG composite cylinders.
Simulation results confirm that adopting PA11 liners and carbon fiber overwraps can raise burst pressure capacity from 50 bar to 70 bar, while maintaining acceptable safety margins. With further optimization in winding, curing, and local material sourcing, Nigeria can produce high-performance, cost-effective, and environmentally sustainable composite LPG cylinders that meet or exceed international standards.

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study examined the existing technologies and processes used in the production of Type 4 LPG composite cylinders, with the aim of identifying their strengths, weaknesses, and areas for improvement. The research reviewed the complete production line at **Don Mac Limited**, including liner molding, surface treatment, filament winding, curing, and hydrostatic testing, in line with **ISO 11119-3:2020** standards.

Engineering simulations demonstrated that replacing traditional HDPE liners with **polyamide (PA11)** and reinforcing with **carbon or hybrid carbon–glass fibers** significantly enhances the structural performance of the cylinder. The improved design achieved a **burst pressure of about 70 bar**, compared to 50 bar for the conventional HDPE–glass configuration, while maintaining a safe factor of safety.

The study concludes that material innovation—particularly the use of high-performance fibers, nano-toughened epoxy resins, and multilayer polymer liners—can greatly improve cylinder strength, reduce weight, and minimize gas permeability. Additionally, automation in filament winding, quality monitoring, and curing processes can increase manufacturing consistency and productivity.

Overall, the findings confirm that **Type 4 LPG composite cylinders** can be effectively produced in Nigeria using locally adaptable technology. With continued investment in material research, local polymer production, and adherence to international standards, Nigeria can achieve large-scale, safe, and cost-effective deployment of composite LPG cylinders for domestic and industrial use.

5.2 Recommendations

Material and Design Optimization

1. **Liner Upgrade:** Replace HDPE liners with Polyamide 11 (PA11) or multilayer PA/EVOH liners to minimize gas permeability and improve mechanical adhesion.

2. **Reinforcement Improvement:** Introduce hybrid carbon–glass fiber winding for higher strength-to-weight ratio and reduced wall thickness.

3. **Resin Enhancement:** Use toughened epoxy or vinyl ester resins to improve fatigue resistance and impact strength.

4. **Boss Redesign:** Replace metallic bosses with polymer composite bosses for corrosion resistance and further weight reduction.

Process and Equipment Enhancement

1. Adopt automated filament winding machines with programmable tension and winding angle control for precision and consistency.

2. Replace flame treatment with plasma or corona discharge surface activation for improved liner–fiber adhesion.

3. Introduce controlled curing ovens with digital temperature and pressure logging.

4. Implement digital process tracking (e.g., RFID or barcode systems) for traceability and quality documentation.

Local Capacity and Industry Development

1. Encourage collaboration between Don Mac Ltd., universities, and composite research institutes for knowledge transfer and skill development.

2. Support local polymer industries (e.g., Indorama Eleme Petrochemicals) to produce PA11 precursors and epoxy resins domestically.

3. Create training and certification programs for technicians in composite fabrication and non-destructive testing (NDT).

Policy and Economic Support

1. The Federal Government and Standards Organisation of Nigeria (SON) should harmonize local production standards with ISO 11119-3 and EN 12245.

2. Introduce tax incentives and import-duty waivers on composite materials and winding equipment.

3. Establish a National LPG Cylinder Replacement Initiative promoting lightweight composite cylinders as safer alternatives to steel.

4. Encourage private-sector investment through public–private partnerships (PPP) to scale up production facilities.

Further Research

1. Conduct long-term fatigue and cyclic-pressure testing on improved composite cylinders.
2. Explore nano-reinforced epoxy systems and thermoplastic composites (e.g., PPS, PEEK) for recyclability.
3. Study hybrid winding patterns (helical/hoop combinations) for stress optimization.
4. Develop predictive AI-based quality monitoring for process control in filament winding and curing.

5.3 Contributions of the Study

This research provides the following contributions:

- A comprehensive evaluation of local Type 4 cylinder production technology.
- Validated simulation data confirming performance improvement with PA11–carbon fiber configuration.
- A set of practical recommendations for process automation and cost reduction.
- A framework for localized composite manufacturing that aligns with Nigeria's industrialization and clean-energy objectives.

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