The North African Journal of Scientific Publishing (NAJSP)
مجلة شمال إفريقيا للنشر العلمي (NAJSP)
E-ISSN: 2959-4820
Volume 3, Issue 2, 2025
Page No: 212-219
Website: https://najsp.com/index.php/home/index
SJIFactor 2024: 5.49 | معامل التأثير العربي (AIF) 2024: 0.71 | ISI 2024: 0.696

Quality and Suitability Assessment of Heavy Fuel Oil in Energy Storage Tanks: A Comparative Study of Environmental and Operational Risks in Three Libyan Sites

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تقييم جودة وملاءمة وقود الزيت الثقيل في خزانات تخزين الطاقة: دراسة مقارنة للمخاطر البيئية والتشغيلية في ثلاثة مواقع ليبية

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Received: May 01, 2025	Accepted: June 15, 2025	Published: June 22, 2025

Abstract:
Heavy fuel oil (HFO) plays a pivotal role in powering thermal plants and heavy industries, serving as an essential energy source for both national and international economies. Despite its critical operational role, the long-term storage of HFO presents significant challenges that affect its physicochemical characteristics, stability, and reliability over time. This study aimed to assess the quality of HFO stored across three key sites in western Libya, we analyses based on established ASTM standards. The primary objective was to evaluate its suitability for continued use in energy generation and to identify key indicators of degradation associated with long-term storage. Results revealed significant site-to-site variations in HFO quality. The Abu Kammash site demonstrated relatively stable oil characteristics, including low acid numbers, low water content, and low sulfur levels, suggesting that its HFO remains suitable for long-term use in thermal generation and heavy industrial applications. In contrast, HFO samples from the Western Tripoli and Zuwara sites exhibited notable signs of oil degradation, including elevated acid numbers, increased water content, and higher concentrations of heavy metals, indicative of long-term storage impacts such as oxidation and corrosion. These changes negatively affect the oil's combustion efficiency, equipment reliability, and operational safety, underscoring the critical role of storage conditions in determining fuel quality. The findings of this study highlight the urgent need for improved storage practices, routine quality monitoring, and preventive maintenance measures. Such practices are vital for preserving the physicochemical properties of HFO, extending equipment service life, and minimizing environmental and operational hazards associated with long-term fuel storage. By addressing these factors, industries can ensure sustained performance, reduce maintenance costs, and mitigate the environmental impacts of HFO degradation.

Keywords: Heavy Fuel Oil (HFO), Long-term Storage, Fuel Degradation, Acid Number, Heavy Metals.

الملخص
يلعب زيت الوقود الثقيل *(HFO)* دورًا محوريًا وحاسمًا في تشغيل محطات الطاقة الحرارية وفي تلبية احتياجات العديد من المنشآت الصناعية، حيث يعد مصدرًا أساسيًا للطاقة الحرارية على مستوى محلي وعالمي. على الرغم من أهميته

الاقتصادية والتشغيلية، فإن جودة هذا الوقود تتأثر بشكل كبير بظروف التخزين طويلة الأمد، مما يشكل تحديًا كبيرًا للحفاظ على خصائصه الفيزيائية والكيميائية وضمان موثوقيته على المدى الطويل. تهدف هذه الدراسة إلى تقييم جودة زيت الوقود الثقيل *(HFO)* المخزن على امتداد ثلاثة مواقع مميزة في غرب ليبيا، هي أبو كماش، غرب طرابلس، وزوارة، وذلك عبر إجراء سلسلة من التحاليل الفيزيائية والكيميائية وفقًا للمعايير القياسية*(ASTM)* ، وذلك للكشف عن مؤشرات التدهور وتقييم صلاحية الزيت للاستمرار في استخدامه ضمن محطات الطاقة. تمثلت النتائج في ظهور تفاوت ملحوظ في جودة زيت الوقود الثقيل عبر المواقع الثلاثة، حيث أظهر موقع أبو كماش خصائص زيت مستقرة، تمثلت بانخفاض الرقم الحمضي، ومحتوى الماء، ومستويات الكبريت، مما يشير إلى جودة عالية ومتانة التركيبة، تؤهل الزيت للاستمرار ضمن عمليات تشغيل المحطات الحرارية بكفاءة عالية. على النقيض، أظهرت النتائج من موقعي غرب طرابلس وزوارة مؤشرات واضحة على تدهور جودة الزيت، متمثلة بارتفاع الرقم الحمضي، وزيادة واضحة في المحتوى المائي، وتركيز أعلى للمعادن الثقيلة، مما يشير إلى تأثير عمليات الأكسدة، التآكل، والتخزين طويل الأمد على جودة الزيت، ويؤثر سلبًا على خصائصه، وكفاءته التشغيلية، وعلى عمر المحطات ومكوناتها الحيوية.

الكلمات المفتاحية: زيت الوقود الثقيل، التخزين طويل الأمد، تدهور الوقود، الرقم الحمضي، المعادن الثقيلة.

Introduction:

Heavy fuel oil (HFO) remains a critical energy source in many parts of the world, especially for industrial heating systems, power generation units, and maritime operations. Despite global efforts to transition to cleaner energy sources, many developing countries and emerging economies continue to rely heavily on HFO due to its availability, cost-effectiveness, and infrastructure compatibility. However, concerns over its environmental footprint, storage stability, and operational risks have drawn increasing attention from both researchers and policymakers.

In the Mediterranean region, including North African countries such as Egypt, Tunisia, and Algeria, the use of heavy fuel oil persists in several sectors, particularly in thermal power plants and steam boilers. These countries have reported varied challenges related to fuel degradation during long-term storage, corrosion in storage facilities, and fluctuations in fuel performance, which can directly affect operational efficiency and safety standards.

Libya, a country with substantial oil reserves and infrastructure, continues to depend on heavy fuel oil in many industrial and energy-producing facilities. However, due to recent instability, disruptions in maintenance, and varying storage conditions, questions have arisen regarding the quality and suitability of stored fuel oil across different sites.

This study focuses on assessing the physicochemical quality and suitability of heavy fuel oil stored in three strategic Libyan locations: the Abu Kammash Industrial Complex, the Western Tripoli Tank, and the Zuwara Port Terminal. These sites represent different operational and environmental contexts, offering an opportunity to evaluate the current condition of stored HFO and its implications for energy efficiency, environmental protection, and operational safety.

Research Problem:

In recent years, Libya has experienced significant challenges in the management and maintenance of its energy infrastructure, including the storage and utilization of heavy fuel oil (HFO). In particular, there have been growing concerns about the quality degradation of HFO stored for extended periods under varying environmental and operational conditions.

Preliminary observations from key locations such as the Abu Kammash Industrial Complex, the Western Tripoli Storage Tank, and Zuwara Port have revealed signs of possible fuel aging, shifts in viscosity and flash point, and inconsistencies in combustion characteristics. These issues may compromise the performance of power generation systems, increase operational risks, and potentially lead to environmental contamination if the fuel is no longer within safe usage parameters.

Despite the continued use of HFO in boilers, turbines, and energy units across the country, there is a lack of updated, site-specific evaluations regarding the physicochemical properties of stored fuel oil and its fitness for use. This gap in knowledge raises serious questions about the safety, efficiency, and environmental sustainability of current fuel storage practices

Significance of the Study:

- This study addresses a critical national need by providing a comparative physicochemical assessment of heavy fuel oil stored at three key Libyan energy facilities. Through systematic sampling and laboratory analysis, it aims to:
- Determine the current quality and suitability of stored HFO for continued use in energy generation.
- Highlight differences between storage sites (climatic conditions, maintenance, tank materials) and how they affect fuel stability.

- Identify potential operational hazards, such as combustion inefficiency or corrosion, that may result from degraded fuel.
- Assess environmental risks associated with the use of aged or unsuitable HFO, including emissions and leaks.
- Provide evidence-based recommendations for improving fuel storage practices, quality control, and environmental protection policies in the energy sector.

By focusing on Abu Kammash, Western Tripoli, and Zuwara, this research offers localized insights that can inform national strategies for safer and more sustainable fuel management.

Research Questions:

- What are the physicochemical characteristics of heavy fuel oil stored in Abu Kammash, Western Tripoli, and Zuwara?
- Are there significant differences in fuel quality among the three storage sites?
- How do storage conditions (time, environment, tank materials) influence the stability and performance of the stored HFO?
- Is the fuel stored in these locations still suitable for safe industrial and energy-related applications?
- What are the potential environmental and operational hazards resulting from the use of aged or degraded fuel?
- What strategies or interventions can be implemented to enhance heavy fuel oil storage and quality control in Libya?

Objectives of the Study:

- Evaluate the physicochemical properties of heavy fuel oil stored in Abu Kammash, Western Tripoli, and Zuwara.
- Compare fuel quality across the three sites.
- Assess the suitability of stored HFO for continued use in energy systems.
- Identify signs of fuel degradation affecting performance and safety.
- Determine potential environmental and operational risks.
- Recommend improvements for storage and quality control practice

Literature Review:

Heavy fuel oil (HFO) remains a widely used energy source in various sectors, particularly in power generation and industrial heating. However, its long-term storage presents significant challenges related to degradation, operational risks, and environmental concerns. Numerous recent studies have addressed these issues from different perspectives. Hossain et al. (2020) investigated the stability of pyrolysis bio-oil blended with HFO and found that blending up to 15% improved combustion and reduced viscosity without causing significant corrosion. However, higher blends led to increased sediment formation and accelerated material degradation in storage tanks. Li and Zhang (2023) focused on residual marine fuels and highlighted the importance of asphaltene stability and blending practices in maintaining fuel quality. Their work led to the refinement of standardized test methods such as ASTM D7157 and D7112-24 for more accurate fuel stability evaluations.

Smith et al. (2024) applied advanced chemometric and GC-MS techniques to track degradation patterns in ultra-low sulfur diesel. Their results indicated rising acidity and oxidative by-products during storage, which could negatively affect fuel performance and engine reliability. Zavareh et al. (2022) assessed the fire and explosion risks of petroleum storage tanks using the Dow Fire and Explosion Index and spatial consequence modeling. They recommended strategic site planning and emergency response frameworks to minimize the risk of pollution and human harm. Oulehlova et al. (2021) examined diesel storage tanks and identified environmental risks resulting from corrosion and leakage, particularly in older or poorly maintained infrastructure. Their findings emphasized the need for modernizing tank materials and improving inspection practices.

In a large-scale hazard study, Kumar Dhurandher et al. (2023) analyzed fuel terminal facilities and emphasized the importance of quantitative risk assessment tools to prevent catastrophic events such as tank fires and spills. Research by Hanaei et al. (2020) showed that petroleum contamination alters the geotechnical properties of sandy soils, including density, cohesion, and permeability. This has serious implications for managing leaks and fuel spills near storage sites. Mocellin and Vianello (2022) modeled the environmental impacts of tank fires using PHAST software and found that fire zones could extend up to 30 meters, affecting both workers and the surrounding ecosystem. They called for implementing emergency buffer zones and fire prevention systems.

Mehanovic et al. (2022) explored fuel storage strategies and found that stability is highly dependent on temperature, storage duration, and blend composition. They recommended controlled environments to prevent degradation in long-term stored fuels.

The Norilsk diesel spill in 2020 served as a global case study, demonstrating the environmental devastation that can result from improper fuel storage and insufficient monitoring systems. Vora et al. (2018) and Alhamdani et al. (2018) used fuzzy analytical hierarchy models to evaluate emission risks in floating roof tanks. Their studies contributed to a better understanding of vapor dispersion and toxicity under various failure scenarios. In a study on refinery fire accidents, Sulistomo et al. (2023) advocated for risk-based inspection and stronger regulatory oversight to reduce fire incidents at petroleum storage facilities.

Smith and Lee (2020) assessed the oxidation stability of biodiesel blends and reported that prolonged storage under high temperatures resulted in significant increases in acid number, water content, and microbial growth, all of which reduce fuel quality. Filippini et al. (2022) investigated carcinogenic spread near petroleum tanks using phytoscreening and groundwater modeling. Their results highlighted the long-term environmental threat posed by poorly contained fuel storage. Godoy et al. (2023) modeled the structural failure of storage tanks under fire and blast conditions, demonstrating the vulnerability of older tanks without adequate safety reinforcements. Several recent ASTM revisions (2022–2024) have improved the reliability of tests used to detect sedimentation and asphaltene destabilization in heavy fuel oil, offering better predictive tools for industry professionals.

Research on optimal storage environments (2021) confirmed that cold, dry, and dark conditions significantly slow down the chemical aging of fuel oils, providing practical recommendations for facilities dealing with extended storage periods. Studies evaluating the environmental risks of fuel stations (2021) emphasized the importance of secondary containment systems, monitoring technologies, and soil protection measures to minimize accidental releases and contamination. A 2019 review on the biodegradation of petroleum hydrocarbons during composting discussed how fuel-contaminated sludge can be safely treated and recycled, offering alternatives to hazardous waste accumulation. Finally, human reliability analysis in petroleum operations (2021) revealed that human error remains a significant contributor to fuel mishandling and accidents, especially in facilities with limited training and oversight. These studies collectively highlight the need for ongoing monitoring, standardized testing, and improved storage infrastructure to ensure the safe and efficient use of heavy fuel oil. Their findings strongly support the rationale for evaluating HFO quality and operational risks in key Libyan storage sites such as Abu Kammash, Western Tripoli, and Zuwara, where variations in storage practices and environmental conditions may significantly impact fuel integrity and safety.

Materials and Methods:

Sample Collection

Heavy fuel oil samples were collected from multiple storage tanks exhibiting signs of corrosion and structural degradation, located at the Abu Kammash complex, Zuwara port, and West Tripoli electric stations in Libya. Sampling was performed following standard protocols to ensure representativeness and avoid contamination. Each sample was assigned a unique identification number and transported to the laboratory under controlled conditions.

Analytical Methods

The physicochemical properties of the heavy fuel oil samples were analyzed in accordance with the standard test methods established by ASTM International. The following methods were employed:

- Density and API Gravity

The density at 15 °C and the American Petroleum Institute (API) gravity were determined using ASTM D1298 (Hydrometer Method). Samples were allowed to equilibrate at the testing temperature before measurement.

- Kinematic Viscosity

Viscosity measurements at 40 °C and 100 °C were carried out according to ASTM D445, employing calibrated viscometers. Each measurement was repeated thrice to ensure accuracy, and the mean value was recorded.

- Viscosity Index

Calculated using ASTM D2270 based on the kinematic viscosity values at 40 °C and 100 °C, indicating the temperature dependence of the oil's viscosity.

- Total Acid Number (TAN)

Acid content was quantified by titration with potassium hydroxide as per ASTM D974, using color indicator titration to identify the endpoint.

- Flash Point

The Cleveland Open Cup method (ASTM D92) was applied to determine the flash point, assessing the temperature at which vapor ignites under specified conditions.

- Pour Point

The lowest temperature at which the oil remained pourable was measured using ASTM D97 to evaluate flow characteristics under low temperature.

- Distillation Range

Simulated distillation was conducted following ASTM D86 to determine the initial boiling point (IBP), 10%, 50%, 80% recovery temperatures, and the end point (EP).

- Water Content

Water content was measured by ASTM D95 via distillation separation, providing the percentage of water present in the samples.

- Sulfur Content

Sulfur concentration was quantified using X-ray fluorescence spectroscopy according to ASTM D2622.

- NOACK Evaporation Loss

The volatility of the samples was assessed by ASTM D8500, which measures the mass loss of oil after exposure to elevated temperatures using the NOACK evaporative tester.

- Dropping Point

Determined by ASTM D2265, indicating the temperature at which lubricating grease solidifies under controlled heating.

- Copper Strip Corrosion Test

The tendency of oil to corrode copper was evaluated using ASTM D4048, involving immersion of a polished copper strip in the oil under static conditions at elevated temperature.

- Color Measurement

The visual color assessment was carried out according to ASTM D1500, providing a standardized color scale rating.

- Heavy Metals Content

Quantitative determination of trace heavy metals (e.g., Fe, Cu, Pb, Zn) was conducted by atomic absorption spectroscopy following ASTM D5155, ensuring precise detection of contaminants.

Quality Control and Data Analysis

All tests were performed in triplicate to ensure repeatability and accuracy. Calibration of instruments was conducted regularly following manufacturer and ASTM guidelines. Data were recorded systematically, and outliers were checked for consistency. Results are presented as mean ± standard deviation where applicable.

Results

The analysis revealed significant variations in fuel quality across sites:

Abu Kammash HFO exhibited lower viscosity, low acid number, low sulphur, and minimal water content, indicating relatively good storage conditions as presented in Table 1.

Western Tripoli HFO showed moderate viscosity, elevated acid numbers, and higher sulphur levels, suggesting early stages of fuel degradation.

Table 1. Comparison of physicochemical properties across the three sites.

Parameter	Abu Kammash	Western Tripoli	Zuwara
Specific gravity @ 15°C	0.8843 - 0.8894	0.8843 - 0.891	0.9623 - 0.9724
API degree	27.32 - 27.59	27.00 - 27.31	15.7 - 17
Kinematic viscosity (40°C, cSt)	8.1 - 8.4	27.1 - 27.2	175 - 18
Kinematic viscosity (100°C, cSt)	2 - 2.19	4 - 4.77	16.5 - 17.5
Viscosity index	43.7 - 44.17	90 - 91.3	98.5 - 99.3
Total acid number (mg KOH/g)	0.41 - 0.44	3.09 - 3.78	3.19 - 3.42
Flash point (°C)	149 - 156	174 - 189	174 - 186
Pour point (°C)	<-20	-4 to -0.2	10 - 12
Water content (%)	0.10	0 - 0.10	38 - 45
Sulphur content (%)	0.04	0.73 - 0.81	0.78 - 0.88
NOACK evaporation loss (%)	4 - 4.1	2.4 - 2.8	14
Dropping point (°C)	123 - 127	260 - 280	122 - 128
Copper strip corrosion	1b	1a	3a
Color	3	<8	<8

Zuwara HFO presented high viscosity, high acid number, substantial water contamination, and elevated heavy metals (especially Fe, Ca, and Na), consistent with significant degradation and contamination, likely due to storage tank corrosion and leakage into surrounding concrete as illustrated in Table 2. These differences suggest that the Abu Kammash fuel may still be suitable for energy applications, while the Zuwara samples pose operational and environmental risks due to contamination and degradation. The Western Tripoli fuel is intermediate in quality but shows signs of aging as shown Figure 1.

Table 2. Concentrations of Metal Elements in Heavy Fuel Oil Samples from Abu Kammash, Western Tripoli, and Zuwara**.**

Element	Abu Kammash	Western Tripoli	Zuwara
Fe	6 - 12	85 - 90	248 - 262
Al	1	3	33 - 42
Cu	1	1	4 - 6
Pb	0	2 - 3	4
Ca	0	122 - 132	470 - 486
Mg	0	3 - 4	36 - 38
Zn	17 - 21	4	8 - 9
Si	4 - 9	3 - 4	66 - 69
Na	0	4 - 8	65 - 70
Others	B, Ba, V, Sn, Ag: all low or non-detectable levels		

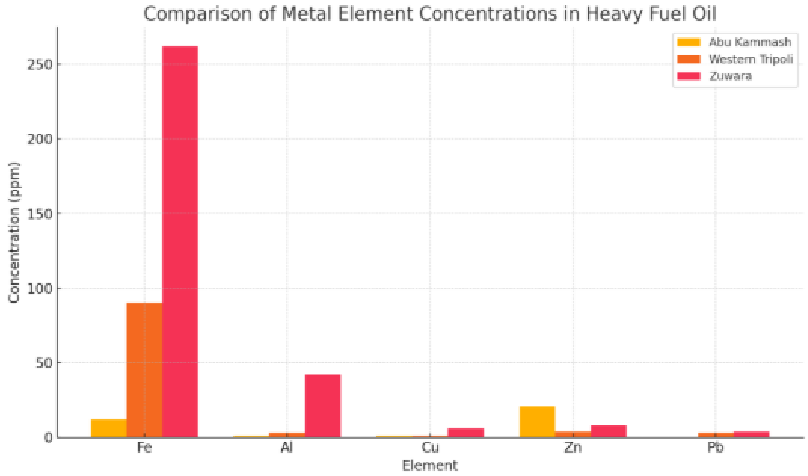

Figure 1. Comparison of Key Metal Element Concentrations (Fe, Al, Cu, Zn, Pb) in Heavy Fuel Oil Samples from Abu Kammash, Western Tripoli, and Zuwara.

Discussion:

The results of this study reveal significant variations in the physicochemical properties of heavy fuel oil (HFO) stored across three sites in western Libya, Abu Kammash, Western Tripoli, and Zuwara. These variations can be attributed to differences in storage conditions, aging effects, and the integrity of storage infrastructure, findings that align with observations from several recent studies on HFO stability and degradation.

At the **Abu Kammash site**, relatively low total acid number (0.41–0.44 mg KOH/g), low sulfur content (~0.04%), and minimal water contamination (~0.10%) suggest that the oil remained relatively stable despite long-term storage. Similar observations were made by Hossain et al. (2020), who found that HFO blended and stored under well-maintained conditions exhibited improved combustion properties and reduced viscosity. The low copper and iron levels further imply minimal corrosion and equipment wear.

In contrast, the **Western Tripoli site** demonstrated moderate levels of acid number (~3.1–3.8 mg KOH/g) and increased sulfur content (~0.73–0.81%), indicative of incipient oxidation and sulfur accumulation during storage. Similar behavior has been reported by Smith et al. (2024), who observed rising acidity and the generation of oxidative by-products in long-term storage conditions. The kinematic viscosity and elevated heavy metal levels (Fe: 85–90 ppm) at this site point to localized contamination and mild tank corrosion, aligning with findings by Oulehlova et al. (2021) that identified environmental and operational risks associated with aging storage infrastructure.

The **Zuwara site** posed the highest risk for operational and environmental compromise, with significant water content (38–45%), higher total acid number (3.19–3.42 mg KOH/g), and increased sulfur levels (0.78–0.88%). Heavy metal contamination, especially iron (248–262 ppm) and calcium (470–486 ppm), further suggests extensive corrosion and possible soil infiltration. These findings echo those of Hanaei et al. (2020), who demonstrated the long-term effects of petroleum contamination on soil properties, and of Mocellin and Vianello (2022), who emphasized the risk of tank fires and environmental damage when water and sediments accumulate in degraded storage units. These observations support the consensus within the literature that HFO quality deteriorates over time due to internal and external factors, including thermal, oxidative, and microbial activity (Mehanovic et al., 2022; Smith and Lee, 2020). The significantly higher acid numbers, water content, and metal contamination observed in the Zuwara site highlight the urgent need for improved tank design and maintenance protocols, as advocated by Zavareh et al. (2022) and Oulehlova et al. (2021), to mitigate the risk of catastrophic spills and fires.

Furthermore, the increased distillation temperatures and altered kinematic viscosity indexes across the three sites point to asphaltene aggregation and molecular changes during long-term storage (Li and Zhang, 2023). Such changes complicate combustion and may impede equipment performance, aligning with the findings of Hossain et al. (2020). The deterioration of the Zuwara site samples, in particular, emphasizes the role that long-term, inadequately monitored storage can play in degrading fuel quality. From an environmental risk and safety standpoint, the contamination levels observed in Zuwara mirror scenarios addressed by Kumar Dhurandher et al. (2023) and Godoy et al. (2023), wherein aging storage infrastructure significantly increases the likelihood of catastrophic failures. This is compounded by the risk of long-term environmental damage to surrounding ecosystems, as evidenced by studies like Filippini et al. (2022). The results underscore the critical role of quantitative risk assessments, regular inspection protocols, and enhanced operator training (Sulistomo et al., 2023; Human reliability studies, 2021) in minimizing such incidents. In brief, the results of this study affirm the urgent need for modernized storage infrastructure, standardized testing practices, and preventive maintenance across HFO storage facilities. By aligning with best practices and recent advances in HFO quality and risk assessment (ASTM, 2022–2024), it is possible to mitigate the operational and environmental hazards posed by long-term storage, especially in aging facilities such as those in Abu Kammash, Western Tripoli, and Zuwara.

Conclusion:

This study confirms that HFO quality across Abu Kammash, Western Tripoli, and Zuwara varies significantly due to differences in storage conditions, tank integrity, and exposure to environmental factors. The Abu Kammash site demonstrated the best fuel quality, making it the most suitable for ongoing use in energy generation. The Western Tripoli site shows early signs of oil aging, suggesting a need for closer monitoring. The Zuwara site exhibited significant contamination and degradation, making its HFO a potential risk for equipment and environmental safety.

Recommendations:

- Implementation of regular inspection and testing of HFO storage facilities.
- Upgrading tank design and materials to mitigate contamination and corrosion.
- Introduction of quantitative risk assessment and preventive maintenance measures.
- Adoption of best practices for long-term HFO storage, including moisture control and sedimentation monitoring.

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