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TOPIC

DEVELOPMENT OF A MAINTENANCE PLAN FOR TRIPLEX PUMPS IN ENAFOR COMPANY

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Abstract

This thesis investigates the development of a specialized Preventive Maintenance Plan (PMP) for National P-Series Triplex Mud Pumps operated by the Algerian national drilling company ENAFOR, under the extreme environmental conditions of the Saharan desert. The study addresses the critical operational challenge posed by accelerated mechanical degradation caused by abrasive silica sand infiltration, severe thermal fluctuations ranging from below 0°C to above 50°C, and the use of high-solids drilling mud — factors that render standard manufacturer maintenance protocols inadequate in the field.

A comprehensive four-phase methodology was applied: a theoretical review of maintenance principles and classification frameworks; a detailed technical and failure analysis of the National 9-P-100 and 12-P-160 models, including a Failure Mode and Effects Analysis (FMEA) and Ishikawa root-cause diagrams targeting the most critical failure modes such as valve cover O-ring failure, liner scoring, and power end contamination; the formulation of a structured preventive maintenance schedule encompassing daily, weekly, bi-weekly, monthly, and semi-annual tasks tailored to Saharan operational conditions; and the design of a digital maintenance tracking tool built on Microsoft Excel, featuring a traffic-light hour-based alert system and a calendar-based programming interface to support proactive spare parts procurement and real-time monitoring.

The results demonstrate that transitioning from the prevailing corrective "run-to-failure" approach to a structured time-based preventive framework can significantly reduce Non-Productive Time (NPT), extend Mean Time Between Failures (MTBF), and lower emergency spare parts expenditure. The digital tracker further strengthens this framework by providing field technicians with an intuitive decision-support tool adaptable to remote rig-site conditions. This work represents a practical engineering contribution toward the digitalization and standardization of maintenance practices within Algeria's upstream oil and gas sector.

Keywords: Triplex Mud Pump · Preventive Maintenance · FMEA · ENAFOR · Saharan Desert · Digital Tracker · Non-Productive Time · MTBF

Résumé

Ce mémoire porte sur le développement d'un Plan de Maintenance Préventive (PMP) spécialisé pour les pompes à boue triplex de la série National P, exploitées par la société nationale algérienne de forage ENAFOR, dans les conditions environnementales extrêmes du désert saharien. L'étude répond au défi opérationnel critique posé par la dégradation mécanique accélérée causée par

l'infiltration de sable siliceux abrasif, des fluctuations thermiques sévères allant de moins 0°C à plus de 50°C, ainsi que l'utilisation de boues de forage à forte teneur en solides — des facteurs qui rendent les protocoles de maintenance standards des fabricants inadaptés aux conditions de terrain.

Une méthodologie globale en quatre phases a été appliquée : une revue théorique des principes de maintenance et des cadres de classification ; une analyse technique et de défaillance détaillée des modèles National 9-P-100 et 12-P-160, incluant une Analyse des Modes de Défaillance et de leurs Effets (AMDEC) ainsi que des diagrammes d'Ishikawa ciblant les modes de défaillance les plus critiques tels que la défaillance des joints toriques de chapeau de soupape, l'usure des chemises et la contamination de la partie mécanique ; la formulation d'un programme de maintenance préventive structuré couvrant des tâches journalières, hebdomadaires, bimensuelles, mensuelles et semestrielles, adaptées aux conditions opérationnelles sahariennes ; et la conception d'un outil numérique de suivi de la maintenance développé sous Microsoft Excel, intégrant un système d'alerte par feux tricolores basé sur les heures de fonctionnement et une interface de programmation calendaire pour soutenir l'approvisionnement proactif en pièces de rechange et le suivi en temps réel.

Les résultats démontrent que la transition de l'approche corrective dominante vers un cadre préventif structuré basé sur le temps peut réduire significativement le Temps Non Productif (TNP), augmenter la Moyenne des Temps entre Pannes (MTBP) et diminuer les dépenses en pièces de rechange d'urgence. L'outil de suivi numérique renforce ce cadre en offrant aux techniciens de terrain un outil d'aide à la décision intuitif et adaptable aux conditions des sites de forage isolés. Ce travail constitue une contribution d'ingénierie pratique vers la numérisation et la standardisation des pratiques de maintenance dans le secteur pétrolier et gazier amont algérien.

Mots-clés : Pompe à boue triplex · Maintenance préventive · AMDEC · ENAFOR · Désert saharien · Suivi numérique · Temps non productif · MTBF

ملخص

يتناول هذا المذكرة تطوير خطة صيانة وقائية متخصصة لمضخات الطين الثلاثية الأسطوانات من سلسلة National P المستخدمة لدى شركة إينافور الجزائرية الوطنية للحفر، في ظل الظروف البيئية القاسية للصحراء الجزائرية. تعالج الدراسة التحدي التشغيلي الحرج المتمثل في التدهور الميكانيكي المتسارع الناجم عن تسرب الرمال السيليكية الكاشطة، والتقلبات الحرارية الشديدة التي تتراوح بين ما دون الصفر وما فوق خمسين درجة مئوية، واستخدام طين الحفر عالي الكثافة — وهي عوامل تجعل بروتوكولات الصيانة القياسية للمصنّعين غير ملائمة للظروف الميدانية.

اعتمدت منهجية شاملة من أربع مراحل: مراجعة نظرية لمبادئ الصيانة وأطر تصنيفها؛ وتحليل تقني وتحليل أعطال مفصل لنموذجي ناشيونال P-100 و P-16012، شمل تحليل أنماط الفشل وآثارها (FMEA) ومخططات إيشيكاوا لتحديد الأسباب الجذرية لأكثر أنماط الأعطال خطورة، كشف حلقات O في غطاء الصمام، وتآكل البطانات، وتلوث الجزء الميكانيكي؛ ثم صياغة برنامج صيانة وقائية منظم يشمل مهام يومية وأسبوعية وشبه شهرية وشبه سنوية، مكيّفة مع ظروف التشغيل الصحراوية؛ وأخيراً تصميم أداة رقمية لمتابعة الصيانة مبنية على برنامج Microsoft Excel، تتضمن نظام تنبيه بالإشارات الضوئية الثلاثية استناداً إلى ساعات التشغيل، وواجهة برمجة تقويمية تدعم التوفير الاستباقي لقطع الغيار والمراقبة الفورية. تُظهر النتائج أن الانتقال من نهج الصيانة التصحيحية السائد إلى إطار صيانة وقائية منظم قائم على الزمن يمكنه تقليص وقت التوقف غير المنتج (NPT) بشكل ملحوظ، وتمديد متوسط الوقت بين الأعطال (MTBF)، وخفض الإنفاق على قطع الغيار الطارئة. كما تعزز أداة المتابعة الرقمية هذا الإطار بتزويد الفنيين الميدانيين بأداة دعم قرار بديهية وقابلة للتكيف مع ظروف مواقع الحفر النائية. يمثل هذا العمل إسهاماً هندسياً عملياً نحو رقمنة وتوحيد ممارسات الصيانة في قطاع النفط والغاز الجزائري في مرحلة الاستكشاف والإنتاج.

الكلمات المفتاحية: مضخة طين ثلاثية الأسطوانات · الصيانة الوقائية · إينافور · الصحراء الجزائرية · أداة المتابعة الرقمية · وقت

التوقف غير المنتج · متوسط الوقت بين الأعطال - FMEA

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ABBREVIATIONS

To ensure technical clarity throughout this work, the following abbreviations are used throughout this document in accordance with international standards and industry conventions:

Abbreviation	Definition
FMEA	Failure Mode and Effects Analysis
RPN	Risk Priority Number (Severity $\times$ Occurrence $\times$ Detectability)
PMP	Preventive Maintenance Plan
PE	Power End (mechanical section of the triplex pump)
FE	Fluid End (hydraulic section of the triplex pump)
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NPT	Non-Productive Time
CMMS	Computerized Maintenance Management System
JSA	Job Safety Analysis
SOP	Standard Operating Procedure
AGMA	American Gear Manufacturers Association
NLGI	National Lubricating Grease Institute (consistency grade)
HSE	Health, Safety and Environment
KPI	Key Performance Indicator
D	Detectability (FMEA criterion)
O	Occurrence / Frequency (FMEA criterion)
S	Severity (FMEA criterion)
SPM	Strokes Per Minute (pump speed measurement)

GENERAL INTRODUCTION

The Algerian energy sector, led by the national company Sonatrach, remains the backbone of the country's economy. Within this framework, ENAFOR (Entreprise Nationale de Forage) plays a strategic role as the leading national provider of drilling and workover services. With a large fleet of rigs operating across the vast Saharan territory—from Hassi Messaoud to the Adrar province—ENAFOR is responsible for the critical task of well construction and maintenance.

At the heart of every ENAFOR drilling rig is the Triplex Mud Pump (typically models like the National 12-P-160). This equipment is vital for the drilling process, as it circulates drilling fluid at high pressures to cool the bit, stabilize the wellbore, and transport cuttings to the surface. Given that a rig cannot operate without its mud pumps, their reliability is synonymous with the operational success of the company. In the competitive landscape of the Algerian oilfield, ensuring the high availability of these assets through a structured maintenance plan is not just a technical requirement, but a financial necessity.

1.1 Problem statement: The challenges of desert maintenance

Despite their robust design, Triplex pumps at ENAFOR face accelerated degradation due to the extreme environmental conditions of the Algerian Sahara. The "Problem" is defined by three main factors that currently challenge the integrity of the equipment:

1. **Abrasive contamination:** The Saharan environment is characterized by fine, highly abrasive silica sand. This sand frequently infiltrates the Power End (mechanical section), contaminating the lubricating oil and causing premature wear on the crankshaft, bearings, and crossheads.
2. **Thermal stress:** Ambient temperatures in the Sahara can fluctuate from below 0°C in winter nights to above 50°C in summer days. These thermal extremes affect the viscosity of lubricants and accelerate the hardening and failure of elastomer seals and O-rings in the Fluid End.
3. **High-Solids Mud:** Drilling through diverse Algerian geological formations often requires high-density mud. If the Liner Wash System is not perfectly maintained, the abrasive particles in the mud cause rapid scoring of the liners and pistons, leading to frequent "washouts" and expensive, unscheduled downtime (Non-Productive Time - NPT).

Currently, maintenance often skews toward "Corrective" (repairing after failure), which leads to high costs in imported spare parts and lost drilling hours. There is a critical need for a Preventive Maintenance Plan specifically tailored to combat these Saharan environmental factors.

1.2 Formulation and systemization of the problem

1.2.1 Formulation of the Problem

The central research problem for this project is formulated through the following fundamental question:

"How can the design and implementation of a specialized Preventive Maintenance Plan (PMP), specifically adapted for the National 12-P-160 model, minimize operational failures and maximize the life cycle of Triplex mud pumps operating under the extreme Saharan environmental conditions of ENAFOR?"[3]

1.2.2 Systematization of the Problem

To provide a comprehensive answer to the central formulation, the problem is decomposed into several technical and investigative sub-problems:

1. Mechanical Analysis: What is the current mechanical condition of the Triplex pumps in the ENAFOR fleet, and what are the specific internal tolerances of the National 12-P-160 that are most vulnerable to Saharan conditions?[4]
2. Failure Mode Identification: Which specific components within the Fluid End (valves, liners, pistons) and the Power End (crankshaft, bearings, crossheads) exhibit the highest frequency of failure due to abrasive sand infiltration?
3. Environmental Impact Assessment: By what specific mechanism does the extreme thermal fluctuation of the Algerian desert (diurnal range of 40°C+) affect the chemical stability of the lubricating oils and the elasticity of the pump's hydraulic seals?[5].
4. Strategic Optimization: What specific maintenance tasks, intervals, and lubrication frequencies must be standardized to transition the current "Run-to-Failure" culture at ENAFOR rig sites into a proactive "Time-Based Preventive" framework?
5. Managerial Control: What set of data collection tools, checklists, and Key Performance Indicators (KPIs), such as MTBF (Mean Time Between Failures), are required to monitor the continuous improvement of the maintenance plan

2.3 Justification of the research

The justification for this research is centered on three fundamental pillars that align ENAFOR's operational needs with academic engineering standards:

2.3.1 Operational and Strategic Justification

Within the drilling industry, the mud pump is considered the "heart" of the operation. Any failure in this critical equipment results in immediate Non-Productive Time (NPT), which can cost drilling contractors thousands of dollars per hour in rig standby rates [6].

By enhancing the reliability of the National 12-P-160 fleet, this project directly ensures the operational continuity of Algeria's national drilling efforts.

2.3.2 Economic Justification

The harsh Saharan environment accelerates component wear, leading to frequent and costly replacements of imported spare parts, such as liners, pistons, and high-pressure valves. A structured

Preventive Maintenance Plan (PMP) is economically justified by its ability to extend the Mean Time Between Failures (MTBF), thereby reducing annual expenditures on emergency procurement and complex logistics to remote sites like Hassi Messaoud and Adrar [7].

2.3.3 Technical and Environmental Justification

Standard manufacturer manuals from National Oilwell Varco (NOV) are typically optimized for temperate or offshore climates. This research provides a technical "localization" of maintenance protocols, specifically addressing the unique challenges posed by fine silica sand infiltration and extreme thermal fluctuations—factors that are often overlooked in general equipment documentation [5].

2.4 Research objectives

The primary objective of this work is to develop a specialized Preventive Maintenance Plan (PMP) for National 12-P-160 Triplex Mud Pumps operated by ENAFOR, designed to minimize operational downtime and mitigate the accelerated mechanical wear caused by the Saharan environment.

- **Technical Diagnosis:** Conduct a detailed analysis of the mechanical architecture and operating principles of the National 12-P-160.
- **Criticality Analysis:** Perform a Failure Mode and Effects Analysis (FMEA) to identify components with the highest Risk Priority Number (RPN) within the ENAFOR operational context.
- **Maintenance Standardization:** Design a comprehensive schedule of daily, weekly, and monthly preventive tasks, emphasizing specialized lubrication and filtration protocols.
- **Implementation Framework:** Develop standardized technical checklists and data collection logs to ensure full traceability of maintenance actions at the rig site.

2.5 Methodological guide

To achieve project objectives, the research follows a four-phase technical methodology:

- **Chapter I: Documentary Research:** Analysis of ENAFOR internal maintenance history, NOV technical manuals, and ISO 14224 standards for reliability data collection.
- **Chapter II: Field Diagnosis:** Identification of recurrent failure patterns in Saharan sectors and the specific impact of sand on Power End integrity.
- **Chapter III: Engineering Analysis:** Application of FMEA and Ishikawa (Fishbone) diagrams to isolate the root causes of recurrent washouts and bearing failures.
- **Chapter IV: Plan Elaboration:** Synthesis of findings into a structured maintenance calendar equipped with Key Performance Indicators (KPIs) to measure long-term success.

CHAPTER I: THEORETICAL FRAMEWORK OF MAINTENANCE

CHAPTER I: THEORETICAL FRAMEWORK OF MAINTENANCE

1.1 Introduction

Maintenance activities, primarily in the form of equipment troubleshooting, have a long history. However, in the absence of formalized methods or procedures, these activities were initially unstructured and rarely managed by specialized personnel. Interventions were largely restricted to reactive repairs following a failure, lacking a preventive framework designed to anticipate and prevent breakdowns. The formalization of maintenance as a concept is a relatively recent development, driven by the increasing automation of production systems, more complex economic and industrial objectives, and stringent regulatory requirements regarding personnel safety and environmental protection. Currently, maintenance is viewed as a holistic discipline covering the entire equipment lifecycle: from the initial selection and design phases to commissioning, the formulation of maintenance plans, logistical coordination, and the long-term monitoring of system performance.

1.2 Upkeep and Maintenance

Upkeep is restricted to reactive interventions on failed systems to restore production and the execution of routine tasks recommended by the manufacturer. This approach fails to consider specific operational variables - such as duty cycles, equipment age, and ambient temperature - often leading to poorly calibrated interventions, whether excessive or inadequate, performed without prior assessment or post-activity analysis.

While upkeep is a reactive process, maintenance is characterized by foresight and anticipation. Maintenance integrates production goals with a deep understanding of equipment behavior, recognizing that "optimal condition" and "efficiency" are relative parameters. Through a structured approach and close coordination with production teams, maintenance serves as a catalyst for productivity. Its primary objective is the continuous optimization of asset availability, directly enhancing the organization's global performance. Today, maintenance is acknowledged as a vital, value-generating activity, contrasting with traditional upkeep, which was frequently perceived as a mere financial burden.

1.3 Classification of Failures

1.3.1 Definitions

1.3.1.1 Failure: In accordance with the AFNOR 60010X standard, a failure is defined as the alteration or cessation of a system's ability to perform its required functions according to the performance levels established in its technical specifications.

1.3.1.2 Fault: A fault corresponds to any discrepancy found between a characteristic observed on a device and its reference characteristic, thus placing the equipment outside of the intended specifications.

1.3.1.3 Breakdown: Breakdown refers to the state of an item that has become unable to perform its required function. This state excludes periods of unavailability related to preventive maintenance, scheduled actions, or a lack of external resources. It is essential to distinguish between the failure, which constitutes the event of rupture, and the breakdown, which represents the state resulting from this event (whether total or partial).

1.3.1.4 Repair: Repair encompasses all physical interventions carried out with the goal of restoring the required function of equipment in a state of breakdown.

1.3.1.5 Troubleshooting: Troubleshooting groups together temporary physical actions that allow a broken-down piece of equipment to perform its functions for a limited duration, while waiting for a permanent repair to be carried out.

1.3.1.6 Failure Causes: These are the factors at the origin of the failure event. These causes can result from several variables: design, manufacturing, or installation errors, inappropriate operation, a false maneuver, or gaps in maintenance.

I.4 Definition of Maintenance

Maintenance constitutes a strategic axis in the management of industrial assets. Far from being limited to simple post-breakdown repair, it represents a structured set of actions aimed at guaranteeing the reliability, availability, and safety of technical equipment throughout its entire life cycle.

According to the NF EN 13306 (AFNOR) standard, maintenance is defined as:

"The set of all technical, administrative, and management actions, during the life cycle of an item, intended to maintain or restore it to a state in which it can perform the required function."

Today, it is perceived as a driver of industrial performance, integrating economic, technological, safety, and environmental challenges.

I.5 Maintenance Orientation and Planning

The maintenance policy defines the strategic orientations and organizational choices that a company implements to effectively manage its equipment fleet. This structural framework specifies the objectives, methods, resources, and required maintenance levels, while taking into account the specific constraints of each industrial environment.

The implementation of a coherent policy makes it possible to address the following challenges:

- Ensuring the sustainability and operational availability of installations.
- Rationalizing the overall costs of maintenance and operation.
- Extending the useful life of equipment.
- Guaranteeing operator safety and regulatory compliance.
- Anticipating breakdowns through preventive or predictive strategies.

As illustrated by Figure (1), these orientations vary depending on the type of maintenance prioritized. While corrective maintenance is dictated by the occurrence of a breakdown, preventive approaches are programmed based on predefined parameters.

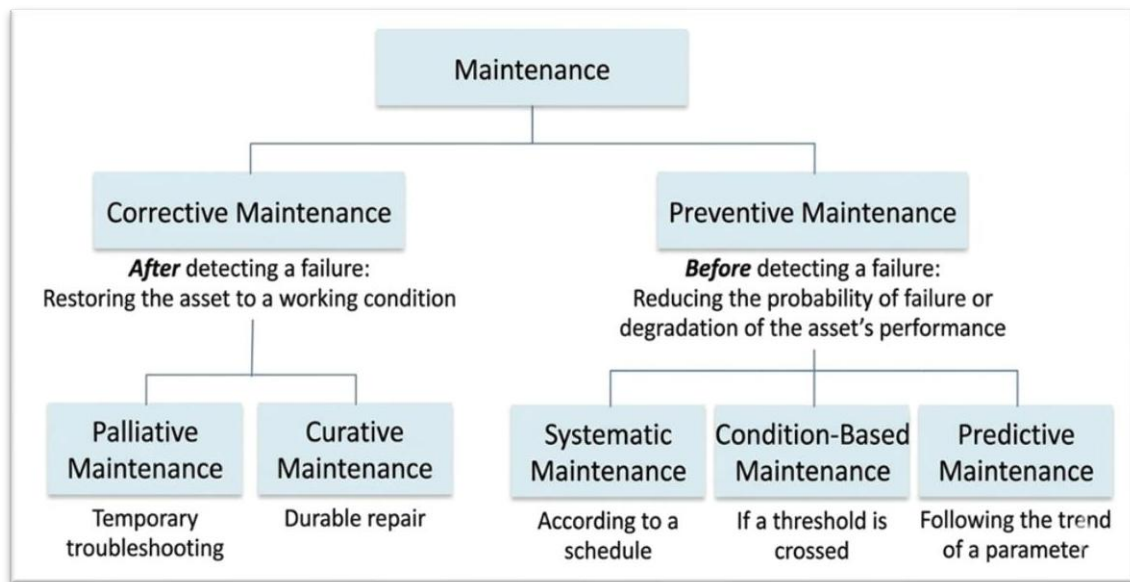


Figure 1:1: Different policies according to the type of studied maintenance.

I.6 Types of Maintenance

I.6.1 Corrective Maintenance:

According to the definition of AFNOR, corrective maintenance is:

“Maintenance carried out after the occurrence of a failure, aimed at restoring an asset to a condition in which it can perform a required function.”

It therefore takes place after a malfunction, incident, or unexpected event, with the objective of putting the equipment back into service. This restoration may take the form of troubleshooting, repair, or the replacement of defective components.

There are two forms of corrective maintenance:

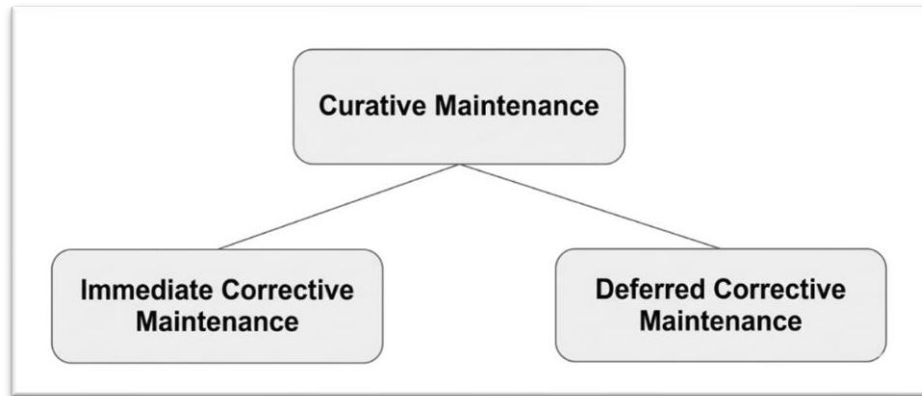


Figure 1:2: Corrective maintenance.

1.6.1.1 Palliative Maintenance:

Palliative maintenance refers to temporary troubleshooting. It allows equipment or tools to be restored to working condition on a provisional basis while waiting for a complete repair. This type of maintenance aims to avoid a total interruption of production by allowing operations to continue in what is known as a “degraded mode.”

► **Troubleshooting:** These are technical actions that enable an asset to function temporarily until a definitive repair is carried out.

Example: If a garden hose is punctured, applying adhesive tape to the leak constitutes palliative maintenance.

1.6.1.2 Curative Maintenance:

Curative maintenance aims to eliminate both the causes and the effects of a failure. Unlike palliative maintenance, it involves a complete and durable intervention, often through the replacement of the damaged part. The equipment thus regains its normal operation [1].

► **Repair:** A set of technical actions aimed at restoring the proper functioning of a failed asset.

1.6.2 Preventive Maintenance:

According to the definition of AFNOR, preventive maintenance is “maintenance carried out at defined intervals or according to specific criteria, intended to reduce the probability of failure or the degradation of the functioning of an asset.”

As its name indicates, preventive maintenance aims to anticipate problems by ensuring regular servicing of equipment or assets. It is based on inspections carried out in accordance with established standards, manufacturer recommendations, and also by taking into account human experience and the history of interventions related to the equipment.

The objectives of preventive maintenance are to:

- ✓ Ensure the optimal availability of the asset,
- ✓ Extend its service life,
- ✓ Reduce the frequency of failures and therefore corrective interventions,
- ✓ Control energy consumption and spare parts usage, thereby contributing to better inventory management.

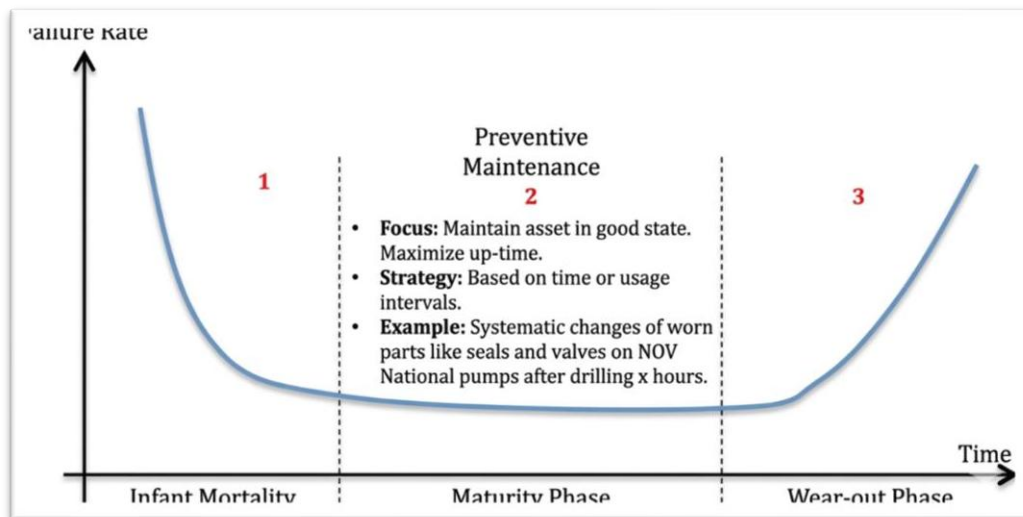


Figure 1:3: Bathtub Curve.

1.6.2.1 Systematic Maintenance:

This type of maintenance is scheduled according to a precise timetable, based on the duration of use or the number of units consumed, without prior inspection of the condition of the asset.

The frequency of interventions is determined from the moment the equipment is put into service or after a partial or complete overhaul.

It is preventive maintenance carried out according to a schedule established over time. To maintain the system in a condition that preserves its initial performance, several operations may be performed, such as:

► Replacement:

- Oil for moving mechanisms
- Filters
- Bearings and bushings

- Sealing gaskets

► **Adjustment:**

- Clearances
- Belt tensions
- Temperatures

► **Inspection:**

- Oil level
- Tightening of bolts

Example: Regularly replacing the oil of a machine after a certain number of weeks of use, without prior inspection, is considered systematic maintenance.

1.6.2.2 Conditional Maintenance:

This form is based on continuous or periodic monitoring of equipment, triggered by a specific event (self-diagnosis, sensor data, etc.). It relies on techniques such as tribology or infrared thermography in order to intervene precisely when the asset reaches a predefined wear or degradation threshold.

The objective is to perform the appropriate intervention at the right time, thus optimizing costs.

Example: Regular analysis of machine oil can detect contaminants, component wear, or lubricant degradation, allowing it to be replaced as soon as its characteristics no longer guarantee proper operation.

1.6.2.3 Predictive Maintenance:

Sometimes called predictive maintenance, it is defined by AFNOR as conditional maintenance based on forecasts derived from the analysis and evaluation of parameters that represent equipment degradation.

It allows maintenance needs to be anticipated accurately by preventing breakdowns or failures before they occur. This approach, often referred to as Maintenance 4.0, relies on continuous monitoring of various parameters, thresholds, and data (for example through a CMMS – Computerized Maintenance Management System) in order to plan the appropriate operation at the right time [2].

1.7 Objectives of Maintenance within the Company:

Today, maintenance has become an essential component of the after-sales service offered by manufacturers. It is perceived as an indicator of quality and a factor that differentiates brands.

A company or production unit that neglects maintenance, or manages it poorly, exposes itself to significant losses. This situation often results from a lack of knowledge of the equipment life cycle or insufficient attention to preserving production tools.

The objectives of a maintenance department vary depending on the nature and activity of the company. Achieving these objectives depends on the manager's ability to control the technical and organizational parameters specific to their industrial environment.

1.8 General Objectives of Maintenance:

Industrial maintenance is not limited to repairing defective equipment. It is a strategic function aimed at ensuring the availability, reliability, and safety of production resources. Its objectives are both technical, economic, environmental, and safety-related.

Among the general objectives of maintenance are:

- ✓ **Ensuring equipment availability:** One of the fundamental goals of maintenance is to maximize the operating time of installations. Good availability helps avoid production interruptions and effectively meet industrial productivity requirements.
- ✓ **Improving reliability:** This involves ensuring that equipment performs its function without failure over a given period. Increased reliability reduces emergency interventions, improves operational planning, and enhances the quality of the final product.
- ✓ **Optimizing operating costs:** By adopting an appropriate maintenance strategy (preventive, condition-based, or predictive), it is possible to reduce costs related to unplanned shutdowns, major repairs, spare-parts storage, and energy consumption.
- ✓ **Extending equipment lifespan:** Regular and targeted maintenance helps delay premature wear of components, maintain the original performance of machines, and postpone replacement investments.
- ✓ **Ensuring the safety of people and assets:** Maintenance actively contributes to the prevention of industrial risks by keeping equipment in a safe condition. It also ensures compliance with regulations related to occupational health and safety.
- ✓ **Reducing environmental impact:** Effective maintenance limits leaks, energy losses, uncontrolled emissions, and industrial accidents, helping organizations comply with environmental standards and support sustainable development.

1.9 Maintenance Levels:

A maintenance level is defined according to:

1. The nature of the intervention.
2. The qualification of the technician performing the task.
3. The resources and tools used.

The degree of maintenance development is classified into five levels. These levels are provided by standards as guidelines to assist maintenance management, and their practical application is not mandatory and may vary depending on agreements between the parties, who define them precisely according to the type of equipment to be maintained.

Table 1.1: Maintenance Levels

1	Simple adjustment or consumable exchange, without disassembly	Operator	Cleaning, refilling oil
2	Low complexity action , on-site	Technician	Filter change
3	Low complexity action , on-site or in workshop	Specialized technician	Pump change
4	Specific intervention , in specialized workshop	Specialized team	Vibration analysis
5	Intervention carried out by the manufacturer or certified company	Manufacturer	Repair, compliance restoration

Level 1:

Simple adjustments provided by the manufacturer using elements accessible without any dismantling or opening of the equipment, or the replacement of consumable components that can be accessed safely, such as indicator lights or certain fuses.

This type of intervention can be carried out by the equipment operator directly on site, without tools, using the operating instructions. The required stock of consumable spare parts is very small.

Level 2:

Troubleshooting through standard replacement of components designed for this purpose and minor preventive maintenance operations such as lubrication or functional checks.

This type of intervention can be carried out by an authorized technician with moderate qualifications, on site, using portable tools defined in the maintenance instructions and following those same instructions. The necessary transportable spare parts can be obtained without delay and close to the operating site.

Level 3:

Identification and diagnosis of failures, repairs through replacement of components or functional elements, minor mechanical repairs, and routine preventive maintenance operations such as general adjustments or realignment of measuring devices.

This type of intervention can be performed by a specialized technician, either on site or in the maintenance workshop, using the tools specified in the maintenance instructions as well as measuring and adjustment instruments, and possibly testing and inspection benches. All necessary maintenance documentation and spare parts supplied by the store are used.

Level 4:

All major corrective or preventive maintenance work except renovation or reconstruction. This level also includes the calibration of measuring instruments used for maintenance and, if necessary, the verification of working standards by specialized organizations.

This type of intervention is performed by a team with highly specialized technical supervision in a specialized workshop.

Level 5:

Renovation, reconstruction, or major repairs carried out in a central workshop or an external unit. By definition, this type of work is performed by the manufacturer or by a reconstruction specialist using means defined by the manufacturer and therefore close to the original manufacturing process.

1.10 Maintenance Operations

1.10.1 Inspections

These are monitoring activities that consist of periodically identifying anomalies and performing simple adjustments that do not require specific tools or stopping the production equipment.

1.10.2 Visits

These are monitoring operations carried out as part of predetermined maintenance schedules.

1.10.3 Troubleshooting

This is a curative maintenance operation performed on failed equipment to restore it to working condition. Given the objective, a troubleshooting action may result in a temporary solution and will therefore be followed by a proper repair.

1.10.4 Repair

This is a definitive and limited operation in curative maintenance carried out after a failure in order to restore the equipment to proper operation.

1.10.5 Overhauls

These operations are carried out to ensure that the asset is protected against any major critical failure for a given period or a specified number of operating units.

1.11 Conclusion

Maintenance is a complex function which, depending on the type of process, can be decisive for the success of a company. The functions that compose it and the actions that implement them must be carefully balanced so that the overall performance of the production system is optimized.

To be effective, it is first necessary to have as clear an understanding as possible of the mechanisms that influence key parameters (number of failures, repair time, logistical delays, preventive maintenance costs, material storage costs, communication actions, etc.). It is then necessary to measure these parameters and develop indicators to evaluate the condition of the maintenance system and identify its weak points.

Finally, the HSE (Health, Safety, and Environment) aspect must not be overlooked, adopting the principle: no accidents and no harm to the environment.

CHAPTER II: TRIPLEX MUD PUMP FAILURE ANALYSIS AND MAINTENANCE

CHAPTER II: TRIPLEX MUD PUMP FAILURE ANALYSIS AND MAINTENANCE

2.1 Conceptual framework

The conceptual framework establishes the fundamental terminology and theoretical boundaries required to analyze the maintenance engineering principles applied to Triplex pumps. For a specialized study within ENAFOR, these definitions are harmonized with the ISO 14224 standard, which provides a comprehensive basis for the collection and exchange of reliability and maintenance data in the petroleum, petrochemical, and natural gas industries [5].

2.1.1 Glossary of terms

2.1.1.1 Administrative Activities

Administrative activities in maintenance encompass the management, planning, and documentation tasks required to support technical interventions. This includes the scheduling of resources, the management of spare parts inventory, and the systematic recording of data within a Computerized Maintenance Management System (CMMS/GMAO). Effective administration ensures that technical tasks are performed within the planned timeframe and that all actions are traceable for reliability analysis [8].

2.1.1.2 Failure Cause

The failure cause refers to the circumstances or physical processes that lead to the functional failure of a component or system. In the context of Triplex pumps operating in the Algerian Sahara, these are categorized as follows:

- **Physical causes:** Primarily involves tribological wear, such as the abrasive action of silica sand on the piston surface and liners.
- **Human causes:** Errors in technical execution, such as improper lubrication intervals or the application of incorrect torque to fluid end cover bolts.
- **External causes:** Environmental stressors, specifically extreme ambient temperatures (often exceeding 50°C in summer) that surpass the design limits of the pump's cooling and lubrication systems.

2.1.1.3 Failure Effect

The failure effect describes the immediate consequences of a failure mode on the operation, productivity, and safety of the drilling rig. This assessment is the cornerstone of Failure Mode and Effects Analysis (FMEA). Within ENAFOR operations, effects are ranked by their severity:

- **Local effects:** Restricted to the pump unit, such as abnormal vibration, noise in the Power End, or a localized drop in discharge pressure.
- **System effects:** Impacting the entire drilling process, most notably the total loss of mud circulation, which necessitates an immediate suspension of drilling activities (NPT).
- **Safety/Environmental effects:** High-risk consequences, including potential high-pressure leaks or "blowouts" if hydrostatic pressure cannot be maintained in the wellbore due to pump failure [9].

2.1.1.4 Maintenance

Maintenance is defined as the combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function. Within the scope of this project, maintenance is subdivided into two primary philosophies:

- **Corrective Maintenance:** Tasks performed after a failure has occurred to restore the pump to operational status. In the Saharan context, relying on this is highly inefficient due to the distance from logistical hubs.
- **Preventive Maintenance:** Tasks performed at predetermined intervals (time-based or usage-based) to reduce the probability of failure. This project focuses on optimizing these intervals to ensure that National 9-P-100 pumps achieve their maximum Mean Time Between Failures (MTBF).

2.1.1.5 Failure Mode

The failure mode is the observed manner in which a failure occurs. It describes the physical transition of a component from an operational to a non-operational state. In Triplex pumps, common failure modes include "leaking" (fluid end valves), "seizing" (bearings), and "fracture" (liner bolts) [5].

2.1.1.6 Operational Tasks

Operational tasks are routine activities performed by the rig crew to ensure the pump remains within its design parameters. These include monitoring discharge pressure, checking oil levels in the Power End, and verifying the flow of the liner wash system.

2.1.1.7 Taxonomy

In maintenance engineering, taxonomy refers to the hierarchical classification of equipment into functional locations, systems, sub-systems, and individual components. ISO 14224 provides a standardized equipment taxonomy for the oil and gas industry. For this project, the taxonomy of the ENAFOR triplex pump is established as: Rig > Mud Circulation System > Triplex Mud Pump > Power End / Fluid End > individual components (crankshaft, bearings, crosshead, liner, piston, valves, seals). This structured hierarchy enables precise failure data collection and root cause analysis.

2.1.1.8 Downtime (NPT - Non-Productive Time)

Downtime, or NPT, is the period during which the drilling rig is unable to perform its primary function (drilling) due to equipment failure. In the Saharan context, NPT is often exacerbated by the "logistical lag" required to transport parts to remote locations [6].

2.1.1.9 Traceability

Traceability in maintenance management refers to the ability to reconstruct the history of an item's interventions, modifications, and component replacements throughout its operational life. Achieving full traceability for ENAFOR's triplex pumps requires the systematic completion of maintenance work orders, inspection checklists, and oil analysis reports. A traceable maintenance record directly enables the calculation of key performance indicators such as Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR), which are indispensable tools for the continuous improvement of the maintenance plan.

2.2 Theoretical framework

The theoretical framework synthesizes the body of knowledge in maintenance engineering and triplex pump technology that forms the scientific basis of this work. It draws on international standards, manufacturer documentation, and academic literature to establish the principles applied in the development of the Preventive Maintenance Plan (PMP) for ENAFOR.

2.2.1 Piston pumps (Triplex Mud Pumps)

The National 9-P-100 is a single-acting, positive-displacement reciprocating piston pump, representing a critical component in the mud circulation system of modern drilling rigs. Its primary function is to generate the hydraulic horsepower required to circulate drilling fluid from the surface, through the drill string and bit nozzles, and back up the annulus for processing and recirculation [10].

The "Triplex" designation refers to its three-cylinder configuration arranged in parallel. This design offers a significant reduction in pressure pulsations compared to older Duplex (double-acting)

designs. By utilizing a 120-degree offset on the crankshaft, the pump ensures that at least one piston is always on a pressure stroke, providing a relatively continuous flow. This uniformity is essential in high-pressure Saharan environments to maintain constant bottom-hole pressure and ensure effective cuttings removal while reducing fatigue stress on the drill string and rig piping [4].

The National Oilwell P-Series has served as an industry standard for decades due to its high power-to-weight ratio and reliability [6]. Within the ENAFOR fleet, operations primarily rely on the 9-P-100 and 12-P-160 models, whose principal technical specifications are summarized in Table 2.1 below.

Table 2.1: principal technical specifications

Parameter	9-P-100	12-P-160	Unit
Rated Power	100	160	HP
Stroke Length	10	12	inches
Max. Liner Diameter	6.5	7.5	inches
Max. Discharge Pressure	3,000	3,000	psi
Crankshaft Gear Bore (C)	0.876 – 0.875	1.126 – 1.125	inches
Gear Nut Torque (D)	380	780	ft-lb
Crankcase Oil Capacity	95 (360)	130 (492)	US gal. (L)
Min. Operating Speed	5	5	SPM

2.2.1.1 The Power End (PE)

The Power End (PE) is the mechanical drive section of the pump. It receives rotary motion from the rig's prime mover (typically a diesel engine or electric motor) via a chain, belt, or direct gear coupling. The PE houses the following primary sub-assemblies [4]:

- **Crankshaft and Gear Assembly:** The crankshaft converts the input rotary motion into the linear reciprocating motion of the crossheads. The gear (pinion) is mounted on the crankshaft with a precise interference fit; for the 9-P-100, the bore tolerance is 0.876–0.875 inches and the assembly bolt torque is 380 ft-lb.

- **Main Bearings and Connecting Rod Bearings:** These anti-friction bearings support the crankshaft under the high cyclic loads generated by pumping against elevated discharge pressures. Contamination of the lubricating oil with abrasive particles is the primary cause of premature bearing failure in Saharan operations.
- **Crosshead and Crosshead Guide:** The crosshead translates the rotary crankshaft motion into a precise linear stroke. The crosshead slides within the crosshead guide (or 'wrist pin bore'), and the quality of lubrication at this interface is critical. At slow pump speeds (5–30 SPM), the manufacturer specifies that crosshead cover plates must be temporarily removed during operation to manually verify that oil is reaching the crosshead surfaces.
- **Crankcase and Lubrication System:** The crankcase acts as the reservoir for the Power End gear oil (AGMA EP specification). The oil is splash-lubricated at operating speed. Magnetic drain plugs are fitted to capture ferrous wear debris, and inspection access covers are provided for internal inspection.

The PE is sealed against the external environment by crankcase gaskets and the pony rod sealing arrangement where the pony rod exits the PE housing toward the FE. Any deterioration of this seal in a sandy environment is a critical failure point, as it creates a direct pathway for abrasive contamination [14].

2.2.1.2 The Fluid End (FE)

The Fluid End (FE) is the hydraulic working section of the pump, where the mechanical energy from the Power End is converted into fluid pressure and flow. It consists of three identical, single-acting pump cylinders (modules), each containing the following components [4]:

- **Liner and Piston Assembly:** The liner is the cylindrical chamber within which the piston reciprocates. The relative motion between the elastomeric piston cup and the liner bore is the primary "wear couple" in the FE. Abrasive particles in the drilling mud accelerate this wear catastrophically, a phenomenon particularly prevalent in Saharan exploration.
- **Liner Wash System:** National Oilwell P-Series pumps utilize a wash system delivering a 50/50 mixture of fresh water and soluble oil. This system cools components and flushes abrasive particles from the liner-piston interface. Maintaining adequate wash fluid levels is the single most critical daily maintenance action for FE longevity.
- **Suction and Discharge Valve Assemblies:** These spring-loaded, non-return valves utilize precision-lapped sealing surfaces. Erosion of these surfaces by drilling fluid causes leakage,

manifesting as reduced efficiency and pressure fluctuations—commonly referred to in the field as "pounding."

- **Valve Cover (Wing Nut) Assembly:** Provides access for maintenance. These are sealed by elastomeric O-rings and secured by heavy-duty wing nuts. Regular inspection of the O-ring and verification of the nut torque are essential to prevent high-pressure washouts.
- **Discharge Module and Pulsation Dampener:** This manifold collects flow from all three cylinders. A pulsation dampener (surge absorber) is connected to the discharge line to attenuate inherent pressure pulsations, protecting downstream rig piping from fatigue [11].

2.2.2 Maintenance principles

The theoretical evolution of industrial maintenance has progressed through three generations, as described by Moubray (1997). The first generation (pre-1950) was characterized entirely by 'fix-it-when-it-breaks' corrective maintenance. The second generation (1950–1980) introduced the concept of preventive maintenance, driven by the belief that all components followed a predictable failure rate that increased with age, corresponding to the 'wear-out' phase of the bathtub curve. The third generation (1980–present) recognized that the majority of equipment failures are not age-related and introduced more sophisticated strategies including condition monitoring and Reliability-Centered Maintenance (RCM).

For ENAFOR's application, the most appropriate strategy is a structured Preventive Maintenance Plan (PMP) based on manufacturer-specified intervals, supplemented by condition monitoring of key parameters (oil contamination, liner wash level, and pressure output). This approach provides a practical, cost-effective framework that can be implemented at remote rig sites without requiring specialized instrumentation [8].

2.2.2.1 Lubrication in maintenance

Lubrication is the primary proactive intervention used to mitigate friction, dissipate heat, and protect the internal surfaces of the Power End (PE). In the high-torque environment of the Algerian Sahara, the lubrication strategy must account for the mechanical transition between different friction regimes and the thermal degradation of oil viscosity [4].

2.2.2.1.1 Analysis of Lubrication Regimes (The Stribeck Curve)

The National 9-P-100 operates primarily under Hydrodynamic Lubrication, where a thick fluid film completely separates the rotating components. However, as illustrated in the Stribeck Curve (Figure 4), the pump may experience Boundary Lubrication during low-speed startups or extreme summer

heat. In these moments, the oil film thins, and metal-to-metal contact is only prevented by the chemical strength of the lubricant additives [12].

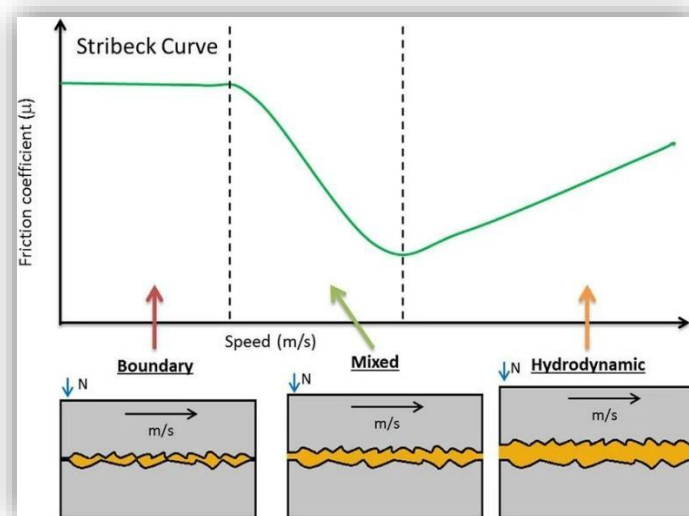


Figure 2.1: Stribeck Curve and Lubrication Regimes in Triplex Pump Operations.

2.2.2.1.2 Technical Specifications and Saharan Grade Selection

The selection of AGMA EP gear oil is governed by ambient operating temperatures. Given that ENAFOR rigs face a range from -5°C (winter nights) to $+50^{\circ}\text{C}$ (summer days), the following grades are utilized to maintain the proper viscosity index and prevent film rupture [13]:

Table 2.2: Lubrication Specifications for the National Oilwell 9-P-100 / 12-P-160 Pump

Point	Frequency	Lubricant Type	Method / Notes
[A] Crankcase	Daily	AGMA EP Gear Oil (see temperature selection below)	Check level with pump stopped. Change semi-annually.
[B] Crosshead Pin	Daily	Lithium-base grease, NLGI Grade 1	Two strokes with hand grease gun.
[C] Liner Wash	Daily	50% fresh water + 50% soluble oil	Check reservoir level and fluid condition daily.
[A] Crankcase	Semi-Annual	AGMA EP Gear Oil (full change)	Drain, flush, and refill. Inspect magnetic drain plugs.

2.2.2.1.3 Additive Chemistry and Functional Protection

To maintain film integrity under the high cyclic loads of the PE, the oil must be fortified with a specific additive package designed for extreme pressures [14]:

- **Anti-wear (AW) Additives:** Typically Zinc Dialkyldithiophosphate (ZDDP), which forms a protective chemical film during boundary lubrication to prevent metal-to-metal scuffing.
- **Extreme Pressure (EP) Additives:** Sulfur-phosphorus compounds that react with metal surfaces at high contact pressures to form a sacrificial layer, preventing the welding or seizing of gear teeth.
- **Anti-foam & Oxidation Inhibitors:** Essential for preventing oil degradation in the 50°C+ heat of Hassi Messaoud and ensuring a stable hydrodynamic film remains present in the crankcase.

2.2.3 Historical Evolution of Maintenance Strategies

The philosophy of maintenance has undergone a significant transformation since the Industrial Revolution, evolving alongside the increasing complexity of mechanical systems. This evolution is generally categorized into four distinct generations, moving from reactive "fix-it" mindsets to data-driven predictive strategies [8].

A. First Generation: Corrective/Reactive Maintenance (Pre-1950s)

Prior to World War II, maintenance was almost entirely corrective ("Fix-it-when-it-breaks"). Because equipment was often over-designed, simple, and labor costs were low relative to equipment costs, the concept of "running to failure" was economically dominant. Downtime was not yet considered a critical economic factor in production.

B. Second Generation: Scheduled Preventive Maintenance (1950s–1970s)

Driven by post-war industrialization and the growth of the aerospace and nuclear industries, it became clear that corrective-only approaches were unacceptable for catastrophic failures. This era saw the emergence of Preventive Maintenance (PM), based on the assumption that component life follows a predictable distribution. Maintenance tasks began to be performed at fixed time intervals to extend equipment life and ensure higher availability [15].

C. Third Generation: Reliability and Condition Monitoring (1980s–2000s)

This period was defined by Total Productive Maintenance (TPM), which integrated maintenance into the production process, and the formalization of Reliability-Centered Maintenance (RCM) by Nowlan and Heap. RCM revolutionized the field by demonstrating that age-related failure was the exception

rather than the rule. Focus shifted toward Condition-Based Maintenance, utilizing sensors for vibration analysis and oil monitoring to intervene only when symptoms of failure appeared [16].

D. Fourth Generation: Predictive Maintenance and Industry 4.0 (Present)

The current generation utilizes Predictive (PdM) and Proactive Maintenance. Driven by "Industry 4.0," this era integrates IoT sensors, digital twins, and machine learning to forecast failures with increasing precision.

E. Strategic Alignment for ENAFOR Operations

While Fourth Generation technologies are relevant to ENAFOR's long-term digital transformation, the practical constraints of remote Saharan rig sites such as intermittent communication infrastructure, power reliability, and the extreme environment require a pragmatic approach. Consequently, a rigorous, Time-Based Preventive Maintenance Plan (as developed in this work) remains the most robust and immediately implementable solution for the National 9-P-100 in the current operational context [4].

2.2.4 Maintenance strategies (Corrective vs. Preventive)

To manage the National 9-P-100 effectively, a clear distinction must be made between the two primary maintenance strategies utilized in the drilling industry:

- **Corrective Maintenance (CM):** This is a reactive strategy where repair is performed only after a functional failure is detected. While simple to manage, it is the most expensive strategy for mud pumps due to the high cost of NPT (Non-Productive Time) and the potential for secondary damage to internal components like the crankshaft or crossheads [6].
- **Preventive Maintenance (PM):** This is a proactive strategy where tasks are performed at predetermined intervals (e.g., daily, weekly, or hourly) regardless of the equipment's current condition. PM aims to reduce the probability of failure by replacing "expendables" (liners, pistons, valves) before they reach the "wear-out" phase. This strategy is modeled on the Bathtub Curve, which illustrates the failure rate of mechanical components over time [5].

Table 2.3: Comparative Analysis of Maintenance Strategies Applicable to ENAFOR Triplex Pumps

Criterion	Corrective Maintenance	Preventive Maintenance (Time-Based)	Predictive Maintenance (Condition-Based)
Trigger	Occurrence of failure	Fixed schedule (hours, date)	Condition monitoring threshold

NPT Impact	Very High (unplanned stoppages)	Low (planned stoppages)	Minimal (intervention before failure)
Spare Parts Cost	High (collateral damage)	Medium (scheduled replacement)	Low (replace only when needed)
Required Skills	Reactive repair capability	Trained technician (Levels 2–4)	Specialist + diagnostic instruments
Suitability for Saharan Remote Rigs	Poor (high logistics NPT)	HIGH (primary recommendation)	Medium (future development)
Implementation Complexity	Low	Medium	High

Table 2.3 provides a structured comparison of the three primary maintenance strategies applicable to the ENAFOR triplex pump context, highlighting their respective advantages and limitations.

2.2.5 Maintenance tools

To implement a high-reliability maintenance culture at ENAFOR, specific analytical tools are required to translate raw operational data into actionable maintenance tasks. These tools provide the structure necessary to manage the National 9-P-100 fleet systematically rather than reactively.

2.2.5.1 Failure Mode and Effects Analysis (FMEA)

FMEA is a systematic, bottom-up methodology used to identify potential failure modes of the National 9-P-100 components (such as valve washouts, piston seal leaks, or bearing seizures). It evaluates each failure based on three critical criteria:

1. **Severity (S):** The impact of the failure on rig safety and operations.
2. **Occurrence (O):** The frequency or probability that the failure will occur.
3. **Detection (D):** The likelihood that the failure will be identified before it causes a system shutdown.

These variables are multiplied to calculate the Risk Priority Number (RPN)), which allows engineers to prioritize maintenance resources on the most critical pump components [17].

2.2.5.2 Flowcharts

Technical flowcharts are utilized to provide a visual standardization of maintenance workflows. For this project, they map the sequence of events from the moment a fault is detected (e.g., a drop in discharge pressure) through the troubleshooting phase, the physical repair, and the final verification. This ensures that the rig crew follows a logical and efficient path, reducing the duration of repair-related downtime [8].

2.2.5.3 Standard Operating Procedures (SOP)

SOPs are detailed, written instructions designed to achieve uniformity and quality in the performance of specific technical functions. Regarding the 9-P-100, an SOP would provide the exact sequence and torque values for tightening fluid end cover bolts—a critical step to prevent the human-caused failures identified in your glossary. By standardizing these actions, ENAFOR ensures that the quality of maintenance is independent of the individual technician's experience level [4].

2.2.5.4 Job Safety Analysis (JSA)

JSAs are risk assessment tools integrated directly into the maintenance workflow. Before any high-risk intervention on the pump—such as the replacement of a heavy crankshaft or a high-pressure valve—the maintenance team must identify potential hazards (e.g., stored hydraulic pressure, suspended loads) and implement specific control measures. This ensures that the objective of equipment "Availability" never compromises the safety of the personnel [18].

2.2.5.5 Cause and Effect Diagrams (Ishikawa)

Also known as "Fishbone" diagrams, the Ishikawa tool is used for deep root-cause analysis. It categorizes potential causes of a specific problem (e.g., "Frequent Liner Washout") into six primary branches: Manpower, Methods, Machines, Materials, Measurement, and Mother Nature (Environment). This is particularly effective for your thesis to demonstrate how Saharan environmental factors (sand/heat) interact with mechanical components to create recurrent failures [19].

The first real problem oil companies face (regarding pumps) is the possibility that a task will not be completed, or will be completed unsatisfactorily, due to the pump's inability to meet the desired operating parameters (figure 2.2). In the past, work opportunities have been lost due to inadequate planning of the quantity and type of spare parts needed during a pumping operation, or due to other unforeseen circumstances that prevented pumps from being available when needed.

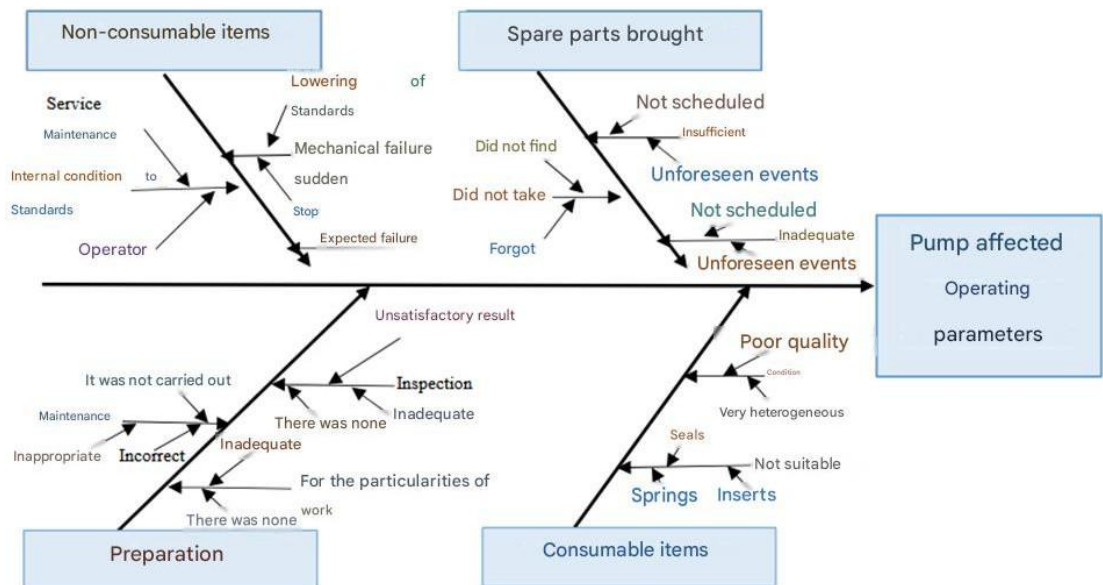


Figure 2:2: Cause and effect diagram. The pump affects the operating parameters.

On pumps in operation at construction sites, excessive erosion of the crankshaft teeth is commonly observed, and the same is true for the drive shaft teeth (figure 2.3).

The pumps continue to operate despite this, and it is striking that the obvious problem of this wear seems to elicit no reaction from the staff, due to the lack of any tangible effect (such as decreased pumping efficiency or increased fuel consumption).

A serious problem facing the organization is precisely its failure to give sufficient attention to the less obvious specifics of events. For example, opening the mechanical hood is a common practice, even in unsuitable environments, as evidenced by the presence of large insects in the filters. Oil changes appear to be irregular: several units have found that the oil is emulsified and gives off a stale oil odor due to contamination, degradation, oxidation, or emulsification.

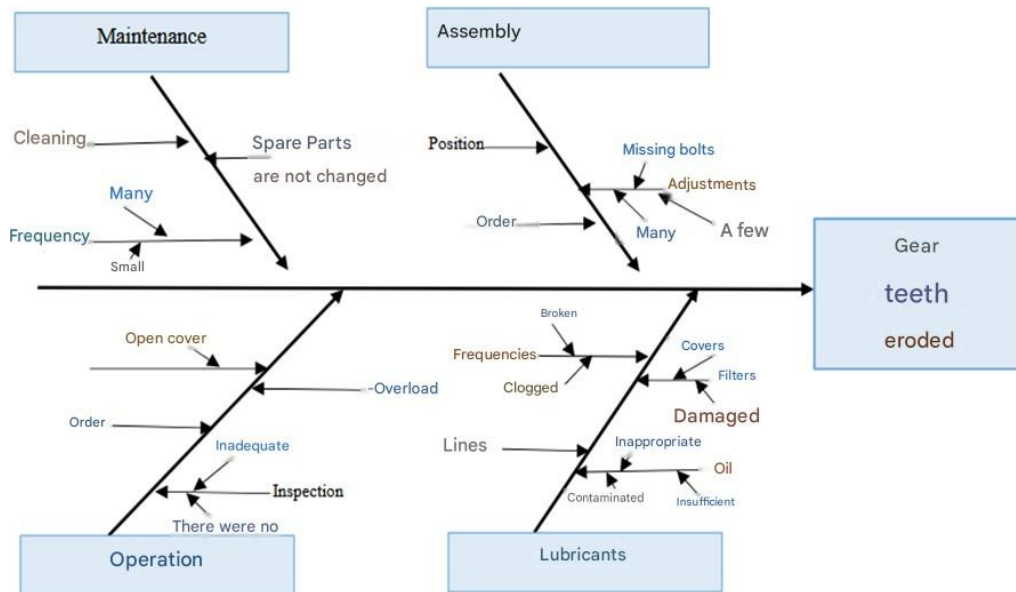


Figure 2:3: Cause and effect diagram. Eroded gear teeth.

The rings inside the seal body are consumables. The manufacturer conducted several material tests before selecting the most suitable material for the oil used and the type of work performed on a triplex pump. However, the oil company uses locally manufactured spare parts, the composition of which is not guaranteed to be identical to that of the imported original part (figure 2.4). Furthermore, an oil not specified by the manufacturer is used to lubricate the seal. As a result, the piston lubrication system does not follow the wear pattern expected according to international practices, and, more worryingly, the actual wear pattern is unknown. The assembly procedure is not standardized among operators, and maintenance is limited to topping up the oil and replacing components in case of leaks.

There is no specific management system for planning maintenance activities based on the type of work performed or the operating fluid used by the pump.

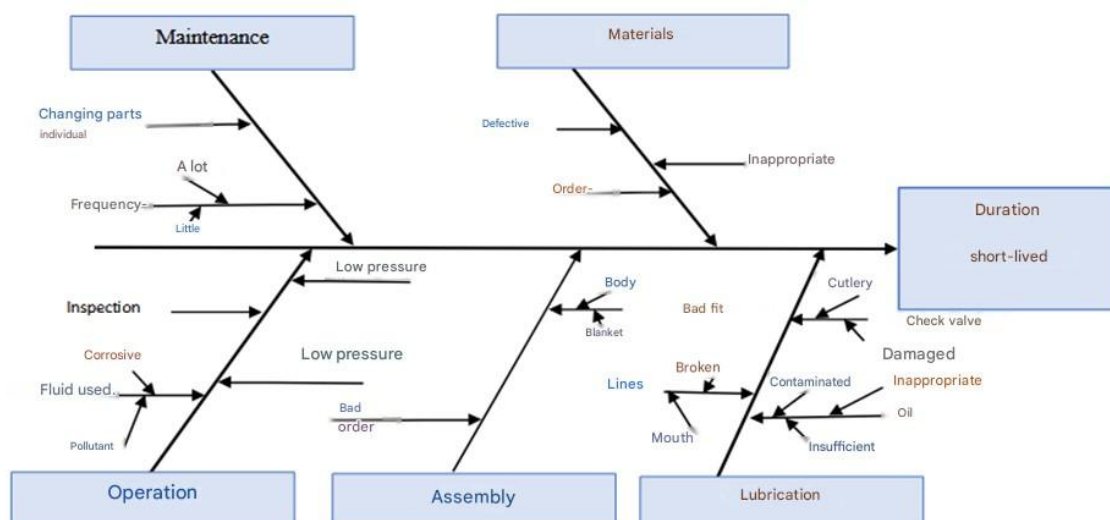


Figure 2:4: Cause and effect diagram. Short seal lifespan.

The service life of inserts in operation is highly variable. Their behavior is unpredictable because impurities and foreign matter in the fluid cannot always be controlled. In the oilfield services industry, pumping requires control of the uniformity of the pumped fluid, but certain precautions can be taken to extend the intervals between insert changes. Valve assembly is not standardized, but it is not a frequent cause of failure; however, it could be improved in terms of frequency and method (figure 2.5). Due to spare parts supply and inventory management issues, some inserts have lost their properties, appearing excessively vulcanized and dry. These inserts may sometimes be used in error.

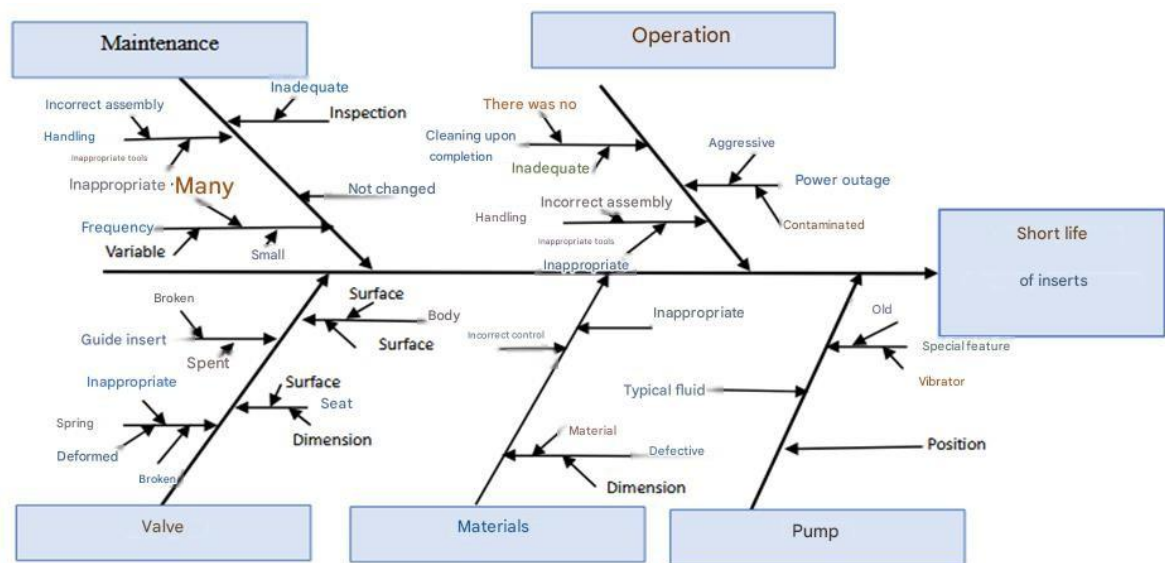


Figure 2:5: Cause and effect diagram. Short insert lifespan.

The monograde oil used to lubricate the mechanical body is perfectly adequate for this type of work. However, higher-performing and better-suited multigrade oils are now available, which will certainly improve lubrication. Moreover, these are recommended by pump manufacturers, but their replacement is not mandatory. Currently, the oil deteriorates and is only replaced when a change in its properties is noticeable. This change is visible through its odor, color, and appearance; in all the pump inspections we observed, the oil was in an apparently unacceptable condition and differed significantly from new oil. The oil frequently contains significant contaminants due to the opening of the mechanical body cover, improper closure, or contamination from other sources. The frequency of oil changes and inspections must be changed, and the condition of the oil must be examined more carefully and according to uniform criteria by users (figure 2.6).

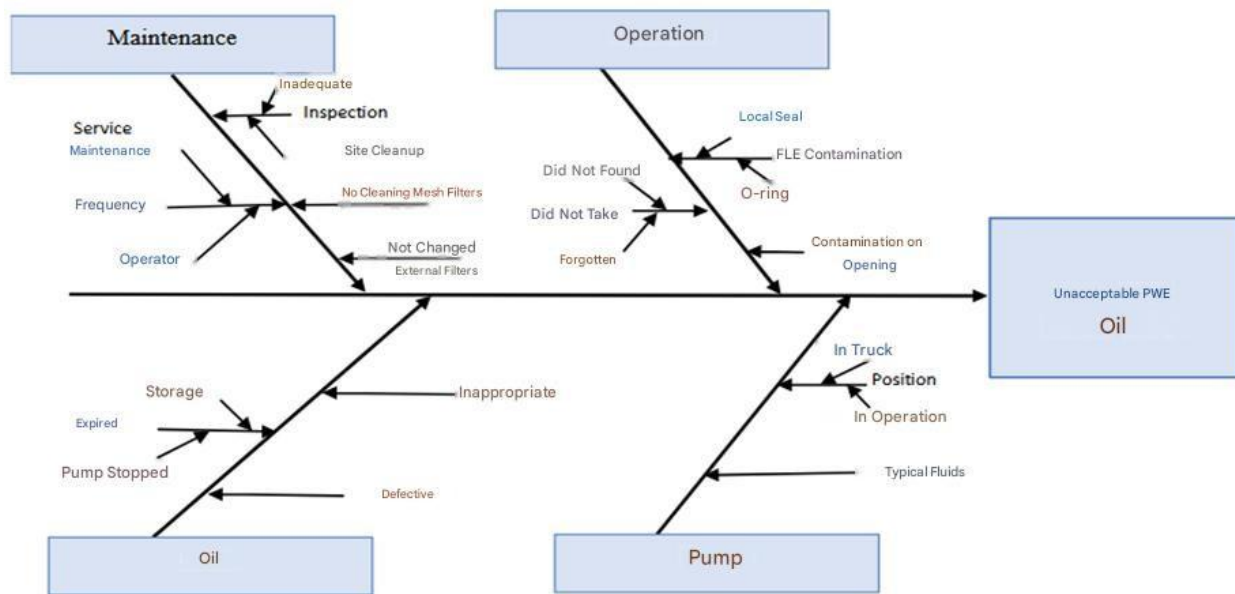


Figure 2:6: Cause and effect diagram. PWE oil not acceptable

Inventory and supply management is a fundamental challenge for the company. However, until now, orders have been placed based on the experience of the unit manager and the judgment of the supervisors. The main weakness of this mechanism lies in its reliance on the unreliability of memory and the varying degrees of objectivity and subjectivity among employees. Furthermore, there is no basis for the unit manager's decisions to be reviewed by administrative staff. This results in orders deliberately exceeding needs, as a smaller quantity than requested is often approved, leading to a surplus of spare parts (figure 2.7). Far from being beneficial, this excess of spare parts leads to a loss of usable warehouse space, an increase in perishable parts (primarily polymer materials), and a reduction in the administrative staff's quota for acquiring other parts. Information on component usage and consumption is generally managed by those closest to the pump: the most frequent operator, the most frequent supervisor, and sometimes others. This information is at risk of being lost or altered during its transmission through the information chain leading to the spare parts purchasing decision process. Not only are there no organized records, but this also makes it impossible to generate a history that would allow for tracking usage trends.

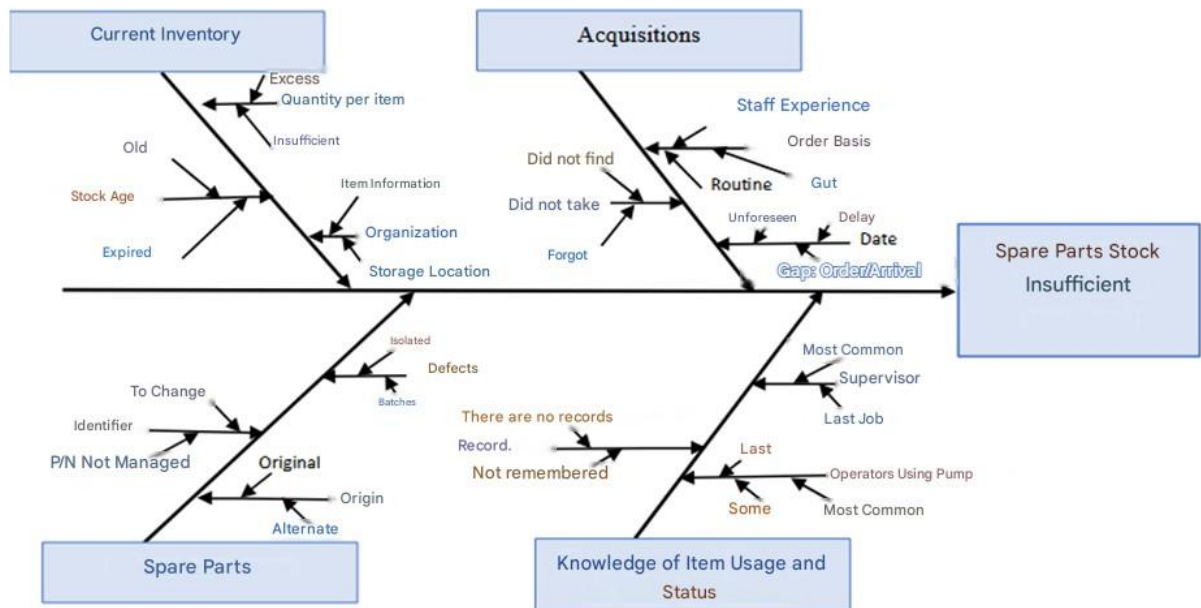


Figure 2:7: Cause and effect diagram. Unsatisfactory spare parts inventory.

Pumps are subjected to heavy use, and their proper operation depends largely on a suitable maintenance strategy. Regular monitoring, proper lubrication, and replacement of wear parts help prevent critical breakdowns, ensure continuous operation, and optimize operating costs.

The triplex pump is a precision pumping system designed for demanding environments. Its modular and robust construction allows for easy maintenance and adaptation to various fluids and operating conditions. Its design also ensures greater operational continuity with wear distributed across the three cylinders, making it a preferred choice for high-performance applications.

2.2.6 Maintenance control and data management

Maintenance control is the process of monitoring activities to ensure they are being performed according to the plan and achieving the desired results. In a Master's level maintenance study, this is represented as a closed-loop system where data drives decision-making.

2.2.6.1 Data Collection and Documentation

For ENAFOR, the control process begins at the rig site. Technical data must be captured accurately to provide a baseline for analysis. This includes:

- **Operating Hours:** Tracking the total running time of the 9-P-100 to trigger interval-based tasks (e.g., oil changes every 1,000 hours).

- **Failure Logs:** Recording the specific component that failed, the failure mode (e.g., washout, fatigue), and the "Down Time" required for repair.
- **Consumable Tracking:** Logging the lifespan of pistons, liners, and valves to identify poor-quality batches or abrasive mud conditions.

2.2.6.2 Key Performance Indicators (KPIs)

Data is transformed into management information through the calculation of specific reliability metrics. According to ISO 14224, the primary indicators for reciprocating pumps include:

- **MTBF (Mean Time Between Failures):** Measures the average time the pump operates before a failure occurs. A decreasing MTBF indicates a need to revise the maintenance interval.
- **MTTR (Mean Time to Repair):** Measures the average time required to bring the pump back to an operational state. High MTTR suggests issues with tool availability or crew training [5].
- **Availability:** The percentage of time the pump was capable of performing its function compared to the total time it was required.

2.2.6.3 The PDCA Cycle (Continuous Improvement)

The ultimate goal of maintenance control is Continuous Improvement, often modeled by the Deming Cycle (Plan-Do-Check-Act):

1. **Plan:** Establish the PMP based on manufacturer specs (National 9-P-100 Manual).
2. **Do:** Execute the maintenance tasks on the rig.
3. **Check:** Monitor the results using KPIs and rig reports.
4. **Act:** Adjust the plan (e.g., if valves fail every 200 hours instead of 500 due to sand, the inspection interval must be shortened) [8].

CHAPTER III: DEVELOPMENT OF THE MAINTENANCE PLAN FOR ENAFOR TRIPLEX PUMPS

CHAPTER III: DEVELOPMENT OF THE MAINTENANCE PLAN FOR ENAFOR TRIPLEX PUMPS

3.1 Introduction

The primary objective of this chapter is to design a comprehensive and optimized Preventive Maintenance Plan (PMP) specifically for the National 9-P-100 Triplex Mud Pump (figure 3.1). While the manufacturer (National Oilwell Varco) provides general guidelines, the unique operational conditions of the Algerian Sahara - characterized by extreme ambient temperatures, high silica concentrations in drilling fluids, and remote logistical challenges - require a more localized and rigorous maintenance approach.

This development process follows a logical progression:

- **Functional Decomposition:** A detailed breakdown of the pump's fluid and power end components to define the specific assets requiring intervention.
- **Failure Analysis:** Utilizing the tools established in Chapter II (FMEA and Ishikawa) to prioritize the most frequent and high-impact failure modes observed at ENAFOR rig sites.
- **Strategy Selection:** Determining the optimal balance between time-based (Preventive) and condition-based (Predictive) tasks for each critical component.
- **The Maintenance Schedule:** The creation of a standardized, hour-based digital tracking tool designed to maximize pump availability and minimize Non-Productive Time (NPT).

By the end of this chapter, the proposed plan will provide ENAFOR with a structured methodology to extend the MTBF (Mean Time Between Failures) of their Triplex fleet, ensuring safer and more cost-effective drilling operations [6].



Figure 3.1: National 9-P-100 Triplex Mud Pump

3.2 Analysis of ENAFOR Triplex Pump Operations

3.2.1 Functioning and Operation of the National P-Series at ENAFOR

The National 9-P-100 operates as a single-acting, reciprocating positive displacement pump. Its primary function is to convert the mechanical energy of a prime mover - typically a Caterpillar 3508 engine at ENAFOR sites - into the hydraulic energy required to circulate drilling fluid throughout the wellbore.

At a typical ENAFOR rig site, however, the pump operates under conditions significantly more demanding than the standard parameters assumed in manufacturer documentation. The following operational characteristics are particularly relevant to the development of this maintenance plan:

- **Continuous Duty Cycles:** The pump typically runs continuously for 12 to 24 hours periods during active drilling, with speeds varying from 30 to 120 strokes per minute (SPM) based on the bit hydraulics program.
- **High-Pressure Saharan Environment:** To survive these high-pressure operations in extreme ambient heat, two distinct lubrication systems (Power End oil and Fluid End liner wash) must function perfectly to prevent catastrophic component failure.
- **Fluid Abrasiveness:** The abrasive nature of the mud used in local formations places extreme stress on the "expendable" parts of the Fluid End, requiring a more aggressive maintenance interval than standard industrial settings.

3.2.1.1 Power End (PE) Lubrication System under Saharan Conditions

The Power End utilizes a dual-method lubrication system designed to protect the crankshaft, bearings, and crossheads from frictional heat and wear:

- **Splash Lubrication:** As the eccentric gear and crankshaft rotate, they agitate the oil reservoir, "splashing" oil onto internal components. This is effective above 30 SPM; however, at lower speeds (5 to 30 SPM), the manufacturer explicitly states that lubrication may be insufficient, requiring manual verification [4].
- **Pressure Lubrication:** A gear-driven internal pump forces oil through a suction strainer, filter, and heat exchanger. In the Algerian desert, where ambient heat causes rapid viscosity breakdown, the Heat Exchanger is a critical maintenance point to prevent oil film thinning.
- **The Abrasive Threat:** The primary threat in the Saharan context is abrasive contamination. Fine desert sand - with a median particle size of 150 to 300 micrometers and a hardness of 7

on the Mohs scale - infiltrates the system through deteriorated pony rod seals, unshielded vent plugs, or incorrectly seated inspection covers. Once these silica particles enter the bearing clearances (typically 0.003 to 0.006 inches), they cause three-body abrasive wear, reducing bearing life from thousands of hours to a few hundred [23].

3.2.1.2 Fluid End Piston/Liner Wash System

The liner wash system is an open auxiliary system designed to cool and lubricate the interface where the piston seal meets the liner wall. It circulates a 50/50 mixture of fresh water and soluble oil via a dedicated centrifugal pump.

➤ **Function and Mechanism:**

- **Thermal Protection:** The fluid cools the piston cup and liner, preventing the thermal degradation of the elastomeric seal material under Saharan heat.
- **Hydraulic Barrier:** It creates a barrier that flushes away any drilling mud and silica sand that "weeps" past the piston seals, preventing backward migration into the liner housing.

➤ **Operational Failures at ENAFOR Sites:** In practice, this system is the most frequent point of failure in the ENAFOR context due to:

- **Neglected Fluid Levels:** Leading to a dry system and catastrophic seal failure in minutes.
- **Contamination:** Failure to replace wash fluid when it becomes saturated with mud, which actually accelerates scoring.
- **Maintenance "Method" Issues:** As identified in the Ishikawa analysis, suction strainers in the wash tank frequently clog with sand and rubber debris, starving the system of cooling fluid [6].

A failed wash system results in a "wash-out" where high-pressure fluid bypasses the piston. This causes a complete loss of efficiency and transforms a simple piston replacement into a costly liner overhaul.

3.2.2 Structure, Components and Description

The 9-P-100 is divided into two primary sections: the Power End, which houses the drive mechanism, and the Fluid End, which handles the high-pressure drilling mud (figure 3.2).

3.2.2.1 Power End (PE)

The Power End is the "engine" of the pump, responsible for converting the rotating motion of the drive shaft into the reciprocating motion required for pumping.

- **The Frame:** A high-strength steel fabrication that houses all internal components and serves as the oil reservoir.
- **Crankshaft and Eccentric Gear:** The core of the drive system. The 120-degree offset of the eccentric gears ensures that at least one piston is always on a pressure stroke, reducing discharge pulsations.
- **Connecting Rods and Crossheads:** These components bridge the PE and FE. The crosshead slides within replaceable guides, ensuring that only linear (straight) force is transmitted to the piston rods, preventing side-loading that would destroy the seals.
- **Bearings:** The pump utilizes heavy-duty roller bearings. In the Saharan context, these are vulnerable to metal fatigue if the lubrication system (Section 4.2.1.1) fails to dissipate heat effectively [4].

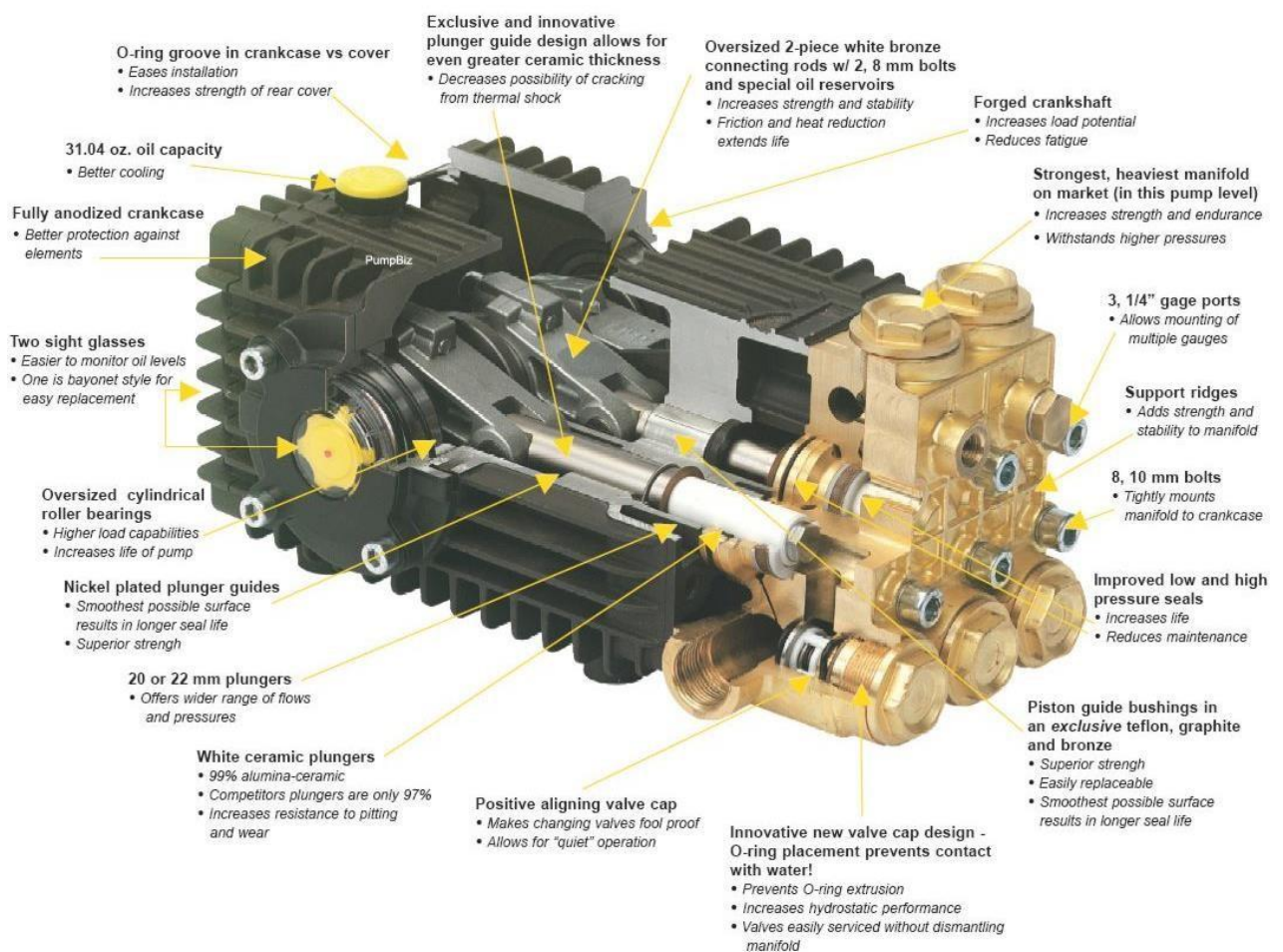


Figure 3.2: triplex pump composition

3.2.2.2 Fluid End (FE)

The Fluid End is where the actual pumping work occurs. It is the section most exposed to the abrasive and corrosive nature of drilling mud.

- **Fluid Modules (Pots):** The 9-P-100 features three separate, interchangeable forged-steel modules. This design allows ENAFOR technicians to replace a single module if it becomes "washed out" without replacing the entire fluid end (figure 3.3).
- **Valves and Seats:** These act as the check valves of the system. The suction valve opens to let mud in, and the discharge valve opens to push it toward the standpipe.
- **Liner and Piston:** These are the primary "expendables." The piston moves inside the liner to create pressure. In Algeria, the high silica (sand) content in the mud creates a "slurry" effect that causes rapid abrasive wear on these surfaces [6].
- **Pulsation Dampener:** Mounted on the discharge manifold, it contains a nitrogen-filled bladder that absorbs the "shocks" from the reciprocating pistons, protecting the downstream piping from fatigue.

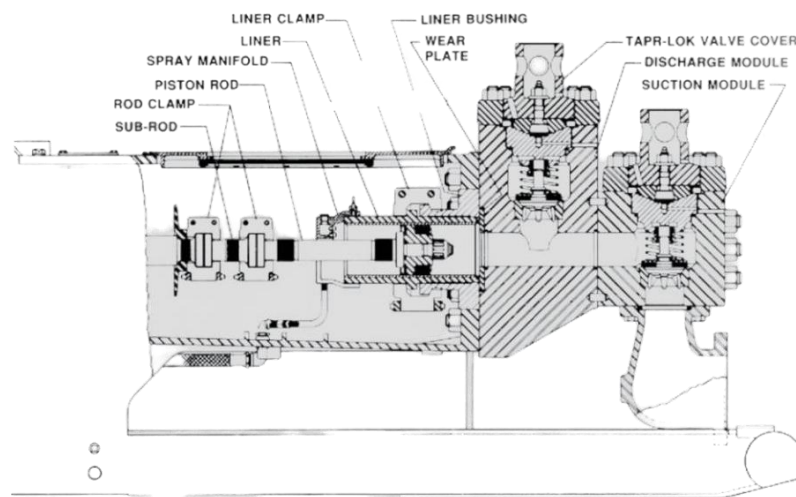


Figure 3.3: Technical Cutaway View of a Triplex Mud Pump Illustrating Internal Architecture.

3.3 Current Maintenance Situation at ENAFOR Rig Sites

3.3.1 Analyze of Operating Procedures

The operational efficiency of a Triplex pump is not solely dependent on its mechanical design, but heavily influenced by the Standard Operating Procedures (SOPs) followed by the rig crew. At ENAFOR, these procedures can be categorized into three critical phases:

1. Pre-Operation and Startup

Before the pump is engaged to circulate mud downhole, several manual checks are performed. However, observations suggest that in high-pressure drilling environments:

- **Priming:** Ensuring the suction line is fully primed to avoid cavitation. Cavitation in the Algerian heat can lead to instantaneous "pitting" of the valve seats.
- **Lubrication Levels:** Checking the oil level in the Power End and the water/lubricant level in the Liner Wash tank.
- **Pre-heating:** In colder Saharan winter nights, jumping straight to high SPM (Strokes Per Minute) without letting the oil reach operating temperature can cause bearing stress [11].

2. In-Service Monitoring

While the pump is running, the "Watch" procedure involves monitoring specific parameters:

- **Discharge Pulsation:** Observing the pulsation dampener gauge. If the needle vibrates excessively, it indicates a bladder failure or incorrect nitrogen pre-charge.
- **Liner Temperature:** Operators often check the temperature of the liners using infrared guns. Excessive heat is a leading indicator of a failure in the Piston/Liner Lubrication (Wash System).
- **Vibration and Noise:** Acoustic monitoring is the primary "Condition-Based" tool used by ENAFOR mechanics to detect internal knocking (often caused by loose crosshead guides or worn bearings) [10].

3. Shutdown and post-operation

The procedure for stopping the pump is just as critical as the startup:

- **Flushing:** If the pump is to be idle for an extended period, the fluid end must be flushed to prevent mud from settling and "drying" around the valves, which would make the next startup much more difficult and damaging to the seals.

4. Critical Observations in the Current SOPs

- **Lack of Digital Logging:** Most operating data is observed in real-time but not always logged for long-term trend analysis.
- **Variation in Skill Levels:** Procedures often vary between different rig crews, leading to inconsistent wear patterns across the ENAFOR fleet.
- **Calculation Errors:** Manual tracking makes it difficult for crews to accurately predict the remaining life of components when a pump is moved between rigs or when drilling conditions change. This often leads to 'Run-to-Failure' scenarios rather than proactive replacement.

3.3.2 Problems Related to Desert Operations

The Saharan environment introduces two primary stressors - extreme heat and high silica (sand) content - that deviate from standard manufacturer operating conditions.

3.3.2.1 Analysis of Sand/Heat Impact on Seals

The high ambient temperatures in regions like Hassi Messaoud reduce the viscosity of the Power End lubricating oil, leading to "Oil Thinning." Simultaneously, fine sand particles act as an abrasive medium.

- **Thermal Degradation:** High heat causes the elastomer seals (piston rubbers and valve inserts) to lose elasticity, leading to "brittle failure."
- **Abrasive Incursion:** Sand bypassing the Liner Wash System creates micro-scratches on the liner surface, which quickly escalate into high-pressure "washouts" [22].

3.3.2.2 Summary of Recurrent Failures

To quantify these problems, a summary of failure frequency was conducted. As shown in the analysis below (Table 3.1), the "Fluid End" components bear the brunt of desert operations.

Table 3.1: Summary of Most Frequent Failure Modes Observed in ENAFOR Triplex Pump Fleet

Component	Failure Mode	Primary Cause (Desert)	Observed Consequence
Piston Cup	Premature wear / wash-out	Dry or contaminated liner wash; heat hardening	Loss of discharge pressure; NPT
Valve Disc/Seat	Erosive wear; disc cutting	High solids content in mud; abrasive fluid	Pressure pulsations; reduced pump output
Crankcase Bearings	Abrasive wear; seizure	Sand infiltration into crankcase oil	Knock; overheating; catastrophic PE failure

Valve Cover O-Ring	Heat cracking; compression set	Thermal degradation; over-torquing	High-pressure leak; safety hazard
Pony Rod Seal	Abrasive wear; leak	Sand exposure; improper installation	Sand enters crankcase; oil leak at PE rear
Liner	Scoring; bore enlargement	Failed liner wash; abrasive piston contact	Piston cup failure; costly liner replacement

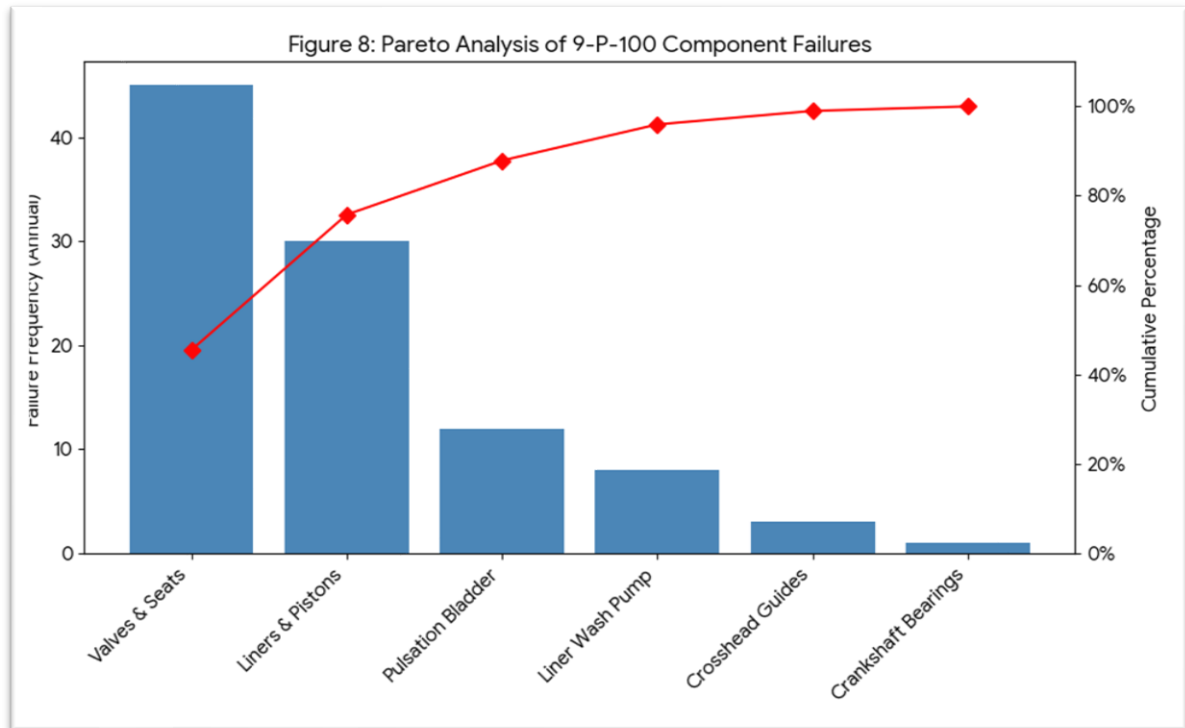


Figure 3.4: Pareto Analysis of 9-P-100 Component Failure Frequency.

Analysis of Figure 3.4: The "Summary of Recurrent Failures" clearly identifies that while the desert environment impacts the entire pump, 80% of the maintenance workload is concentrated on the expendable parts of the Fluid End.

3.4 FMEA – Failure Mode and Effects Analysis for the National 9-P-100 / 12-P-160

The FMEA was conducted on the primary components of both the Power End and Fluid End of the National P-Series pump, with specific consideration of the ENAFOR Saharan operating conditions. The RPN scores reflect the operational experience documented in Table 3.2 and the theoretical severity of each failure mode.

The RPN is calculated as: $RPN = \text{Severity (S)} \times \text{Occurrence (O)} \times \text{Detectability (D)}$, where each factor is rated on a scale of 1 to 10. The threshold for priority preventive action is set at $RPN \geq 100$.

Table 3.2: FMEA for National P-Series Triplex Mud Pump – Power End and Fluid End

Component	Failure Mode	Effect of Failure	Probable Cause	S (1-10)	O (1-10)	D (1-10)	RPN (S×O×D)
Piston Cup	Wash-out / leakage past piston	Loss of discharge pressure; NPT	Dry liner wash; sand in mud	7	9	3	189
Suction Valve Disc/Seat	Erosive wear; seat pitting	Pump pounding; reduced output	Abrasive mud; high solids	6	8	4	192
Discharge Valve Disc/Seat	Erosive wear; disc extrusion	Pressure loss; NPT	Abrasive mud; high pressure spikes	7	7	3	147
Main Crankshaft Bearings	Abrasive wear; seizure	PE catastrophic failure; major NPT	Sand-contaminated gear oil	9	5	4	180
Conn. Rod Bearings	Abrasive wear; knock	Crankshaft damage; major repair	Contaminated oil; delayed oil change	8	5	4	160
Valve Cover O-Ring	Extrusion; compression set failure	High-pressure fluid leak; personnel hazard	Heat; over-torquing; age	8	6	5	240
Pony Rod Seal	Wear; leakage	Sand enters crankcase; oil contaminated	Abrasive sand; aged seal	7	6	3	126
Liner (Chrome Bimetal)	Scoring; bore enlargement	Piston cup failure; total liner replacement	Dry liner wash; abrasive piston	6	4	5	120
Pulsation Dampener	Diaphragm failure; loss of dampening	Pressure surges; drill string damage	Over-inflation; check not performed	6	4	4	96
Crosshead / Guide	Wear; misalignment	Lateral forces on liner; accelerated cup wear	Insufficient grease; sand infiltration	5	5	6	150

Analysis of Table 3.2 reveals that the five highest-priority failure modes ($RPN \geq 147$) are: the valve cover O-ring ($RPN = 240$), the suction valve disc/seat ($RPN = 192$), the piston cup ($RPN = 189$), the main crankshaft bearings ($RPN = 180$), and the discharge valve disc/seat ($RPN = 147$). These five items constitute the critical path of the Preventive Maintenance Plan developed in Section 3.6.

3.4.1 ESTABLISHING MAINTENANCE INTERVALS

The core of the proposed solution is a transition from static, calendar-based maintenance to a Dynamic Hour-Based Tracking System. By utilizing the read hours from the pump's counter, the plan ensures that maintenance is performed exactly when the mechanical wear requires it, regardless of whether the rig is drilling or moving.

1. Functional Grouping of Tasks

To simplify the workflow for ENAFOR technicians, the maintenance requirements for the National 9-P-100 have been organized into five specialized categories, as reflected in the digital tracker:

- **Group A (Lubrication & Daily Checks):** High-frequency tasks performed every 8 hours. This includes critical Saharan checks like Power End oil levels and cam-shaft greasing.
- **Group B (Fluid End - The "Vital Few"):** This group targets the components identified in our Pareto analysis. Intervals are aggressive to combat sand abrasion, ranging from 25 to 250 hours for valves, seats, and piston seals.
- **Group C (Power End):** Intermediate mechanical inspections scheduled every 500 hours to monitor internal clearances and oil filtration quality.
- **Group D (Auxiliary Systems):** Monthly or 250 hours checks of pulsation dampeners and discharge strainers to protect downstream high-pressure lines.
- **Group E (Major Overhauls/Jalons):** Strategic milestones at 2000 and 3000 hours for full fluid-end and power-end revisions (e.g., the overhaul completed in January 2026 at 2600 h).

2. Digital Tracking and "Traffic Light" Logic

The proposed Excel-based tool eliminates human calculation errors by using an automatic status algorithm. As seen in figure 3.5, the system compares the "Current Counter" against the "Next Due" hour to provide instant visual feedback:

- **✓ OK:** The component is within its safe operating window.
- **🔔 BIENTÔT (Soon):** A predictive alert triggered when a component has ≤ 20 hours of remaining life. This allows the tool-pusher to prepare spare parts before the pump actually needs to stop.
- **⚠ DÉPASSÉ (Overdue):** A critical red alert indicating that the maintenance window has been missed, significantly increasing the risk of a "washout" or mechanical failure.

PROGRAMME DE MAINTENANCE — POMPE À BOUE TRIPLEX NATIONAL OILWELL 9-P-100																			
Équipement :		Pompe à Boue Triplex 9-P-1		N° Série : 9P-100-2025-0042		Année : 2026		Drilling Site — Champ Hassi Berkine											
Heures compteur (cumul mensuel) :		2,600	2,650	2,700	2,750	2,800	2,850	2,900	3,000	Heures cumulées lues sur le compteur chaque fin de mois									
		PLANIFICATION MENSUELLE 2026 (✓ = Fait, X = Non fait, — = Non applicable, ⇄ = Plannifié)																	
N°	ACTIVITÉ DE MAINTENANCE	FRÉQ. (Heures)	JAN	FEB	MAR	AVR	MAI	JUN	JUL	AOU	SEP	OCT	NOV	DEC	RESPONSABLE	OBSERVATIONS			
A — GRAISSAGE ET LUBRIFICATION																			
A1	Vérifier niveau huile engrenage (pompe arrière)	Journalier	8 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	A. Benati	Huile AGMA EP#7 — niveau OK tous les jours			
A2	Graisser roulements arbre à came (2 coups manuel)	Journalier	8 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	A. Benati	Graisse NLGI 1 — 2 coups/jour			
A3	Vérifier niveau fluide chimise (50% eau + 50% huile)	Journalier	8 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	A. Benati	Mélange 50/50 — niveau contrôlé quotidiennement			
A4	Changement d'huile engrenage + nettoyage carter	Semestriel	1 000 h	—	—	—	—	—	—	—	✓	⇄	⇄	⇄	M. Khaldi	3ème vidange à 3 000 h effectuée en Sep — 360 L AGMA EP#7 — Prochaine à 4 000 h			
B — HYDRAULIQUE / FLUID-END																			
B1	Observer état chemises & pistons – vérifier by-pass	Journalier	8 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	A. Benati	Chemises remplacées à 2 750 h (Apr) — by-pass normal depuis			
B2	Nettoyer Chambres de chemise si nécessaire	Journalier	8 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	A. Benati	Nettoyage hebdo intégré à la ronde quotidienne			
B3	Vérifier serrage écrous à oreilles + buses vaporisation	Journalier	8 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	A. Benati	Buses débouchées en Mar — OK depuis			
B4	Vérifier charge amortisseur d'aspiration	Journalier	8 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	A. Benati	Pression maintenue à 15 psi — rechargé en Jun (pompe air manuel)			
B5	Nettoyer coins de blocage + enduire pâte plomb	Hebdomadaire	50 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Effectué chaque semaine — pâte frittage renouvelée			
B6	Nettoyer bouchon conique + inspecter garniture cylindre	Hebdomadaire	50 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Garniture remplacée en Mar à 2 800 h — OK depuis			
B7	Inspecter guide supérieur tige de vanne	Hebdomadaire	50 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Plèce rapportée remplacée en Fév — état bon			
B8	Inspecter soupapes & sièges – remplacer si usés	Hebdomadaire	50 h	✓	✓	X	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Disques remplacés en Mar et Juil — sièges OK			
B9	Remplacer écrou de blocage tige de piston (max 3x)	Hebdomadaire	50 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Écrous renouvelés à 2 600 / 2 700 / 2 850 h — compteur réinitialisé			
B10	Nettoyer couvercles + filets vis/écrou de bague	Semi-hebdo.	100 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Nettoyage bi-mensuel — pâte plomb appliquée à chaque fois			
B11	Vérifier serrage goujons & écrous cylindres	Mensuel	250 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Serrage au couple dynamométrique — aucun desserrage anormal			
B12	Nettoyer raccord de décharge en croix	Mensuel	250 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Crépine nettoyée chaque mois — dépôts normaux boue			
B13	Inspecter & remplacer lécumeurs de tige si usés	Mensuel	250 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Lécumeurs remplacés en Avr et Aoû — usure normale			
C — MÉCANIQUE / POWER-END																			
C1	Vérifier tension courroies / chaînes de transmission	Hebdomadaire	50 h	✓	✓	✓	✓	✓	✓	✓	✓	⇄	⇄	⇄	M. Khaldi	Tension ajustée en Mar et Jun — aucun dommage roulement			
C2	Nettoyer et inspecter aimants dans les aubes (capot)	Semestriel	1 000 h	✓	—	—	—	—	—	—	✓	⇄	⇄	⇄	M. Khaldi	Inspecté à 2 000 h (Jan) et 3 000 h (Sep) — dépôts ferreux normaux			
C3	Vérifier aimant et bouchon de vidange (changement huile)	Semestriel	1 000 h	✓	—	—	—	—	—	—	✓	⇄	⇄	⇄	M. Khaldi	Vérifié lors des vidanges à 2 000 h (Jan) et 3 000 h (Sep)			
C4	Nettoyer bacs à huile – changement complet d'huile	Semestriel	1 000 h	✓	—	—	—	—	—	—	✓	⇄	⇄	⇄	M. Khaldi	Bacs nettoyés lors des vidanges — aucune contamination eau détectée			
C5	Vérification générale roulements & paliers	Annuel	2 000 h	✓	—	—	—	—	—	—	—	⇄	⇄	⇄	Chief maint.	Révision effectuée en Jan 2026 à 2 600 h — roulements en bon état — prochaine à 4 600 h			
D — SOUPAPES DE SÉCURITÉ & AMORTISSEURS																			

Figure 3.5: Digital Interface for Real-Time Hour-Based Maintenance Tracking.

SUIVI DE MAINTENANCE PAR HEURES — POMPE À BOUE TRIPLEX NATIONAL OILWELL 95P-100											
5) FONCTIONNEMENT AUTOMATIQUE — 1) Mettez à jour E5 (orange) avec les heures actuelles du compteur → tout se recalcule. 2) Après chaque intervention : saisissez les heures dans col. E (jaune) → le compteur repart à zéro pour cette tâche. 3) Statut automatique : ✓ OK / ⚡ BIEN TÔT (<20h) / ⚠ DÉPASSÉ											
→ Compteur actuel : 3 000 h Mettre à jour à chaque lecture Toutes les colonnes recalculent automatiquement											
HEURES COMPTEUR ACTUEL : 3,000											
N°	ACTIVITÉ DE MAINTENANCE	DURÉE DE VIE (heures)	DERNIÈRE INTERV. (h)	PROCHAINE ÉCHÉANCE (h)	HEURES RESTANTES	% VIE UTILISÉE	STATUT	DATE INTERV.	TECHNICIEN	ÉTAT PIÈCE	OBSERVATIONS
A1	Vérifier niveau huile engrenage	8	2,998	3,006	6	25%	⚡ BIEN TÔT	21/04/2026	A. Benali	BON	Niveau OK — huile AGIMA EP#7 vérifiée en fin de poste
A2	Graisser roulements arbre à came (2 coups manuel)	8	2,998	3,006	6	25%	⚡ BIEN TÔT	21/04/2026	A. Benali	Bon	2 coups graisse NLGI 1 effectués
A3	Vérifier niveau fluide chimie (50% eau + 50% huile)	8	2,998	3,006	6	25%	⚡ BIEN TÔT	21/04/2026	A. Benali	Bon	Mélange 50/50 — niveau correct
B1	Observer état chemises & pistons - by-pass	8	2,998	3,006	6	25%	⚡ BIEN TÔT	21/04/2026	A. Benali	Bon	Chemises remplacées à 2 750 h — by-pass normal depuis
B4	Vérifier charge amortisseur aspiration	8	2,998	3,006	6	25%	⚡ BIEN TÔT	21/04/2026	A. Benali	Bon	Pression 15 psi stable — recharge en Juin à 2 850 h
D1	Contrôler pression amortisseur aspiration	8	2,998	3,006	6	25%	⚡ BIEN TÔT	21/04/2026	A. Benali	Bon	Pression stable 15 psi — aucune intervention requise
E1	Inspection visuelle — fuites, bruits anormaux	8	2,998	3,006	6	25%	⚡ BIEN TÔT	21/04/2026	A. Benali	Bon	Fuite joint défectueux en Fév — remplacé immédiatement
B5	Nettoyer coins de blocage + pâte plomb	50	2,975	3,025	25	50%	✓ OK	18/04/2026	M. Khaldi	Bon	Nettoyage hebdo — pâte fléage renouvelée
B6	Inspection garniture + cylindre bouchon	50	2,975	3,025	25	50%	✓ OK	18/04/2026	M. Khaldi	Bon	Garniture remplacée à 2 800 h (Mai) — OK depuis
B7	Inspection guide supérieur tige de vanne	50	2,975	3,025	25	50%	✓ OK	18/04/2026	M. Khaldi	Bon	Pièce rapportée remplacée à 2 850 h (Fév)
B8	Inspection soupapes & sièges – remplacer si usés	50	2,975	3,025	25	50%	✓ OK	18/04/2026	M. Khaldi	Bon	Disques remplacés à 2 700 h (Mar) et 2 900 h (Jui)
B9	Remplacer écrou blocage tige piston (max 3x)	50	2,975	3,025	25	50%	✓ OK	18/04/2026	M. Khaldi	Bon	3ème jeu écrous posés à 2 950 h — prochains à 3 025 h
C1	Vérifier tension courroies / chaînes	50	2,975	3,025	25	50%	✓ OK	18/04/2026	M. Khaldi	Bon	Tension ajustée à 2 700 h (Mar) et 2 850 h (Jun)
B2	Nettoyer chambres de chemise si nécessaire	50	2,975	3,025	25	50%	✓ OK	18/04/2026	A. Benali	Bon	Nettoyage intégré à la ronde hebdomadaire
B3	Vérifier écrous oreilles + buses vaporisation	50	2,975	3,025	25	50%	✓ OK	18/04/2026	A. Benali	Bon	Buses débouchées à 2 700 h (Mar) — OK depuis
B10	Nettoyer couvercles + filets vis/écrou bague	100	2,950	3,050	50	50%	✓ OK	15/04/2026	M. Khaldi	Bon	Nettoyage bi-mensuel — pâte plomb appliquée
B11	Vérifier serrage goujons & écrous cylindres	250	2,850	3,100	100	60%	✓ OK	01/04/2026	M. Khaldi	Bon	Serrage dynamométrique — aucun desserrage anormal
B12	Nettoyer raccord de décharge en croix	250	2,850	3,100	100	60%	✓ OK	01/04/2026	M. Khaldi	Bon	Crépine nettoyée — dépôts normaux boue
B13	Inspection & remplacer fileurs de tige	250	2,750	3,000	0	100%	⚠ DÉPASSÉ	15/03/2026	M. Khaldi	Remplacé	Lecheurs remplacés à 2 750 h (Avr) et 2 950 h (Août)
D2	Tester soupape de décharge (70 psi aspiration)	250	2,850	3,100	100	60%	✓ OK	01/04/2026	M. Khaldi	Bon	Tarage vérifié et ajusté à 2 750 h (Avr)
D3	Contrôler amortisseur de pulsation retourlement	250	2,850	3,100	100	60%	✓ OK	01/04/2026	M. Khaldi	Bon	Membrane remplacée à 2 800 h (Mai) — OK depuis
D4	Inspection tamis / crépine de décharge	250	2,850	3,100	100	60%	✓ OK	01/04/2026	M. Khaldi	Bon	Comatage partiel noté à 2 900 h (Jui) — nettoyé
E2	Vérifier serrage boulonnerie générale	250	2,850	3,100	100	60%	✓ OK	01/04/2026	M. Khaldi	Bon	Boulons chassias resserrés à 2 700 h et 2 950 h
A4	Changement huile engrenage complet (350 L)	1,000	3,000	4,000	1,000	0%	✓ OK	21/04/2026	M. Khaldi	Bon	2ème change d'huile à 3 000 h — AGIMA EP#7 — prochaine à 4 000 h
C2	Inspection aimants dans les auges (capot)	1,000	3,000	4,000	1,000	0%	✓ OK	21/04/2026	M. Khaldi	Bon	Nettoyage à 2 000 h (Jan) et 3 000 h (Sep) — dépôts ferreux
C3	Vérifier aimant + bouchon de vidange	1,000	3,000	4,000	1,000	0%	✓ OK	21/04/2026	M. Khaldi	Bon	Vérifié lors des vidanges à 2 000 h et 3 000 h — BAS
C4	Nettoyer bacs à huile – vidange complète	1,000	3,000	4,000	1,000	0%	✓ OK	21/04/2026	M. Khaldi	Bon	Bacs nettoyés lors des vidanges — aucune contamination eau
C5	Vérification générale roulements & paliers	2,000	2,600	4,600	1,600	20%	✓ OK	15/01/2026	Chief maint.	Bon	Révision entrecuée à 2 000 h (Jan 2026) — prochaine à 4 600 h
E3	Révision complète fluid-end	2,000	2,600	4,600	1,600	20%	✓ OK	15/01/2026	Chief maint.	Bon	Kit révision NOI – durée 2 jours — prochaine à 4 600 h
E4	Révision complète power-end	2,000	2,600	4,600	1,600	20%	✓ OK	15/01/2026	Chief maint.	Bon	Engrenages et roulements OK — prochaine à 4 600 h

Figure 3.6: Annual Preventive Maintenance Schedule and Task Forecasting.

3.5 Ishikawa Root Cause Analysis – Primary Failure Mode: Valve Cover O-Ring Failure

The valve cover O-ring, with the highest RPN of 240 in the FMEA, is selected as the primary subject of an Ishikawa root cause analysis to illustrate the structured diagnostic approach applied in this

thesis. The failure is defined as: premature leakage or extrusion of the valve cover O-ring, leading to a high-pressure fluid leak at the FE module.

The causal analysis, organized by the six main categories, reveals:

- Machine: Over-pressurization due to water hammer events caused by improper pump startup procedures; excessive surface roughness in the O-ring groove due to corrosion or mechanical damage.
- Method: Over-torquing the wing nut (compressing the O-ring beyond its design compression ratio, causing extrusion); improper installation alignment of the valve cover; failure to apply lubricant to the O-ring before installation.
- Material: Use of O-rings with incorrect elastomer grade (e.g., natural rubber instead of HNBR or polyurethane in high-temperature summer conditions); storage of spare O-rings at elevated temperatures on the rig, causing pre-aging.
- Man: Lack of training on correct wing nut torque values; failure to inspect O-ring condition prior to re-installation; no systematic replacement interval defined in the current procedures.
- Measurement: Absence of pressure gauge on the liner wash system, making it impossible to detect internal leakage at the O-ring as an early warning sign; no systematic dimensional check of O-ring groove condition.
- Milieu (Environment): Extreme heat ($> 45^{\circ}\text{C}$ ambient) accelerates thermo-oxidative degradation of elastomers, dramatically reducing the service life of the O-ring beyond the manufacturer's temperate-climate specification.

The root cause analysis directly informs the maintenance plan: O-ring replacement must be scheduled weekly (not only at visible failure), the correct elastomer grade must be specified for Saharan conditions, and wing nut torque must be applied with a calibrated torque wrench to prevent over-compression.

3.6 Proposed Preventive Maintenance Plan – Detailed Schedule

The Preventive Maintenance Plan (PMP) presented in this section is derived from three primary sources: (1) the National Oilwell P-Series Maintenance Manual (the authoritative manufacturer specification), (2) the FMEA criticality analysis presented in Table 3.1, and Table 3.2 the Sahara-specific environmental adjustments justified by the field situation analysis of Section 3.3. Where manufacturer intervals are deemed insufficient for the Algerian desert environment, reduced intervals (increased frequency) are specified and the technical justification is provided.

Table 3.3: Daily Preventive Maintenance Tasks – National P-Series Triplex Mud Pump at ENAFOR

No.	Component / System	Task Description	Method / Tool	Reference / Justification
D-01	Power End – Crankcase Oil [A]	Check oil level. Oil must be visible on sight glass. Top up if below MIN mark. Inspect oil color: discard if cloudy, black, or contains visible particles.	Sight glass; dipstick. Pump STOPPED.	NOV Manual p.43; FMEA Main Bearings (RPN 180)
D-02	Crosshead Pin Grease [B]	Apply 2 strokes of NLGI Grade 1 lithium-base grease to each of the three crosshead pin grease fittings using a hand grease gun.	Hand grease gun; NLGI 1 grease.	NOV Manual p.43; FMEA Crosshead (RPN 150)
D-03	Liner Wash System [C]	Check liner wash fluid reservoir level. Fluid must be 50% fresh water + 50% soluble oil. Top up if below 1/2 level. Inspect fluid color; replace if brown/muddy. Verify all three spray nozzles are unobstructed.	Visual inspection; measure fluid.	NOV Manual p.43; FMEA Piston Cup (RPN 189)
D-04	Piston / Liner Assembly	Monitor discharge pressure and stroke counter. Compare actual output vs. expected output based on liner size and spm. A pressure drop of >5% at constant spm indicates possible piston cup wash-out. Record values in log.	Pressure gauge; stroke counter; log sheet.	FMEA Piston Cup (RPN 189); ISO 14224
D-05	Valve / Module Inspection	Listen for abnormal knock or pressure fluctuation ('pounding') indicative of valve disc or seat damage. Record any anomaly in log.	Auditory monitoring; pressure recorder.	FMEA Suction Valve (RPN 192); NOV Manual
D-06	Pulsation Dampener	Check dampener charge pressure as per sight gauge on dampener body. Charge is typically 15 psi (1 bar) pre-charge before pump start. Verify no fluid leak at dampener flange.	Visual; pressure gauge on dampener.	NOV Manual; FMEA Dampener (RPN 96)

D-07	Crankcase Exterior / Vent Plugs	Inspect crankcase exterior for any oil seepage at rear seal (pony rod area) or inspection cover plates. Ensure vent plugs are clean and unobstructed. Remove sand accumulation from vent plug area.	Visual; brush for sand removal.	Section 3.3.2.1 – Sand infiltration analysis
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Table 3.4: Weekly Preventive Maintenance Tasks – National P-Series Triplex Mud Pump at ENAFOR

No.	Component / System	Task Description	Method / Tool	Reference / Justification
W-01	Valve Cover O-Ring and Wing Nut	STOP PUMP. Remove valve cover. Inspect O-ring; replace if any hardening, cracking, or permanent deformation is visible. Clean O-ring groove. Lubricate new O-ring lightly with compatible grease before installation. Re-torque wing nut to manufacturer specification. Apply anti-seize to threads.	Torque wrench; O-ring pick; anti-seize compound.	FMEA O-Ring (RPN 240) – Highest Priority. NOV Manual p.44 (point 7, Weekly).
W-02	Suction and Discharge Valve Inspection	Remove valve cover (per W-01). Lift out valve assembly. Inspect disc face and seat surface for pitting, grooving, or material loss. Replace disc if any damage visible. Inspect spring; replace if deformed. Clean seat with lint-free cloth. Reassemble per SOP.	Valve removal tool; lapping kit if required; new valve kits.	FMEA Suction Valve (RPN 192); NOV Manual p.44 (point 9).
W-03	Pony Rod and Seal Area	Inspect the area around the pony rod where it exits the rear PE housing. Check for oil seepage (indicating worn seal) or sand accumulation around the seal area. Replace pony rod seal if any leak is detected.	Visual; clean rag; seal replacement kit.	FMEA Pony Rod Seal (RPN 126); Section 3.3.2.1.
W-04	Wing Nut Thread Cleaning	Clean both sides of each valve cover wing nut blocking element. Apply a lead-based thread compound for coarse threads (anti-seize). Inspect valve cover guide (upper valve rod guide) for wear; replace if worn.	Wire brush; anti-seize compound (lead-based per NOV spec.).	NOV Manual p.44 (points 6 and 7).
W-05	Liner Wash Nozzle Inspection	Remove and inspect each liner wash nozzle for blockage by sand or dried mud. Clean with compressed air. Verify spray pattern direction is correct (aimed at liner / piston cup contact zone).	Compressed air; nozzle cleaning kit.	Section 3.3.1 – Neglected liner wash system analysis.

W-06	Nut and Bolt Torque Check	Check tightening of all cylinder rod lock nuts (wing nuts). Check tightening of all module-to-module and module-to-PE bolts. Apply required torque with calibrated torque wrench. Replace any lock nut that has been used 3 times (stretched bolt risk).	Calibrated torque wrench; torque chart from manual.	NOV Manual p.44 (point 10); NOV safety warning re: piston rod nut torque.
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Table 3.5: Bi-Weekly / Semi-Monthly Preventive Maintenance Tasks

No.	Component / System	Task Description	Method / Tool	Reference / Justification
BW-01	Piston Cup and Liner Condition Check	With pump stopped and pressure bled, remove valve cover and access the piston area through the module. Using a light and mirror, inspect the condition of the liner bore surface for scoring or corrosion streaks. Inspect piston cup for wear or deformation. Record wear observation in log. Replace piston cup if wear indicator grooves are no longer visible.	Inspection light; mirror; piston cup gauge.	FMEA Piston Cup (RPN 189); NOV Manual p.44 (point 1).
BW-02	Crankcase Inspection Covers	Remove and clean inspection covers on both sides of the crankcase. Inspect for the presence of sand deposits inside the crankcase, which indicate pony rod seal leakage. Inspect the crankshaft and gear teeth for abnormal wear or pitting. Replace covers, checking gasket condition.	Inspection light; clean rags; gasket material.	NOV Manual p.44 (point 16); Section 3.3.2.1 sand analysis.

Table 3.6: Monthly Preventive Maintenance Tasks

No.	Component / System	Task Description	Method / Tool	Reference / Justification
M-01	All Module Studs and Cylinder Nuts	Verify tightening torque of all module stud nuts and cylinder flange bolts according to the torque table in the NOV manual. Thermal cycling in the Sahara loosens threaded connections; this check is increased to monthly from the manufacturer's recommended interval.	Calibrated torque wrench; torque specification chart.	NOV Manual p.44 (points 12); ENAFOR adaptation for Saharan thermal cycling.
M-02	Discharge Cross and Safety Relief Valve	Remove and clean the discharge cross manifold; inspect the internal sieve/strainer screen. Clean or replace if blocked. Inspect and test the discharge safety relief valve; it must be set at 10% above the maximum line pressure. If in doubt, replace.	Pipe wrench; pressure test kit; clean rags.	NOV Manual p.44 (points 13, 14); API RP 7L Section 5.
M-03	Crosshead Guide Clearance Check	Measure the diametral clearance between the crosshead and crosshead guide (wrist pin bore) using feeler gauges. Maximum permissible clearance per NOV specification: 0.010 inches. If exceeded, crosshead or guide must be replaced at next scheduled shutdown to prevent lateral forces on piston rod.	Feeler gauge set; NOV tolerance tables.	FMEA Crosshead/Guide (RPN 150); Section 3.2.2.1.
M-04	Crankcase Oil Sampling	Withdraw a 100ml sample of crankcase gear oil using a clean sample syringe from the drain port. Send sample to oil analysis laboratory for: viscosity check, water content, particle count and classification (ISO 4406), and wear metal spectrometry (Fe, Cu, Pb, Si). Si content > 50 ppm indicates sand infiltration and requires immediate oil change and source investigation.	Sample syringe; sample bottle; laboratory submission form.	ISO 14224 data collection; FMEA Main Bearings (RPN 180); Section 3.3.2.2.
M-05	Crosshead Cover Lubrication Verification	Temporarily remove crosshead cover plates with pump running slowly (5–30 SPM). Verify that oil is visibly reaching the crosshead sliding surfaces. If dry, adjust the crosshead wiper arm to correct oil delivery. Reinstall covers securely.	Wrench; inspection light. SAFETY: ensure no personnel contact with moving parts.	NOV Manual p.11 (Fonctionnement basse vitesse) ; FMEA Cross Head (RPN 150).

Table 3.7: Semi-Annual Preventive Maintenance Tasks (Major Overhaul)

No.	Component / System	Task Description	Method / Tool	Reference / Justification
SA-01	Full Crankcase Oil Change and Flushing [A]	Pump stopped and locked out. Drain the entire crankcase gear oil. Remove and inspect both magnetic drain plugs; quantify and classify metallic debris. Flush crankcase interior with a light flushing oil. Refill with new, correct-grade AGMA EP gear oil per ambient temperature range (Table III.3). Record oil grade, quantity, and date in log.	Oil drain containers; flushing oil; new oil (95 gallons / 360L for 9-P-100; 130 gal / 492L for 12-P-160).	NOV Manual p.43 (Calendrier de Graissage, Semestrial); ISO 14224 data recording.
SA-02	Main and Connecting Rod Bearing Inspection	Remove crankcase inspection covers (both sides) and main bearing caps. Inspect main bearing shells for abrasive wear, pitting, or corrosion. Measure bearing clearance (Plastigage method). Replace bearing shells if clearance exceeds 0.005 inches (general guideline). Inspect connecting rod bearings through crank access.	Bearing puller; Plastigage strips; micrometer; NOV tolerance manual.	FMEA Main Bearings (RPN 180); NOV Manual p.44 (point 15).
SA-03	Crankshaft Gear and Bearing Magnet Inspection	Inspect drive gear teeth for pitting, spalling, or excessive wear. Verify gear-to-crankshaft assembly bolt torque (380 ft-lb for 9-P-100; 780 ft-lb for 12-P-160). Check and clean the magnet within the crankcase sump and the magnetic drain plug; ferrous particles indicate internal wear.	Torque wrench (high capacity); inspection mirror; NOV gear data table.	NOV Manual p.44 (points 15, 16) and gear mounting table; AGMA 9005-F16.
SA-04	Complete Fluid End Overhaul	Disassemble all three FE modules. Replace: all piston cups (mandatory), all valve disc and seat kits (mandatory if RPN indicates service > 1500 hrs), all valve cover O-rings (mandatory). Inspect liner bore: replace if bore shows scoring or enlargement beyond 0.030 inch above nominal bore. Reassemble per SOP using calibrated torque wrench.	Full FE overhaul kit; bore gauge; torque wrench; NOV assembly procedures.	FMEA Piston Cup (189), Valves (192/147), Liner (120); NOV Manual.
SA-05	Pony Rod Seal Replacement	Mandatory replacement of all three pony rod seals regardless of visible condition. In the Saharan environment, thermal cycling and sand abrasion degrade these seals faster than the manufacturer's temperate-climate specification. This is a proactive replacement based on the Saharan FMEA adjustment.	Pony rod seal kit (3 seals); seal driver tool.	FMEA Pony Rod Seal (RPN 126); Section 3.3.2.2 – Thermal effects on seals.

SA-06	Safety System Functional Test	Functional test of the discharge safety relief valve at 110% of maximum operating pressure. Verify correct operation of the suction dampener. Inspect all high-pressure discharge piping welds and connections for corrosion or fatigue cracking.	Pressure test equipment; qualified HSE personnel.	API RP 7L Section 5; NOV Manual Warning notices.
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3.7 Limitations of the Proposed Maintenance Plan

While the proposed 3000 hours digital plan represents a significant upgrade over traditional manual logging, its successful implementation at ENAFOR is subject to several real-world human, technological, and economic constraints [8].

A. Human and Organizational Factors

The effectiveness of the "Traffic Light" system depends entirely on the accuracy of the input data and the discipline of the rig crew.

- **Data Integrity & Literacy:** Transitioning from paper logs to digital entry requires training. If the "Current Counter Hours" are not updated daily, the predictive alerts (BIENTÔT) lose synchronization with the physical state of the pump.
- **Organizational Commitment:** At remote rig sites, high personnel turnover and the pressure of 24 hours drilling can lead to maintenance being deferred. The plan must be supported by management commitment and clear accountability for each task.

B. Technological and Environmental Limitations

The "Sahara Factor" poses a direct threat to the hardware and the specialized tasks required by this solution.

- **Hardware Vulnerability:** Standard laptops fail in the 50°C heat and high-silica dust of Hassi Messaoud. This tool requires ruggedized industrial tablets (IP65/67 rated) for pump-side operation.
- **Oil Analysis Logistics:** Task M-04 (Oil Sampling) requires an accredited laboratory. In the Sahara, sample turnaround time can be slow; by the time results arrive, additional damage may have occurred. Future enhancements should include portable on-site oil quality kits.
- **Connectivity:** While the Excel tool works offline, synchronizing data across the entire ENAFOR fleet requires reliable satellite or GSM links, which are often intermittent at exploration sites.

C. Economic and Data Constraints

- **Inventory Holding Costs:** To respect proactive alerts, ENAFOR must maintain a higher upfront inventory of "Expendables" (piston cups, O-rings) compared to a "Run-to-Failure" approach.
- **Data Maturity:** The current FMEA RPN values are based on available field data and literature. As ENAFOR's digital records grow, these values should be updated via a dedicated statistical study of fleet records spanning at least three years [5].

Conclusion

This chapter has presented a technically justified Preventive Maintenance Plan for the National Oilwell 9-P-100/12-P-160 pumps operated by ENAFOR. By synthesizing the manufacturer's specifications with a custom FMEA analysis, a dynamic hour-based strategy was established to address the specific challenges of the Algerian Sahara.

The analysis identified four "Critical Failure Modes": Valve Cover O-rings (RPN 240), Suction Valves (RPN 192), Piston Cups (RPN 189), and Crankshaft Bearings (RPN 180). To mitigate these, the plan introduces Saharan-specific adjustments, including reduced O-ring replacement intervals, mandatory semi-annual pony rod seal changes, and precise lubricant grade selection for extreme temperatures.

CHAPTER IV: DEVELOPMENT OF THE DIGITAL MAINTENANCE TRACKER

CHAPTER IV: DEVELOPMENT OF THE DIGITAL MAINTENANCE TRACKER

4.1 Introduction

The preceding chapters of this work have established a comprehensive Preventive Maintenance Plan (PMP) for the National Oilwell 9-P-100 Triplex Mud Pump operated by ENAFOR at the Hassi Berkine drilling site. That plan defines what must be done, when, and by whom. However, the practical implementation of a maintenance schedule at a remote Saharan rig site immediately confronts a fundamental human challenge: the complexity of tracking dozens of tasks with different periodicities, every 8 hours, others every 50, 250, or 1000 hours in a working environment characterized by shift rotations, operational pressure, and limited administrative resources [23].

To meet this implementation challenge, a digital maintenance tracking tool specifically designed for this purpose was developed within this project. The tool is an Excel-based workbook comprising two interactive worksheets: the 'Programme Maintenance' (Annual Planning Sheet) and the 'Suivi par Heures' (Hour-Based Tracking Dashboard) designed to serve as the rig-side interface between the paper-based PMP and the daily reality of pump maintenance.

This chapter documents the architecture, programming logic, user interface design, functional benefits, and operational constraints of the Digital Maintenance Tracker. It represents the practical and applied dimension of this work and therefore the technical analysis can be translated into a tool that can be used today by a mechanic or a platform supervisor without specialized training in maintenance management software.

4.2 Architecture and Logic of the Tracker

4.2.1 Workbook Overview

The workbook was developed specifically for the National Oilwell 9-P-100 pump (Serial No. 9P100-2025-0042) at the Hassi Berkine field, covering the 2026 operational year from 2600 to 3000+ cumulative pump hours. It contains two worksheets, each fulfilling a distinct management function:

- Sheet 1 — 'Programme Maintenance': An annual calendar-based planner that tracks monthly execution status using standardized visual symbols, assigns responsibility to named technicians, and provides a running observations log for each maintenance task.

- Sheet 2 — 'Suivi par Heures': A dynamic, formula-driven dashboard that converts the pump's running hour counter into automatic status alerts for each task, eliminating all manual calculation of maintenance deadlines.

The two sheets are complementary: the 'Suivi par Heures' sheet tells the user what needs to be done now (or soon), while the 'Programme Maintenance' sheet provides the historical record of what was done, by whom, and with what result. Together they constitute a complete rig-side maintenance management system that requires no specialist software.

4.2.2 Data Architecture: Inputs and Outputs

The tracker is built around a strict separation between data input (raw information entered by the mechanic) and data output (processed information displayed as actionable alerts). This separation ensures that the system is self-correcting — any input update immediately propagates through all connected calculations [5].

The data architecture can be described as a three-layer system:

Table 4.1: Data Architecture of the Digital Maintenance Tracker

Layer	Element	Description
Layer 1 (Raw Input)	Current Counter (Heures Compteur Actuel)	A single orange cell in the 'Suivi par Heures' sheet (Row 4) where the mechanic enters the pump's current running hour reading. This is the master input from which all deadlines recalculate.
Layer 1 (Raw Input)	Last Intervention Hour (Dernière Interv.)	One yellow cell per task (Column D): the mechanic enters the pump hours at which the last maintenance intervention was performed. This resets the 'countdown' for that specific task.
Layer 2 (Formula)	Next Deadline, Hours Remaining, % Life Used	Three auto-calculated columns derived entirely from Excel formulas using the Layer 1 inputs. No manual calculation by the technician is required or possible — the values update in real time.

Layer 3 (Output)	STATUS Column (Traffic Light Alert)	The final output: a text status indicator automatically generated by the IF/IFS formula logic. The status drives the visual color-coding that forms the core of the user interface.
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4.2.3 Core Programming Logic: The Formula Engine

The intelligence of the 'Suivi par Heures' sheet resides in a set of interconnected Excel formulas that automate what would otherwise require manual calculation at every shift change. The logic operates as follows for each row (each maintenance task) [24]:

4.2.3.1 Next Deadline Calculation

The most fundamental calculation is the determination of the next service deadline. The formula takes the form:

$$\text{Next Deadline } (h) = \text{Last Intervention } (h) + \text{Task Lifecycle } (h) \dots\dots\dots (4.1)$$

In Excel notation, if Column B contains the task lifecycle in hours (e.g., 8 for a daily task, 50 for a weekly task, 1000 for a semi-annual task), and Column D contains the hour reading at which the last intervention was performed, then the formula in Column E reads: =D7+B7.

This formula is the core of the system's predictive capability: every time the mechanic enters new intervention hours in Column D, the next deadline automatically updates without any additional user action. For example, when Mechanic A. Benali performs the daily gear oil level check (Task A1) and enters '2998' as the hour of the last intervention, the formula instantaneously calculates the next deadline as $2998 + 8 = 3006$ hours.

4.2.3.2 Hours Remaining Calculation

The 'Hours Remaining' column provides the most operationally critical information: how much time is left before the next intervention is required. The formula is:

$$\text{Hours Remaining} = \text{Next Deadline } (h) - \text{Current Counter } (h) \dots\dots\dots (4.2)$$

In Excel notation, with the Current Counter stored as an absolute reference in a fixed cell (e.g., \$D\$4): =E7-\$D\$4. The absolute reference (\$D\$4) is critical — it ensures that when the formula is copied down to all task rows, every row refers back to the single master counter cell. When the

mechanic updates the Current Counter, all 'Hours Remaining' values recalculate instantaneously across the entire task list.

As the pump approaches a service deadline, the Hours Remaining value decreases toward zero, then becomes negative when the deadline is passed. Both the near-zero and the negative conditions are captured by the STATUS formula described below.

4.2.3.3 Percentage Life Used Calculation

The '% Life Used' column provides a normalized measure of task urgency that is comparable across tasks with very different lifecycles. A daily task (8 hours) and a semi-annual task (1000 hours) both show 100% life used when they are exactly at their deadline, regardless of the absolute hour values. The formula is:

$$\% \text{ Life Used} = (\text{Current Counter} - \text{Last Intervention}) / \text{Task Lifecycle) (4.3)$$

In Excel notation: $= (\$D\$4 - D7) / B7$. This percentage can be used to sort the task list by urgency or to generate a visual 'battery depleting' indicator, as implemented in the conditional formatting of the 'Suivi par Heures' sheet. A value approaching 1.00 (100%) provides the same information as the Hours Remaining approaching zero, but in a format that is more intuitive for technicians accustomed to visual gauges.

4.2.3.4 The STATUS Alert Formula: The Decision Logic

The STATUS column is the most user-visible output of the formula engine. It translates the calculated Hours Remaining value into one of three text alerts using a nested IF (or IFS) formula that implements a simple but robust decision tree [25]:

$$\text{STATUS} = \text{IFS} (\text{Hours Remaining} < 0, \text{"⚠ DÉPASSÉ"}, \text{Hours Remaining} \leq 20, \text{"⚡ BIENTÔT"}, \text{TRUE}, \text{"✓ OK"}) (4.4)$$

The three conditions and their meanings are:

- ✓ OK (green): Hours Remaining > 20. The task has more than 20 hours before its next deadline. No action required at present. The task is within its scheduled service window.
- ⚡ BIENTÔT (yellow/amber): Hours Remaining ≤ 20 AND Hours Remaining ≥ 0. The task will reach its deadline within the next 20 pump operating hours — equivalent to approximately 2.5 shifts at standard operating speed. This is the advance warning window: the maintenance technician and store man should confirm spare parts availability and

schedule the intervention before the deadline is reached.

- Δ DÉPASSÉ (red): Hours Remaining < 0 . The task has exceeded its scheduled deadline. Immediate intervention is required. The degree of overrun (the magnitude of the negative value) should be recorded in the Observations column.

The 20 hours advance warning threshold was deliberately chosen to correspond to the typical minimum lead time required to prepare for an intervention at a remote Saharan rig site, locating the relevant spare parts, preparing the work area, and scheduling the shutdown of the pump. For tasks with very short cycles (8 hours daily checks), a 20 hours warning represents approximately 2.5 cycles of advance notice, which is appropriate. For longer-cycle tasks (250 hours or 1000 hours), the 20 hours window represents a smaller proportional fraction of the cycle, which is equally appropriate since these tasks generally require more preparation [26].

4.2.4 The 'Programme Maintenance' Sheet: Calendar Logic

The Annual Planning Sheet uses a different, complementary logic. Rather than being formula-driven, it serves as the official documentary record of execution, combining a visual calendar with narrative observations. Its structure is based on:

- Monthly status columns (JAN through DEC 2026), each corresponding to an approximate 50 hours operating block given the pump's usage profile.
- A standardized symbol vocabulary that eliminates ambiguity in the status recording: ✓ = Task performed and completed satisfactorily; X = Task was due but not performed (must be documented with a reason in the Observations column); — = Task not applicable in this period (e.g., a semi-annual task due only at 1000 hours intervals will show '—' for the months in which it is not due);  = Task is scheduled for this period (future months).
- A Cumulative Hours row at the top of the sheet, which maps the monthly calendar columns to the pump's running hour counter, providing the cross-reference between calendar time and operating time.
- A named Responsible (RESPONSABLE) column that records the specific technician accountable for each task, creating individual traceability.

- An Observations column that captures component-specific events (replacements, anomalies, parameter readings) that are critical for calculating MTBF and for the next technician's situational awareness.

4.3 User Interface and Visual Management

4.3.1 The 'Suivi par Heures' Dashboard: Traffic Light System

The visual management philosophy of the 'Suivi par Heures' sheet is based on the internationally recognized 'traffic light' color coding system, adapted for the specific operational context of the ENAFOR rig site [27]. The system is designed to be interpretable by a mechanic with no training in maintenance management theory: green means continue, yellow means prepare, red means act now.

At the operational level of the 'Suivi par Heures' sheet as populated for the 3000 hours milestone of the 9-P-100 pump (Hassi Berkine, April 2026), the dashboard presents the following distribution of statuses:

Table 4.2: Status Distribution at 3000 Hours Milestone — National 9-P-100, Hassi Berkine

Status	Symbol	Count	Tasks in This Category at 3000 h
OK	✓ OK	16	All weekly (50h), bi-monthly (100h), and monthly (250h) tasks recently completed. Gear oil change (A4) just performed at 3000 h.
BIENTÔT	⚡ BIENTÔT	7	All 8 hours daily tasks (A1, A2, A3, B1, B4, D1, E1): next deadline in only 6 hours (at 3006 h). Parts readily available; no procurement action needed.
DÉPASSÉ	⚠ DÉPASSÉ	1	Task B13 — Inspection of piston rod wipers (racleurs de tige de piston): last replaced at 2750 h, lifecycle 250 h, deadline was 3000 h. Immediate replacement required.

This snapshot (Table 4.2) illustrates the primary value of the dashboard: without performing any calculation, the rig mechanic can see at a glance that 16 tasks are under control, 7 need attention within the next shift, and 1 requires immediate action. The entire actionable picture of the pump's maintenance status is communicated in a single screen read.

The 'BIENTÔT' (coming soon) category deserves particular emphasis, as it is the most operationally innovative element of the tracker. Traditional paper-based maintenance systems are inherently binary: a task is either 'due' or 'not due.' The 20 hours advance warning window converts this binary system into a graduated one, giving the maintenance team a predictive horizon. In the example above, the 7 daily tasks showing 'BIENTÔT' at the 3000 hours mark (next due at 3006 hours) alert the mechanic that before the next shift begins, the daily round must be performed. If AGMA EP#7 oil or NLGI 1 grease stock is low, the storekeeper can be informed before the deadline not after [4].

4.3.2 The 'Programme Maintenance' Sheet: Accountability and History

While the 'Suivi par Heures' sheet addresses the operational question of 'what do I need to do now?', the 'Programme Maintenance' sheet addresses the managerial question of 'what was done, by whom, and what was observed?'. It serves four distinct management functions:

4.3.2.1 Annual Planning and Visualization

The 12 months structure of the sheet provides a complete visual overview of the annual maintenance program for each pump. A manager reviewing the sheet in a single glance can identify: the overall compliance rate across all tasks and all months; any months with a high density of 'non-applicable' (—) markers, indicating that certain major tasks are clustered in specific periods (e.g., both semi-annual oil changes in January and September); and any isolated 'X' symbols indicating missed tasks that require follow-up.

4.3.2.2 Individual Accountability

The RESPONSABLE column creates a direct, named link between each maintenance task and the technician who performed it. In the Hassi Berkine 9-P-100 tracker, two technicians are consistently named:

- A. Benali: Responsible for all daily tasks (8 hours cycle) — daily oil level checks, crosshead greasing, and liner wash monitoring. His name appears against tasks A1, A2, A3, B1, B2, B3, B4, D1, and E1.
- M. Khaldi: Responsible for all weekly, bi-monthly, monthly, and semi-annual tasks. His name appears against tasks B5 through B13, C1 through C5, D2 through D4, and E2.

This explicit attribution of responsibility is a significant cultural step for ENAFOR. It creates an audit trail, enables performance evaluation, and provides the data needed to identify whether a recurring failure is associated with a specific technician's technique or a specific shift's practices [28].

4.3.2.3 Component Life Traceability

The Observations column functions as a compact maintenance logbook for each task. The entries in the Hassi Berkine 9-P-100 tracker demonstrate the type of information that must be recorded to build a meaningful component life history:

- 'Chemises remplacées à 2750 h (Apr) — by-pass normal depuis' (Task B1): Records the exact hour of liner replacement and confirms the normal status of the bypass flow since replacement — directly enabling the calculation of liner service life in hours.
- 'Garniture remplacée en Mai à 2800 h — OK depuis' (Task B6): Records the replacement hour for the cylinder packing, establishing a data point for MTBF calculation.
- '3ème vidange à 3000 h effectuée en Sep. — 360 L AGMA EP#7 — Prochaine à 4000 h' (Task A4): Records the oil change quantity (360 L, confirming the correct fill volume for the 9-P-100), the grade used, and the calculated next interval — all critical for audit and logistics purposes.

These observation entries, when consolidated across multiple wells and multiple pumps, form the empirical dataset required to calculate MTBF values and to validate or adjust the maintenance intervals defined in the PMP [29].

4.3.2.4 Non-Compliance Recording

The presence of a 'X' symbol in the monthly grid is equally important to the '✓' symbols. In the Hassi Berkine tracker, Task B8 (valve inspection) shows a 'X' for March (2700 h). The Observations column records: 'Disques remplacés en Mar et Juil — sièges OK.' This entry reveals that a planned inspection was missed in March but that the failure was identified and corrected (the valve discs were in fact replaced during that month), and that the valve seats were found to be in acceptable condition. This is precisely the type of transparent, self-auditing behavior that a mature maintenance culture requires and that a properly designed tracking tool encourages [30].

4.4 Functional Benefits and Added Value

4.4.1 Elimination of Manual Calculation and Human Error

In the absence of the Digital Maintenance Tracker, a rig mechanic at the end of a 12 hours shifts in 50°C ambient heat is required to mentally or manually calculate: 'The last oil level check was at 2992 hours. The pump is now at 3000 hours. That is 8 hours since the last check. The interval is 8 hours. Therefore, the check is due now.' For a single daily task this is trivial. Applied simultaneously to 26

tasks with intervals of 8, 50, 100, 250, and 1000 hours, the cognitive load becomes significant and the probability of error is high.

The tracker eliminates this cognitive burden entirely. The mechanic's only required input is to update the Current Counter cell (one number, entered once per shift) and to update the 'Last Intervention' cell for tasks that were performed. All deadline calculations, percentage-of-life consumed, and status alerts are generated automatically by the formula engine. The human role is reduced from 'calculator' to 'decision-maker' — a far more appropriate use of a field technician's expertise.

The practical consequence is the elimination of an entire class of maintenance failure that can be described as 'deadline miscalculation error': the mechanic believes a task is not yet due when it is, or calculates the wrong next interval after an out-of-schedule intervention. These errors are invisible in a paper system but are prevented by design in a formula-driven tracker.

4.4.2 Predictive Spare Parts Procurement: The 20 Hours Alert Window

Perhaps the most economically significant benefit of the tracker is its ability to provide a forward-looking procurement alert. The 'BIENTÔT' status, triggered when a task's deadline is within 20 pump operating hours, creates a predictable procurement horizon that is aligned with the practical logistics of the Saharan rig site.

To illustrate this concretely: at the 3000 hours milestone, Tasks B13 (piston rod wipers, due now) and B8 (valve inspection, upcoming) have been highlighted by the dashboard. A storekeeper reviewing the tracker before the morning shift would know to confirm that: replacement wiper kits are available on the rig for an immediate B13 intervention; a valve inspection kit is staged for the next B8 inspection due at 3025 hours.

This 'pull-based' procurement signal - derived automatically from the pump's operating hours - is a fundamental improvement over the current 'push-based' system in which parts are re-ordered only after they are consumed. At a remote Saharan location such as Hassi Berkine, where the supply chain from Hassi Messaoud to the rig may take 24 to 72 hours, the difference between a 20 hours advance warning and a zero-hour emergency is the difference between a planned 2 hours maintenance stop and an unplanned 48 hours NPT event waiting for parts.

Table 4.3: Comparison of Maintenance Response: With and Without the Digital Tracker

Scenario	Without Tracker (Current ENAFOR Practice)	With Digital Tracker
Deadline Awareness	Mechanic manually calculates or relies on memory. High probability of error or missed deadline.	Automatic STATUS alert. Zero calculation required. Deadline visible on single screen.
Parts Pre-Positioning	Reactive: parts ordered after failure or at time of maintenance, often causing delays.	Proactive: BIENTÔT alert 20 hours before deadline allows parts to be confirmed and staged.
Response to Missed Task	May not be noticed. No automatic escalation. No formal record of non-compliance.	DÉPASSÉ alert immediately visible and persistent until task is performed. Forced accountability.
Historical Record	Inconsistent. Relies on paper logbooks that may be incomplete, illegible, or lost.	Observations column provides a structured, always-current digital logbook per task.
MTBF Calculation	Not possible without complete historical records.	Last intervention hours recorded per task enable direct calculation of inter-failure intervals.
Training Required	Relies entirely on technician knowledge and experience.	Tool can be understood in < 30 minutes. Logic visible and self-explaining.

4.4.3 Transitioning ENAFOR Toward Rig-Side Digitalization

The Digital Maintenance Tracker, while built in Microsoft Excel, represents a transitional tool on ENAFOR's path toward a fully integrated Computerized Maintenance Management System (CMMS). Its importance in this context extends beyond its immediate operational utility.

By introducing the concept of a single, structured digital record for all pump maintenance activities at the rig site, the tracker creates a foundation of digital literacy and data discipline that is a prerequisite for the adoption of any more sophisticated CMMS platform. The behavioral changes it requires - entering the pump counter once per shift, recording intervention hours, writing structured observations - are precisely the data entry habits that a full CMMS requires. Personnel who develop these habits on a familiar Excel interface will transition to a dedicated CMMS with significantly lower resistance.

Furthermore, the data structure of the tracker - particularly the 'Suivi par Heures' sheet with its task IDs (A1, A2, B5, etc.), lifecycle values, last intervention hours, and observation notes - is directly mappable to the data model of most commercial CMMS platforms. The historical data accumulated in the tracker can, in principle, be exported and imported as the seed dataset for an ENAFOR CMMS deployment, avoiding the 'cold start' problem of implementing a CMMS with no historical failure data.

The tracker's structure also provides ENAFOR's engineering team at Hassi Messaoud with a standardized reporting format. If the completed monthly workbook is transmitted from each rig site to the base at the end of each month, the base can aggregate MTBF statistics across the fleet — achieving a fleet-level performance visibility that currently does not exist.

4.5 Operational Constraints and Implementation Challenges

A rigorous assessment of the Digital Maintenance Tracker must acknowledge its limitations alongside its benefits. The following constraints represent the practical 'reality section' of this chapter — the gap between the tool's theoretical capabilities and the conditions of its deployment at a remote ENAFOR rig site.

4.5.1 Human Constraints

4.5.1.1 Data Entry Discipline

The tracker's effectiveness is entirely contingent on the consistent, accurate entry of two data types: the Current Counter reading (daily) and the Last Intervention hours (after each maintenance event). If the Current Counter is not updated, the STATUS alerts do not refresh and the tool provides no benefit over a paper system. If Last Intervention hours are entered incorrectly, the Next Deadline calculation will be wrong and the STATUS alert will be misleading.

This dependency on human data entry discipline is the most significant behavioral constraint. At remote rig sites operating under production pressure, there is a persistent tendency to defer administrative tasks — including the updating of maintenance records. The tracker mitigates but does not eliminate this risk. Management enforcement of the 'end-of-shift counter update' as a mandatory procedure is essential.

4.5.1.2 Training and Change Management

The introduction of any digital tool in a work environment accustomed to paper-based systems requires a structured change management process. In the ENAFOR context, this means:

- Initial training: A minimum of a 4 hours practical training session for all rig mechanics and superintendents who will use the tracker, covering the Current Counter update procedure, the interpretation of the three STATUS alerts, the correct recording of Last Intervention hours, and the writing of structured Observations.
- Champion designation: Each rig site should designate a 'Maintenance Tracker Champion' (ideally the rig mechanic) who is responsible for maintaining the data quality of the workbook and mentoring new personnel.
- Supervisor verification: The rig superintendent should perform a weekly audit of the tracker (verifying that the Current Counter is up to date and that all DÉPASSÉ alerts have been addressed) as part of the formal weekly reporting routine.

4.5.2 Technological Constraints

4.5.2.1 Hardware Availability at Remote Sites

The tracker requires a computer running Microsoft Excel. This requirement, while seemingly basic, presents a practical challenge at some ENAFOR rig sites where the only computing devices available may be the company man's or tool pusher's personal laptops, which are not dedicated to maintenance

functions. The ideal deployment scenario involves a dedicated, ruggedized laptop or industrial tablet assigned to the rig maintenance function.

In the Algerian desert environment, standard consumer-grade laptops face accelerated degradation from:

- Fine silica dust infiltrating keyboard mechanisms and cooling vents.
- Thermal stress: the internal temperature of a laptop left in a rig office in summer can significantly exceed the 35°C maximum safe operating temperature for hard disk drives.
- Vibration from rig machinery, which can damage hard drives and connectors over time.

For a permanent deployment, ENAFOR should specify IP65-rated ruggedized tablets or laptops designed for industrial field use. While the initial cost is higher than a consumer laptop, the operational reliability justifies the investment when the cost of data loss or tracker unavailability is considered.

4.5.2.2 Software Compatibility and Version Management

The tracker was developed in Microsoft Excel and uses standard Excel functions (IF, IFS, arithmetic operators) that are compatible with all Excel versions from 2013 onward. The conditional formatting and symbol-based STATUS indicators use features available in all current Excel versions. No macros or VBA code are used, which avoids both the security restrictions that many organizations apply to macro-enabled workbooks and the compatibility issues that can arise with complex VBA code.

A risk of version drift exists if the workbook is opened in LibreOffice Calc or Google Sheets, which may render the conditional formatting or symbol characters differently. ENAFOR should standardize on a single Excel version across all rig sites to ensure consistent behavior.

4.5.2.3 Data Backup and Loss Prevention

The tracker represents an accumulating, irreplaceable maintenance history. If the device on which it is stored is lost, damaged, or stolen without a backup, all historical data is lost — returning the rig to a zero-information state with respect to component life history. A formal backup protocol is mandatory:

- Daily automatic backup to a USB drive or network share.
- Monthly transmission of the completed workbook to the ENAFOR base at Hassi Messaoud via email or satellite data link for centralized archiving.

- A version-naming convention (e.g., '9P100-HB-2026-v09.xlsx' for the September version) to prevent overwriting of historical versions.

4.5.3 Economic Constraints

4.5.3.1 Initial Implementation Cost

The direct cost of implementing the Digital Maintenance Tracker is modest, primarily comprising the cost of hardware (ruggedized tablet or laptop: approximately 200 000 to 300 000 DA per unit), software (Microsoft 365 license: approximately 26 556,06 DA/year per user), and the initial training session for rig personnel (estimated 4 to 8 hours per site). These costs are negligible compared to the cost of a single day of pump-related NPT, which can reach 2655606,00 to 6639015,00 DA per day depending on the day rate of the rig.

4.5.3.2 Indirect Cost: The Observation Quality Investment

The most significant economic investment in the tracker is not financial but temporal: the time required for technicians to write meaningful, specific observations rather than generic entries. The difference between 'Remplacé' (replaced) and 'Chemises remplacées à 2750 h (Avr) — by-pass normal depuis' (Liners replaced at 2750 h (Apr) — bypass normal since) is a matter of 15 to 20 additional seconds of typing. Yet the second entry provides MTBF data (liner lasted 750+ hours), condition data (bypass normal after replacement), and timing data (April), while the first provides none of these.

Training technicians to write the second type of entry, consistently, requires a sustained management investment in quality standards and periodic reinforcement. This is an ongoing operational cost of the tracker that has no direct financial expression but is the primary determinant of the tool's long-term analytical value.

4.5.3.3 Scalability Limitations

The Excel-based tracker, as designed, is optimized for a single pump. Scaling to an entire rig fleet (ENAFOR operates multiple pumps per rig, and multiple rigs) requires either: creating and maintaining separate workbooks for each pump, with the management overhead that implies; or developing a consolidated workbook with multiple pump sheets and a summary dashboard. Neither approach scales as efficiently as a purpose-built CMMS, which can manage unlimited equipment items through a single relational database.

This scalability limitation defines the tracker's appropriate role in ENAFOR's development roadmap: as a transitional tool for the current phase, with a planned migration to a lightweight CMMS as the logical next step when ENAFOR's digital infrastructure and personnel capabilities support it.

4.6 Conclusion

The Digital Maintenance Tracker developed for the National Oilwell 9-P-100 Triplex Mud Pump at ENAFOR's Hassi Berkine drilling site represents the practical application layer of the Preventive Maintenance Plan elaborated in Chapter 3. Its two-sheet architecture: a formula-driven hour-based dashboard ('Suivi par Heures') and an annual accountability planner ('Programme Maintenance'), addresses the three fundamental weaknesses of the current ENAFOR maintenance management system: the absence of automatic deadline calculation, the lack of a standardized data collection format, and the absence of an advance warning system for procurement and scheduling.

The tool's core innovation is the 'traffic light' STATUS alert system driven by the IFS formula engine, which provides a zero-calculation, single-screen overview of the pump's entire maintenance status at any moment. The 20 hours BIENTÔT warning window is specifically sized for the Saharan rig logistics context, providing sufficient lead time for predictive spare parts procurement that can eliminate the NPT events currently generated by reactive, post-failure part orders.

While the tracker is subject to human, technological, and economic constraints that must be managed with discipline, its cost-benefit profile is overwhelmingly favorable: a modest investment in hardware, software, and training, against the potential elimination of NPT events costing tens of thousands of dollars per occurrence. Most importantly, the data discipline it instils - accurate counter updates, structured observations, named accountability - prepares ENAFOR personnel and processes for the eventual transition to a full CMMS, making the tracker a foundational investment in ENAFOR's digital maintenance future.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This work has been dedicated to the elaboration of a Preventive Maintenance Plan (PMP) for the National Oilwell P-Series Triplex Mud Pumps - specifically the 9-P-100 and 12-P-160 models - operated by ENAFOR in the context of the extreme environmental conditions of the Algerian Sahara. The work has been structured in four chapters, leading from a theoretical foundation in maintenance principles through the analysis of the specific operational context, to the development and presentation of the PMP itself.

The principal conclusions of this work are:

1. The Saharan operating environment constitutes a unique and under-addressed challenge for triplex mud pump maintenance. The combination of fine silica sand abrasion (quartz, Mohs hardness 7), extreme diurnal temperature variation (exceeding 40°C in summer), and the remoteness of rig sites from spare parts supply chains creates a degradation environment fundamentally different from the temperate-climate conditions assumed in manufacturer documentation. Standard NOV maintenance intervals are insufficient for ENAFOR's operational context and must be adapted.
2. The FMEA analysis identified five critical failure modes requiring priority preventive action. In descending order of Risk Priority Number (RPN), these are: valve cover O-ring failure (RPN = 240), suction valve erosion (RPN = 192), piston cup wash-out (RPN = 189), main crankshaft bearing abrasive wear (RPN = 180), and connecting rod bearing wear (RPN = 160). Together, these five failure modes account for the majority of pump-related Non-Productive Time (NPT) at ENAFOR.
3. The Liner Wash System is the most critical preventive maintenance intervention. The FMEA and field situation analysis consistently identify neglect of the liner wash fluid system as the primary trigger for the most frequent and costly failure mode — piston cup wash-out. The first and most impactful improvement ENAFOR can make is to enforce the daily liner wash check (Task D-03) and bi-weekly wash fluid change (Task BW-03) as non-negotiable operational requirements.
4. The correct selection of gear oil grade for the ambient temperature range is a safety-critical decision, not merely a cost optimization. Operating the 9-P-100 or 12-P-160 with an oil that is too viscous for winter startup conditions can starve bearing surfaces during the critical first minutes of operation; operating with an oil that is too light in summer creates an insufficient hydrodynamic film.

The AGMA EP grade selection table (Table 2.2) must be implemented as standard procedure at all ENAFOR rig sites.

5. The transition from corrective to preventive maintenance requires an organizational change, not only a technical one. The success of the proposed PMP depends on management commitment, clear accountability structures, training of rig mechanics and operators, and the establishment of a disciplined maintenance recording culture. Without consistent data collection, the iterative improvement of the plan — and the calculation of meaningful KPIs such as MTBF — is impossible.

6. The proposed PMP represents a structured, evidence-based foundation for a mature maintenance management system. When combined with the data collection instruments and KPI framework proposed in Chapter IV, it provides ENAFOR with the tools to progressively reduce pump-related NPT, extend component service life, and optimize annual expenditure on emergency spare parts procurement.

Recommendations

Based on the conclusions of this work, the following recommendations are addressed to ENAFOR's engineering and management personnel:

1. Short-term recommendations (0 to 6 months):

- Immediately implement the daily maintenance tasks (D-01 through D-07) as formal, mandatory operational procedures across all rig sites. Distribute the inspection checklists (Tables 3.3 to 3.7) to all rig mechanics and superintendents, accompanied by a brief training session on the technical justification for each task.
- Procure and pre-position the minimum spare parts inventory defined in Table 4.3 at each rig site before the start of each drilling campaign. Establish a reorder-point system to ensure that piston cup sets and valve kits are never at 'stockout' status.
- Begin recording maintenance data immediately, even before a full CMMS is operational. Simple paper-based daily pump logs and maintenance work orders (per the formats proposed in Chapter IV) will provide the baseline data needed to calculate MTBF and demonstrate the value of the PMP.
- Implement the correct AGMA EP gear oil grade selection procedure for the winter season (grade #2 for sub-0°C ambient temperatures) to prevent cold-start bearing damage.

2. Medium-term recommendations (6 to 18 months):

- Evaluate and implement a Computerized Maintenance Management System (CMMS) appropriate for ENAFOR's operational scale. Even a simple, cloud-based platform accessible from both rig sites (via satellite) and the Hassi Messaoud base would dramatically improve data collection, work order management, and KPI calculation capabilities.
- Establish a formal oil analysis program: collect monthly crankcase oil samples from each pump in the fleet and submit them to a laboratory for particle count and wear metal analysis. The Si (silicon) content is the most direct indicator of sand infiltration and is the single most important early warning parameter for the ENAFOR context.
- Conduct a pilot validation of the complete PMP on a selected rig for a period of six months. Document the MTBF values achieved, the NPT incidents, and the total maintenance cost. Use this data to validate and refine the PMP before full fleet rollout.

3. Long-term recommendations (18 months and beyond):

- **Condition-Based Monitoring:** Investigate transitioning to portable vibration analyzers or acoustic emission sensors for the Power End. Handheld IIoT devices have made this increasingly accessible for field applications.
- **High-Performance Materials:** Evaluate tungsten carbide coated or ceramic-insert liners for abrasive formations. The upfront cost is typically offset by the reduction in NPT within 1–2 well sections.
- **ENAFOR-Specific Manual:** Develop a formal manual that integrates NOV documentation with the Saharan adaptations developed in this thesis, serving as the definitive reference for the fleet.
- **Predictive Technologies:** Explore vibration-based fault detection as demonstrated in the simulation work by Benmebarek and Bellamri (2025) [31] to eventually allow maintenance intervals to be adjusted dynamically based on real-time data.

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