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Original Paper

Empirical case study of black-out incident caused by incomplete combustion and blow-by in ship generator engines

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Abstract: The International Maritime Organization (IMO) has been strengthening regulations to control the air pollution caused by ship propulsion systems and power generators, and promoting CO_2 reduction through enhanced engine efficiency. Consequently, efforts have been directed towards improving the incomplete combustion problem of ship generators as they visibly impact atmospheric pollution and fuel efficiency. This empirical case study highlights the significance of incomplete combustion in ship generators from the perspective that this can also lead to component failures, directly affecting normal ship generator operations. A stable power supply in ships is considered crucial among maritime professionals as disruptions such as blackouts can jeopardize safe navigation, leading to casualties and significant property loss. This study focuses on an incident in which a Very Large Crude Carrier (VLCC) en route from the Far East to the Middle East for oil loading experienced a blackout while transiting through the Singapore Strait, potentially leading to a major accident. Investigations and experiments regarding this incident were conducted in stages. Firstly, similar incidents involving the vessel were examined, and the "Lubricating-oil (LO) Pressure" trend of the generator at the time of blackout was analyzed using its Alarm Monitoring System (AMS), indicating a decrease in LO pressure likely due to carbon deposition within the LO pump relief valve. Subsequent dismantling and inspection of the five components of the LO supply system revealed carbon deposition, which hindered proper LO pressure regulation. Following maintenance, experiments were conducted to measure the LO, cylinder explosion, and chamber pressures at various loads. The results indicated normalized LO pressure, while abnormal readings of cylinder explosion and chamber pressures suggested incomplete combustion; this led to a combustion gas blow-by that disrupted the LO system and caused the blackout. Engine failures pose a significant risk during ship maneuvers, strait transits, and adverse weather navigation, emphasizing the importance of design and operational improvements to address incomplete combustion in engines.

Keywords: Incomplete combustion, IMO, Pollution, Propulsion, CO_2

Abbreviation

IMO	International Maritime Organization
NOx	Nitrogen Oxides
SOx	Sulfur Oxides
CO_2	Carbon Dioxide
CII	Carbon Intensity Index
VLCC	Very Large Crude Carrier
G/E	Generator Engine
L.O.	Lubricating Oil
AMS	Alarm Monitoring System
PMS	Planned Maintenance System
P&ID	Piping & Instrument Diagram
EGCS	Exhaust Gas Cleaning Systems
SCR	Selective Catalytic Reduction
EGR	Exhaust Gas Recirculation
P-max	Maximum Pressure of Combustion
ESD	Energy Saving Devices
EPL	Engine Power Limitation

1. Introduction

1.1 Background and Motivation

There is an increasing concern about the air pollution due to SOx **[3][4]**, NOx **[2]**, and CO2 emissions **[5]**. The International Maritime Organization (IMO) has been aggressively legislating

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and managing these concerns, as detailed in many research papers **[1][6]**. Specifically, for marine diesel engines, methods to minimize the emission of these air pollutants include applying an Exhaust Gas Cleaning System (EGCS) or using low-sulfur fuel to reduce SOx emissions **[9]**, using Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR) to reduce NOx and CO2 emissions, and maximize performance efficiency through Energy Saving Devices (ESD), Engine Power Limitation (EPL), and alternative fuel usage to comply with the Carbon Intensity Index (CII). Several studies are actively investigating these topics **[7][8][10]**.

Although there is significant interest in the development of marine diesel engines to minimize air pollution, there is a lack of case studies related to accidents in this context. Most accident prevention diagnostics and operational performance analyses have been conducted through land-based test beds or simulations **[13][14][16][17]**.

1.2 Research Objectives

This study aims to provide a detailed analysis of an actual incident of incomplete combustion that led to a blackout on a Very Large Crude Carrier (VLCC). This analysis aims to identify the root causes of this incident, evaluate the effectiveness of existing maintenance practices, and propose specific recommendations for preventing similar occurrences in the future. The importance of stable power supply for ships, which is a crucial factor, has been studied in many papers **[11][12][15]**.

1.3 Structure of the Thesis

This thesis is organized into five main chapters. Chapter 1 introduces the background and motivation for this study, outlining the regulatory context and the need for more case studies on marine diesel engine failures. Chapter 2 provides a detailed description of the case study, including the specifics of the vessel, blackout incidents, and immediate actions taken by the crew. Chapter 3 delves into the analysis of accident causes, focusing on the lubricating oil (LO) system and evidence of incomplete combustion. Chapter 4 presents an experimental analysis conducted to validate the findings and better understand the dynamics of the incident. Finally, Chapter 5 concludes the study with key findings, recommendations for engine designers and operators, and suggestions for future research.

2. Case Study Description

2.1. Overview of the Vessel

This case study focuses on a VLCC constructed in a prominent domestic shipyard. This vessel, with the capacity to transport millions of barrels of crude oil, was designed to operate on long-haul routes between the Far East and Middle East. The ship was ten years old at the time of the incident, a period during which many of its critical systems, including the propulsion and power generation systems, began to show signs of wear and aging.

The vessel was equipped with three diesel generator sets, each rated at 1,277 kW. These generators provide essential electrical power for ship operations such as navigation and communication as well as for cargo handling systems. Given the size and complexity of the vessel, the reliability of these generators is of paramount importance, particularly during critical phases of navigation, such as transiting narrow straits or operating in congested waters.

2.2. The Blackout Incident

The blackout incident occurred when the VLCC was near the entrance of the Singapore Strait, which is one of the busiest and most strategically important maritime chokepoints in the world. The vessel was then operating with only one of its three online generators, Generator No. 2. This operational configuration, while not unusual, placed significant demands on the active generator, particularly in terms of maintaining stable power output under fluctuating loads. The circumstances surrounding the blackout incident on this vessel are listed in **Table 1**.

Table 1: Blackout Incident Details on the Case Vessel

Item	Contents
Vessel Type	Very Large Crude Carrier (VLCC)
Generators	1,277 kW x 3 sets
Sailing Route	From the Far East to a loading port in the Middle East
Incident Location	Near the entrance of the Singapore Strait
Incident Description	During solo operation, Generator No.2 tripped suddenly, resulting in a blackout onboard and loss of maneuverability due to the main engine shutdown. Within approximately 10 seconds, Generator No.1, which was on standby, was started up and connected to the main power supply, preventing a major accident such as grounding or collision.

At approximately 01:52 AM, a sudden steering maneuver was executed to avoid a potential collision with another vessel. This maneuver, combined with the operation of the air compressor, introduced significant load fluctuations in Generator No. 2.

Subsequently, Generator No.2 tripped, resulting in a complete blackout onboard. The loss of electrical power led to the immediate shutdown of the main engine, causing the vessel to lose its maneuverability. In the congested waters of the Singapore Strait, this poses a serious risk of grounding or collision.

Fortunately, within approximately 10 s, Generator No. 1, which had been on standby, automatically started and was reconnected to the main power supply. This swift response restored power to the ship and prevented a major maritime disaster.

2.3. Immediate Response and Initial Findings

In the immediate aftermath of the incident, the ship crew conducted a rapid assessment to determine the cause of blackouts. The initial findings suggested that the trip of Generator No. 2 was due to a sudden drop in the LO pressure. The Alarm Monitoring System (AMS) data indicated that the LO pressure had begun to decrease approximately 25 s before the generator tripped, eventually falling to a critical threshold of 3.0 bar, at which point the generator safety systems automatically shut down to prevent damage.

The crew's initial actions focused on restoring the normal operating conditions and ensuring the continued safety of the vessel. Generator No. 2 was shut down for further inspection, and the ship continued its voyage using the two remaining generators. However, the incident raised significant concerns about the reliability of the ship's power generation system, particularly in light of similar incidents involving Generator No. 2.

2.4. Historical Context: Previous Incidents

A detailed review of the ship’s Planned Maintenance System (PMS) revealed a troubling pattern of incidents involving Generator No. 2 over the past year, all of which were associated with a decrease in the LO pressure. Notably, these incidents occurred three times within one year, each time resulting in a blackout similar to that investigated in this study, as shown in **Table 2**.

Table 2: Recent One-year History of Generator No. 2 Engine Black-out

Case	Ship’s Action	Result
Case No.1	Renewing the pressure sensor	L.O. Pressure : 4.5 bar (Normal)
Case No.2	Flushing the L.O. Line of the pressure pick-up to the sensor	L.O. Pressure : 4.5 bar (Normal)
Case No.3	Renewing the pressure sensor	L.O. Pressure : 4.5 bar (Normal)

Each of these incidents was addressed by the ship's engineering team through various maintenance activities such as replacing pressure sensors and flushing LO lines. After these interventions, the LO pressure was consistently recorded at 4.5 bar, which is considered satisfactory. However, this pressure level represents a 0.5 bar discrepancy from the manufacturer’s recommended standard (5.0 bar), a critical detail that has not been fully addressed or understood in previous incident reports.

1. Recurring Issue: Lubricating Oil Pressure Discrepancy

The persistent recording of a 4.5 bar LO pressure, contrary to the 5.0 bar recommended by the manufacturer, suggests a systemic issue within the LO system of Generator No. 2. This discrepancy is significant because the manufacturer’s standard of 5.0 bar is designed to ensure optimal lubrication of the moving parts of the engine, prevent wear, and maintain engine reliability under varying operational loads.

The 0.5 bar shortfall, although seemingly minor, indicates that the LO system did not function at its full capacity. This reduced pressure can lead to inadequate lubrication of critical engine components, thereby increasing the risk of mechanical wear, overheating, and formation of carbon deposits. These effects compound over time, particularly under high-load conditions, making engines more susceptible to failure.

2. Investigation into the Root Cause

Considering the recurring nature of these incidents and consistent pressure discrepancy, a deeper investigation into the root cause is warranted. The maintenance records indicated that each time the pressure sensor was replaced, the pressure reading returned to 4.5 bar, which was considered normal by the ship's crew, but below the manufacturer's specifications. This pattern suggests that the issue was not merely sensor-related but possibly due to a more complex problem within the LO system.

2.5. Detailed Analysis of AMS Trend Data

The analysis of the AMS data, illustrated in **Figure 1: AMS Trend of No.1 & No.2 G/E LO Pressure**, provides critical insights into the events leading up to the blackout incident. This section discusses the specific factors that contributed to the pressure decline and subsequent generator shutdown.

Figure 1 displays the time-series data of the LO pressure for Generator No. 1 and 2. At the outset, the LO pressure for Generator No. 2 was maintained at 4.5 bar, which was slightly below the manufacturer’s recommended pressure of 5.0 bar, and was considered stable by the crew based on historical operational data.

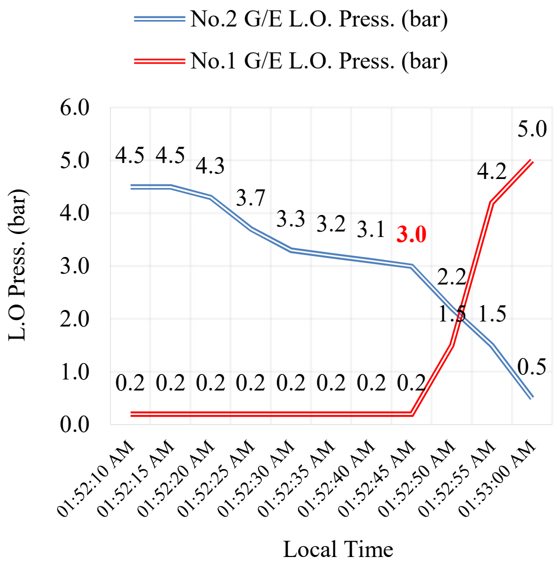

Figure 1: AMS Trend of Generator No. 1 & 2 Engine Lubricating oil (G/E LO) Pressure

2.5.1. Initial Stable Conditions

At the beginning of the monitoring period, the LO pressure of Generator No. 2 was stable at 4.5 bar. This pressure, which was lower than the manufacturer's specifications, was consistent with that in previous operations and did not immediately indicate a critical issue. Generator No. 1, which was on standby, showed a nominal pressure reading of 0 bar.

2.5.2. Sudden Load Fluctuations

A sudden manipulation of the ship's steering occurred at 01:52:15 AM, as represented in **Figure 1**. This maneuver introduced significant load fluctuations in Generator No. 2. As the steering action introduces an abrupt change in the power distribution, the generator experienced a sharp increase in the load. Simultaneously, an air compressor, which was operational at that time, added to the overall load on the generator.

The combination of these factors—steering-induced load changes, operation of the air compressor, and fluctuating demands on the generator—placed substantial strain on the LO system. The LO system, which was already operating at a marginally lower pressure, was unable to quickly adjust to these dynamic conditions. The increased load likely caused a temporary temperature spike, affecting the viscosity of the LO and further complicating its flow within the system.

2.5.3. Pressure Decline and Blackout

As the system struggled to maintain adequate oil flow and pressure under these intensified conditions, the LO pressure of Generator No. 2 began to decline. As shown in **Figure 1**, the pressure drop started at 4.5 bar and gradually decreased over the following 25 s. This decline accelerated as the generator continued to experience the compounded effects of the steering maneuver, air compressor load, and oil viscosity changes.

- **At 4.3 bar**: the pressure exhibited signs of instability. Although not yet critical, this decrease indicates that the system was in duress.
- **At 3.7 bar**: the pressure drop became more pronounced, indicating that the lubrication system failed to compensate for the operational stresses.
- **At 3.3 bar**: the generator approached the critical failure point. The ongoing inability of the LO system to stabilize the pressure led to increased mechanical friction and heat, further exacerbating the problem.
- **At 3.0 bar**: the pressure decreased to the shutdown threshold. Recognizing the imminent risk of severe mechanical damage, the generator safety systems automatically initiated a shutdown to protect the engine.

This sequence of events underscores the sensitivity of the LO system to rapid load fluctuations and the importance of maintaining adequate pressure, particularly under challenging operational conditions.

2.5.4. Generator No.1 Response

As the LO pressure of Generator No. 2 dropped to 3.0 bar, it shut down, and Generator No. 1 was immediately activated, as represented in **Figure 1**. Within approximately 10 s, the LO pressure of Generator No.1 rapidly increased from 0–4.2 bar and then quickly stabilized at 5.0 bar, as per the manufacturer's specifications. This rapid response was critical for restoring power to the ship and averting further incidents.

2.5.5. Causes of Pressure Decline

The analysis suggests that the primary factors contributing to the pressure decline were:

1. Sudden Steering Maneuver: The abrupt change in steering direction imposed a significant and unexpected load on Generator No. 2, disrupting the stability of the LO system.
2. Air Compressor Operation: The Concurrent operation of the air compressor added to the overall load and compounded the stress on the LO system.
3. Cooling Water Impact: The changes in the LO flow and viscosity due to fluctuating cooling water temperatures further challenged the system's ability to maintain a stable pressure.

These factors collectively overwhelmed the already compromised LO system, leading to an observed pressure drop and generator shutdown.

2.5.6. Implications for Future Operations

A detailed analysis of **Figure 1** reveals that even small deviations from the recommended operational parameters can have cascading effects, particularly under sudden and demanding conditions. This incident highlights the critical need to ensure that the LO system operates within the manufacturer's specified parameters and is capable of responding to rapid changes in load.

This case emphasizes the importance of proactive maintenance and real-time monitoring systems that can detect and address issues before they escalate into critical failures.

3. Analysis of the Accident Cause

3.1. Lubricating Oil Pressure System Overview

The LO system in a marine diesel engine is essential for ensuring the proper operation and longevity of the engine moving parts. The system provides continuous lubrication, reduces friction, cools the engine components, and removes contaminants that can cause wear or damage. Maintaining an appropriate LO pressure is crucial for engine performance and safety.

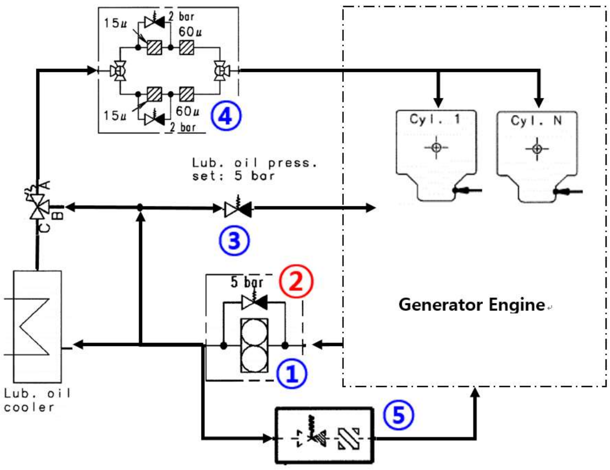

Figure 2: G/E LO System P&I Diagram

Figure 2 illustrates the components and flow of the LO system within the generator engine. The LO pump, relief valve, pressure-regulating valve, and various filters are the key components that are critical for maintaining the correct pressure and ensuring that the engine operates smoothly.

3.2. Key Components Inspection and Findings

A comprehensive inspection of the system was conducted to understand the root cause of the pressure drop in the LO that led to the blackout. This inspection involved disassembling and examining each component of the LO system as outlined in **Table 3**.

Table 3: Components of G/E LO System

No.	Component Name	Remark
1	L.O. Pump	
2	*L.O Pump Relief Valve*	*Set : 5bar*
3	L.O. Pressure Regulating Valve	Set : 5bar
4	L.O. Fine & Relief Valve	
5	L.O. Centrifugal Filter	

3.2.1. LO Pump Relief Valve

Figure 3: G/E LO Pump Relief Valve

The "LO Pump Relief Valve" is designed to maintain the discharge pressure from the LO pump at a constant level, typically set to 5 bar as per the manufacturer's specifications. However, during inspection, it was discovered that this valve had accumulated a significant amount of carbon sludge. **Figure 3** provides a visual evidence of the condition of the relief valve before and after maintenance.

In the "Before Maintenance" state, the valve showed heavy carbon deposits that had hardened over time, leading to the loss of elasticity in the internal spring. This buildup compromised the valve's ability to maintain the correct pressure, contributing directly to the pressure drop observed in Generator No. 2.

3.2.2. LO Pressure Regulating Valve

The "LO Pressure Regulating Valve" is responsible for maintaining a consistent system pressure. Although this component was in relatively better condition than the relief valve, minor carbon deposits were still present. These deposits, although less severe, likely contributed to the gradual degradation in the system performance, particularly under high-load conditions.

3.2.3. LO Pump and Filters

The LO pump and centrifuge filters were inspected. The LO pump functioned adequately with no significant wear or damage. The centrifugal filters, while effective in removing some contaminants, were not sufficient to prevent the buildup of carbon deposits in other critical components, such as the relief and regulating valves.

3.3 Evidence of Incomplete Combustion

Ship engineers had already recognized chronic issues related to incomplete combustion in the vessel generators (No. 1–3) based on their operational characteristics and the findings from a piston overhaul conducted on Generator No. 2 six months before the blackout incident. The observations are detailed below.

1. **Operational Characteristics of the Generators**
   - Abnormal Exhaust Gas Temperatures: Under normal operating conditions, the exhaust gas temperature at the inlet of the turbocharger should be within the range of 450–550 °C. However, it was frequently observed that this temperature exceeded the acceptable limit, often rising above 580 °C. This abnormal increase in temperature was occasionally accompanied by a surging phenomenon, indicating instability in the combustion process.
   - Carbon Deposition on Turbocharger Components: To address these issues, engineers routinely disassembled the turbocharger to clean significant carbon deposits found on the exhaust side of the turbine rotor and nozzle ring. After reassembling the cleaned components, the exhaust gas temperature temporarily returned to normal. However, this is a short-lived solution, as an abnormal temperature increase would reoccur after approximately 1,000–1,500 h of operation.
   - Visual Evidence: **Figure 4** illustrates the condition of the turbine rotor and nozzle ring before and after maintenance, highlighting the extent of carbon deposition due to incomplete combustion.

Figure 4: G/E Turbocharger

2. **Generator No. 2 Overhaul Report**
   - Carbon Clogging in Piston Components: During overhaul of Generator No. 2, it was discovered that the grooves of the piston and oil scraper rings were clogged with carbon deposits. These deposits blocked the drain holes, significantly impairing the functionality of these components.
   - Replacement of Components: As a corrective measure, all affected piston rings and oil scraper rings were replaced. In addition, the upper section of the cylinder liner, particularly the explosion area, exhibited a high wear rate.
   - Improvement in Operational Performance: Following the overhaul, a significant improvement in generator performance was observed. Daily sump oil consumption

decreased from approximately 60 L to a normal level of approximately 10 L.

- Visual Evidence: **Figure 5** shows the condition of the piston ring grooves before and after the overhaul, emphasizing the effect of carbon buildup on engine performance.

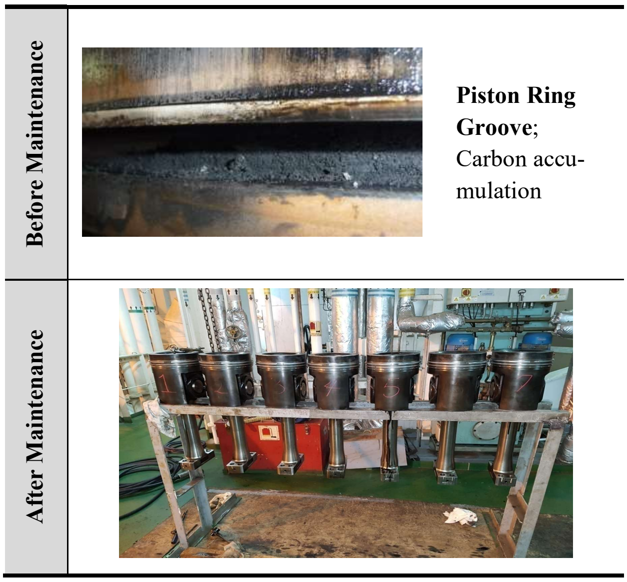

Figure 5: G/E Piston

Despite these maintenance efforts, the issue of incomplete combustion persisted, leading to repeated carbon deposition and associated mechanical problems. Ship engineers have been working closely with engine manufacturers to find a definitive solution; however, a clear resolution has yet to be achieved. The chronic nature of these combustion issues suggests that there may be underlying design or operational factors contributing to the persistent incomplete combustion and its resulting effects on engine performance.

3.4. Impact of Incomplete Combustion and Mechanical Wear

The presence of carbon sludge in the LO pump relief valve and other system components has raised serious concerns regarding the source and impact of these contaminants. The carbon deposits were traced back to the incomplete combustion within the engine cylinders, where soot and other carbonaceous materials were produced. These materials entered the L.O. system and gradually accumulated in areas with slower oil flow, such as within the relief valve.

Incomplete combustion contributes significantly to the mechanical wear of critical engine components, particularly cylindrical liners and piston rings. The following details elucidate the process that leads to the degradation of these components and their subsequent consequences.

1. Increased Cylinder Liner and Piston Ring Wear:

- **Abrasive Carbon Particles**: Incomplete combustion results in the formation of abrasive carbon particles that mix with the LO. As this contaminated oil circulates through the engine, it increases the friction between the cylinder liner and piston rings, accelerating the wear on these components. Over time, this wear compromises the seal between the piston and the cylinder wall, leading to decreased compression and efficiency.
- **Loss of Seal Integrity**: The wear down of the cylindrical liner and piston rings reduces their ability to maintain a proper seal, allowing more combustion gases to escape from the combustion chamber into the crankcase, a phenomenon known as blow-by.

2. Exhaust Gas Blow-by to Sump Oil Tank:

- **Increased Blow-by**: As cylinder liner and piston rings wear, the volume of the blow-by gases increases. These exhaust gases, along with the unburnt fuel and soot, enter the crankcase and subsequently mix with the LO in the sump oil tank. This contamination degrades the oil, reducing its ability to effectively lubricate and cool the engine.
- **Contamination of Sump Oil**: The continuous ingress of blow-by gases into a sump oil tank leads to significant contamination of the LO. The presence of combustion residues and unburnt fuel in oil reduces its viscosity and lubricating properties, further contributing to the wear of engine components.
- **Effect on Lubricating Oil Pressure**: The LO contamination and the resulting wear of critical engine components adversely affect the ability of the system to maintain a stable LO pressure. As the quality of the oil degrades and the mechanical wear increases, the LO system struggles to sustain adequate pressure, particularly under varying load conditions. This reduced pressure compromises the lubrication of the engine components, exacerbates wear, and increases the risk of system failure.

The above process follows a vicious cycle in which incomplete combustion leads to increased mechanical wear; this exacerbates the blow-by of exhaust gases, further contaminating the LO and impairing the ability of the system to function effectively. The cumulative effects of these issues contributed significantly to the conditions that led to the failure of the generator and subsequent blackout incidents.

3.5. Consequences of Incomplete Combustion

Incomplete combustion was identified as the root cause of carbon build-up in the LO system and increased mechanical wear on the cylinder liner and piston rings. Several factors contribute to this issue.

- **Aging Engine Components**: The engine piston and scraper rings, which were designed to seal the combustion chamber and prevent blow-by, were worn out. This allowed the combustion gases to enter the LO system, leading to contamination.
- **Suboptimal Fuel–Air Mixture**: Variations in the fuel–air mixture, possibly owing to inconsistencies in the fuel injection system or changes in the engine load, contributed to the incomplete combustion, resulting in the production of soot and other carbonaceous materials.

The resulting blow-by not only contaminated the LO system but also increased the mechanical wear on the engine components, setting off a vicious cycle of degradation that ultimately led to the failure of the generator.

3.6. Summary of Findings

The inspection and analysis of the LO system components, as demonstrated in **Figures 3, 4,** and **5**, clearly indicate that the primary cause of the blackout incident was the failure of the LO system to maintain adequate pressure owing to carbon sludge accumulation. This failure was exacerbated by the incomplete combustion within the engine, which introduced contaminants into the LO system, increased the mechanical wear on the cylinder liner and piston rings, and led to exhaust gas blowing into the sump oil tank.

The analysis highlights the importance of maintaining the LO system according to the manufacturer's specifications, and the need for more frequent and thorough inspection of key components, particularly in older engines that are more susceptible to such issues. Regular maintenance is crucial to prevent the buildup of carbon deposits and ensure the long-term reliability and safety of marine diesel engines.

4. Experimental Analysis of the Case Study Incident

4.1. Experiment Design and Methodology

To validate the findings from the inspection and better understand the dynamics of the incident, a series of controlled experiments were conducted using Generator No. 2. The experiments were designed to replicate the conditions leading up to a blackout and to measure key parameters such as the LO pressure, cylinder explosion pressure, and sump-tank pressure under varying loads.

The generator was operated at three load levels: 25, 50, and 75% of its rated capacity. These load levels were selected to simulate the typical operating conditions of a generator during normal shipboard operation. Each load level was maintained for a specific period, allowing sufficient time for the system to stabilize and facilitate accurate measurements.

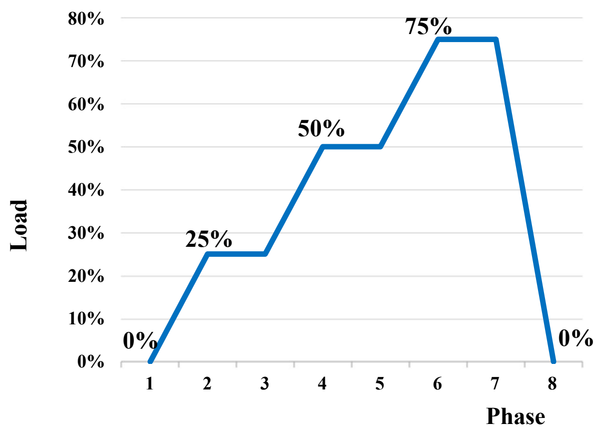

Figure 6: No. 2 G/E Load Test

Table 4: No. 2 G/E Load Test Phases

Phase	G/E Load		Min.
1→2	0→25%	0kW → 300kW	10
2→3	**25%**	**300kW**	**60**
3→4	25→50%	300 → 600kW	10
4→5	**50%**	**600kW**	**60**
5→6	50→75%	600 → 900kW	10
6→7	**75%**	**900kW**	**60**
7→8	75→0%	900kW → 0kW → Stop	10

Figure 6 shows the experimental setup and load conditions used during the tests. The generator load was increased incrementally, as detailed in **Table 4** (No. 2 G/E load test phase).

4.2. Experimental Procedure

The experimental procedure involved the following steps:

1. **Preparation**: Before starting the experiments, the generator was thoroughly inspected and any remaining carbon deposits were removed from the LO system. Fresh LO was added, and all sensors and measurement devices were calibrated.

2. **Load Testing**: The generator was initially started at no load and then gradually increased to 25% of its rated capacity. The generator was operated at this load for 60 min, during which the LO, cylinder explosion, and sump tank pressures were continuously monitored and recorded.
3. **Incremental Load Increase**: After the initial load test, the generator load was increased to 50% and then to 75%, with similar monitoring and recording at each load level.
4. **Data Collection and Analysis**: The data collected during the load tests were analyzed to identify any trends or anomalies in the system performance. Particular attention was paid to changes in the LO and cylinder explosion pressures, which are key indicators of incomplete combustion and potential mechanical failure.

4.3. Results and Observations

The results of the experiments confirmed the findings of the initial inspection. At all load levels, the LO pressure stabilized at 5.0 bar, indicating that the cleaning and maintenance procedures restored the system to its proper operating conditions. However, the cylinder explosion pressure was consistently lower than the manufacturer's design specification by approximately 3–5%, suggesting that incomplete combustion still occurred to some extent.

Table 5 summarizes the key parameters measured during the load tests.

Table 5: Result of No. 2 G/E Load Test

Phase	Load	Lub. Oil Press. (bar)		P-max (bar)		Sump Tk (+ / -)
		Shop Test	**Test Result**	Shop Test	**Test Result**	**Test Result**
2→3	300kW	4.8	**4.9**	73	**70**	**Positive**
4→5	600kW	4.7	**4.9**	109	**105**	**Positive**
6→7	900kW	4.7	**4.9**	144	**137**	**Positive**

The sump tank pressure remains positive throughout the tests, further indicating the presence of blow-by gases in the crankcase. This finding is consistent with earlier observations of worn piston and scraper rings, which allowed combustion gases to escape into the LO system.

4.4. Discussion of Experimental Findings

The experimental findings reinforced the conclusion that incomplete combustion was the primary cause of blackouts. The persistent presence of blow-by gases in the LO system, even after maintenance, suggests that the engine components were significantly worn and required extensive repairs or replacements.

Figure 6 illustrates the process by which incomplete combustion leads to carbon build-up within the engine. This carbon deposition accelerates the wear of critical components, such as piston rings and cylinder liners, leading to blow-by and subsequent contamination of LO.

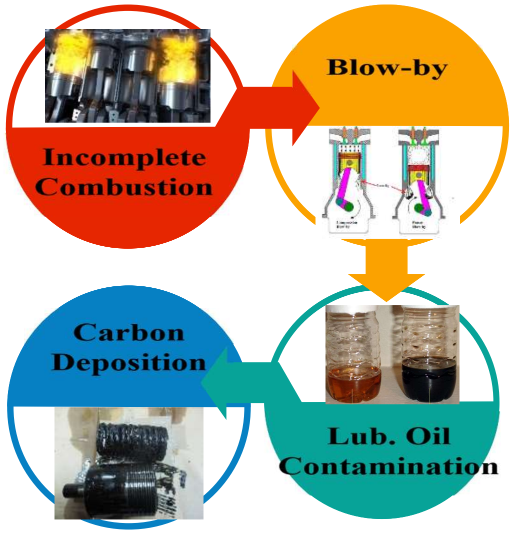

Figure 6: Illustration of the mechanical failure due to incomplete combustion

The lower-than-expected cylinder explosion pressure indicated that the engine did not operate at peak efficiency, likely owing to a suboptimal fuel-air mixture or other factors affecting the combustion process. This reduced efficiency not only increases the risk of mechanical failure but also contributes to higher fuel consumption and emissions, further underscoring the importance of addressing incomplete combustion in marine diesel engines.

The positive sump pressure trend observed during the tests also suggests that the blow-by gases contributed to the contamination of the LO, which in turn affected the viscosity of the oil and its ability to maintain proper lubrication and cooling of the engine components.

5. Conclusion and Recommendations

5.1. Summary of Key Findings

This study conducted an in-depth analysis of a blackout incident on a VLCC caused by a mechanical failure in one of its generator engines. Their investigation revealed that the root cause was incomplete combustion, which led to carbon deposition in the engine. These carbon deposits significantly accelerate the wear of critical components such as piston rings and cylinder liners, resulting in blow-by gases contaminating the LO system.

The experimental analysis confirmed that despite maintenance efforts, the generator continued to exhibit lower-than-expected cylinder explosion pressures and positive sump-tank pressures, indicating ongoing incomplete combustion and mechanical wear. The following key findings were identified:

1. **Incomplete Combustion**: The primary cause of mechanical failure is incomplete combustion, which results in the formation of carbon deposits in the engine. These deposits contribute to the accelerated wear of critical engine components, reduced engine efficiency, and increased likelihood of mechanical failure.
2. **Mechanical Wear**: Significant wear on the piston rings and cylinder liners compromised the sealing of the combustion chamber, allowing exhaust gases (blow-by) to enter the crankcase. This blow-by-contaminated LO degrades the quality and exacerbates engine wear.
3. **Lubricating Oil Contamination**: The presence of blow-by gases and combustion residues in the LO reduces its viscosity and ability to lubricate effectively, creating a cycle of increasing mechanical wear and declining engine performance.
4. **Impact on Engine Performance**: The experimental tests showed that, while the LO pressure was maintained, the generator engine suffered from reduced cylinder explosion pressure and increased sump pressure, indicating suboptimal operating conditions that increased the risk of further mechanical failure.

5.2. Recommendations for Engine Designers

Based on the findings, several recommendations are proposed for engine designers:

1. **Enhanced Combustion Efficiency**: Engine designs should incorporate advanced technologies that optimize fuel–air mixtures and ensure complete combustion. This may include precision fuel injectors, variable timing mechanisms, and real-time monitoring systems that adjust the combustion parameters based on the operating conditions.
2. **Improved Material Durability**: Considering the observed wear on piston rings and cylinder liners, it is recommended that these components be made from more wear-resistant materials or coatings to extend their operational life and reduce maintenance frequency.
3. **Advanced Lubrication Systems**: The development of advanced lubricating systems with enhanced filtration capabilities and the use of synthetic or specialized lubricants that resist contamination and degradation from blow-by gases are recommended to maintain oil quality over extended periods.

5.3. Recommendations for Engine Operators

Engine operators should adopt the following maintenance practices to ensure optimal performance and mitigate the risk of incidents:

1. **Lubricating Oil Renewal Cycle**: While manufacturer's manual recommends a LO renewal cycle of 2,000 h, it is advisable to adjust this interval based on regular laboratory oil analyses conducted every 3–6 months. This approach allows operators to extend or shorten the renewal cycle based on the oil conditions and contamination levels.
2. **Piston Overhaul Interval**: The recommended overhaul interval of 16,000 h should be initially reduced to 8,000 h based on the observed wear. Further extensions may be considered based on engine performance and condition assessments during shortened intervals.
3. **Air Supply System Maintenance**: To ensure stable scavenging of air pressure according to the engine load, it is recommended that scavenging air filters be replaced weekly, air coolers undergo annual chemical cleaning, and turbochargers be cleaned with water during operation, according to the manufacturer's guidelines.
4. **Performance Monitoring and Diagnostics**: Although retrofitting existing engines with advanced sensors for real-time monitoring may be impractical, operators should prioritize these features when acquiring new engines. For existing engines, regular manual inspections and performance tests should be conducted to detect the early signs of wear and deterioration.

5.4. Considerations for the Use of Alternative Fuels

The shift towards using liquefied natural gas (LNG) and liquefied petroleum gas (LPG) as alternative fuels in marine diesel engines is driven by the need to comply with stringent NOx, SOx, and CO2 emission regulations **[19]**. However, this transition introduces new challenges in achieving complete combustion, particularly in engines that were not originally designed for dual-fuel operation.

Incomplete combustion in dual-fuel engines can lead to unburnt gases entering the crankcase, thereby increasing the risk of explosions **[21]**. Therefore, the development of advanced combustion control systems is essential to ensure safe and efficient operation of these engines. In addition, the variability in retrofitting costs based on engine type, output, and ship design highlights the complexity and financial implications of such modifications.

5.5. Mechanical Challenges and the Necessity for Further Research in Response to Emission Regulations

The integration of systems such as the EGCS, SCR, and EGR in response to emission regulations has brought about various mechanical challenges. Examples include the backflow of washwater in the EGCS, which leads to pipe corrosion, and the malfunction of exhaust valves in SCR systems, which causes engine shutdowns. Additionally, the adoption of low-sulfur fuels in non-EGCS-equipped vessels lead to mechanical issues such as fuel pump sticking owing to reduced lubricity **[18][20][22][23]**.

With the increasing use of gas fuels, such as LNG and LPG, achieving complete combustion has become even more critical. The ongoing shift towards cleaner emissions and alternative fuels necessitates further research to mitigate these mechanical challenges and ensure the safety and reliability of marine diesel engines.

5.6. Future Research Directions

To address the identified mechanical challenges, future research should focus on the following areas:

1. **Mechanical Impact of Emission Control Systems**: It is crucial to investigate the long-term mechanical effects of integrating EGCS, SCR, and EGR systems, particularly on engines not originally designed to accommodate these technologies. Strategies to mitigate the mechanical stresses introduced by these systems must be developed.
2. **Optimization of Lubricating Management**: Further research on the best practices for lubrication management, especially in engines operating with low-sulfur fuels and emission control systems, is necessary. This includes the development of advanced lubricants and additives that can better withstand the challenges posed by the operating conditions.
3. **Compatibility of Alternative Fuels with Engine Designs**: Studies should assess the compatibility of LNG, LPG, and other alternative fuels with various engine designs, particularly in terms of combustion efficiency and mechanical wear. Such studies will help guide future engine designs and retrofitting decisions.
4. **Development of Advanced Combustion Technologies**: Continued innovation in combustion technology is essential to meet the challenges posed by new fuel types and strict emission regulations. Research should focus on developing systems that can achieve higher efficiency and lower emissions, while maintaining engine reliability and safety.

In conclusion, while the adoption of cleaner fuels and stricter emission controls is necessary, it introduces significant mechanical challenges that require ongoing research and innovation. Ensuring the reliability and safety of marine diesel engines in this new regulatory landscape depends on developing solutions that can effectively manage these emerging risks.

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