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Grease Analysis as a Predictive Maintenance Concept for Offshore Crude Export Mechanical Assets

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Abstract

Offshore crude export systems depend on a small population of grease lubricated mechanical assets whose failure carries disproportionate commercial and environmental consequences. Single point mooring (SPM) buoy main bearings, floating production storage and offloading (FPSO) turret and swivel assemblies, marine loading arm slewing rings, export pump and driver bearings, hose reel and winch drives, and pedestal crane slew bearings are all grease lubricated, difficult to access, and in several cases impossible to replace without extended export shutdown. Conventional condition monitoring on these assets is constrained: Vibration signatures from slow rotating, intermittently loaded bearings are weak, and oil analysis does not apply because there is no circulating oil to sample. This paper develops the case, as it stood in 2023, for in-service grease analysis as the primary predictive maintenance technology for this asset class. It reviews the failure behavior of grease lubricated offshore export

equipment, the maturation of grease sampling and testing standards (notably ASTM D7718 for sampling and ASTM D7918 for die extrusion testing of small in-service samples), the diagnostic parameters that correlate with incipient bearing and gear distress, and a practical implementation framework covering sampling design, laboratory selection, limit setting, competence, digital architecture, data governance, cybersecurity, spares strategy, assurance, and economics. Drawing on a wide body of adjacent research in condition monitoring, integrity management, remote inspection, energy autonomous sensing, industrial safety analytics, supply chain readiness, and asset lifecycle data governance, the paper argues that grease analysis converts the largest blind spot in offshore export asset condition monitoring into a measurable, trendable data stream at low cost and with minimal intrusion, and it identifies the organizational, digital, and technical prerequisites for a successful program.

Keywords: Grease Analysis, Predictive Maintenance, Condition Monitoring, Single Point Mooring, FPSO, Crude Oil Export, Slew Bearing, ASTM D7718, ASTM D7918, Reliability Centered Maintenance, Asset Integrity

1. Introduction

1.1 Commercial Context of Offshore Crude Export

Crude oil export is the final and most commercially exposed step in the offshore production chain. Whether crude leaves the field through a single point mooring buoy at the end of a subsea export line, across the bow of an FPSO through an offloading system, or over a fixed jetty through marine loading arms, the export path is a series arrangement of mechanical assets with little or no installed redundancy. When an export bearing, swivel, or loading arm fails, production is either curtailed into limited storage or shut in entirely. Deferment costs for a mid-sized terminal handling 200,000 to 400,000 barrels per day are measured in millions of dollars per day, before any consideration of contractual demurrage, reputational damage, or the environmental risk associated with a mooring or transfer system failure during a tanker operation.

The scale of that exposure is documented across the energy operations literature. Modeling of port logistics efficiency in emerging market export operations shows that demurrage and loading delays impose penalties large enough to justify dedicated elimination programs in their own right (Okonkwo, Agbabiaka, Ogunwole, Mayo, and Okeke, 2020). Risk management modeling for engineering, procurement, and construction and gas processing projects demonstrates that single points of mechanical failure propagate rapidly into downstream commercial commitments (Agbabiaka, Okonkwo, Ogunwole,

Mayo, and Okeke, 2019), and supply chain resilience frameworks for critical infrastructure identify unmonitored, long lead, single point assets as the dominant driver of extended outage duration (Ogunwole, Okonkwo, Agbabiaka, Mayo, and Okeke, 2021). Procurement optimization studies in oil and gas operations reach the same conclusion from the commercial side, namely that the cost of an unplanned outage is dominated not by the repair itself but by the acquisition lead time of the item that failed (Okonkwo, Ogunwole, and Okeke, 2018a; Okonkwo, Ogunwole, Okeke, and Mayo, 2019). Predictive analytics work on demand forecasting in supply chain operations reinforces that anticipation, rather than reaction, is the lever that changes this economics (Aifuwa, Oshoba, Ogbuefi, Ike, Nnabueze, and Olatunde-Thorpe, 2020).

1.2 The Asset Population and the Monitoring Gap

The mechanical assets on this export path share a defining characteristic: Nearly all of their critical rotating and articulating elements are grease lubricated. SPM buoy main roller bearings, turntable and turret bearings, product swivel path bearings, loading arm slewing rings and swivel joints, mooring hawser and hose reel winch gearboxes and open gears, export pump motor rolling element bearings, and pedestal crane slew rings all rely on grease rather than circulating oil. Grease is chosen for good reasons. It stays in place in slow, oscillating, heavily loaded contacts, it seals against salt spray and washdown water, and it tolerates long intervals between attention. However, the same properties that make grease the correct lubricant make the assets it serves nearly invisible to the two condition monitoring technologies that dominate offshore predictive maintenance: Vibration analysis and circulating oil analysis.

Vibration analysis performs poorly on large diameter, slow rotating bearings, where rotational speeds are often below one revolution per minute, defect frequencies fall below practical measurement bandwidths, and signal energy from early stage damage is buried in structural and wave induced noise. Oil analysis simply does not apply, because there is no oil reservoir or circulating system to sample. The result, common across offshore export terminals through the early 2020s, is that the most consequential mechanical assets in the export chain were maintained on time based regreasing schedules and periodic visual or internal inspection, with failure development between inspections essentially unmonitored. Because inventory availability and materials readiness models both show plant uptime to be governed by whether the right long lead spare is held and released in time (Okonkwo, Ogunwole, and Okeke, 2018b; Okonkwo, Agbabiaka, Ogunwole, Mayo, and Okeke, 2021), an asset class that gives no advance warning of its own degradation is precisely the class that defeats those models.

1.3 The Concept in Brief

Grease analysis closes this gap. The concept is straightforward: Grease in service accumulates a chemical and physical record of the contact it lubricates. Wear metals from raceways, rolling elements, gear teeth, and cages embed in the thickener matrix. Water, salt, and process fluid contamination alter grease consistency and chemistry. Oxidation and additive depletion signal thermal distress and end of useful grease life. By extracting small, representative

in-service samples and subjecting them to a structured laboratory test slate, an operator can trend the health of both the lubricant and the machine, detect incipient failure months before functional failure, and time interventions such as purge regreasing, seal replacement, or bearing change out to actual condition rather than to the calendar.

Although grease analysis as a laboratory discipline is decades old, three developments made 2023 a credible inflection point for adopting it as a formal predictive maintenance concept on offshore export assets. First, standardization matured: ASTM D7718 provided a recognized practice for obtaining representative in-service grease samples, and ASTM D7918 established a die extrusion method that yields wear, contamination, consistency, and oxidation data from samples as small as one gram. Second, commercial laboratories and field kits made routine grease analysis logistically practical for remote offshore locations. Third, the reliability community, informed by ISO 14224 failure data structures and industry experience with SPM main bearing and turret bearing failures, recognized that this asset class needed a monitoring technology of its own.

1.4 Objectives and Scope

The objectives of this paper are fivefold: To characterize the failure behavior and monitoring constraints of grease lubricated offshore crude export assets; to review the state of grease sampling and analysis technology and standards as of 2023; to define a diagnostic parameter set and alarm philosophy suitable for this asset class; to present an implementation framework covering organization, competence, digital architecture, security, spares, and assurance; and to establish the economic case. The scope covers export path mechanical assets at SPM and conventional buoy moored terminals, FPSO offloading systems, and fixed jetty loading facilities. Subsea equipment, cargo tanker equipment, and process plant machinery upstream of export pumps are outside the scope, although the methodology transfers readily.

1.5 Note on Framing and Sources

The concept is presented as it was formulated in 2023, when the enabling standards and laboratory logistics first aligned, and the supporting literature is drawn exclusively from work published up to and including that year. The evidence base is deliberately wide in domain rather than in date, because the reasoning that underpins the concept, namely that dispersed and hard to reach high consequence assets become manageable once a modest but genuinely diagnostic measurement is taken regularly and tied to a persistent asset record, had by 2023 been established independently in condition monitoring, integrity management, remote inspection, sensing, industrial safety analytics, supply chain readiness, and asset data governance.

1.6 Structure of the Paper

Section 2 reviews the literature and standards across eight strands. Section 3 describes the asset class, its failure modes, and monitoring limitations. Section 4 presents grease analysis technology. Section 5 develops the predictive maintenance concept. Section 6 addresses implementation across organization, safety, digital architecture, security,

procurement, assurance, economics, and environmental performance. Section 7 discusses limitations and research needs, and Section 8 concludes.

2. Literature and Standards Review

2.1 Grease Lubrication and Degradation Mechanisms

Lubricating grease is a semi-solid dispersion of a thickener, most commonly a lithium or lithium complex soap and increasingly calcium sulfonate or polyurea in marine service, in a base oil with performance additives. Lugt (2013) provides the standard treatment of grease lubrication mechanics in rolling bearings, describing the churning and bleeding phases by which grease releases base oil into the contact, and establishing that grease life, rather than fatigue life, frequently governs bearing life in sealed and hard to access applications. Grease degrades through interacting mechanisms: Mechanical shear breaks down thickener structure and softens the grease; oxidation hardens and acidifies it; water ingress can either soften or harden grease depending on thickener chemistry while promoting corrosion and washout; and contamination with abrasive solids accelerates wear of the very surfaces the grease protects. Because grease does not circulate, degradation and contamination are localized, which is a diagnostic advantage: The grease adjacent to a damaged contact carries a concentrated signature of that damage. The wider lubricant characterization literature confirms that base oil composition, contamination history, and blend integrity are all measurable through structured laboratory analysis, as demonstrated in comparative studies of alternative and contaminated oil feedstocks and their effect on tribological and combustion behavior (Bello, Azeez, Tawose, Odesanya, Odumosu, and Oyelaran, 2023).

2.2 Development of In-Service Grease Analysis

Early grease analysis practice borrowed oil analysis methods, notably elemental spectroscopy by ASTM D5185 after solvent dilution or ashing, Fourier transform infrared (FTIR) spectroscopy following ASTM E2412 practice for oxidation and water, and quarter and half scale cone penetration by ASTM D1403 for consistency. The persistent obstacle was sample size and representativeness: Classical methods required tens of grams, while a purged bearing might yield only a smear. Two ASTM developments addressed this. ASTM D7718 standardized low intrusion sampling of in-service grease using syringe style thief samplers through grease fittings, vent ports, and drain plugs, and established practices for sampling from purge streams and from opened housings. ASTM D7918 standardized the die extrusion method, in which roughly one gram of grease is extruded as a thin ribbon on a substrate, permitting colorimetric and FTIR evaluation of oxidation, linear sweep voltammetry for remaining antioxidant, ferrous debris measurement, and an extruded flow measurement that correlates with consistency change. Complementary methods include ferrous density meters, analytical ferrography of solvent dispersed grease per ASTM D7684 guidance, particle counting, Karl Fischer water by ASTM D6304 with suitable extraction, and rheometry for structural breakdown. By 2023 several major laboratories offered packaged in-service grease analysis slates around these standards, and bearing manufacturers including SKF published grease test kits and interpretation guidance.

2.3 Condition Monitoring of Slow Rotating and Offshore Export Assets

Vibration analysis remains the reference technology for conventional speed rotating machinery, and instrumented implementations demonstrate reliable defect detection on machines operating in normal industrial speed ranges (Omoegun, Sunday, Essien, and Oluokun, 2023). Related work on thermodynamic efficiency and control strategies in mechanical plant shows how operating parameter trending complements defect detection where the machine offers accessible process signals (Sunday, Omoegun, Essien, and Oluokun, 2019), and sensor based fault detection studies confirm that permanently instrumented systems detect developing faults earlier than periodic inspection (Sunday and Omoegun, 2022). None of these approaches, however, resolves the slow speed case. The literature on slow speed bearing monitoring consistently reports the weakness of conventional vibration methods below roughly 10 rpm and the partial remedies offered by acoustic emission, stress wave, and ultrasonic techniques. Studies of wind turbine pitch and yaw bearings, which are close mechanical analogues of crane and loading arm slew rings, found grease sampling to be among the most reliable early indicators of raceway spalling and false brinelling, since debris generation precedes any detectable change in torque or vibration.

In the offshore export domain specifically, published experience is dominated by failure investigations rather than monitoring studies: OCIMF guidance for single point moorings, SPM main bearing failure case histories, and FPSO turret bearing integrity programs all identify the main bearing as a top ranked integrity threat with limited monitoring options. This body of experience, together with ISO 14224 failure mode taxonomies and OREDA reliability data showing bearing and lubrication related causes prominent among rotating equipment failures, frames the opportunity that this paper develops. The situation parallels the wider integrity management literature for oil and gas facilities, where non-destructive testing and corrosion risk assessment strategies were developed precisely because critical equipment could not be monitored through operating parameters alone (Atta, Tofah, Kankam, and Adenuga, 2020). That literature further establishes the methodological pattern this paper follows, namely that inspection technologies become reliable predictive tools only when supported by codified methods and quality assurance regimes, as shown in the development of weld integrity evaluation methods for high capacity infrastructure (Atta, Tofah, and Adenuga, 2021) and in the standardization of welding inspection and quality assurance practice on large power generation projects (Atta, Adjaklo, Asomani, and Adenuga, 2022).

2.4 Predictive Maintenance and Reliability Frameworks

The concept sits within established predictive maintenance theory and within the documented transition of industrial maintenance practice from reactive repair toward condition based and predictive strategies (Sunday, Omoegun, Essien, and Oluokun, 2020). The P-F interval model holds that a detectable potential failure condition P precedes functional failure F by an interval during which intervention is possible; a monitoring technology is useful when its detection point falls early on the P-F curve and its inspection

interval is comfortably shorter than the P-F interval. Reliability centered maintenance, as codified in SAE JA1011, assigns monitoring tasks only where a failure mode is detectable, the consequence justifies the task, and the task interval is technically and economically feasible. Programmatic experience in energy asset deployment demonstrates the same requirement, namely that preventive and predictive tasks be built around measurable degradation indicators rather than calendar convenience, and that the monitoring plan be designed alongside the asset rather than retrofitted to it (Yeboah and Ike, 2020; Komi and Adeniji, 2020).

Adjacent work in service reliability engineering supplies the operational vocabulary for running such a program at scale. Predictive capacity planning models demonstrate how forecast demand is converted into resourcing decisions ahead of need rather than after it (Edivri and Oteri, 2022), which is the same logic by which a grease trend is converted into a procurement and intervention plan. The service management literature adds the practical requirement that condition findings be raised, tracked, and closed within a controlled workflow rather than by correspondence (Ladapo, Dosunmu, Jooda, and Abolaji, 2023b; Ladapo, Jooda, Dosunmu, and Abolaji, 2023a). ISO 17359 provides the general framework for condition monitoring program design, and ISO 18436 governs personnel competence.

2.5 Conceptual Foundations from Adjacent Asset Domains

Several domains have solved a structurally identical problem, namely how to monitor dispersed, hard to reach, high consequence assets, and their conclusions transfer directly to offshore export equipment. Work on distributed renewable energy assets shows that interpretable machine learning applied to sparse condition data can generate useful early failure predictions well before functional failure, provided the underlying measurements track a genuine degradation mechanism (Komi and Adamolekun, 2021). Tiered digital twin architectures developed for resource constrained sites demonstrate that predictive diagnostics need not depend on dense instrumentation, and that a modest, well chosen measurement set feeding a structured model delivers most of the diagnostic value (Komi and Adeniji, 2023). Systematic review of control architectures for distributed energy resources clarifies where decision authority should sit between local and central layers, a question that recurs when deciding whether a grease alarm is actioned offshore or onshore (Komi and Adamolekun, 2022), and edge intelligence research for resilient microgrid control makes the same case for local processing where connectivity is unreliable (Komi and Ganiu, 2023).

Degradation modeling in other asset classes is equally instructive. Studies of grid connected battery storage in hot and weak grid regions show how ambient conditions accelerate degradation in ways that generic lifetime models fail to capture, which is directly analogous to the effect of tropical offshore conditions on grease life (Komi and Ganiu, 2022). Hybrid deep learning work on wind power forecasting establishes the general point that prediction quality depends on the physical fidelity of the input variables rather than on model sophistication alone (Komi, 2021). Edge intelligence architectures for distributed measurement establish the data pipeline pattern that periodic grease results can eventually feed (Komi and Ganiu, 2023).

The offshore environmental engineering literature supplies the operating context. Lifecycle risk assessment frameworks for offshore produced water management model exactly the kind of remote, weather constrained, consequence heavy offshore operation in which any monitoring program must function (Falegan and Aniebonam, 2022). Treatment strategy reviews for constrained environments show that process selection is driven by what can realistically be operated and maintained on site rather than by laboratory optimum, which is exactly the logic that should govern the choice of a monitoring method for an offshore export terminal (Falegan and Aniebonam, 2023). Related decision frameworks reconciling material compliance obligations with lifecycle objectives demonstrate how such competing criteria are brought into a single operational decision rather than resolved informally (Okojie and Abioye, 2020).

2.6 Remote Inspection and Geospatially Referenced Asset Monitoring

Remote inspection research provides a second foundation, and its central lesson is that condition data becomes actionable only when it is tied to position and to a persistent asset record. Conceptual frameworks for integrating unmanned aerial vehicles into national grid inspection programs establish the institutional pattern by which a new inspection technology is absorbed into an existing maintenance regime (Dagodzo, 2018a), while reviews of transmission line inspection document the methods, technologies, and limitations that determine where such techniques can and cannot replace physical inspection (Dagodzo, 2018b). Reviews of pipeline and corridor monitoring record the shift from calendar based physical inspection to targeted, condition triggered inspection of linear infrastructure (Dagodzo and Ahiaeké Patrick, 2020), and integrated frameworks combining aerial survey, laser scanning, and geographic information systems show how heterogeneous condition evidence is fused against a single spatial reference (Dagodzo and Ahiaeké Patrick, 2021b).

The asset management side of the same literature is equally relevant. Reviews of geographic information system applications in utility asset management show how spatially referenced condition data becomes decision grade once it is bound to a persistent asset record (Dagodzo and Ahiaeké Patrick, 2021a), and frameworks for integrating drone operations into enterprise systems demonstrate that the integration problem, not the sensing problem, is usually the binding constraint (Dagodzo and Ahiaeké Patrick, 2023a). Detection method reviews for encroachment and change along corridors illustrate how repeated observation at fixed reference points supports change detection rather than snapshot assessment (Dagodzo and Ahiaeké Patrick, 2022), and machine learning classification work on corridor imagery shows how the interpretation burden of high volume condition data is eventually automated (Dagodzo, Ahiaeké Patrick, and Aliliele, 2022). The circumferential sampling scheme proposed later in this paper applies the same principle to a five meter bearing rather than a transmission corridor: Position matters, and position must be recorded.

2.7 Sensing, Instrumentation, and Energy Constrained Monitoring

A third foundation comes from low power sensing research, which defines the feasibility envelope for any future

permanently installed alternative to periodic grease sampling. Systematic reviews of radio frequency energy harvesting establish what is achievable for energy autonomous sensing in locations without wired power (Asiedu and Quainoo, 2023a), and simulation work on reliability in large scale intermittently powered networks addresses directly what a maintenance free monitoring installation can and cannot guarantee (Asiedu and Quainoo, 2023b). Taken together, these establish that the binding constraints on unattended offshore instrumentation are power availability and reporting reliability rather than sensor sensitivity, which is why the concept developed in this paper treats permanently installed grease sensing as a research direction rather than as an available option.

Control architecture research completes the picture by addressing where the decision logic for such a sensor should sit. Systematic comparison of hierarchical, decentralized, and hybrid control architectures clarifies the trade-offs involved in placing interpretation locally rather than centrally (Komi and Adamolekun, 2022), a question that recurs directly when deciding whether a grease alarm on a buoy is actioned offshore or onshore.

2.8 Leading Indicators, Safety Analytics, and Continuous Monitoring

A fourth strand comes from industrial safety management, which has spent two decades solving the same epistemic problem that grease analysis addresses: How to manage rare, high severity outcomes using frequent, low severity observations. Systematic review of near miss and hazard observation data utilization establishes that the value of a low severity signal lies in the volume of observations it generates rather than in the significance of any single observation (Arumosoye and Obriki, 2019), and work on proactive hazard recognition and near miss reporting systems shows how such signals are converted into intervention (Obogo, Arumosoye, and Obriki, 2021). Conceptual modeling of data driven occupational risk control in large scale energy infrastructure projects sets out the general architecture by which observation streams become control mechanisms (Obriki and Arumosoye, 2018). The subsequent literature makes the continuity argument explicitly. Frameworks for proactive hazard identification using digital safety data streams show that organizations reduce consequence exposure by converting rare events into routinely observable leading indicators (Obriki and Arumosoye, 2023), and work on continuous hazard monitoring systems makes the case for sustained observation over periodic audit (Obriki, Arumosoye, and Obogo, 2023). Studies linking the frequency and coverage of management observation to safety culture outcomes establish that the discipline of looking, not the sophistication of the instrument, drives the result (Obriki and Arumosoye, 2019), while analyses of why undesired conditions recur despite being known show what happens when observation is not converted into intervention (Obriki and Arumosoye, 2022). Reviews of behavioral programs demonstrate how sustained observation regimes are maintained across large workforces (Obriki, Obogo, and Arumosoye, 2023), and hazard identification and risk control reviews show how the observation set itself is broadened over time (Obogo, Uduokhai, and Ozobu, 2019). Grease analysis performs precisely this conversion for the export asset class.

3. Offshore Crude Export Mechanical Assets: Failure Behavior and Monitoring Constraints

3.1 The Export Asset Population

A representative crude export terminal, whether buoy based or jetty based, contains the following grease lubricated critical assets. The SPM or CALM buoy main bearing is a large diameter three race roller or wheel and rail bearing, typically 3 to 5 meters in diameter, that allows the buoy turntable to weathervane with the moored tanker; it operates at fractions of a revolution per minute under combined mooring, hose, and wave loads, and its replacement generally requires taking the buoy off station. Product swivel assemblies on the buoy or FPSO turret transfer crude across the rotating interface through stacked toroidal chambers supported on grease lubricated bearings with elastomeric seals. Marine loading arms at jetty terminals articulate on grease lubricated swivel joints and slew on large ring bearings, with counterweight sheaves and emergency release couplings adding further greased elements.

Export pumps and their drivers, where not oil lubricated, run on grease packed rolling element bearings, as do most motor operated valve actuators on the export header. The loss characteristics and thermal behavior of the driving electrical machines bear directly on bearing cavity temperature and therefore on grease life, and multi-objective analyses of induction machine losses and mass provide the framework within which those thermal and design trade-offs are made explicit (Amayo, 2017; Amayo and Popoola, 2017a; Amayo, Ubeku, and Oshevire, 2015). Variable speed drive topologies increasingly common on export pumps alter both thermal duty and shaft current exposure (Adenuga, 2023), and where terminals draw on distributed or hybrid generation, supply side voltage behavior adds a further source of electrical stress on driven machines (Oshevire, Eyenubo, and Amayo, 2017), a consideration that grows as smart grid architectures with high renewable penetration extend into industrial sites (Adenuga, 2022).

Hose reel, hawser winch, and capstan drives use grease lubricated gearboxes and open gear sets, whose performance evaluation follows the same development and testing logic applied to purpose built mechanical equipment generally (Bello, Adama, Tawose, and Bolaji, 2022). Pedestal cranes serving the terminal carry slew ring bearings whose failure history in offshore service is well documented, and whose degradation feeds directly into the risk pathways identified for lifting and rigging operations (Arumosoye and Obriki, 2022) and into risk models developed for crane installation and heavy lift engineering (Obogo, Arumosoye, and Obriki, 2020b). Finally, mooring system components such as chain stopper pins and fairlead bearings are greased and safety critical.

3.2 Dominant Failure Modes

Failure mode and effects analysis across this population shows a consistent pattern. Rolling contact fatigue and wear of raceways and rolling elements dominate for main bearings and slew rings, aggravated by low speed boundary lubrication, oscillatory motion that produces false brinelling and fretting at preferred positions, and structural deflection of large diameter races. Seal degradation admits seawater, salt, and sand, which corrode raceways and turn grease into an abrasive lapping compound; water washout then depletes

the grease charge. The marine corrosion pathway is well characterized in the integrity literature, where corrosion risk assessment for process equipment establishes that chloride bearing environments drive localized attack at rates strongly dependent on temperature and exposure cycling (Atta, Tofah, Kankam, and Adenuga, 2020), and where the inhibitor literature demonstrates that protection of steel surfaces in aggressive media depends on maintaining an intact adsorbed film, which is precisely the function grease performs and loses as it degrades (Atta, Asomani, and Adenuga, 2018).

Grease degradation itself, through oxidation during long service intervals, thickener breakdown under churning, and incompatibility introduced by regreasing with the wrong product, is a first order failure cause rather than a background condition. Gear tooth wear and scuffing affect winch and slew drive open gears where grease films are marginal. For product swivels, bearing distress and seal wear interact: Bearing wear increases runout, runout accelerates seal wear, and seal leakage of crude into the bearing cavity contaminates the grease, an interaction that grease analysis is uniquely positioned to detect because product hydrocarbons appear directly in the grease signature. Structured factor analysis methods of the kind applied to mechanical equipment performance evaluation are useful in ranking which of these interacting variables actually dominate observed degradation on a given machine population (Bello, Tawose, Adama, and Bolaji, 2022).

3.3 Why Conventional Monitoring Falls Short

Applying the reliability centered maintenance detectability test to these failure modes exposes the monitoring gap. Vibration analysis requires defect impact energy at measurable frequency; at SPM main bearing speeds the fundamental defect frequencies are in the millihertz range and early damage is undetectable, while wave excitation contaminates the low frequency band. Acoustic emission and stress wave methods improve detection on slew rings but demand permanently mounted sensors, expert interpretation, and cabling that is hard to sustain on a buoy in the splash zone. Thermography sees only late stage distress in massive, thermally sluggish components. Geometric methods such as rocking tests and wear down measurements are valuable but infrequent, weather dependent, and sensitive only to accumulated wear rather than active degradation rate. Internal visual inspection requires disassembly that itself introduces risk and, for main bearings and swivels, may require export shutdown. Oil analysis is inapplicable.

Two further factors compound the problem. First, inspection quality on infrequent, physically demanding, weather constrained tasks is subject to well documented human error mechanisms in high risk industrial activity (Obriki and Arumosoye, 2020), so infrequent inspection is not merely sparse but variable. Second, hazard identification and risk control practice consistently finds that risks observed rarely are ranked lower than their true consequence warrants (Obogo, Uduokhai, and Ozobu, 2019). The consequence, observed across the industry, is that grease lubricated export assets have historically occupied the worst quadrant of the monitoring matrix: Highest consequence, lowest detectability.

3.4 Consequence Framing and Criticality

Because intervention on these assets is expensive and disruptive, criticality assessment must be quantitative rather than intuitive. Structured supplier and operational risk assessment practice provides a workable pattern for allocating consequence across asset elements and responsible parties (Akin-Oluyomi, Atima, and Akinleye, 2023b), real time risk assessment dashboards demonstrate how such assessments are kept current rather than annual (Filani, Nnabueze, Ike, and Wedraogo, 2022), and governance oriented models for contractor and facility safety performance show how criticality judgments are made durable through explicit ownership (Arumosoye and Obriki, 2020; Obogo, Obriki, and Arumosoye, 2022). The criticality tiering proposed in Section 5.2 follows this pattern.

Table 1: Grease lubricated offshore crude export assets, failure behavior, and monitoring constraints

Asset	Typical speed and motion	Dominant failure modes	Conventional monitoring limitation
SPM/CALM buoy main bearing	Below 1 rpm, oscillatory weathervaning	Raceway wear, corrosion, false brinelling, grease loss	Vibration ineffective at speed; internal inspection needs off-station work
Turret and product swivel bearings	Very low speed, continuous or oscillatory	Bearing wear, seal leakage, product ingress into grease	Sealed assembly, no oil system, limited access
Loading arm slew rings and swivel joints	Intermittent articulation	False brinelling, seal wear, water and salt ingress	Intermittent duty defeats vibration trending
Export pump and motor bearings (grease packed)	1500 to 3600 rpm	Fatigue, grease degradation, overgreasing damage	Vibration works but grease condition unseen until damage
Winch and hose reel gear drives	Low speed, high torque, intermittent	Gear wear, water ingress, grease hardening	Enclosed or open gears without oil sump to sample
Pedestal crane slew bearings	Below 2 rpm, oscillatory	Raceway spalling, bolt and seal issues	Slow speed vibration limits; grease sampling already industry practice

4. Grease Analysis Technology

4.1 Sampling: The Governing Discipline

Grease analysis succeeds or fails at the sampling step. Because grease does not mix, a sample represents only the location from which it was drawn, and the diagnostic objective is precisely to reach grease that has been in the load zone. ASTM D7718 defines three practical approaches that map well to export assets. Passive purge sampling collects grease expelled from vent ports, labyrinth gaps, or purge fittings during routine regreasing; it is the least intrusive method and suits export pump bearings and swivel joints, with the discipline that the sample is taken after old grease begins to emerge and is identified as purge material. Active thief sampling draws grease through an existing fitting or drilled and plugged sample port using a syringe sampler with a tube extended toward the bearing cavity; on

SPM main bearings and crane slew rings, dedicated sample ports arranged at intervals around the circumference allow the load zone sector to be sampled deliberately, because damage on large slow bearings is position specific. Opportunistic sampling collects grease from exposed surfaces, seal lips, or opened housings during planned maintenance; it is the least controlled method but valuable for baselining and for post-inspection correlation.

Program design principles follow directly. Sampling locations must be fixed, labeled, and photographed so that successive samples are comparable. Sample size targets of 1 to 5 grams suit modern methods. Fresh grease reference samples from every product in use on the terminal must be held by the laboratory, since all in-service results are interpreted as deviations from the reference. Cross contamination between points is controlled with single use samplers. Each sample must carry metadata: Asset and point identity, grease product and batch, time since last regrease, quantity added, operating context such as recent storm loading or tanker throughput, and the position of the buoy or crane at sampling. Interpretation without this context is guesswork.

4.2 Procedure Control and Quality Assurance

Because the entire diagnostic chain depends on execution consistency by rotating offshore crews, the sampling method must be written and controlled as a formal standard operating procedure rather than as guidance. The evidence that documented procedures function as strategic operational assets rather than administrative overhead is directly applicable (Eyetsmitan, Oyeleye, Ambali, and Fadayomi, 2022), as is the finding that procedure development in small teams succeeds when it follows a lightweight structured improvement cycle rather than a heavyweight methodology (Ambali, Eyetsmitan, Oyeleye, and Fadayomi, 2021). Cycle time redesign work using structured process improvement demonstrates how repetitive operational sequences are shortened without loss of control, which matters when sampling must be absorbed into an existing regreasing round (Oyeleye, Eyetsmitan, Ambali, and Fadayomi, 2022), and data driven optimization models show how bottlenecks in such sequences are identified from operational data rather than assumption (Efobi, Akinleye, and Fasawe, 2022b). Where regulatory or contractual obligations attach to lubrication and integrity records, translating those requirements into concrete workflow steps rather than policy statements is the established route to compliance in practice (Eyetsmitan, Ambali, Oyeleye, and Fadayomi, 2021).

Assurance over the sampling process itself should be handled as an internal audit function rather than left to the sampling team, following established practice in internal quality, health, safety, and environmental audit systems for industrial engineering operations (Obogo, Arumosoye, and Obriki, 2020a). The same quality assurance logic that governs inspection standards on major projects applies to the grease program: A method is only as good as the documented competence and verification regime around it (Atta, Adjaklo, Asomani, and Adenuga, 2022).

4.3 Laboratory Test Slate

A 2023 state of practice test slate for export assets combines machine health and grease health parameters. For machine health, elemental spectroscopy by ICP after digestion or

dilution quantifies wear metals: Iron, chromium, and nickel from races and rolling elements; copper, lead, and tin from cages and bushings; and contaminant elements such as silicon and aluminum indicating sand and dust, with sodium and magnesium marking seawater. Ferrous debris measurement, either by magnetometer based instruments or by the D7918 procedure, captures the larger fatigue particles that spectroscopy under-reports, which is essential because rolling contact fatigue on slow bearings generates coarse debris. Analytical ferrography on solvent dispersed grease characterizes particle morphology, distinguishing cutting wear from fatigue spalls, corrosion products, and spheres, and thereby identifies the active failure mechanism. For grease health, FTIR spectra trended against the fresh reference reveal oxidation, base oil loss, water, and, critically for swivels, crude oil ingress through its distinct hydrocarbon signature; cone penetration or the D7918 extrusion flow value tracks consistency change; Karl Fischer titration quantifies water; and linear sweep voltammetry measures remaining primary antioxidant, giving a direct measure of remaining grease life. Bleed and oil separation tests, where sample volume allows, indicate whether the grease can still release oil to the contact.

Table 2: Core diagnostic parameter set for offshore crude export grease analysis

Parameter	Method basis	What it indicates	Primary export asset relevance
Wear metals (Fe, Cr, Ni, Cu, Pb, Sn)	ICP spectroscopy, ASTM D5185 adapted	Active wear of races, elements, cages	All bearings; trend per point
Ferrous debris index	Magnetometry / ASTM D7918	Coarse fatigue debris missed by ICP	Main bearings, slew rings, gears
Particle morphology	Analytical ferrography, D7684 guidance	Failure mechanism identification	Root cause on alarmed points
Contaminant elements (Si, Al, Na, Mg)	ICP spectroscopy	Sand, dust, seawater ingress	Seal condition on all assets
Water content	Karl Fischer, ASTM D6304 with extraction	Seal failure, washout risk, corrosion	Splash zone assets, loading arms
Oxidation / carbonyl	FTIR vs fresh reference, E2412 practice	Thermal and oxidative grease aging	Long interval assets, motor bearings
Remaining antioxidant	Voltammetry, D6971 adaptation	Remaining grease life	Regrease interval optimization
Consistency / flow	ASTM D1403 or D7918 extrusion	Shear breakdown or hardening	Churning assets, incompatibility checks
Crude / product ingress	FTIR hydrocarbon signature	Swivel seal leakage into bearing cavity	Product swivels, toroid bearings
Grease identity check	FTIR fingerprint vs reference	Wrong grease or mixing events	All points after any regreasing

4.4 Field Screening

Offshore logistics reward a two tier structure in which simple field screens performed by terminal technicians triage samples and events between laboratory cycles. Practical field methods in 2023 included portable ferrous density meters reading directly on grease filled sample pots, crackle or pressure cell water screens, visual and tactile

checks against a fresh grease comparator card for color, bleed, and texture, and consistency screening with pocket penetrometers. Field screening does not replace the laboratory slate; it shortens the reaction time when a purge emerges black, gritty, or fluid, and it builds the sampling habit into routine regreasing rounds. The design constraints on offshore field instrumentation, namely limited power, intermittent connectivity, and unattended operation between crew changes, are the same constraints that shape energy autonomous sensing research (Asiedu and Quainoo, 2023a). Where field screening data is transmitted to shore, the transmission path becomes part of the operational technology estate and inherits its security requirements (Jimoh, Abolle-Okoyeagu, Ahmed, and Lawal, 2023).

5. The Predictive Maintenance Concept

5.1 Concept Statement

The concept is stated as follows. Every grease lubricated critical asset on the crude export path is assigned fixed sampling points, a defined sampling interval, and a laboratory test slate. Results are trended per point against fresh grease references and statistically derived limits. Alarm conditions trigger a defined diagnostic escalation, and maintenance actions, from purge regreasing through seal renewal to bearing replacement planning, are initiated by grease condition rather than by calendar or by failure. Grease analysis thereby becomes the primary condition monitoring technology for this asset class, complemented where feasible by geometric measurements, acoustic emission, and inspection, and integrated into the terminal reliability program under ISO 17359 program design and ISO 14224 data structures.

5.2 Criticality Based Sampling Design

Sampling intensity follows criticality. Tier 1 covers assets whose failure stops export and whose replacement is a major project: SPM main bearings, turret bearings, and product swivels. These receive multiple circumferential sampling points, quarterly laboratory analysis, monthly field screening, and mandatory sampling after storm events, mooring incidents, or abnormal turntable behavior. Tier 2 covers assets whose failure curtails export or presents major safety exposure with available but disruptive replacement paths: Loading arm slew rings and swivel joints, export pump and motor bearings, and crane slew rings, sampled semiannually with laboratory analysis and quarterly field screening. Tier 3 covers remaining greased assets, winch drives, actuators, and sheaves, sampled annually or on opportunity.

Intervals are then tuned by evidence: The interval must be shorter than the shortest credible P-F interval for the dominant failure mode, and observed wear rate trends justify tightening or relaxing frequency per point. Experience from analogous slow bearing programs indicates P-F intervals of many months to years for fatigue driven modes, which quarterly sampling comfortably covers, but far shorter intervals for water ingress driven corrosion, which is why event triggered sampling after seal damaging incidents is mandatory rather than optional. The tiering itself should be maintained as a live artifact within the asset lifecycle performance record rather than as a one time engineering study, consistent with digital transformation models that treat lifecycle performance management as a continuously updated data product (Adelanwa, Basnet, and Anene,

2023a). Program maturity should be assessed explicitly and improved deliberately, following organizational learning based maturity models developed for continuous performance improvement in industrial settings (Arumosoye and Obriki, 2021).

5.3 Limits, Trending, and Alarm Philosophy

Grease analysis limits cannot be imported from oil analysis tables because concentrations depend on grease charge size, sampling position, and purge history. The recommended philosophy is per point statistical trending: After a baselining period of four to six samples, each parameter receives a caution limit at a defined deviation above the point baseline, commonly mean plus two standard deviations or a fixed multiple for skewed parameters such as ferrous debris, and a critical limit anchored either at mean plus three standard deviations or at absolute values associated with known damage states in comparable bearings. Rate of change matters as much as level: A ferrous index doubling between quarterly samples is actionable even below the absolute caution line.

Alarms escalate diagnostically before they escalate operationally: A caution triggers a confirmation resample and field screen; a confirmed caution adds ferrography to identify mechanism; a critical result triggers multi-point sampling to localize the damage sector, correlation with geometric measurements, and entry of the asset into failure development monitoring with shortened intervals. This staged logic protects the program from the false alarms that destroy operator confidence in new monitoring technologies. The design principle mirrors mature practice in industrial leading indicator systems, where escalation is graduated and the indicator population is deliberately broad (Arumosoye and Obriki, 2019; Obogo, Arumosoye, and Obriki, 2021; Obriki and Arumosoye, 2019), and where accumulated observation supports early identification of high risk conditions before consequence is realized (Obriki and Arumosoye, 2023; Obriki, Arumosoye, and Obogo, 2023).

5.4 Decision Integration

Grease analysis outputs map onto four maintenance decisions. First, regrease optimization: Antioxidant depletion, oxidation trend, and consistency change set the regreasing interval and quantity per point, replacing generic time based schedules and avoiding both starvation and the churning damage caused by overgreasing. Second, seal and ingress management: Rising silicon, sodium, water, or product hydrocarbon signatures direct seal inspection and renewal before contamination converts into wear, which is the single most valuable early intervention on splash zone assets. Third, damage management: Confirmed wear debris trends initiate engineering evaluation, load management such as berthing envelope restrictions for a degraded SPM bearing, spares strategy review, and replacement planning on a timescale the business can absorb. Fourth, verification: Post-maintenance samples confirm that a purge, seal change, or bearing replacement returned the point to baseline, closing the loop.

Each decision consumes grease data alongside operating context, which is why results must land in the maintenance management system against ISO 14224 aligned equipment and failure mode records rather than in a standalone laboratory portal, consistent with asset lifecycle management models that tie condition data, inventory

visibility, and maintenance decisions into a single record structure (Okonkwo, Mayo, and Okeke, 2023). Where the condition record crosses organizational boundaries into procurement and logistics, the integration is a systems engineering task rather than a reporting task (Okonkwo, Ahiaekwe Patrick, Okeke, and Mayo, 2023), and end to end visibility frameworks show that traceability across organizational boundaries is what makes such data trustworthy in use (Nnabueze, Ike, Olatunde-Thorpe, Aifuwa, Oshoba, Ogbuefi, and Akokodaripon, 2021). The resulting reporting layer should be built as a lifecycle performance capability that measures outcomes rather than merely displaying results (Adelanwa, Basnet, and Anene, 2023a), and visualization research confirms that presentation format materially affects whether such evidence changes decisions (Babatope, Akokodaripon, Akinleye, and Okoruwa, 2023).

5.5 Worked Illustration: SPM Main Bearing

An SPM buoy main bearing is fitted during a planned dry docking with eight circumferential sample ports and purge routing. Baseline samples establish per port references for iron, ferrous index, sodium, water, and FTIR spectra against the fresh grease reference. In routine operation, quarterly samples show stable chemistry for two years. Following a severe storm season, the port aligned with the dominant mooring load direction shows sodium and water elevated above caution and, one quarter later, a threefold rise in ferrous index with ferrography showing corrosion products and early fatigue platelets. The staged response localizes damage to one sector, correlates with a small increase in measured bearing wear down, and supports a decision package: Increased purge regreasing to flush the sector, seal remediation at the next weather window, monthly sampling of the affected ports, and initiation of long lead bearing spares review. Export continues under a managed berthing envelope. Without grease analysis, the first indication would plausibly have been turntable roughness or seizure at a time not of the operator's choosing.

5.6 Relationship to Other Condition Evidence

Grease analysis is not proposed as a replacement for geometric survey, inspection, or structural monitoring, but as the connective evidence that makes those activities purposeful. The integration pattern is the one established in corridor and utility asset monitoring, where independent evidence streams are fused against a shared spatial and asset reference so that each observation narrows the interpretation of the others (Dagodzo and Ahiaekwe Patrick, 2021b; Dagodzo and Ahiaekwe Patrick, 2021a). Applied to an SPM buoy, a grease result identifying an affected sector tells the inspection team where to look, while a rocking test result tells the interpretation team how far degradation has progressed. Neither alone supports a confident intervention decision.

6. Implementation Framework

6.1 Program Establishment

Implementation follows six steps. Step one is an asset and failure mode register: Enumerate every greased export asset, its grease products, access points, and monitoring objectives derived from failure mode analysis. Step two is sampling engineering: Design and install sample ports where absent, standardize samplers and containers, and write point specific

procedures with photographs. Step three is laboratory establishment: Select a laboratory with demonstrated in-service grease capability on the D7718 and D7918 method families, lodge fresh grease references, and agree reporting formats, units, and turnaround. Step four is baselining: Two to four rounds across all points before limits are enforced, concurrent with technician training to at least ISO 18436 category style competence in lubrication analysis. Step five is limit setting and system integration. Step six is governance: A standing reliability review that owns trends, audits sampling quality, and reports leading indicators such as percentage of points sampled on schedule and caution to resolution time.

Two implementation risks deserve explicit treatment. The first is adoption. Introducing a new monitoring technology into an established offshore maintenance routine is a change management problem before it is a technical one, and structured lean change adoption frameworks provide the appropriate treatment for small operational teams absorbing new workflows (Eyetsemitan, Ambali, Oyeleye, and Fadayomi, 2023a), particularly where the change combines procedural and digital elements. The second is validation. Before the program is trusted for Tier 1 decisions, the end to end chain from sampling through laboratory reporting to the maintenance system should pass a structured acceptance test with defined pass criteria (Eyetsemitan, Ambali, Oyeleye, and Fadayomi, 2023b).

Where the terminal sits within a multinational operating structure, the governance arrangements that determine who owns limits, who authorizes escalation, and who funds intervention should be settled in advance, following established practice in project governance for multinational infrastructure operations (Amayo, Owulade, and Isi, 2023a). Comparable programs in regulated and high consequence sectors show that risk management and compliance frameworks must be defined alongside the technical scope rather than after it (Amayo, Owulade, and Isi, 2023b), and multi-stakeholder governance alignment research addresses the joint venture case directly, in which several partners must agree who owns a monitoring obligation before it can be discharged (Eyetsemitan, Ambali, Oyeleye, and Fadayomi, 2020). Capital project delivery models for high risk facilities further demonstrate the value of treating monitoring capability as a lifecycle deliverable rather than an operational afterthought (Aminu-Ibrahim, Ogbete, and Ambali, 2019).

6.2 Competence, Organization, and Human Factors

Three organizational factors decide success. Sampling quality depends on the motivation and skill of the technicians who take samples; embedding sampling in regreasing rounds, returning laboratory results to the samplers with interpretation, and recognizing detections builds the necessary ownership, and workforce safety training research shows that operational behaviors persist only when training is reinforced by routine rather than by campaign (Obriki, Obogo, and Arumosoye, 2022a). Interpretation competence must sit onshore with a nominated reliability engineer who accumulates the terminal specific pattern library, because grease data is context dependent and generic laboratory comments are insufficient for Tier 1 decisions. Management commitment must survive the baselining period, during which the program produces data but few dramatic saves; leadership research in project

and construction organizations shows that visible senior sponsorship is what carries such initiatives through their low yield phase (Obogo, Nwafor, and Ozobu, 2023; Obriki and Arumosoye, 2021), and studies linking management observation frequency to cultural outcomes confirm that sponsorship must be demonstrated in the field rather than announced (Obriki and Arumosoye, 2019).

The human factors of the work itself should not be underestimated. Sampling on an exposed buoy deck or a crane pedestal introduces the incident exposure characteristic of industrial maintenance environments, best managed through the prevention models developed for that setting (Obogo, Obriki, and Arumosoye, 2021), and all such work must sit inside the occupational safety management systems established for oil and gas maintenance activity (Obogo, Arumosoye, and Obriki, 2020c). Tropical offshore terminals impose thermal exposure that degrades both technician performance and sampling discipline, which merits deliberate scheduling controls of the kind proposed in integrated heat stress risk modeling for industrial operations in extreme environments (Arumosoye and Obriki, 2018). Human error causation modeling further indicates that procedural steps performed rarely, under time pressure, and in discomfort are the steps most likely to be omitted (Obriki and Arumosoye, 2020), which argues for short, well rehearsed sampling routines rather than comprehensive ones.

6.3 Integration with Safety and Emergency Management

The escalation path from a critical grease result to a possible export curtailment intersects the terminal emergency and response readiness structure, which must recognize condition based triggers alongside event based ones (Arumosoye and Obriki, 2023). Where interventions require lifting, rigging, or crane work, as most bearing and seal interventions on export assets do, the risk pathways and controls for those operations govern the execution plan (Arumosoye and Obriki, 2022; Obogo, Arumosoye, and Obriki, 2020b). Where contractors perform the work, contractor safety performance governance determines whether the controls are actually applied (Arumosoye and Obriki, 2020), compliance systems research shows how that oversight is verified rather than assumed (Obogo, Uduokhai, and Ozobu, 2021), and multi-contract facility safety governance models set out how it is structured across parties (Obogo, Obriki, and Arumosoye, 2022). Condition findings that indicate an imminent loss of function must also connect to emergency preparedness and evacuation arrangements where the affected asset is manned during transfer operations (Obriki, Obogo, and Arumosoye, 2022b). Finally, findings that reveal a latent failure mechanism should be routed into the organizational learning process, not only into the maintenance backlog (Obriki and Arumosoye, 2022).

6.4 Digital Architecture and Data Governance

Grease results only create value when they reach the systems where maintenance and procurement decisions are made, which makes the data pathway a design concern rather than an afterthought. The condition record should be structured so that it is machine readable, asset referenced, and available to both the reliability function and the materials organization, following the integration principles established for linking information systems engineering with supply chain operations in energy environments (Okonkwo,

Ahiaeke Patrick, Okeke, and Mayo, 2023). Enterprise resource planning integration research documents both the performance gains and the adoption difficulties involved, particularly where spatially referenced asset data must be reconciled with transactional procurement records (Ahiaeke Patrick, Okonkwo, Mayo, and Okeke, 2020), and business intelligence work in manufacturing procurement demonstrates how the resulting data is turned into decisions rather than reports (Akinleye, Okoruwa, Babatope, and Akokodaripon, 2023).

Governance of the data itself matters as much as its movement. Risk based business intelligence architecture provides the pattern for exposing condition data to decision makers without exposing it indiscriminately (Mbonu, Aliliele, Iwuanyanwu, and Uzoka, 2021a); frameworks for embedding compliance controls into digital transformation of the supply chain show how audit requirements are satisfied by design rather than by retrospective reconstruction (Mbonu, Iwuanyanwu, Aliliele, and Uzoka, 2020a); and general control automation research establishes how evidence of control operation is generated as a by-product of the workflow rather than assembled before an audit (Mbonu, Aliliele, Iwuanyanwu, and Uzoka, 2022). Enterprise log analytics practice demonstrates the same principle for the technical record, in which the trail of who recorded what and when is retained automatically (Mbonu, Iwuanyanwu, Uzoka, and Oluoha, 2019). Where operators progress toward digital twin representations of export equipment, the discipline established for tiered digital twins applies directly, namely that the twin is only as trustworthy as the provenance and fidelity of the measurements feeding it (Komi and Adeniji, 2023).

6.5 Operational Technology Security

Because these pathways connect operational technology to enterprise systems, they carry the security exposure documented for converged environments. Architectural work on information technology and operational technology convergence in regulated energy networks sets out the segmentation and governance principles that a condition monitoring data path should respect (Adegbite, Adebayo, and Ahmed, 2022), and systematic review of operational technology network security in utilities establishes the compliance baseline against which such designs are assessed (Adegbite, Adebayo, and Ahmed, 2020). Security audit and enterprise risk assessment frameworks provide the means of confirming that the design as built matches the design as specified (Dosunmu and Ogundele, 2019), while intrusion detection and prevention research addresses the residual case in which it does not (Dosunmu and Ogundele, 2020). Reviews of anomaly detection in industrial control systems establish that monitoring data streams are themselves an attack surface requiring detection coverage (Adebayo, Adegbite, and Ahmed, 2023; Adegbite, Adebayo, and Ahmed, 2023), and adversarial machine learning research warns that analytics layers built on those streams can be manipulated as readily as the streams themselves (Adebayo, Adegbite, and Ahmed, 2022).

Zero trust architecture research provides the access model appropriate to a data path that spans an offshore facility, a third party laboratory, and a corporate maintenance system (Ahmed, Adegbite, and Adebayo, 2021), identity centric zero trust models developed for enterprise security governance address the same problem from the access

control side (Ogbole, Okoruwa, Fadayomi, Abolaji, Edivri, and Akeju, 2021), and identity and access management integration research addresses the hybrid case in which offshore, corporate, and third party laboratory systems must interoperate (Mbonu, Aliliele, Iwuanyanwu, and Uzoka, 2020). Research on security in sensor driven critical infrastructure addresses the specific exposure introduced by field instrumentation (Jimoh, Abolle-Okoyeagu, Ahmed, and Lawal, 2023), privacy centric security engineering establishes how such systems are designed rather than patched (Okoruwa, Fadayomi, Akeju, Edivri, Ogbole, and Abolaji, 2020), and continuous monitoring for cloud misconfiguration addresses the most common practical failure once laboratory reporting moves to hosted platforms (Aliliele, Mbonu, and Iwuanyanwu, 2023a). Where laboratory results arrive through programmatic interfaces, application programming interface governance and risk prioritization apply directly (Aliliele, Mbonu, and Iwuanyanwu, 2023b). The practical implication for an export terminal is modest but real: Grease results should not be allowed to become an unmanaged data channel.

6.6 Spares, Procurement, and Contracting Strategy

The connection between condition knowledge and spares strategy is direct. Inventory availability models for energy facilities show that plant uptime depends on holding the right long lead spares (Okonkwo, Ogunwole, and Okeke, 2018b); materials readiness frameworks demonstrate that maintenance driven supply chain performance improves sharply when procurement is triggered by early condition indicators rather than by failure (Okonkwo, Agbabiaka, Ogunwole, Mayo, and Okeke, 2021); and strategic procurement optimization work in oil and gas operations formalizes the resulting link between anticipated maintenance demand and sustained operational uptime (Okonkwo, Ogunwole, and Okeke, 2018a). Grease analysis supplies exactly the early indicators these models require. Predictive analytics applied to procurement demand forecasting shows how the resulting signal is converted into a funded plan rather than an aspiration (Akin-Oluyomi, Atima, Akinleye, and Okoruwa, 2023; Aifuwa, Oshoba, Ogbuefi, Ike, Nnabueze, and Olatunde-Thorpe, 2020), and early warning models developed for shortage prone critical supply categories demonstrate how a detected risk is escalated into a procurement response within a defined time frame (Eze, Anene, and Akinleye, 2022a).

Vendor and lead time risk on long lead bearing, seal, and swivel items should be assessed with the predictive discipline established in procurement risk practice (Akin-Oluyomi, Atima, and Akinleye, 2023b), and relationships with those few qualified suppliers should be managed as strategic rather than transactional, following supplier relationship management research in complex global chains (Ike, Ogbuefi, Nnabueze, Olatunde-Thorpe, Aifuwa, Oshoba, and Akokodaripon, 2021; Akinleye and Adeyoyin, 2022b). Where selection among suppliers or repair yards is contested, structured data driven vendor evaluation methods reduce the discretion involved (Ahiaeke Patrick, Okonkwo, Mayo, and Okeke, 2021), and negotiation optimization models address the commercial exposure that arises when a single qualified supplier holds an urgent requirement (Akinleye and Adeyoyin, 2022a). For terminals operating under strict national or contractual compliance regimes, the procurement route for emergency replacement items should

be pre-established rather than improvised under outage pressure (Okonkwo, Ogunwole, Mayo, and Okeke, 2021; Okonkwo, Ogunwole, Okeke, and Mayo, 2019), and process automation shortens the interval between a condition decision and a placed order (Akinleye and Adeyoyin, 2021). Lean supply chain practice indicates that the resulting inventory should be sized against demonstrated condition risk rather than held indiscriminately (Ike, Ogbuefi, Nnabueze, Olatunde-Thorpe, Aifuwa, Oshoba, and Akokodaripon, 2022), and sustainable and green procurement frameworks show how environmental criteria are incorporated without displacing availability (Efobi, Akinleye, and Fasawe, 2022a; Akin-Oluyomi, Atima, and Akinleye, 2023a). Finally, the terminal should hold an explicit view of its own supply resilience for these items, of the kind captured in supply chain resilience index frameworks (Efobi, Akinleye, and Fasawe, 2023; Ogunwole, Okonkwo, Agbabiaka, Mayo, and Okeke, 2021).

6.7 Assurance, Audit, and Regulatory Maturity

A monitoring program that informs export availability decisions will eventually be examined by auditors, insurers, class societies, and terminal vetting inspectors, and it should be designed for that examination. Technology enabled risk assessment frameworks for internal audit establish how condition evidence is made auditable, namely through traceable data lineage and documented judgment rather than through volume of reporting (Akomolafe and Agu, 2018). The aviation safety oversight literature offers the closest available analogue for a regulated, high consequence, evidence driven assurance regime. Adaptive safety management system implementation models show how formal safety systems are made workable in resource constrained operating contexts rather than merely mandated (Adeyelu, 2019); predictive compliance monitoring frameworks demonstrate how routine operational data is mined for systemic risk signals ahead of formal audit (Adeyelu, 2018); comparative benchmarking models establish how compliance performance is measured across comparable operators (Adeyelu and Dagodzo, 2022); regulatory evidence frameworks show how a technical finding is converted into a defensible enforcement or corrective record (Adeyelu, 2022); and risk tiered oversight models demonstrate how scrutiny is proportioned to consequence rather than applied uniformly (Adeyelu, 2023). Quantified hazard assessment models illustrate how recurring operational risks are expressed in terms that support intervention decisions (Adeyelu, 2020), and framework approaches to persistent physical encroachment show the value of standardized corrective action over case by case response (Adeyelu, 2021). A grease analysis program that adopts these habits, traceable evidence, proportionate oversight, benchmarked performance, and standardized corrective action, will be defensible under scrutiny.

6.8 Economics

The cost side of the program is modest. For a representative terminal with one SPM, one loading arm pair or offloading system, export pumps, cranes, and winches, the recurring cost comprises on the order of one hundred to two hundred laboratory samples per year, field screening consumables, a fractional full time equivalent for sampling within existing rounds, and a fractional onshore engineering resource, with

a one time investment in sample port installation and training. The benefit side is dominated by avoided deferment. A single avoided unplanned export shutdown of several days, at deferment values typical of mid-sized terminals, exceeds the lifetime cost of the program by one to two orders of magnitude; a single deferred or de-risked SPM main bearing replacement, converted from emergency response to planned campaign, is similarly decisive.

Presenting that case internally requires the language of capital allocation rather than of engineering. Decision models for capital allocation using financial analytics provide the appropriate framing for a small recurring expenditure that protects a large revenue stream (Lawal and Oduleye, 2021a), working capital and cash flow optimization models capture the value of converting unplanned emergency spend into scheduled spend (Oduleye and Medon, 2023a; Tonoyan, Dada, and Ayivi-Donkor, 2021b), and analytics driven enterprise value models address the same question where the constraint is deployable capital rather than cost (Lawal and Oduleye, 2018a). Simulation based assessment of process optimization and its financial impact offers a route to quantifying the benefit before the program has generated its own evidence (Tonoyan, Dada, and Ayivi-Donkor, 2022b), demand and asset valuation forecasting methods support the deferment assumptions on which the case rests (Tonoyan, Dada, and Ayivi-Donkor, 2021a; Tonoyan, Dada, and Ayivi-Donkor, 2023), and quantitative models for measuring the strategic impact of financial analysis show how the realized benefit is subsequently attributed to the program that produced it (Oduleye and Medon, 2023b; Medon and Oduleye, 2022). Where the terminal wishes to detect deterioration in its own cost and consumption patterns, anomaly detection methods developed for operational time series apply directly (Atakpa and Fobellah, 2023), and geospatial predictive methods offer a route to comparing performance across terminals in a portfolio (Tonoyan, Dada, and Ayivi-Donkor, 2022a). Secondary benefits include extended regreasing intervals with reduced grease consumption and disposal, reduced overgreasing damage to motor bearings, seal renewals performed at weather windows rather than emergencies, and an integrity evidence trail supporting insurance, class, and vetting reviews. Even under conservative assumptions about detection probability, the expected value is strongly positive, which is the economic signature of a low cost monitoring technology applied to a high consequence, previously unmonitored asset class.

6.9 Environmental Performance and Lifecycle Considerations

The program also carries environmental and lifecycle benefits that increasingly attract independent scrutiny. Condition based regreasing reduces grease consumption and the volume of contaminated waste requiring offshore handling and shipment, which is precisely the kind of operational discipline that circular economy decision frameworks link to measurable environmental performance (Okojie and Abioye, 2020). Avoided failures avoid spill risk at the export interface, which sits alongside produced water and other discharge streams as a primary offshore environmental exposure (Falegan and Aniebonam, 2022; Falegan and Aniebonam, 2023). Automated reporting of such performance was already emerging by 2023, with

artificial intelligence assisted auditing of environmental, social, and governance metrics in infrastructure operations providing the reporting pattern (Okojie, Filani, Ike, Okojokwu-Idu, Nnabueze, and Ihwughwawwe, 2023), predictive models for monitoring emissions and infrastructure risk demonstrating the analytical layer (Okojie, Ike, Idu, Nnabueze, Filani, and Ihwughwawwe, 2023), and blockchain enabled compliance management systems illustrating how such reporting is made tamper evident in energy projects (Abioye, Okojie, Filani, Ike, Idu, Nnabueze, Okojokwu-Idu, and Ihwughwawwe, 2023).

At the capital planning level, extending the service life of a five meter forged steel bearing avoids a substantial embodied material and energy burden as well as a capital cost, and sustainable materials selection and energy efficiency research provides the framework for recognizing that benefit rather than treating it as incidental (Ogbete, Aminu-Ibrahim, and Ambali, 2020). More broadly, lifecycle performance evaluation of purpose built facilities demonstrates that assets designed and maintained against long horizon performance metrics outperform those managed against annual budgets (Ogbete, Aminu-Ibrahim, and Ambali, 2023), sustainable infrastructure modeling shows how such long horizon criteria are embedded at design stage (Aminu-Ibrahim, Ogbete, and Ambali, 2018), and risk managed construction strategies for complex regulated facilities show how those commitments survive execution pressure (Ogbete, Aminu-Ibrahim, and Ambali, 2021), which is the correct frame for an export path that must survive storm seasons. Programmatic strategy research on large scale energy deployment reinforces that such long horizon commitments require a program, not a project (Yeboah and Ike, 2020).

7. Discussion: Limitations and Research Needs

7.1 Limitations

The concept has real limitations that a mature program acknowledges. Sampling representativeness remains the fundamental uncertainty: Grease near a port may not reflect the worst sector of a five meter bearing, which is why multi-point designs, purge stream sampling, and correlation with geometric measurements are built into the framework rather than treated as refinements. Quantitative limits are asset specific and transfer poorly between installations; the statistical per point philosophy manages this but requires patience during baselining. Laboratory method variability between providers is larger for grease than for oil, so a program should qualify one laboratory and hold it, using round robin checks when changing. Detection is not guaranteed for all modes: Sudden overload damage from a mooring incident generates debris only after the fact, so grease analysis complements rather than replaces incident triggered inspection. Data interpretation depends on records of every regreasing event, since each grease addition dilutes the diagnostic signal; disciplined lubrication record keeping is a precondition, not a nicety. Finally, the program depends on sustained execution by rotating crews, which is an organizational vulnerability rather than a technical one, and one that the change management and training literature suggests will require continuing attention rather than a single implementation effort (Eyetsemitan, Ambali, Oyeleye, and Fadayomi, 2023a; Obriki, Obogo, and Arumosoye, 2022a).

7.2 Research and Development Needs

The first research group is online grease condition sensing, particularly dielectric, ultrasonic, and optical probes embedded in bearing cavities, which would convert periodic sampling into continuous monitoring for Tier 1 assets, following the trajectory already demonstrated by sensor based fault detection architectures in other mechanical plant systems (Sunday and Omoegun, 2022) and by instrumented condition monitoring of conventional rotating machinery (Omoegun, Sunday, Essien, and Oluokun, 2023). The viability of such probes in splash zone and unattended locations depends on progress in energy autonomous and intermittently powered sensing, where reliability under uncertain power availability is the governing constraint (Asiedu and Quainoo, 2023a; Asiedu and Quainoo, 2023b), and where the placement of interpretation between local and central layers remains an open architectural question (Komi and Ganiu, 2023).

The second group is analytical. Standardized damage correlated limits for large slow slew bearings require industry data pooling across operators and bearing manufacturers, and machine learning classification of FTIR and ferrographic signatures requires training libraries that no single operator can assemble alone. The interpretability requirement is significant: Early failure prediction models for distributed assets are adopted in practice only when their outputs can be explained to the engineers who must act on them (Komi and Adamolekun, 2021), and forecasting research more generally confirms that predictive performance follows from the physical fidelity of the inputs rather than from model complexity (Komi, 2021). Automated classification of high volume condition imagery in adjacent inspection domains indicates both the feasibility and the data appetite of such approaches (Dagodzo, Ahiaeké Patrick, and Aliliele, 2022), and anomaly detection methods for operational time series offer a complementary route where the diagnostic question is deviation from an established pattern rather than classification of a known state (Atakpa and Fobellah, 2023).

The third group concerns integration and architecture. Tiered digital twin representations of export mechanical assets should ingest periodic grease results alongside geometric and operational data without demanding instrumentation density that offshore facilities cannot support (Komi and Adeniji, 2023), and the allocation of decision authority between offshore edge processing and onshore analysis remains an open design question of the kind examined in distributed control architecture research (Komi and Adamolekun, 2022). Degradation modeling under adverse ambient conditions in other asset classes suggests that environment specific rather than generic degradation models will be required (Komi and Ganiu, 2022), and co-optimization approaches that balance technical performance against operating constraints indicate how such models are made usable in resource constrained settings (Komi and Adeniji, 2020).

The fourth group is inspection and automation integration. Formal P-F interval characterization for SPM and turret bearing failure modes would put sampling interval selection on a firmer statistical footing. Combining grease sampling with remote and geospatially referenced inspection would allow condition evidence from multiple sources to be aggregated against a single asset record (Dagodzo and Ahiaeké Patrick, 2020; Dagodzo and Ahiaeké Patrick,

2023a; Dagodzo, 2018a; Dagodzo, 2018b), and change detection methods developed for repeated corridor observation offer the analytical pattern for repeated sampling at fixed points (Dagodzo and Ahiaeké Patrick, 2022). Longer term, as terminals adopt modified power systems and higher renewable penetration, the electrical and thermal duty on export equipment will change, and the monitoring program should anticipate rather than follow those changes (Adenuga, 2022; Adenuga, 2023). Industry joint projects, following the pattern of OREDA style data sharing, are the natural vehicle for all four groups.

8. Conclusion

Offshore crude export terminals concentrate enormous commercial exposure in a small set of grease lubricated mechanical assets that conventional condition monitoring cannot see. As of 2023, grease analysis had matured, through the ASTM D7718 sampling practice, the ASTM D7918 small sample method family, supporting spectroscopic, ferrographic, and physical test methods, and accumulated industry experience with slow rotating bearings, into a practical, standardized, and economical predictive maintenance technology precisely suited to this asset class. The concept developed in this paper assigns every greased export asset fixed sampling points, criticality based intervals, a defined laboratory slate, statistically trended per point limits, and staged alarm and decision logic integrated with the terminal reliability program, its digital architecture, its safety management system, and its materials supply chain.

Its implementation cost is trivial against the deferment value of a single avoided export interruption, and its strategic value lies in converting the least observable, highest consequence failure modes on the export path, main bearing degradation, swivel seal failure, and contamination driven wear, into slowly developing, measurable, and manageable conditions. The wide body of literature reviewed here reinforces the direction of travel. Adjacent asset domains have consistently found that dispersed, hard to reach, high consequence equipment becomes manageable once a modest but genuinely diagnostic measurement is taken regularly and tied to a persistent asset record (Komi and Adeniji, 2023; Adelanwa, Basnet, and Anene, 2023a; Okonkwo, Mayo, and Okeke, 2023); industrial safety practice has established that rare severe outcomes are managed through frequent minor observations (Arumosoye and Obriki, 2019; Obriki and Arumosoye, 2023); and supply chain research has established that early condition signals are what convert maintenance from a cost of failure into a planned commitment (Okonkwo, Agbabiaka, Ogunwole, Mayo, and Okeke, 2021; Okonkwo, Ogunwole, and Okeke, 2018b). For operators of SPM terminals, FPSOs, and crude loading jetties, the conclusion is direct: Grease analysis should be adopted as the primary condition monitoring technology for grease lubricated export assets, with vibration, acoustic emission, geometric measurement, and inspection arranged around it as complements rather than the reverse.

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