بسم الله الرحمن الرحيم

Sudan University of Science & Technology

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Developing a Total Productive Maintenance Framework with RAM (Reliability, Availability and Maintainability) Techniques in Gas Compression Plants

تطوير إطار للصيانة بالانتاجية الشاملة مع تقنية الفعالية، التوفر وقابلية الصيانة في محطات ضغط الغازات

A THESIS SUBMITTED TO THE COLLEGE OF GRADUATE STUDIES IN FULLFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF Ph.D. IN MECHANINCAL ENGINEERING

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الآية

بسم الله الرحمن الرحيم

((الله نور السموات والارض مثل نوره كمشكاة فيها مصباح المصباح في زجاجة الزجاجة كأنها كوكب دري يوقد من شجرة مباركة زيتونة لا شرقية ولا غربية يكاد زيتها يضئ ولو لم تمسسه نار نور علي نور يهدي الله لنوره من يشاء ويضرب الله الامثال للناس والله بكل شئ عليم))

صدق الله العظيم

Abstract

The gas compression plant is one of the major unit in gas industries and always classifies as critical and hazard zone due to high surrounding processing parameters with associated risks. Thus, such plants are designed and constructed through high competent technical entities with high values. Investment in gas industries is always attractive due to continuous demand of gas and its products.

This study is focused on a new gas compression plant consist of three identical compression units recently commissioned in year 2015 but high failures were recorded considering it was well designed and constructed from reputed entities having international testing and manufacturing certificates. Nevertheless, the working team are following the manufacturer's maintenance recommendations and common maintenance practices. Gas compression loss leads to have power trips from gas turbines as well affect the power generation at the nearby villages. The study is conducted for single unit (A) along the duration from May 2015 to April end 2019 (1,460 days as total time) with loading time equal to 19,500 running hours (812.5 days). In this period, the recorded failures were 34 caused 460 days unplanned down time. A new maintenance proposed framework was built to apply a new integrated maintenance frame work. This proposed framework was assessed by using of RAM and OEE % techniques from July 2019 to May 21, 2020. Forty five days were the total down time that contained thirteen failures and the gained results showed clear improvement in the unit (A) availability from 68.5% to 86.2% as well there was an improvement in the overall equipment effectiveness (OEE%) from 48.7% to 60.44%. The research offered clear constructive new method on how to rank a list of failures based on their contribution into the total down time. This new technique is known as the total down time (TDT) importance and also improved the key performance indicator for the large maintenance sectors.

المستخلص

تعتبر وحدات ضغط الغازات من الوحدات الاساسية في محطات انتاج ومعالجة النفط والغاز .تصنف محطات ضغط الغازات علي انها محطات حرجة وخطيرة لما تحيط به عوامل تشغيلية عالية بالاضافة الي احتمالية الحوادث التي يمكن تؤثر علي صحة العاملين، السلامة والبيئة في حالة تسرب للغاز او حدوث حرائق. تشتمل الدراسة علي تقييم محطة ضغط غاز انشئت حديثا عام 2015م بواسطة شركات عالمية الا ان عدد الاعطال والتوقف الغير مخطط له عالي علي الرغم من اتباع ارشادات المصنع حرفيا في عمليات التشغيل والصيانة. اي توقف للمحطة يؤثر في عملية الانتاج ، السلامة، العائد الربحي، وانقطاع التوليد الكهربائي للمحطات المصاحبة لبعض المدن المجاورة. كما ايضا يمكن ان يؤثر علي اسم الملاك وسمعه القائمين علي العمل. الاعطال المسجلة ليست في قطعة محددة او مكان معين. فعليه خضعت الدراسة لتقييم الوحدة (أ) في محطة ضغط غاز في الفترة من مايو 2015 وحتي ابريل 2019 (1,460 يوما") وكانت مدة عمل الوحدة 19,500 ساعة (812.5 يوما") وتسببت هذه الاعطال في توقف غير مخطط له وقدره 460 يوما". تم تمت دراسة كل انواع الصيانة المتبعة في تلك الفترة كاستراتيجيات، خطط واجراءات وتم تحديد اماكن العجز والنقص. فاثمرت الدراسة بتحديد خطوات تساهم في بناء هيكل صيانة موحد يحوي اكثر من برنامج واستراتيجيات للصيانة والفحص كالوقائية، التصحيحية، التنبؤية، الفعالية المركزية وكذلك برامج فحص وتحديد المخاطر مجملة معا" وتمت اضافة كل نقاط النقص فيها وتحسينها وتم ربطها مع الصيانة الانتاجية الشاملة وسمي الهيكل المقترح بهيكل الصيانة الموحد. تمت عملية المقارنة لمعرفة تاثير واداء الهيكل وذلك اسخدام طريقة حساب الوفرة وحساب الفعالية الكلية للوحدة في الفترة من يوليو 2019 وحتي 21 مايو 2020 والتي سجل فيها توقف غير مخطط له لمدة 45 يوما" وباستخدام للوحدة لمدة 5,407 ساعة (225.3 يوما"). فأثبتت النتائج ان الوفرة لاستخدام الوحدة قد زادت من 68.5 % الي 86.8 %وان الفعالية الكلية للوحدة ايضا ارتفعت من 48.7 % الي 60.4 %. كذلك استنبط البحث كيفية لرصد الاعطال حسب اولوياتها وتأثيرها وسميت حساب أهمية زمن التوقف الكلي وايضا تناول البحث تحسين معايير القياس والاداء لتلائم الهيكل المحدث وتفعيل استخدامه بصورة اوسع.

Dedication

First, *thanks, appeal and prays to our almighty Allah the most merciful for the strength, peace and a lot of uncountable graces. This study is wholeheartly dedicated to our beloved partners who have been my source of inspiration:*

My Mother: *I dedicate my humble effort to you for prays, love, encouragement, affection; for many things and for everything…*

My Father's soul: *You are always keep catching my hand. I am still remember your words. I wish your soul to rest in peace at higher paradise and Allah bless you.*

My Second Mother's soul: *Safia, I will keep asking our god to forgive you and rest your soul in peace at higher paradise.*

My Wife: *Your endless support gave me success, enthusiasm, trust and honour. You have always been my strength throughout the times.*

My Sisters: *you proved that we are all in one, your emotional support make it happen.*

My Children: *you are indeed a mercy, gift and treasure from our Allah.*

My Supervisors & Teachers: *your guidance, leadership and knowledge are unforgettable*

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Table of Contents

CHAPTER FOUR :PROBLEM's STATEMENT DETAILS AND IMPACT

CHAPTER FIVE : FRAME WORK PROPOSAL

List of Figures

List of Tables

Abbreviations

AE	Acoustic Emission
AM	Autonomous Maintenance
API	American Petroleum Institute
ASME	American Society of Mechanical Engineering
BDM	Breakdown Maintenance
Bopd	Barrel Oil Per Day
BSC	Balanced scorecard
CBM	Condition Based Maintenance
CCR	Customer Cost of Reliability
CM	Corrective Maintenance
CMMS	Computerized Maintenance Management Systems
CNOOC	China National Offshore Oil Corporation
CSF	Critical Success Factors
DCS	Distributed Control System
DNFT	Digital No Flow Timer
E	After Cooler (Exchanger)
ECA	Equipment Criticality Analysis
EI	Employee Involvement
E-Maintenance	Electronic Maintenance
ESD	Emergency Shutdown
FIP	Field Improvement Proposal
FMECA	Failure Mode Effects and Criticality Analysis
FTA	Fault Tree Analysis
HH	High -High
HP	High Pressure
HSE	Health, Safety and Environment
IEC	International Electro technical Commission
IR	Infra-red
JIPM	Japan Institute of Plant maintenance
JIT	Just In –Time
K	Compressor No.
KNNR	K-Nearest Neighbours Regression
KPI's	Key Performance Indicators
L	Level
LCC	Life Cycle Cost
LCP	Local Control Panel
LNG	Liquefied Natural Gas
LP	Low Pressure
LSV	Leadership Site Visit
LV	Level Control Valve
M	Motor No.
MA	Maintenance Analytics

MAMT	Mean Active Maintenance Time
MCB	Main Control Board
MDT	Mean Down Time
MINLP	Mixed Integer Nonlinear Programming
MMScf	Million Standard Cubic Feet
MP	Maintenance Procedure
MRQA	Maintenance Reporting Quality Assessment
MTBF	Mean Time Between Failures
MTBM	Mean time between Corrective and Preventive Maintenance Actions
MTTF	Mean Time to Fail
MTTR	Mean time to repair
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
P	Performance Efficiency
P&ID	Piping and Instrument Diagram
PFD	Process Flow Diagram
PIA	Pressure Indicating Alarm
PIT	Pressure Indicating Transmitter
PK	Package
PLC	Programmable Logic Control
PM	Preventive Maintenance
PSV	Pressure Safety Valve
PT	Penetrant Test
PV	Pressure Control Valve
QM	Quality Management
QM	Quality Rate
RAM	Reliability, Availability and Maintainability
RBD	Reliability Block Diagrams
RBI	Risk Based Inspection
RCFA	Root Cause Failure Analysis
RCM	Reliability Cantered Maintenance
RH	Running hours
RPN	Risk Priority Number
RUL	Remain Useful life
SCADA	Supervisory Control and Data Acquisition
SDV	Shutdown Valve
SK	Skid Tag No.
SNDT	Surface non-destructive tests
TDT	Total down time
TIA	Temperature Indicating Alarm
TIT	Temperature Indicating Transmitter
TPM	Total Productive Maintenance
TQM	Total Quality Management
UCR	Unit Cost of Reliability

UT	Ultrasonic Test
V	Vessel Tag No.
VVCP	Variable Volume Clearance Pocket
A	Availability
A_a	Achieved Availability
A_o	Operating Availability
M	Maintainability
R	Reliability
t	Measured time (Period)
t_{lt}	Loading time
t_{ot}	Operating time
t_{pdt}	Planned down time
t_{pm}	Preventive Maintenance time
t_r	Repair time
t_{st}	Set time
t_{udt}	Unplanned down time
λ	Failure Rate
μ	Constant Maintenance Rate

CHAPTER ONE

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Maintenance management is an essential core at all valuable facilities, important industries and leading manufacturing. A systematic management will provide several efforts in cost saving, health, safety, working environment, consumptions, resources optimization, reputation and enhance internal and external auditing for further development. Therefore, the type of the applied maintenance management system depends on the work nature, process conditions and environment.

Maintenance management is a set of systematic processes using efficient planning, organizing, evaluating, monitoring and control the maintenance activities and used mechanisms. Maintenance management leads to obtain better outcomes and goals by having a body of maintenance strategies, policies, identify resources, budgets, key performance indicators (KPIs) and reporting which definitely will support achieving the set goals and objectives. Maintenance engineering is to apply an engineering concepts for equipment optimization and procedures to gain better equipment maintainability, availability and reliability. The Maintenance engineering and management implementation have different uses for each location based on the location design, product type, process capacity, surrounding environment, operating conditions and equipment's type, etc. But the most core factor is the criticality of the plant and product processing. Criticality is always classified based on the impact on human safety, health and environment and then the impact on product quality and cost consumption. These are the main factors to classify a field into criticality I, II or III.

Gas compression plants is usually classified as high critical plants due to the surrounding risk associated from the processing parameters such as high operating pressures, high temperatures and flow rates as well due to gas toxicity and the pressurized equipment. Therefore, always gas processes are using expensive and costly equipment with unique design to avoid ruptures, leaks and production downtime.

Gas industries are considered as stable business and investment compared to the oil industries due to frequent price fluctuation of oil production in recent years. Nevertheless, gas price is lower than oil price in the global market, but at least it remains stable since past years. Gas products have wide uses and several kinds of products, thus particular countries are focusing on gas processing and its production due to rich reservoirs with the sustainability of the gas production for lead periods, so focusing on this area is increased and highly considered for further researches, upgrades and development. Generally, the gas product either received from downhole reservoirs or released from oil process plants during the processes handling and treatments. Based on the received amount, the plants will be designed accordingly and depend on the gas specification, amounts & contents. Therefore, based on the required final products and commercial investment, the plant will be designed like refineries, fuel for power generations, flaring and heating systems, etc. The gas production fields business and their managements are focusing now on the competition to have a proud reputation as providers for raw or treated gas in the global market, thus stable demand will be one of the key points in parallel with the required quantities and quality. However, in recent years, core business companies continue developing and engaging to use modern maintenance programs and best practices in line with validated suitable integrated management programs, modern techniques and latest technologies to ensure continuous supply and stable production. In critical gas compression plants, the produced gas will be either exported, injected, treated or used as fuel and sometimes jointly. Therefore, any failure in such plant will result an impact as follows:-

- Down time of the production processes (production loss).
- High Probability of affecting the health, safety and environment.

- Possibility of costly repair and start-up.
- Have a danger zone classification (Hazard) and potential of risks.
- Tension on the working team and management.

Advance techniques and integrated types of maintenance management could be applied in such critical gas plant which contains static, rotary equipment, multi systems and utilities which need particular and unique maintenance programs besides optimizing the cost utilization to avoid any unplanned failures and consequent impacts with continuous monitoring and assessment. More advance, if possible to link modern maintenance type like the total productive maintenance (TPM) with maintenance engineering such as RAM (reliability, availability and maintainability) which is one of the research objectives. TPM is a complete maintenance program with increasing employee morale and job satisfaction. TPM will bring maintenance to focus as necessary vital part of the business as a proactive approach with the goal of removing deficiencies from machines to minimize or eliminate defects and downtime. TPM extends beyond simple preventive maintenance and includes comprehensive management of people, processes, systems, and the environment. So, the integrated framework of comprehensive maintenance management system will be studied and utilized the raw data of a critical gas compression plant in an oil field at south of Iraq by using TPM and analysis with reliability, availability and maintainability technique (RAM). Plant consists of two separate gas plants and each one contains three identical high pressure compression units (each plant receiving 110 MMScf of gas), thus the research will focus on one unit trend. It is observed from the past and present operating logs , these compression units have major failures which sometimes are critical, lead to production loss, affect the equipment, cause a power loss in nearby cities and impact the consequent processes.

1.2 Problem Statement

An important gas compression plant constructed and commissioned in early of year 2015. Plant mainly consists of three high pressure (HP) compressors as main units. It is considered a new plant compared to the design lifetime and current working running hours (19,500 RH). These high pressure compressors are well designed, properly operated and selected based on a lot of testing and standard testing and certifications prior installation.

There is an existing maintenance programs following the manufacturer recommendations but a lot of failures occurred which are not neither identical nor at same positions. Some of these failures were very critical and really dangerous, some was costly and affect the processes. Such trips in the plant will affect multi areas such as processing plants, power generation, gas production, electricity at the city uses gas fuel, etc). It means the existing applied maintenance and strategies need to be reviewed and developed within the optimal cost through proper engineering management knowledge. The major problems' statements are in below:-

1) A gas Plant is modern, advanced and recently commissioned (2015) and compared to the designed lifetime made by famous manufacturers from USA , Europe and China, but nevertheless the number of unplanned trips/failures are high considering the follow up of the manufacturer's maintenance plans.
2) Failures occurrence are not the same, not planned/predicted and affecting multi consequent areas (considering such plant is well designed, tested, certified and properly operated). Loss of compression package leads into the following:-

    I. Power loss of the production plant.
    II. Power trip in the surrounding province/villages (sometimes both affects-No. of houses ~300,000 buildings).

III. Package failures (increase spares consumptions, extra manpower utilization/outsourcing, operation disturbance, etc).

IV. Possibility to impact health, safety, environment and plant processes.

V. Impact on working reputation and revenues.

1.3 Research Objectives

For such complicated and critical gas compression equipment installed at high risk zones, implementing of modern types of integrated maintenance is required. The objectives of the research are:-

1) Propose a comprehensive maintenance frame work using multi modern maintenance strategies and customize them as an integrated maintenance system for critical gas compression plants.

2) Link the proposed frame work (one modern strategy) with evaluation techniques and continuous improvement systems.

3) Assess the relationship between the proposed framework and the gained results.

1.3.1 Novelty of the Research

1) In general, Gas industries are considered as unique profitable business therefore, researches in gas industries are getting more focusing and high attention.

2) Most of previous studies in gas plants are used common maintenance plans for failures repair, enhance condition monitoring and limited studies were conducted in maintenance engineering.

3) Globally, gas compression plants have almost similar design/equipment, so the outcomes will be suitable for all gas compression plants.

4) The study will show the road map to build a comprehensive maintenance systems which can be used for other critical industries with minor customization.

1.4 Methodology

The research methodology as described in Figure [1.1] below will be proceeded as follows:-

1) Literature review from previous studies in maintenance management and TPM techniques. As well, basic principles about compression plant.
2) Data collection for the area of study through the steps below:-
    a) From live-plant history , log sheet and monitoring systems
    b) Manufacturer’s documentations.
    c) Existing applied maintenance program, reports and the plant resources.
    d) Site verification for the main systems/sub systems like lubrication, control, materials and spare parts as primary stage.
3) Categorized and sort the collected data and measure the performance for the plant based on the operation log sheets (up and downtime) and from the failures history.
4) Develop and construct the proposed integrated framework.
5) Implement and assess the gained results after monitoring period.

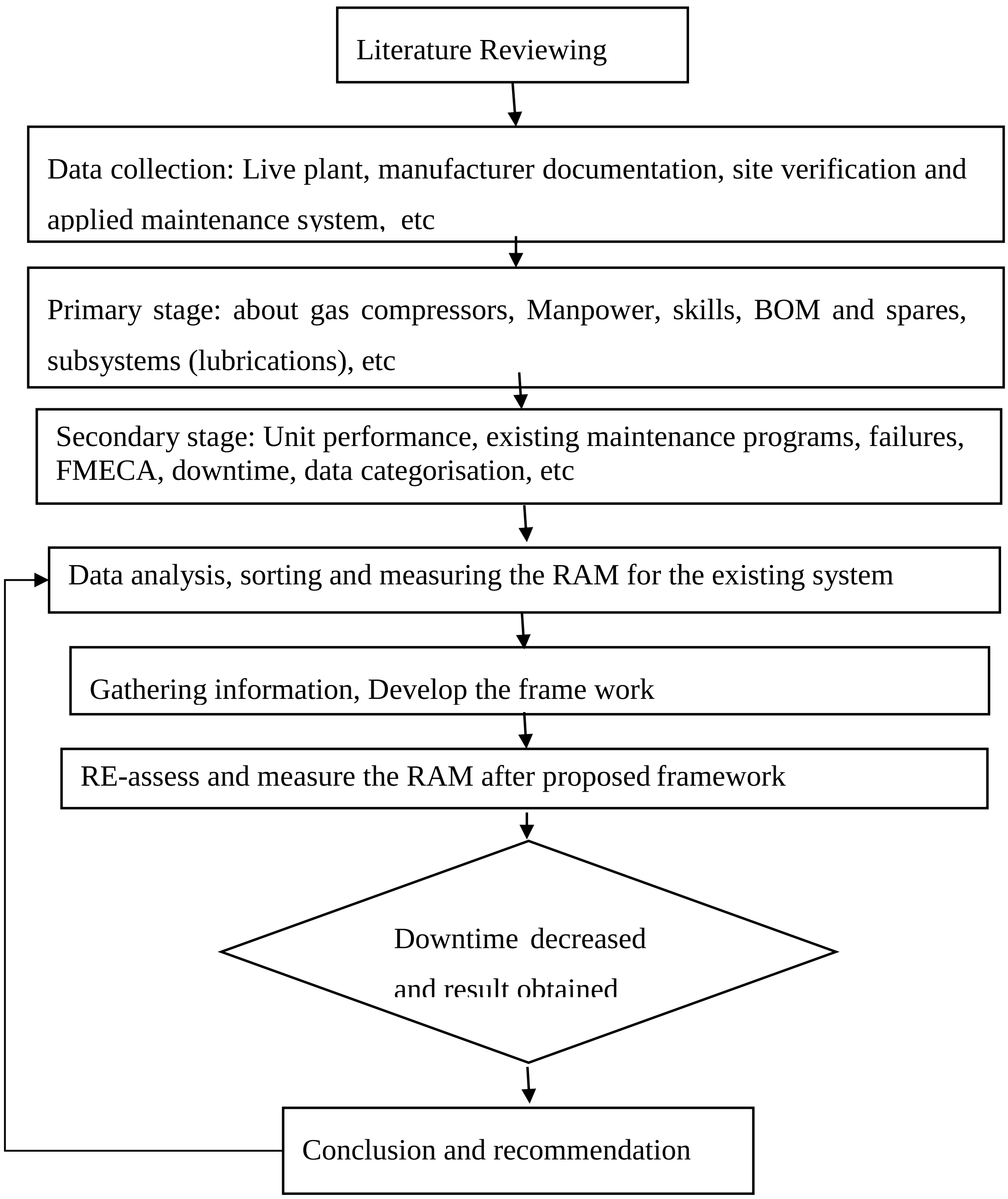

Figure [1.1] Research methodology

CHAPTER TWO

CHAPTER TWO

LITREATURE REVIEW

2.1 Maintenance Definition and Objectives

While using an equipment for production, manufacturing or self-using, definitely it needs to be maintained either due to equipment's life cycle, aging, failures, misuse or deterioration. The proper maintenance program shall provide several merits in lowering the production cost, equipment loss, reducing risk, increasing of the quality and the efficiency.

Maintenance as a word has different described definitions, but all are come to same meaning at the end. So, it means the activity or multi activities organized and executed in sequence into the equipment to ensure achieving the required objectives which are the downtime reduction, avoid production loss, cost and resources optimization and maximizing the equipment efficiency without risk.

J. Lee [1] defined the maintenance 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 into a state in which it can perform the required function (function or a combination of functions of an item which are considered necessary to provide a given service). Also, it demonstrated the maintenance management definition as "All the activities of the management that determine the maintenance objectives or priorities (defined as targets assigned and accepted by the management and maintenance department), strategies (defined as a management method in order to achieve maintenance objectives) and implement them by means such as maintenance planning, maintenance supervision and several improving methods including economic aspects in the organization".

J. Wakiru et al [2] defined maintenance as the activities aimed at restoring from fault and renewing a component to a condition whereby it can physically perform as required. It incorporated reactive repairs and replacement triggered by failures as well as planned and predictive tasks such as preventive replacement, inspection, scheduled repairs and others.

J. Wakiru et al [3] proposed a concept for knowledge discovery in maintenance with focus on huge data and analytics which called Maintenance Analytics (MA). Maintenance Analytics consist of four interconnected phases which are maintenance descriptive analytics (monitoring), maintenance diagnostic analytics, maintenance predictive analytics and maintenance prescriptive analytics. Result validated and verified the proposed MA on railway maintenance study.

N. Kurniati et al [4] described maintenance as items or equipment failed to operate or perform its intended function, the option of maintenance may be carried out, including repairs or replaces. Also, they defined the maintenance purpose in order to keep the items in good condition by rectifying the failures and to restore the item to its operational state following failure or deterioration condition. Through using maintenance policy (corrective maintenance, preventive maintenance, etc), maintenance strategy (repair, replace, etc), in-house or outsourcing maintenance and scheduled or unscheduled maintenance might influence the forthcoming product quality which in general highlighted the concept of maintenance management.

J. Abreu et al [5] defined the maintenance as “combination of all technical, administrative and management activities of the life cycle of an asset in order to keep it or return it to a state where it can perform its required function” and extended the definition into the maintenance management as a significant role in achieving the development of overall efficiency in the services of an organization, helping to maintain continuity and avoiding costly downtime. Also, the definition was extended by monitor the implementation of the maintenance management system in an airports of Portugal starting with infrastructure, systems and equipment through the organizational structure with respect to the different departments and ending with implemented business processes and settings for future implementations.

The maintenance management processes divided into two parts which are the definition of the strategy and the strategy implementation. The first part as the definition of the maintenance strategy requires the definition of the maintenance objectives as an input. For the implementation of a selected strategy should have a different significance level which deal with the efficiency of management mainly for costs and its processes like (planning, scheduling, controlling and improving). Achieving each objective will probably have a different level of outcome. Therefore, Adolfo Crespo determined the different maintenance goals to make sure those goals are realistic in accordance with the situation and then start planning for strategies to achieve those goals [6]. Thus, the maintenance strategy was extracted from the premises objectives and demonstrated in how to formulate a strategy and the required strategy levels for implementation

2.1.1 Maintenance Strategies and Policies

Maintenance Management introduces properly the approach for planning, organizing, monitoring and evaluating maintenance activities and their costs. The maintenance management has two main parts which are the strategies and strategies implementation. Maintenance strategy requires the definition of the maintenance objectives for the system or equipment in order to set the required suitable maintenance types.

Traditionally, maintenance was only run-to-failure which known as breakdown maintenance (BDM). The equipment will just be in use till fail. Then preventive maintenance (PM) became in use after obtained several implementation merits. The concept of the preventive maintenance is time base (age or running hours).Then, further progress obtained after developing the condition monitoring supported which depend on motioning tools and modern predicting equipment use sensing and measuring technologies. After that, reliability cantered maintenance (RCM) created to dig on the root causes of the failures' occurrence and to study the required action to avoid failures.

Lorenzo Fedele indicated the maintenance policy of various strategies [7]. It was updated in modern classification of maintenance forms (types) into three main categories as unscheduled maintenance, scheduled (programmed) and improvement maintenance as per below figure [2.1].

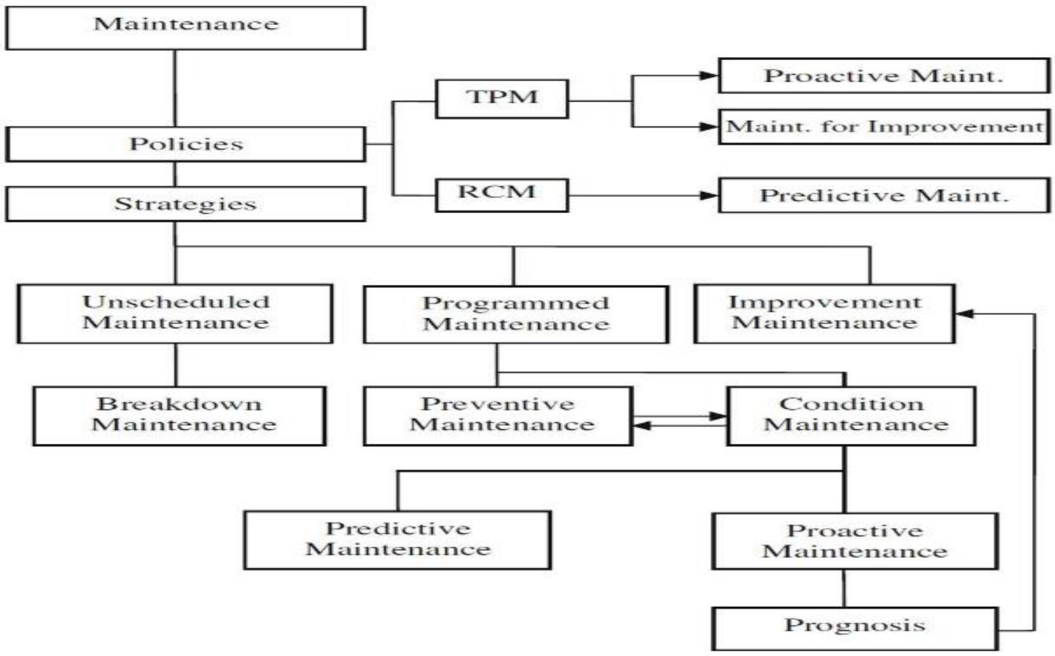

Figure [2.1] Forms of maintenance

The common types of maintenance (strategies) are described as in below:-

1) Unscheduled Maintenance: It will be executed when not clear program or time based had set. Thus, it is considered as run to fail type which known as break down maintenance.
2) Programmed Maintenance: Which had schedule task, taskforce team and planned materials on identified timeframe which mainly understood as preventive maintenance (PM). Preventive maintenance also has a direct link with condition based monitoring maintenance (CBM) as predictive techniques prior getting failure based on operating condition or expected lifecycle.

3) Improvement maintenance: It is more involved in prognosis and involving the inspection and corrosion assessment in the program.

Total productive maintenance (TPM) and reliability centred maintenance (RCM) considered as high classes for main polices. The TPM and RCM as an advanced types of maintenance that require higher planning and investments were allocated. T. Nakagawa [8] defined them as in below:-

1) The Total Productive Maintenance: means promoting the revolution along the production line through the incorporation of free of break, defect and accidents. The concept is where operators are motivated and trained to carry out checks, quick checks and maintenance actions on the operating equipment.
2) The Reliability Cantered Maintenance: the objectives of maintenance are defined by the functions and performance standards required for any item in their operating environment and its application is an ongoing process and should be re-evaluated frequently while experience is accumulated.

Maintenance strategy described as the initial part of the maintenance management which determines the effectiveness of the subsequent implementation of the maintenance plans, schedules, controls and improvements [1]. Thus, for proper maintenance management continuous assessment for working team competencies, work management, resources availabilities and plans execution is needed. D. P. Norton and R. D. Kaplan [9] proposed the balanced scorecard (BSC) to be used for premised objectives and always accomplished to the organization objectives such as (the investor, customer, short and long terms plans and improvement). Maintenance strategies defines the rules in sequence for planned works which related to implementation (types of maintenance) and resources management.

Therefore, the identification of maintenance strategies will come by selecting the suitable maintenance type required. R. S. Angeles [10] summarized the strategies in three levels:-

1. Basic Maintenance Strategies:-
    i. Training and education
    ii. Maintenance key performance indicators (KPI)
    iii. Autonomous maintenance (AM)
    iv. Basic equipment condition
    v. Understanding of preventive maintenance
2. Intermediate Maintenance Strategy:-
    i. Root cause failure analysis (RCFA)
    ii. Lubrication strategy
    iii. Reliability initiatives
    iv. Life Cycle and spare parts management
3. Advanced Maintenance Strategy:-
    i. Condition-based monitoring (CBM)
    ii. Computerized maintenance management systems (CMMS)

Maintenance policies described what and where to repair, manage stock level , identify the maintenance and required resources [4]. This technique is currently used as modern type of maintenance with several softwares as electronic maintenance (E- maintenance).

2.1.2 Managing Electronic Maintenance (E-Maintenance)

Recently, more development and techniques were established to ensure time and cost saving, spare parts management, work mechanism and reporting systems such as Just In –Time (JIT), quality management (QM) and total quality management (TQM). Table [2.1] is showing the slight difference between TQM and TPM [11].

Table [2.1]: the difference between TQM and TPM

Category	TQM	TPM
Object	Quality (Output and effects)	Equipment (Input and cause)
Mains of attaining goal	Systematize the management. It is software oriented	Employees participation and it is hardware oriented

Target	Quality for Produced parts	Elimination of losses and wastes.

For instance, total quality management (TQM) philosophy suggested the process control inspection along production line rather than final inspection only. The maintenance best practises focus on resources identification and failures root cause analysis in line with continuous improvement.

A. Kelly [12] added points for the main resources for the basis of maintenance generally are:-

I. Manpower: considering experience, fitness, working hours, roles and responsibilities. In addition to direct hired or outsources to perform the maintenance workload by organizational characteristics such as :-
   a. First line maintenance for preventive and corrective maintenance.
   b. Second line maintenance for corrective maintenance and minor construction activities.
   c. Third line maintenance for corrective maintenance beside overhauling and modification tasks.

II. Skills: which will focus on the required skills and qualifications.

III. Materials: spares parts, consumables and lubrications availabilities and inventory management.

IV. Machines: when fabrication, spare refurbishment or machining works are required. This will lead to workshop management and to have safe working location organization. The resources identification shall have proper planning, clear scheduling, tasks assignment (work centre), frequencies, etc.

Modern maintenance framework started by considering the single details related to product quality, safe working location and reputation. Thus more focussing and several studies also generated on the sides of risk, quality and safety. Therefore, further development in the world was in line with computerized systems by O. Durán [13].

A maintenance management system is composed of an indispensable tool known as computerized maintenance management system (CMMS). S. Haroun and E. Elhussein [14] studied the maintenance improvement by using computerized management system and highlighted different valuable outcomes for the gained benefits and improvements of such implementation in the currency press industry. Research [7] also explained the general benefits in computer support for maintenance management and relation with the applied strategies. Study briefed that computerized systems are the way of the development into asset maintenance which called e-maintenance [15].

2.1.3 Maintenance Related to Safety, Risk and Quality

Safety in maintenance is emphasized though the occurred maintenance related accidents. Study provided some of the reasons for safety problems in maintenance such as poor training to maintenance workers, poor management, inadequate work tools, limited working time to perform required maintenance tasks, poor safety standards and tools, lack of written maintenance instructions and procedures and rarely can happen due to poor equipment design and construction [16].

One of the recent studies related to safety in maintenance indicated that how are the workers aware of the safety practices during maintenance works [17]. Nevertheless, maintenance related accidents can occurred also due to miscommunication connections and wrong maintenance implementation. Therefore, the taskforce team awareness has a direct effect to ensure safe location free of incidents' occurrence. Thus, risk is defined as the combined effect of the probability or frequency of occurrence of an undesirable event and the consequence of that event.

For a successful asset management, understanding of the risk profile associated with the asset portfolio and how will change over the time are essential. Research [18] studied the dynamic criticality-based maintenance approach where asset criticality is modelled as a dynamic quantity and changes in asset's criticality to optimize maintenance plans to have a better risk management with cost savings.

There were some factors affecting the preventive maintenance interventions even with considering the human factor. Mentioned that, the human factor also is strictly related to the concept of imperfect maintenance and may lead to risk attendance if technician does not has the enough competencies (knowledge and performing) [19]. The impacts of human errors described toward the equipment operation in scenarios as in below [20]:-

i) General impact which maintenance should bring a machine to better conditions. But due to human error, it may not improve its condition or it may even worsen it to further deterioration state.

ii) Occasional impact for a machine is possible to be identified in a failure state where it is actually not. This human error may result in taking the machine into "random failure" state.

2.2 Maintenance and Inspection

Both, inspection and maintenance have an important role in production system. A Result [21] provided interacting framework between inspection and maintenance to provide better quality assurance and extended the study by determining the maintenance policy based on the demonstrated quality history rather than the condition of the machine which provided more reliable maintenance decision. Also, A. Lesage and P. Dehombreux [4] proposed and studied two approaches for the framework of interaction between quality inspection and maintenance focused on how the maintenance aspects may affects the products' quality.

2.3 Maintenance Cost and Reporting

A maintenance optimization model is a mathematical model in which both costs and benefits of maintenance are quantified to obtain optimum balance between them.

Generally, cost and reliability objectives are in conflict, as increased reliability usually means higher maintenance cost, especially for distribution systems with aging equipment. The costs associated with equipment not only include inspections, maintenance activities and repair costs that are apparent, but also contain penalty of costs associated with failures that are unapparent [22]. The maintenance related costs were divided into utility cost of reliability (UCR) and customer cost of reliability (CCR) and claimed that one of the main maintenance objectives to minimize the total cost of reliability (TCR) by combining the two costs [23].

Maintenance reporting gives clear view of the past, ongoing and forecasting activities in different layers and archiving mechanisms. If quality of the reported data is too low, it could results in wrong decision making and loss of money. A Result [24] developed a maintenance reporting quality assessment (MRQA) dashboard that enables any company stakeholder to assess and rank the terms of maintenance reporting quality at all levels (strategic, tactical, operational) which will help identifying the relevance of the required data at these levels. The maintenance practices enables the premises to achieve a competitive advantage compared to others. Research summarized that, the maintenance practises are fallen within eleven categories as shown in Figure [2.2] for maintenance management pyramid [25].

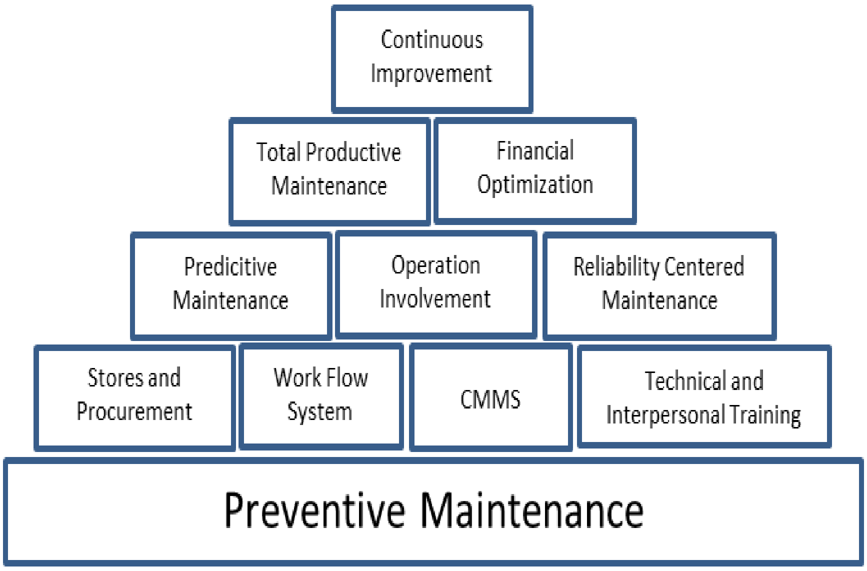

Figure [2.2] Maintenance Management Pyramid

2.4 Total Productive Maintenance (TPM)

2.4.1 Total productive Maintenance (TPM) Overview

TPM as a modern maintenance practise is created to increase the equipment effectiveness improving overall efficiency by establishing a comprehensive productive-maintenance system covering the entire life of the equipment or packaging systems. [26] S. Nakajima had pioneering works and had given basic definition of TPM, its importance, objectives of TPM and steps to be followed for TPM implementation in a work location. Also, it was described the method of calculating the overall equipment effectiveness (OEE) to assess the gap of having better results and higher scorecards.

[27] G. Chand and B. Shirvani research described the TPM as a Japanese concept of equipment management that allow improving the equipment performance through the involvement of all employees. [28] Also, F. Lee Cooke gave a comprehensive description on the objective of TPM as it is continuously improving the equipment availability and prevent the degradation of equipment to achieve maximum effectiveness. These objectives require strong management support as well as maximize the work teams' involvement.

TPM is analysed into three words:-

I. Total: This means every individual in the company from top management level to the shop floor workmen level.

II. Productive: This means no wasted activity or the production of goods and services that meet or exceed customer's expectation by maintaining systems integrities.

III. Maintenance: keeping equipment and plant in good working conditions.

2.4.2 TPM Pillars

H. Singh Rajput and P. Jayaswal demonstrated that Japan Institute of Plant maintenance (JIPM) proposed the introduction of TPM program for implementation in eight pillars [29]. These pillars are the core activities to implement TPM in a systematic way and to optimize plant and equipment efficiencies by creating perfect relationship between workmanship and equipment. The naming and the number of pillars may differ slightly [30]. Figure [2.3] represents a common structure of TPM and showing the TPM eight pillars.

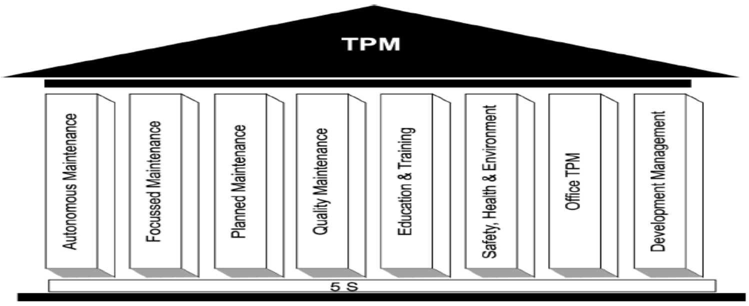

Figure [2.3] the eight pillars of TPM

TPM started with 5S as a foundation for TPM implementation following the Japanese way of housekeeping (problems cannot be recognized is the work place if it is unorganized). Cleaning and organizing the workplace helps to pop up the problems by making problems visible and seen to the working team and giving an opportunity of improvement. If these 5S are not taken up seriously, then it leads to 5D's (Delays, Defects, Dissatisfied customers, Declining profits and Demoralized employees). Meaning of each 'S' of TPM foundation is explained in Table [2.2] [31].

Table [2.2] Meaning of each 'S' of TPM foundation

Japanese Term	**Translation to English**	**Equivalent S-Meaning**
Seiri	Organize	Sort, Simplify
Seiton	Tidiness	Systematize, Set in order
Seiso	Cleaning	Sweep-Scrub
Seiketsu	Standardization	Standardize, Side-Wide
Shitsuke	Discipline	Self-discipline, Sustain

Also, He achieved increasing the overall equipment effectiveness (OEE%) more by applying the TPM in shot peening machine as a study which had poor performance, poor safety and bad housekeeping and obtained better results in machine availability and lowering the maintenance expenses. [32] A theoretical framework was proposed for understanding the use of TPM and how it depends on managerial factors such as Just-in-Time (JIT), Total Quality Management (TQM) and Employee Involvement (EI) as well as environmental and organizational factors such as country, industry and company characteristics by conducted this study in several companies by adopting the TPM programs.

Study showed and pointed out to comply with the TPM steps implementation and made a comparison between literatures and actual cases to understand the successful factors of TPM implementation [33]. Also, it was highlighted the scale and key success factors for TPM implementation by focusing on critical success factors (CSF) on management and technical categories [34]. Research described the TPM as a plant improvement methodology which enables continuous and rapid improvement of the manufacturing process through the use of employee involvement, employee empowerment and closed-loop measurement of results [10].

More definitions were added for the TPM that, TPM activities is to involve all employees starting from top management till operators' levels [35]. TPM program is marked to increase production while at the same time to increase employee morale and job satisfaction.

2.4.3 The Pillars Identification

From Figure [2.3], the pillars classified and well explained as in below [36]:-

1. Health & Safety

   They are important to emphasize the needs to protect workers which shall cover risk assessments, hazard and other safety concepts in details and encouraged to help with the development of the safe working procedures and working safety conditions.

2. Education & Training

In general, without proper training, TPM simply will not work. This pillar explains what knowledge is necessary, how to teach it, how to confirm it is understood.

3. Autonomous Maintenance (AM)

Operators could be trained to carry out the basic maintenance tasks rather than using of high skilled technicians to carry out the simple maintenance tasks without direct cost effective in order to free up the technicians to work on complex and major tasks.

4. Planned Maintenance

Maintenance plans will be set depending on equipment nature, type and manufacturer recommendations. Maintenance history and records are useful for the troubles analysis and use in modern maintenance practises.

5. Quality Maintenance

This pillar utilizes cross-functional teams to analyse areas of equipment performance where the product variation should be reduced. Once a cause has been found, the team would investigate if a modification or an upgrade might be implemented to increase yield.

6. Focused Improvement

Cross-functional teams are used to investigate the outstanding issues (upgrade/reengineering) and to find optimal solutions.

7. Office TPM

Team functions are to set the working mechanism, implementation and reporting lines while execution and implementation. Final records and TPM maintenance history (log) should be well documented and recorded.

8. Development Management

This is the organizational or planning pillar which always come with what, why, when, where with their related methodologies and action plans. Also, to identify and resolve the problems like lack of spares, time and work management and general improvement and standardization for enhancement.

2.4.4 TPM Frameworks

A Result elaborated more on a frame work for a Fertilizer Process Plant and described the implementation consequences [35]. It gained better results after the implementation by focusing on particular pillars of enhancing the working environment and reducing the downtime.

TPM also implemented in several areas even in hospitals as new management paradigm. K. E. McKone et al [37] explained such implementation as dramatic change compared to the nature and concepts of traditional maintenance system which is used in healthcare departments.

TPM also applied to improve maintenance in at Mahasawat Water Treatment Plant as well implemented in a small workshop [31]. A Study focused on developing an effective TPM model to improve the maintenance system at a chemical manufacturing company in Zambia and identified the gaps in the maintenance system [39]. Also, it determined the key performance indicators to be included in the TPM model for effective implementation. Generally, B. G. Mwanza and C. Mbohwa achieved better results rather that initial programs in different ranges and obtained losses reduction, reduced rework and increase profitability. In Table [2.3], a study briefed and indicated the TPM aims and its required targets as shown below [11]:-

Table [2.3]: the TPM aims

Motives of TPM	1. Adoption of life cycle approach for improving the overall performance of production equipment. 2. Improving the productivity by job enlargement due to more workers involvement. 3. Identifying the cause of failure/possible plant and equipment modifications.

Uniqueness of TPM	The major difference between TPM and other concepts is the operators' involvement in the maintenance process.
TPM Objectives	1. Avoid failures and accidents. 2. Involve people in all levels of organization.
TPM Targets	1. Obtain high OEE (Overall Equipment Effectiveness) 2. No customer complaints. 3. Cost reduction and perfect supply chain 4. Safe working conditions
TPM direct benefits	1. Increase the productivity and OEE (Overall Equipment Efficiency) 2. Reduce accidents. 3. Reduce down time 4. Improve maintenance records and outcomes.
TPM Indirect benefits	1. A clean, neat and attractive work place (favourable change in the attitude of the operators). 2. Achieve goals and continuous improvement. 3. Sharing knowledge and experience. 4. Familiarity with equipment operation and having quick proactive actions in case of expected risk or failures.

A Study resulted that TPM had strong contribution to the strength of the whole organization and had the ability to improve manufacturing performance as well for the implemented world class programs such as JIT, TQM and TPM that should not be evaluated in isolation or individual (in order to be evaluated along with the overall organization) [37]. A SWOT (strength, weakness, opportunity and threat) analysis for different total productive maintenance frameworks. The common elements identified and studied from the analysis are as follows [40]:-

1) Focused improvement / Kobetsu Kaizen
2) Autonomous maintenance / Jishu Hozen
3) Training and education
4) Maintenance prevention / Early equipment management
5) Quality maintenance / Process quality management
6) Administrative TPM / Office TPM
7) Safety, health and environment
8) Planned maintenance

It was also found that among the frameworks surveyed, only very few frameworks are unique while most of them are almost similar (only the naming and the number of pillars/elements had slight different).

Research illustrated the time frame for an operating equipment or manufacturing time process as per below Figure [2.4] [38]:-

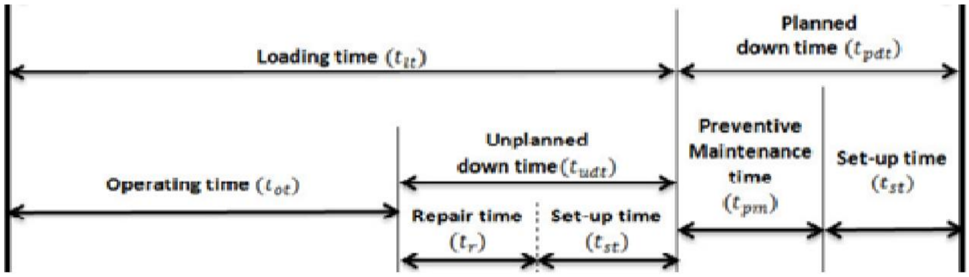

Figure [2.4] Time Model for OEE evaluation

I. Loading time (t_{lt}) is the period of time that expected to operate.

II. Planned down time (t_{pdt}) is the period of time equipment intentionally stopped operating due to Preventive Maintenance time (t_{pm}) or set up time (t_{st}) for starting up.

III. Operating time (t_{ot}) is the period of actual time operated.

IV. Unplanned down time (t_{udt}) is the period of time that does not operate in breakdown status which includes Repair time (t_r) as the period of time that chlorinator is repaired plus the (t_{st})

2.5 Overall Equipment Effectiveness (OEE %)

K. Sripriyan and R. Janakiraman focused on the methodology of improving the productivity through overall equipment effectiveness (OEE %) with help of lean manufacturing technique in compressor manufacturing industries [38], [41] . Lean manufacturing techniques is to significantly identify the waste mainly and eliminate it from the manufacturing processes. The OEE calculation was one of the ways to improve the performance and study made manufacturing unit for improving OEE with help of 5S techniques. The investigation’s result showed that the OEE has been improved from 45.9% to 55.8%.Study resulted the losses into six major categories as follows [26]:-

1) Breakdown losses: these losses are due to sporadic/chronic failures.
2) Set-up and adjustment losses: This refers to time losses from the end of the production of the previous item.
3) Minor/idling stoppage losses: Minor stoppage occurs when production is interrupted by a temporary malfunction or when a machine is idling.
4) Reduced speed losses: that occurs because of the equipment speed is slow.
5) Defect/rework losses: Defect/rework losses are defined as volume losses due to defects and rework.
6) Start-up losses: for consideration of start -up losses

Moreover, he defined the first two losses as time losses, the third and fourth losses as speed losses that measure the performance efficiency of equipment. The last two losses as quality losses. These losses directly affect the quality, so the measurement are categorized as availability (A), performance efficiency (P) and quality rating (Q) which are known as overall equipment effectiveness (OEE) which is seen to be the standard method for the measurement of equipment performance in percent. Availability (A) is the ability of an item to be ready to perform a required function at a given time. The definition of the quality of the product (Q) is the ratio of the amount of acceptable products made to the total amount of products made (including any unacceptable product).

Many authors wrote the OEE and summarized the equations as follows [41]:-

$$\text{OEE }\% = \text{A} \times \text{P} \times \text{Q} \tag{2.1}$$

For availability:

$$A = \left(\frac{t_{ot}}{t_{lt}}\right) \times 100\% \tag{2.2}$$

Where t_{ot} the operating is time and t_{lt} is the loading time.

$$A = \frac{Operatng\ time}{Total\ Available\ time - Planned\ Down\ time} \quad (2.3)$$

$$P\ (for\ production\ equipment) = \frac{Ideal\ time\ to\ produce\ a\ piece\ \ x\ \ total\ produced\ pieces}{Operating\ time} \quad (2.4)$$

For quality rating (Q):

$$Q = \frac{Total\ Parts\ Run - Total\ Deftects}{Total\ Parts\ No.} \quad (2.5)$$

2.6 Reliability, Availability and Maintainability (RAM) Assessment

These three main performance measures for an equipment or system in maintenance perspective are called (RAM) parameters which they are reliability, availability and maintainability[8]. RAM is one of the modern maintenance engineering and risk evaluation models applied in maintenance and safety integrity management systems for assessment. Study demonstrated an approach for the integration of (RAM) and risk analysis as a guide for maintenance policies to reduce the failures frequency and maintenance costs [42]. However, it is required to consider the in time and right decision making gained from (RAM) for the frequency of failures and their consequences which explained in their study in the multi safety instrumented systems (SIS). A new study used (RAM) for reciprocating compressors and the targeted value assessed the compressor availability during normal production and proposed preventive maintenance tasks to increase its availability [43],[30].

2.6.1 Reliability

The reliability ($R_{(t)}$) was defined as the probability of equipment to perform its required function under stated conditions for a stated period of time. Researches extended the reliability definition as it is the probability of the equipment or process functioning without failure when operated as prescribed for a given interval of time under stated conditions [44],[45]. Failure is a loss of function when the equipment function is needed. Newly, [46] (RAM) objectives were listed as a software application programing. It was summarized RAM's objects as in below:-

1) Determine the availability for the facility equipment to ensure having maximum operating period.
2) Identify the failure modes & consequence impact for the equipment and their down time effects.
3) Aware about the equipment behaviour in up and down time which will give predicted behaviour in advance.

It deals with reducing the frequency of failures over a time interval and is a measure of the probability for failure-free operation during a given interval period. Thus, reliability is defined as the ability of an item to perform a required function under the given environmental and operational conditions for a stated period of time. The most common methods of system and reliability analysis are reliability block diagrams (RBD), fault tree analysis (FTA), and failure mode effects and criticality analysis (FMECA). So, reliability is often expressed as in equation (2.6) [47] :-

$$R_{(t)} = exp(-t/MTBF) = e^{-\lambda t} \quad (2.6)$$

Where (λ) is the constant failure rate and MTBF is mean time between failures. MTBF measures the time between system failures and is easier to understand than a probability number. For exponentially distributed failure modes, MTBF is a basic figure-of-merit for reliability failure rate (λ) is the reciprocal of MTBF. For a given mission time, to achieve high reliability, a long MTBF is required. Also reliability may be the product of many reliabilities of in series connected units as shown in equation [2.7]

$$R_{(t)} = R_{unit1} \times R_{unit2} \times \dots etc. \quad (2.7)$$

$$where\ R_{unit}\ is\ the\ relaibility\ of\ unit$$

For in parallel connected systems which the redundancy will increase the overall reliability, the total reliability is describes in equation [2.8].

$$R_{(t)} = 1 - [(1 - R_{unit1}) \times (1 - R_{unit2}) \times \dots etc] \quad (2.8)$$

[48] Reliability techniques have been applied in three main areas in process industries as shown:-

1) production availability studies in conceptual design (RAM analyses)
2) Safety (risk analysis)
3) Maintenance activities (criticality analysis, life cycle cost (LCC))

2.6.2 Availability (A)

It deals with the duration of up time for operations and is a measure of how often the system is working. It is often expressed as (up time) / (up time + downtime). Also availability (A) may be the multiplication of many different availabilities explained by [49] as shown in equation [2.9]:-

$$A = A_{hardware} \times A_{software} \times A_{human} \times A_{interfaces} \times A_{process} \quad (2.9)$$

Availability issues deal with at least three main factors. [50] Grant Ireson et al pointed out these factors to achieve growing availability by increasing the time to failure, decreasing down-time due to repairs or scheduled maintenance and accomplishing the above two in a cost-effective manner. He also defined three terms for availability as in below:

2.6.2.1 Inherent availability

It is as seen and detected by maintenance's personnel (excludes preventive maintenance outages, supply delays, and administrative delays) and defined as below equation (2.10):-

$$Availability = \frac{Uptime}{Total\ time} = \frac{MTBF}{(MTBF + MTTR)} \quad (2.10)$$

Where MTBF is the mean time between failure and MTTR is the mean time to repair.

2.6.2.2 Achieved availability (A_a)

It is seen by the maintenance department (includes both corrective and preventive maintenance but does not include supply delays and administrative delays) as in equation (2.11).

$$A_a = MTBM/(MTBM + MAMT) \qquad (2.11)$$

Where MTBM is mean time between corrective and preventive maintenance actions and MAMT is the mean active maintenance time.

2.6.2.3 Operational Availability (A_o)

[50] It defined the operational availability as equation (2.12):

$$A_o = MTBM/(MTBM + MDT) \qquad (2.12)$$

Where MDT is mean down time.

2.6.3 Maintainability M(t)

Maintainability is a consequence of design and installation expressed as the probability that an item will be retained in, or restored to a, specified condition within a specified period of time, so Maintainability is related to the durations of outages. [45] H. P. Barringer and M. Kotlya mentioned that maintainability analysis is used to evaluate the design and layout with respect to maintenance procedures and resource requirements and expressed by as equation (2.13):

$$M(t) = 1 - e^{\left(-\frac{t}{MTTR}\right)} = 1 - e^{(1-\mu t)} \qquad (2.13)$$

Where μ is constant maintenance rate and MTTR is mean time to repair. MTTR is an arithmetic average of how fast the system is repaired and is easier to visualize than the probability value.

P. EL Blanchard BS and Verna DF [51] described the many tools and methods available to assess RAM and LCC to apply risk analysis during each product's development. RAM tools such as failure mode effect and criticality analysis (FMECA), fault-tree analysis (FTA) and event-tree analysis (ETA) are useful in assessing product characteristics and product support.

An integrated study carried on RAM and risk analysis about the maintenance function in the Nigerian electric power industry and recommended for proper RAM training to be well oriented. Moreover, he studied the integration of RAM with risk analysis in combination with life cycle cost for making the fundamental in maintenance decision is accomplished to the success of the organization [52]. Also, a study was made by using RAM to assess the situation in reliability and availability assessment of seabed storage tanks using fault tree analysis [53].

In general, gas compression plant is a specific plant usually constructed for gas production fields, oil processing facilities, refineries and in limited manufacturing premises use the compressed gases. Compression unit requires for gas handling to subsequent stages and for gas transportation by using suitable type of compression systems. Compressors are the main unit in gas plant work with comprehensive systems mainly include the followings:-

1) Compressor driving system (electric motor, turbine or engine).
2) Lubrication loop system.
3) Piping, scrubbers and pulsation vessels.
4) Cooling systems.
5) Instrument and control systems (for operation, monitoring, protection and control).

There are several types of gas compressors for different us J. Hollingsworth et al [54] explained in details the common types of reciprocating gas compressors and their advantages and disadvantages. Compressor's condition has a gradual degradation on its performance. Degradation may happen due to life cycle, operating condition, non-efficient operation and maintenance procedures or due to manufacturing quality. In case of any incident or gas leak, it may cause harm to the working team, equipment, environment and plant process. So, any down time in gas plant will not be ordinary and also affects the investor's revenues.

Maintenance and inspection programs are vital for such areas to ensure having efficient plant and safe working location with minimum downtime. Normally, working team follow the manufacturer recommendations and standard practices. Recently, some studies conducted for compressors to increase the condition monitoring on the compressors to predict failures at earlier stages. Moreover, prognoses any abnormalities to be recorded in planned maintenance work rather than having any unexpected failure. Also, limited studies went through the modern maintenance engineering practices to come with high equipment effectiveness.

Reference to recent conducted researches in gas compression plants use gas reciprocating compressors type found the focused areas which the condition monitoring and applied maintenance engineering studies.

2.7 Gas Compression Plant Condition Monitoring and Management

Many researches are giving codes and nick names for their area of study due to confidentiality. Researches described the effective application of an optimized condition based maintenance philosophy to reciprocating compressors on an offshore oil and gas company (FPSO) in the Northern Sea. Intrusive maintenance of these compressors obviously was required by analysing the system data and focused on compressors valves temperature and monitor the rod positioning which conducted by the operator and a company named DEI [55], [56]. Mainly, after review found the oil coolant in the packing rings had been incorrectly set causing high packing temp, thus watch keeping parameters installed to ensure coolant flowing and gave detection of incipient valves failures demonstration. Also, it created a monitoring for the rod positioning system to monitor the wear in ring bands. Therefore, the set condition monitoring guided to call out the equipment manufacturer for overhauling at earliest time based on the monitoring trends and features and saved equipment from further damages.

One relevant effect of mechanical degradation was caused a drop in the efficiency by the time. D. P. Xeno et al [57] used the general mixed integer nonlinear programming (MINLP) formulation for the simultaneous optimization of the operation and maintenance of a parallel connected compressors network. The case of condition-based maintenance and operational optimization compared with the applied preventive maintenance strategy for compressors efficiencies. The objective of the optimization was to reduce operational and maintenance cost for the network of air compressors which it is part of an air separation plant. The method used a mathematical modelling considered a fixed scheduling horizon that is divided into a set of uniform periods took into account the deterioration of the performance of a compressor over time. It compared the condition-based maintenance approach with a typical preventive maintenance case. The condition-based approach achieved reduction in the overall cost by (11 %), especially in the start-up, shut-down and maintenance costs compared to the benchmark preventive maintenance strategy.

Most of compressors concerns coming into the excessive vibration which will impact the compressor, pipes and auxiliaries as well some parts may be affected due to high temperature. The cause of severe vibration problem was also investigated and used a model analysis, piping re-calculation and velocity frequency spectrum analysis and pressure pulsation measurement [58] . Study found that the inlet pipelines avoided low frequency resonance region and the actual length of the inlet pipelines was in the second resonant piping length. Also, the pressure pulsation was 34.26 mm/s which far exceeded the standard of American Petroleum Institute (API) 618 that is 17.8 mm/s. The results indicated that large pressure pulsation and acoustic resonance occurred on the inlet pipelines were the key factors inducing vibration. Vibration elimination treatments included enlarging the buffer volume of gathering manifold, adjusting the inlet piping length to avoid acoustic resonance and increasing the curvature radius of bend. After remodelling of the inlet pipelines, the test data indicated that the vibration level of the inlet pipelines reduced to an acceptable level and reduced the vibration sources.

Researches presented the statistics of faults and analysed vibro-activity of reciprocating compressor valves as one of the most often failed components [59], [60]. The data were provided by one of the Russian oil refineries and resulted that five systems and components of compressors caused about 76.5% of all unplanned compressors shutdowns. Faults of valves made up to 36% of total faults and consumed 50% of the total repair costs. However, piston-cylinder units caused a significant percentage (over 30%) of all faults, where the ring failures were more than 25% .Special research in gas flow through the valves helped to find solutions to form gas flows and controlled gas dynamics conducted by the specialists of KSK-Service company and implemented the solution. Specialists designed a poppet spring less valve and ensured laminar flow of gas passing through the valve. Experimental study significantly increased the valve life and improved its vibroacoustic characteristics.[61] The effects of pressure pulsations on reciprocating natural gas compressor performance thermodynamically were used a nonlinear model of hybrid numerical. Such Model considered the interaction between the compressor and the pipeline system. Through the study's examination of the pressure pulsation influence, it was observed in the suction system that the first harmonic response reduced the mass flow rate but significantly increased specific work. Similarly, the second harmonic response had a strong supercharging effect, but the specific work increased slightly. Model developed and achieved the mutual interaction of the two systems. So, the Study assessed the predicted hybrid numerical model and concluded that in-cylinder temperature for the real gas model was about 5.9 K temperature degree higher than used ideal gas model during the compression and the discharge phases, because of the mass flow rate. Also, it provided more response in harmonic responses in the suction and discharge systems.

Moreover, a study examined the reliability impact as a result of upgrading the temperature monitoring devices on the connecting rods of electric driven reciprocating compressors [62]. In addition to that, the cost analysis presented to demonstrate the upgrades in hardware and software which eventually yield saving in the operating cost. The studied compressors used eutectic temperature sensors in the connecting rods, but the study proposed upgrading in temperature sensors which consisted of a wireless radar system without the need of an external power source. The wireless sensor replaced the eutectic device in the connecting rod’s thermowell. An antenna replaced the pneumatic switch and received timely a signal from the wireless sensor once per revolution. The processing unit software calculated the temperature and transmitted into the supervisory control and data acquisition (SCADA) system. The study resulted a better on-time update in the temperature monitoring on the connecting rods of the reciprocating compressors.

A proposed technology principle in diagnosing and monitoring of reciprocating machines [63]. It showed that only five vibroacoustic signal sensors on reciprocating compressors (Cylinder, pressure inlet valves, crosshead, fundamental bearing and the shaft angle position) sensors could form fifteen diagnostic parameters of signals in case of malfunctions according to the signal of each sensor. Using these parameters signals system diagnostics and monitoring on unconditional algorithm automatically determined 36 causes’ vibrational activities in reciprocating compressors. The result of monitoring provided more control of almost 80% bounce of commonly occurring failures.

Compressor valves are the weakest component in the compressor and being the most frequent failing element and accounting for almost half of the maintenance cost. Study used data for valve temperature and presented the combination of algorithms analysis output by using several methods such as multiple linear regression, polynomial regression, K-Nearest Neighbors Regression (KNNR) along with remain useful life method (RUL)[64].

A research was made in pressure pulsations in the piping system of the reciprocating compressor that produced excessive noise and even damaging the piping and machinery [65].

The finite disturbance theory used to solve the nonlinear partial differential equations for the unsteady one-dimensional compressible gas flow in the complex piping system by predicting the large amplitudes of pressure pulsations in the piping system. The result of the experiment showed that the finite disturbance theory was more precise than the acoustic method in large amplitude pressure pulsation because (the acoustic theory neglected the second order terms) brought by the disturbance in the continuity and Euler equations as a linear equation. So, the result was only an approximation (not a precise solution) .The difference between the value of calculation and the value of experiment using the finite disturbance theory found to be 15%, moreover, the same difference by using the acoustic wave theory found to be 77%. Thus, it suggested that when pulsation pressure/average pulsation ratio is greater than 8%, the acoustic wave theory would not provide a satisfactory solution to the problem.

An investigation of using a volume low-pass filter for pulsation attenuation in a reciprocating compressor piping system [66] . A study was focused on its frequency response characteristics and influence on the actual attenuation effects. A three-dimensional acoustic model of the gas pulsation established for a compressor discharge piping system with and without the volume choke-volume filter. It was based on which the gas column natural frequencies of the piping system and the pressure wave profiles predicted by means of the finite element method. The model was validated by comparing the predicted results with the experimental data. The results showed that the characteristic frequency of the filter was sensitive to both diameter and length of the choke but independent of the parameters of the piping beyond the filter.

The pressure pulsation levels in the piping system downstream of the filter were significantly attenuated especially for the pulsation components at frequencies above the filter's characteristic frequency. It found that the measured peak-to-peak pressure pulsation at the outlet of the filter was approximately 61.7% lower than that of the surge bottle with the same volume.

An elaboration was done more in fault diagnosing of reciprocating compressor valves by using an integrating method of acoustic emission signal to simulate the valve motion which evaluated the current valve condition and predicted the forecast condition based on generated trends and curves of working conditions [67].

It is necessary to have a proactive maintenance program in order to avoid abnormal conditions, failures and incidents in gas plants equipment. [68] Research was introduced a case study on the development of a condition base maintenance system for an oil and gas offshore plant at a liquefied natural gas (LNG) floating production storage and offloading vessel at FPSO field which using powerful compressors. Any unexpected or prolonged downtime of these units has a large impact on plant availability. Study identified and solved problems in advance before damage to equipment occurred by detecting abnormal states of shaft vibration throughout sensor data monitoring, diagnosing abnormal types, predicting remaining useful life. It undertook the proactive maintenance by building a system architecture, work flow, event, test algorithm and established the diagnosing and prognostic modules. Such intelligent diagnostics criterion was more advanced technique than the conventional method which widely used in condition monitoring.

Furthermore, a fault-diagnosis system proposed by Keerqinhu et al. [69] who used a machine learning techniques to detect potential faults for compressors. The system evaluated by using an operation data collected from China National Offshore Oil Corporation (CNOOC) .The analyzed data demonstrated that the system could efficiently diagnose the potential faults in compressors with 80% accuracy. Several method used parameters such as pressure, temperature, vibration, and acoustic emission (AE) signals to diagnose faults in reciprocating compressors. Two types of data were obtained from compressors which structured and unstructured data. Structured data related to the status of compressors such as temperature, speed, and acceleration, but unstructured data are from video surveillance. Study focused on analyzing structured data. All experiments were generated by using software "Matlab 2014a" and "Visual Studio 2013" community edition mixed in a private cloud with 300 servers. It resulted and indicated that the system identified most of the faults automatically with more than 80% accuracy.

2.8 Review of Applied Maintenance Engineering Studies

A Study collaborated with a private company named RC to analyze the behavior of their used reciprocating compressor and aimed to identify and evaluate the effects of reliability, availability and maintainability (RAM) [70]. Study presented the most relevant aspects and findings by assessing the operational performance of reciprocating compressor system .Also, it reviewed the maintenance activities, outlined failures and main events contributing to jeopardize the production process. It highlighted the generated preventive maintenance tasks and planning on reciprocating compressor API 618 and recognized the needs for a constructive approach to implement RAM. The used methodology was the bibliographical research, documentary and contents analysis of soring most of maintenance problems. Research output reflected the importance of using RAM for plant lifecycle control and reviewed the RAM performance as well highlighted the usefulness of learning RAM principles to the process engineers to apply.

Due to associated risk in pressurized compression plant and potential of any damage will be great, a study was made on risk based inspection (RBI) method for gas compressor station and reflected the applied integrity management of a gas compressor station was insufficient [71]. Thus, he reviewed the basic principle of risk based inspection (RBI) in the gas compressor station and determined the corrosion mechanism and process loops.

The probability of failure was calculated by using the modified coefficient and the consequence of failure determined by the quantitative method.

Effective measures were taken to eliminate the impact of risk. The results showed the cumulative risk and average risk were much higher which mainly due to the potential of piping and equipment for sulphide stress corrosion cracking. According to the analysis output, it has found that about 10% of the compressor accounted for about 80% of all the risk in the plant and by developing a targeted inspection plan would effectively control the risk and reduce costs. A Research focused on the methodology of improving the productivity through overall equipment effectiveness (OEE) with help of lean manufacturing technique in compressor manufacturing industries [72]. Lean manufacturing technique is used to identify the waste, losses and eliminate it from the process. The study carried on two high pressure air compressor manufacturing unit and addressed in three aspects namely the availability, performance and quality which quantify OEE. The investigation results showed that the OEE has been improved from 45.9% to 55.8% by studying the influence of the overall equipment effectiveness which compared before and after implementing the lean tools. The end results gained 75% reduction of tool searching time, 23% of down time and productivity has been increased in range of 12.5% and overall equipment effectiveness had increased by 17.7%.

Iran khodro is one of the largest manufacturing company in Iran is one of the largest manufacturing company in Iran and in the Middle East. In order to optimize its production lines, electricity had been substituted by compressed air power. A Research investigated the status of the equipment and proposed new definitions and changes in OEE parameters. There was no Q (quality) factor for OEE calculation, because the point of measurement of the volumetric flow was exactly at the outlet of the compressor and there was no rejected air. Therefore, in the calculations for the OEE index instead of having three components, only two were considered which availability (A) and Performance (P).The calculation considered a schedule time as 365 days a year and 24 hours a day.

In order to assure the calculations were made to possible real value, study recommended to multiply the OEE with capacity coefficient factor [73]. Therefore, the used equations (2.14),(2.15) were in below:-

$$Capacity\ coefficient = \frac{Actual\ capacity}{Nominal\ capacity} \qquad (2.14)$$

The used OEE% equation was in below:-

$$OEE\% = \frac{Load\ time * Capacity\ coefficient}{Total\ Time} * 100\% \qquad (2.15)$$

2.9 Criticality

Criticality is defined as the relative importance of piece of equipment in the operating conditions which will assess to set priorities for maintenance and reliability initiatives along with resources optimization and identify the equipment criticality analysis (ECA). It is indicated by D. Priyanta study [74] for protocols of offshore carbon steel static mechanical equipment and resulted to find the boundaries between negligible and significant probability of failure as well as between acceptable and unacceptable consequence of failure.

The criticality analysis used to rank the risk associated with each failure mode identified during the failure modes by assessing the severity and the likelihood of failure. The likelihood of failure can be determined by using one of two approaches as explained [7] in below:-

1) Quantitative: if the available data can be counted, measured and expressed using numbers.
2) Qualitative: it is used if data can be descriptive, conceptual and can be categorized.

To quantify risks, such things as equipment data, emergency work orders, overtime, regulatory information audits and experience are required. However, with proper consideration using reliability, availability and risk analysis in maintenance, the frequency of failures can drop the related severities and consequences [52]. Thus, only after hazard been associated with a probability and consequence, then it becomes a risk. That is why currently in huge industries a classification of working areas are being classified in zones based on the criticality and associated risks.

CHAPTER THREE

CHAPTER THREE

THE GAS COMPRESSION PLANT OVERVIEW

3.1 Produced Gas Separation Units

In general, gas removal (either sweet gas or sour) and its treatment are required to be separated from the produced liquid (oil and water) considering that some gas already released freely. This separation is to avoid the impact on the process handling, material selection of the equipment and final product specifications. Gas solubility decreased in oil with decreasing pressure and the separation efficiency mainly depends on residence time of crude oil and the added chemicals.

The area of study has four sets of 1st production separators located in parallel with the inlet manifold. One separator vessel SK-21740 is set to receive sweet crude which will provide sweet gas for fuel gas system. The separated sweet gas will be flowed to fuel gas scrubber (V-23910) and distributed to the plant consumers (fuel gas for heater, purge gas and pilot gas for flares, blanket gas for oil tanks and closed drain vessel). The other three identical separators SK-21710A/B/C are used for sour crude production and the separated sour gases are sent to the high pressure (HP) export gas compression header to feed the HP export gas compressors K-23210A/B/C. The separated gas from the 1st stage separators (1.05MPag, 20~70℃) is routed to the suction header of HP gas compressor packages PK-23210A/B/C. The discharge pressure of HP gas compressor will meet the requirement for exporting at 3.5MPag. For the 2nd stage separators of the three oil treatment trains, the produced gas is used for low pressure (LP) gas compressor package PK-23610A. LP gas compressor discharge is routed to the suction header of HP gas compressor packages PK-23210A/B/C. In case the LP gas compressor was not running, the 2nd stage gas separated will be sent for flaring. The plant plot diagram for the production process is in Figure [3.1] and process flow diagram (PFD) in Figure [3.2]. Figure [3.3], Figure [3.4] are showing the piping and instrument diagram (P&ID) for compression plant and gas compression overview.

3.1 High Pressure (HP) Gas Compression Elements

HP gas compressor is the major equipment in the compression unit contains reciprocating elements such as cylinders, pistons, valves, scrubbers, lubrication system, instrument and control systems. HP compressor is reciprocating type with two stages/four cylinders which is heavy duty continuous running equipment. The gas suction and discharge is controlled by two suction valves as well two discharge valves located in cylinder head. These valves are mechanical valves that typically operate automatically by differential pressures, each cylinder has unloaders suction valves that control the percent of full load carried by the compressor at a given rotational speed of its driver. Unloaders manipulate the suction valves' action to allow the gas to recycle. First and second stages have scrubbers at inlet to condensate the liquids and release the gas through demister to the compressor cylinders. Pulsation bottles also located to reduce pulsation and gas pressure fluctuations and excess vibration caused by reciprocating movement. The main driver is the electrical motor and connecting with crank case which contain the crank shaft and connecting rod. Crosshead is the case of converting the circular motion from crank shaft into liner reciprocating movement to piston rod and then into the piston.

There is a distance space element contains wiper and pressure ring to prevent gas leak from compressor into crank case as well wipers to prevent the lubricant to enter from the crank case into the cylinder.

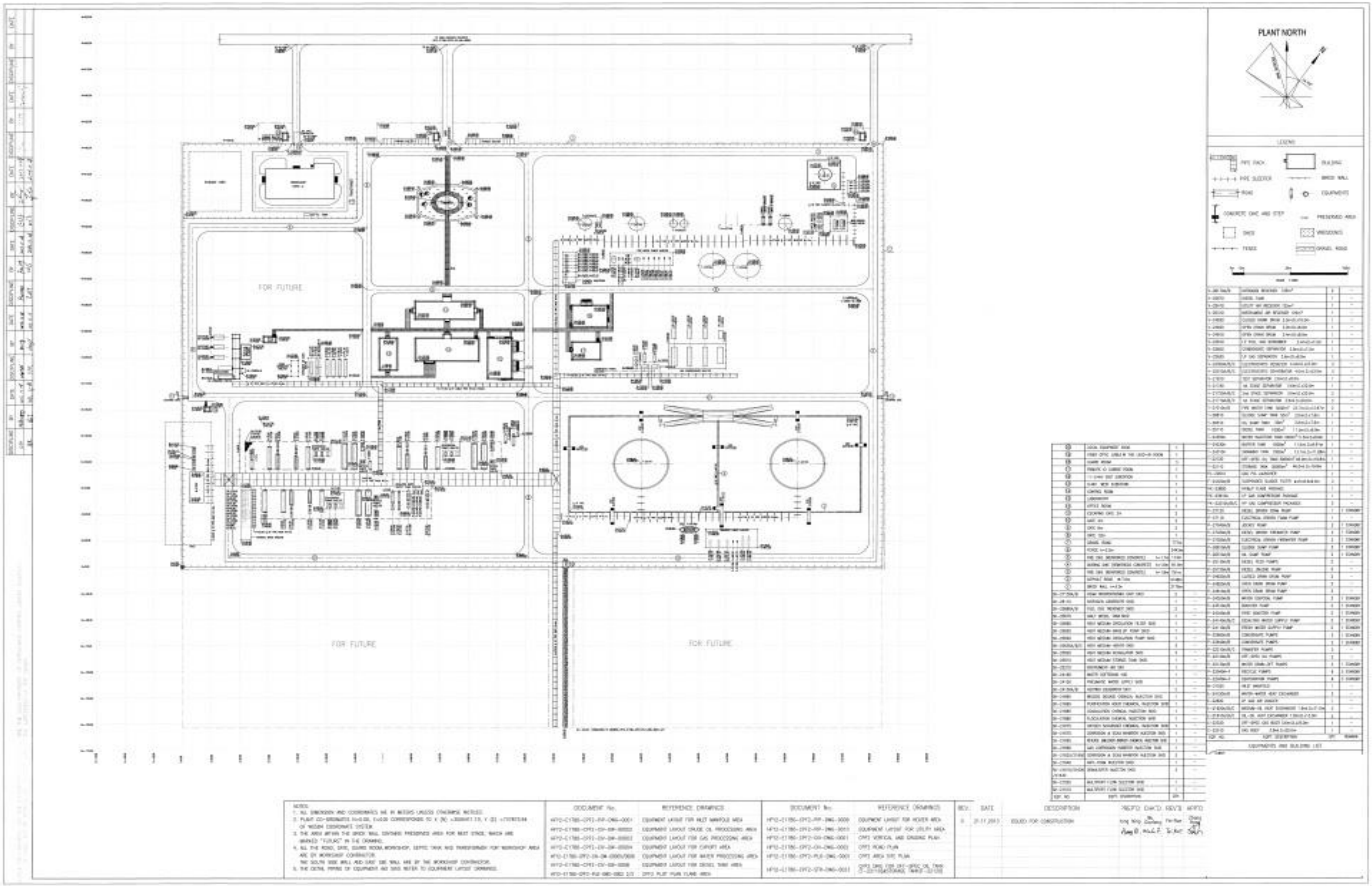

Figure [3.1] the plant plot diagram details for the process

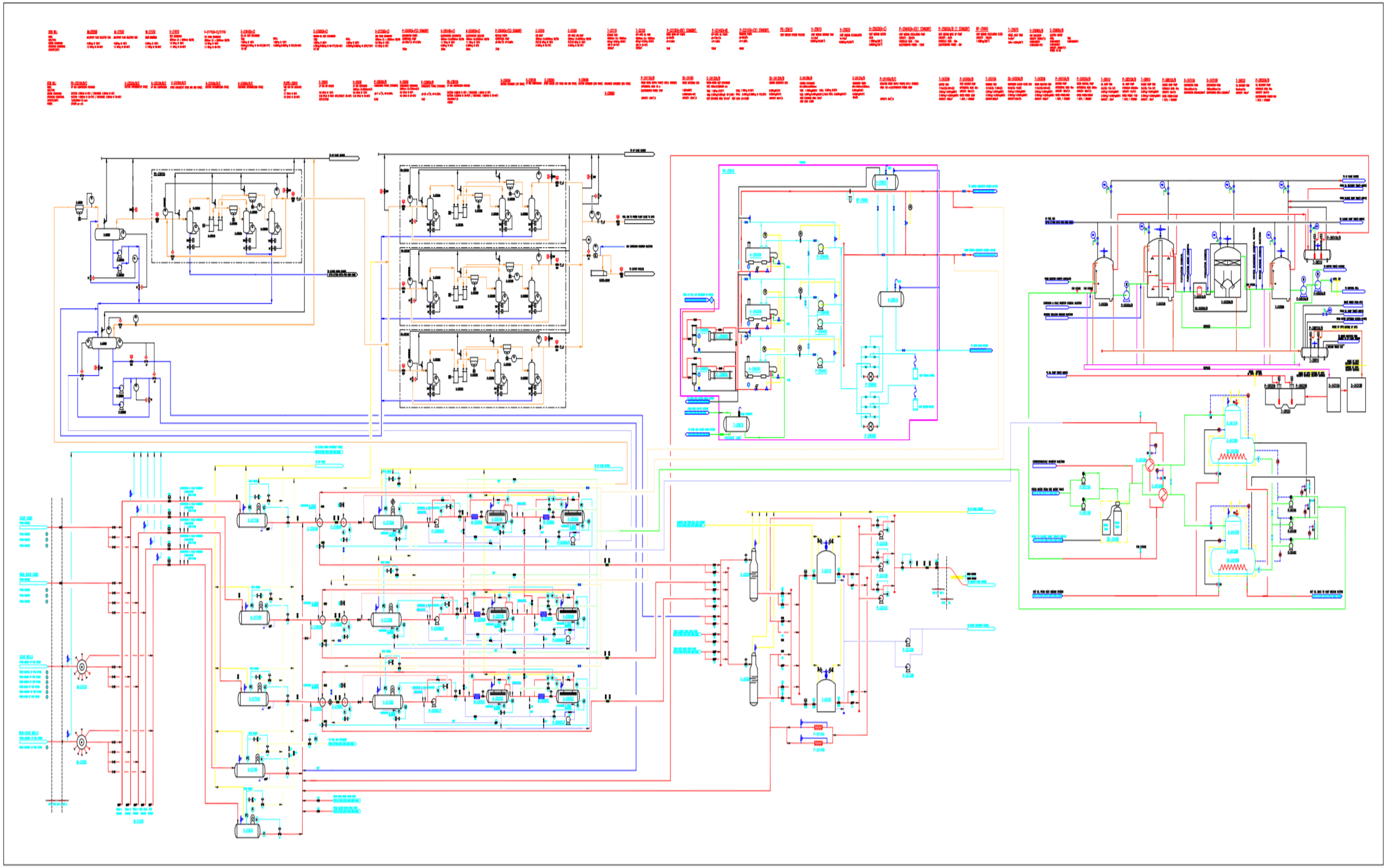

Figure [3.2] The plant process flow diagram (PFD)

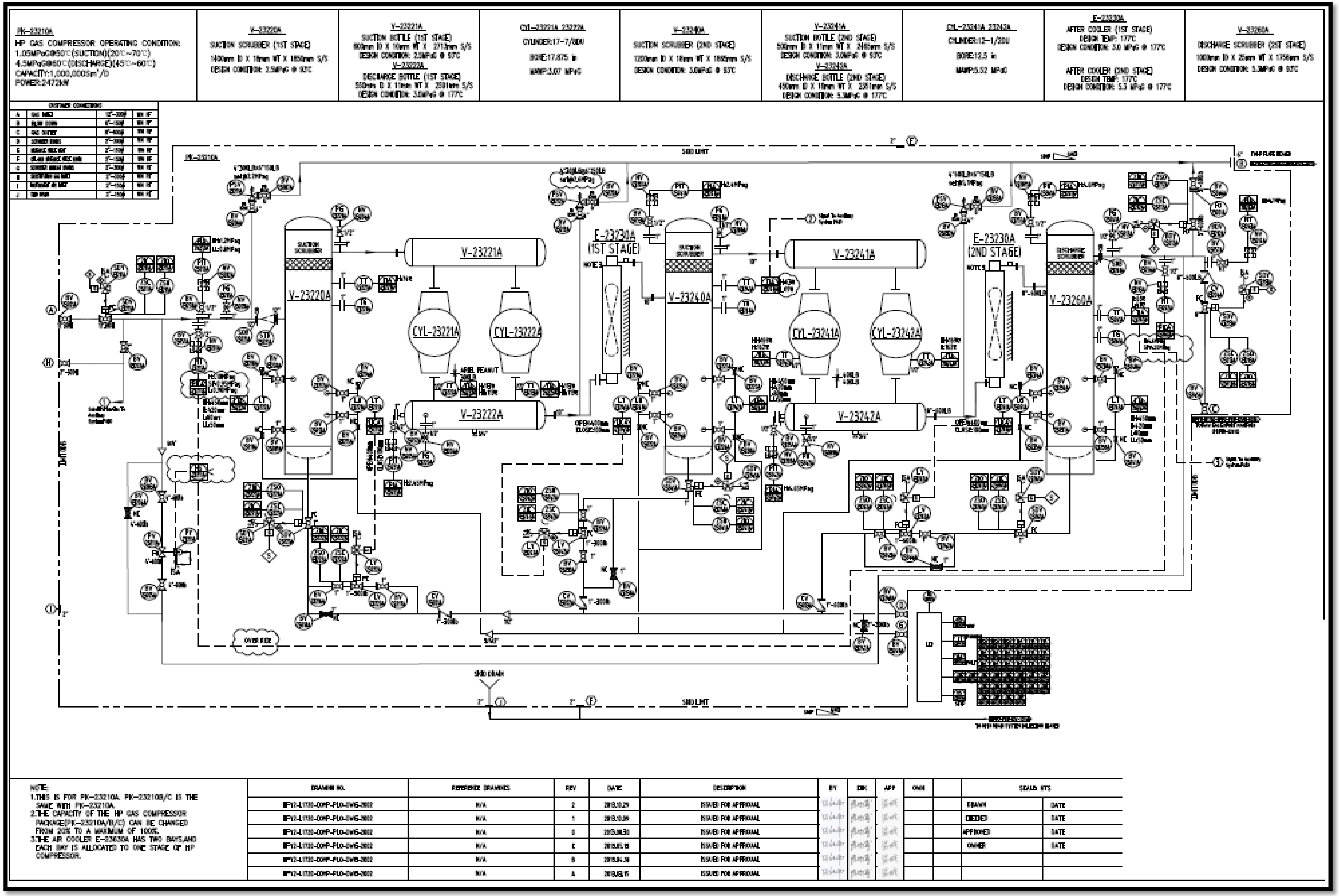

Figure [3.3] Piping and instrument diagram (P&ID) for compression plant

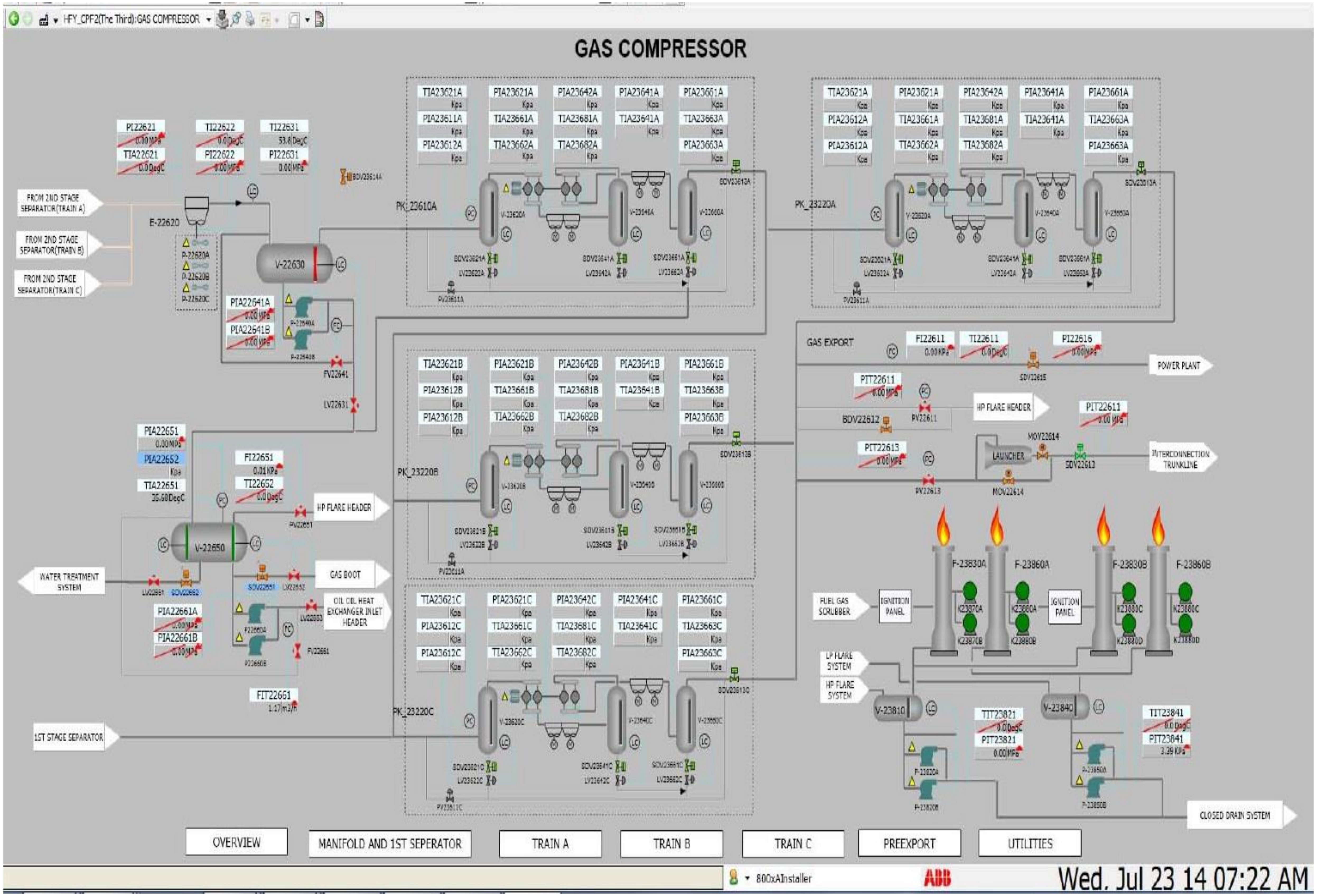

Figure [3.4] Gas compression overview

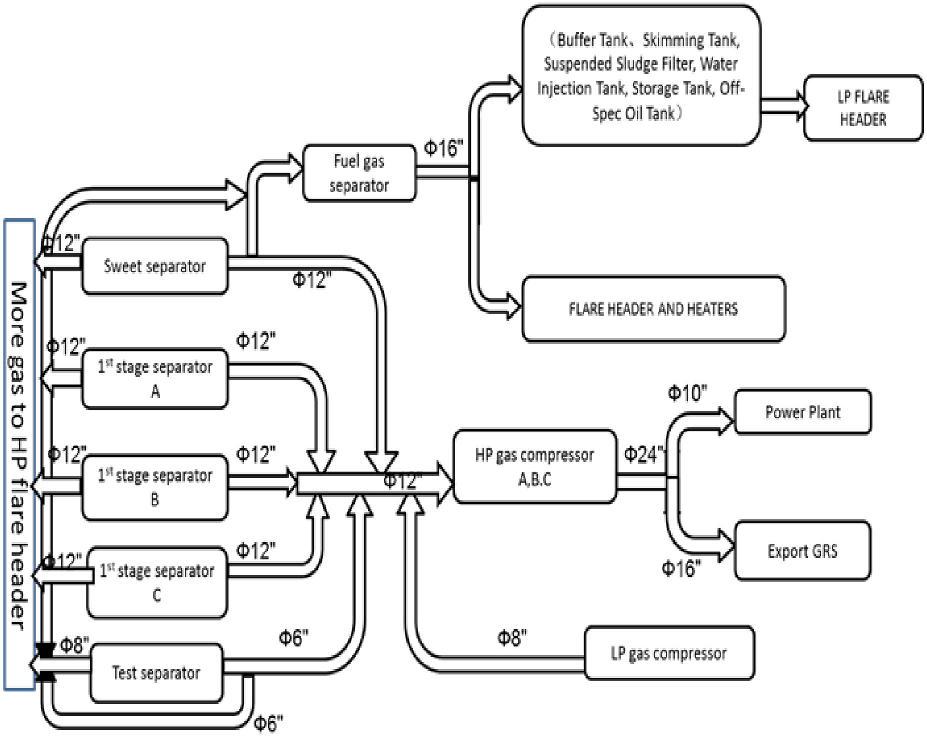

Figure [3.5] The interconnection between produced gases and compression units

Aerial cooler are used to cool down the lubricant oil loop prior re-accumulating for cooling cycle. Cooling oil lubricates and cool down the compressors parts and exchange its high temperature with forced air fans (aerial cooler radiators). Figure [3.6] shows the compression unit and aerial cooler.

Figure [3.6] The compression units and Ariel coolers

The system is monitored and protected by instrument and control systems and several axillaries. Table [3.1] shows the main parameters of compression unit.

Table [3.1] : Parameters of compression unit

Item	**Description**
Compressor stage (number/throw)	2 stage/ 4throw
Medium	Natural gas
Inlet pressure / Inlet temperature	≈1.0MPa/≤50 C◦
Final discharge pressure /	4.5 MPa/≤60 C◦
Design capacity	100 x 10^4 Sm^3/d
Ambient temperature / Cooling type	-2-55 C◦/ Air cooling
Lubricant method / oil consumption	Forced lubrication/≈35.64 L/d
Lube oil pressure	0.31MPa-0.41Mpa
Drive type	Coupling
Rated speed / Brake power	995RPM/2700KW
Noise	≤85dB(A)
Piston stroke	139.7mm :5.5 in
Piston rod diameter	63.5; 2.5in
MTBF	8000 h
Service life of the compressor	20 year
Skid mound dimension	LxWxH 32845x 6500x 3500 mm
Package weight	115000kg

3.1.1 Design Specifications for the Compressor

Manufacturer installed the compression unit in a simple frame for easy operation and maintenance. Compressors' manufacturer has wide experience and have years of satisfactory performance .The main specification for the existing type are in Table [3.2].

Table [3.2] : Main specification for the compressor unit

Specification	Compressor ranges
Stroke, inches (mm)	5-1/2 (140)
Speed, RPM/ Piston Speed, FPM (m/s)	995/ To 1100
Horsepower (kW)	To 4140 (3087)
Height - Bottom to Crankshaft Centre line inch	22 (559)
Connecting Rod Centre line to Centre line inch	17 (432)
Approximate Weight with Cylinders lb. (kg)	27,400 (12 430)
Sump Capacity, US gallons (L)	68 (257)
Piston Rod Diameter, in. (mm)	2.500 (64)
Compression Tension lbf. (kN)	114,000 (507)
Tension, lbf. (kN)	57,000 (254)
Compression, lbf. (kN)	60,000 (267)

3.1.2 Skid Design and Fabrication

The skid is designed with enough stiffness and strength so the compressor was mounted flat with no bending or twisting of the compressor frame, crosshead guides, or cylinder, this may be accomplished by steel shims, grout chocks, grout sole plates, careful rail or full bed grouting or adjustable chocks under all support points. The initial vibration alarm will be activated in 3.4mm/s and trip setting once reach 7.1 mm/s. Table [3.3] shows the vibration levels for the compressor.

Table [3.3]: Typical vibration levels for the compressor

Typical vibration limits for the compressor	
Model	**Vibration (mm/s^2)**
Skid	< 5.1
Compressor frame	< 13
Compressor cylinder	< 25

3.1.3 Instrumentation and Control

Main instruments were located in low lube oil pressure which the shutdown set to stop the unit if oil pressure downstream of the filter falls below 45 psig (3.1 barg) and operating the compressor for only a few seconds without oil pressure will result in major damage. Normally, the oil pressure at full rated speed and normal operating temperature should be about 60 psig (4.1 barg) when oil pressure exceeds 45 psig (3.1 barg) at start-up, the low oil pressure shutdown must be active. Compressors with automated pre-lube systems are to provide 10 psig (0.7 barg) minimum pressure for a minimum of 30 seconds prior to starting. There must be a no-flow shutdown for the force feed cylinder lubrication system. Also, a rupture disc assembly must be located just upstream of the no-flow shutdown. There are level transmitters to detect high liquid level in the scrubbers and shutdown the unit. Pressure and temperature gauges are normally located at each inter and discharge stages pressure and discharge pressure and each cylinder must be protected from high rod load and over pressure in compliance with the rod load and pressure limits. A high suction pressure shutdown may be desired to protect the driver from overload. The normal operating discharge temperatures shall not exceed the maximum discharge temperature shutdown setting 350°F (177°C).

Gas compression units control system architecture has separate Local Control Panel (LCP) for each unit, the LCP works by PLC (Programmable Logic Control) system. The architecture of PLC as in Figure [3.7] mainly consists of the following:-

1) Processor Unit: where the programs was built in to perform the local control as per the approved operation sequences (Start/Running, Stop and Shutdown Sequence).

2) Communication Module: to send selective (real-time) data and receive remote command from main distributed control system (DCS).
3) Set of Input & Output modules: to communicate directly with filed devices such as:-
   I. Sensors: for measuring analogue values (temperature, Pressure, level, flow, vibration, etc.) and discrete status (position, alarm limit).
   II. Transmitters: to convert analogue signals to (4-20mA).
   III. Final elements: motors, solenoids and shut down valves.
4) Local human machine interface: to allow field operators to monitor the compressor variables and locally control the unit.

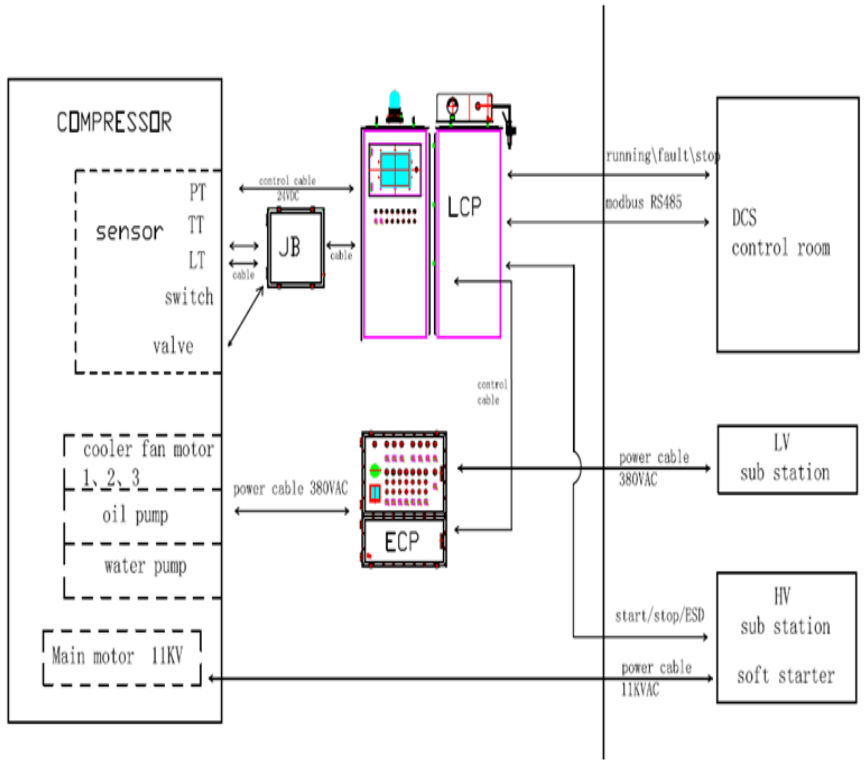

Figure [3.7] Gas compression unit control system architecture

Gas compressors control logic philosophy depends on three main sequences which are the start - up and running sequence, normal stop and shutdown sequence. These logic sequences and other sub routines configured using one of simplest program language named LLD (Ladder Logic Diagram) which is characterized by speeding up the implementation of instructions and easiest one in tracing the System fault similar to Figure [3.8].

For the electrical motor control and protection, the stator windings are manufactured according to temperature limit in 155°C (300°F). A high temperature will affect the insulation and shorten the lifetime of the winding. Therefore, thorough consideration should be made when deciding the temperature trip and alarm levels for the winding.

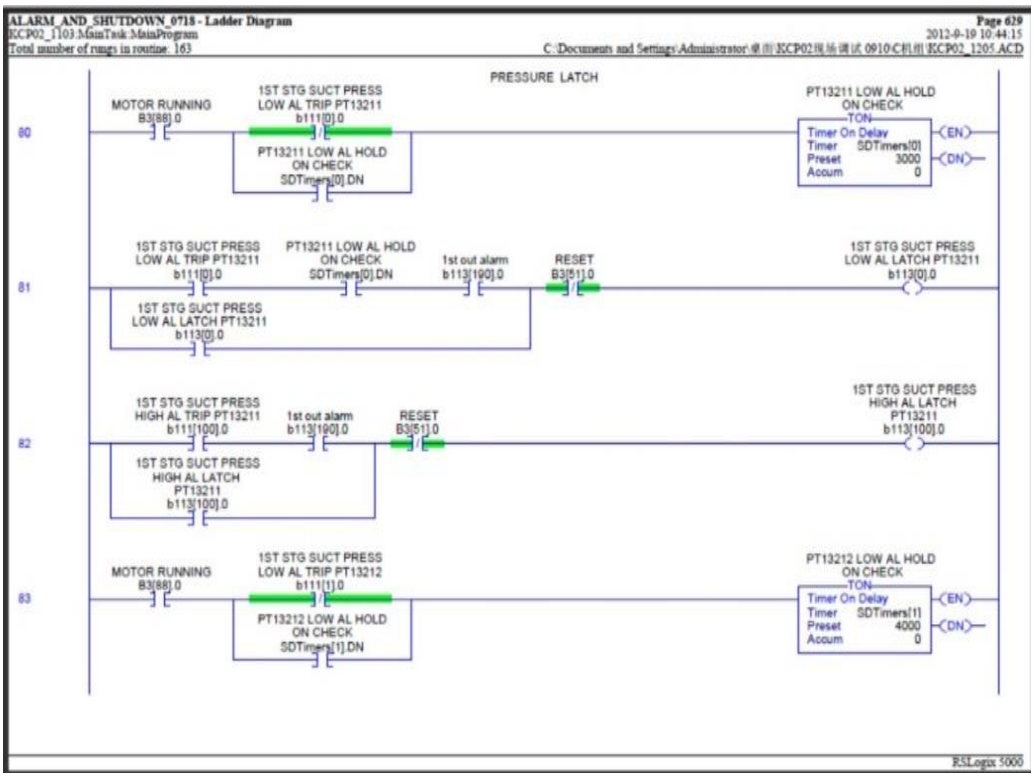

Figure [3.8] Part of the program language LLD (Ladder Logic Diagram)

Thus, the bearings are equipped with temperature detectors for monitoring the bearing temperatures. If the temperature of a bearing unexpectedly starts to rise, the machine should be shut down immediately as the temperature rise might indicate a bearings' failure.

3.1.4 Lubrication System

There are two independent systems for lubricating the compressor. These are the frame oil system and the force feed system. The frame oil system is a pressurized circulating system that supplies a constant pressurized supply of oil to the crankshaft, connecting rods and crossheads. The force feed system is a low volume high pressure injection system that supplies small quantities of oil at regular intervals to lubricate the piston rod packing and the piston rings. The break-in and normal lube timing rates which are stamped on the lubricator box information plate are calculated according to the manufacturer's lube specifications to set the proper force-feed lubricator pump flow rate and read the cycle time on the electronic lubricator fluid-flow monitor/no-flow timer switch. So, if the digital no-flow timer switch (DNFT) provides lubrication dose from the initial movement of the indicator pin at the fully retracted position to the time when the pin returns to the fully retracted position and just begins initial movement back out again.

3.1.5 Highlights on Operating Procedure

There are a lot of details for start-up, shut down and operational procedures. The main major check elements prior starting up are in below:-

1) Lubrication system: to ensure all lubrication system (oil level, valves, controller, etc) are checked.
2) Cooling system: to Inspect the cooling oil loop and coolant system.
3) Process gas system: inspect the process gas pipeline of compressor unit, purging, scrubber valves, instrument, control and electrical systems (switches, PLC, voltage, etc).
4) Instrument gas system: open inlet valve of instrument gas system.

3.1.6 Recommended Maintenance Intervals

As per the original equipment manufacturer (OEM) recommendations, it is mandatory to follow the maintenance intervals program and operation procedures in order to ensure having safe and efficient units. Maintenance intervals were set for daily and monthly activities beside to be continued based on the running hours (RH).

3.1.6.1 Daily Maintenance Tasks

The recommended tasks log to check the followings:-

1) Compare the operating running main parameters (like gas pressure and temperatures) are within the design parameters and highlight any variations.
2) Measure bearing temperatures and frame oil pressure at operating temperature.
3) Check the oil filter differential pressure and check frame oil level.
4) Check force feed lubricator box oil level. It should be full to the overflow line. Check for gas, oil, and coolant leaks as well if any unusual noises or vibrations.
5) Check suction valve unloader actuator vents for leakage.
6) Verify the high discharge gas temperature shutdown (shall not exceed the maximum discharge temperature shutdown setting).

3.1.6.2 Monthly Maintenance Tasks

1) Perform all Daily maintenance tasks and verify the safety shutdown functionality.
2) Test and analyze the frame oil in a lubricant lab to find out if any increasing levels of lead, tin, or debris indicates. In case of

any findings, then to change the oil, oil filter and clean the oil strainer with a suitable solvent.

3.1.6.3 Six-Month (4,000 Hour) Maintenance Tasks

1) Shut down unit and allow sufficient time for components to cool. Then to perform same monthly maintenance task list.
2) Drain and replace force feed lubricator box oil and clean oil filter on the force feed lubrication system or at every main oil filter change.
3) Change oil filter, crank case oil and check cylinder lubrication.

3.1.6.4 One-Year (8,000 Hour) Maintenance Tasks

1) Inspect force feed lubricator box and visually inspect the pump cams and gear.
2) Measure main bearing, connecting rod bearing, crank shaft jack and thrust clearances.
3) Piston rod run out and remove valves and valve gaskets and visually inspect the valve pockets as well visually inspect the suction valve unloader actuator.
4) Inspect cylinder bores and inspect piston rings and rod.
5) Check and re-calibrate all required instrumentation.

3.1.6.5 Two-Year (16,000 Hour) Maintenance Tasks

1) Perform all Daily, Monthly, Six-Month, and One-Year maintenance.
2) Rebuild oil wiper cases and check the requirement if need to use new piston and stem seals to rebuild actuators on suction valve unloader.

3.1.6.6 Three-Year (24,000 Hour) Maintenance Tasks

1) Perform all Daily, Monthly, Six-Month, and One-Year maintenance.
2) Replace the connecting rod bearings.

3.1.6.7 Four-Year (32,000 Hour) Maintenance Tasks

1) Perform all Daily, Monthly, Six-Month, One-Year, and Two-Year maintenance tasks.
2) Measure and log crosshead pin to crosshead pin bore and connecting rod bushing bore clearances.

3.1.6.8 Six-Year (48,000 Hour) Maintenance Tasks

1) Perform all Daily, Monthly, Six-Month and One, two, three and four year's maintenance tasks.
2) Replace lubricator distribution blocks.
3) Replace crosshead and connecting rod bushings and connecting rod bearings.

3.1.7 Maintenance Programs

The maintenance program is based on four levels of maintenance which rotate according to operating running hours. So, maintenance programs will be executed in series based on the running hours following level 1(L1) then level 2 (L2) and so on. L1 includes mainly quick visual inspections and L4 more demanding measurements and replacements.

3.1.7.1 Level 1 (L1)

Level (1) maintenance consists of visual inspections and light maintenance. The purpose of this maintenance is to do a quick check whether problems are beginning and cause unscheduled maintenance breaks. It gives also suggestions what maintenance issues must be performed in the next service.

The first Level (1) maintenance should be performed after 4,000 RH equivalent to six months after commissioning. Subsequently, the L (1) maintenance should be performed yearly halfway between L (2) maintenances.

3.1.7.2 Level 2 (L2)

This maintenance consists mainly of inspections, tests and small maintenance tasks. The purpose of this maintenance is to find out whether there are problems in the operation of the machine and to do small repairs to ensure uninterrupted operation. The first Level 2 maintenance should be performed after 8,000 RH equivalent to one year after commissioning.

3.1.7.3 Level 3 (L3)

This maintenance level consists of performing extensive inspections, tests and larger maintenance tasks that have come up during L1 and L2 maintenances. The purpose of this maintenance is to repair encountered problems and replace parts subjected to wear. The preparations consist of opening the inspection covers, the bearings and the water cooler.

3.1.7.4 Level 4 (L4)

It consists of performing extensive inspections and maintenance tasks and the purpose is to restore the machine into a reliable operating conditions. The preparations consist of opening the inspection covers, bearings and water cooler (if applicable) and the removal of rotor.

The amount of spare parts required for this level of maintenance needs to be determined before the maintenance and at least the recommended spare part is needed. The Level (4) maintenance should be performed after every 80,000 equivalent operating running hours. Table [3.4] shows the maintenance object and maintenance interval recommendations.

Table [3.4] Maintenance object and interval recommendations

Maintenance Object	Maintenance Interval In equivalent to operating running hours or time period and for whichever comes first			
	L1	L2	L3	L4
	4,000 RH 12,000 RH 20,000 RH 28,000 RH ½ Year	8,000 RH 16,000 RH Annual	24,000 RH 3-5 Years	80,000 RH Overhauling

3.2 Existing Plant Maintenance Manpower and Management Systems

Existing manpower hierarchy are involving in the overall oil and gas plant (not dedicated team for gas plant). Team are either from operation team to operate the plant and monitoring or maintenance and inspection team to perform the maintenance and inspection programs based on the program intervals. Operators are distributed based on area wise and normally in gas compression plant there is one permanent operator for 24 hours communicating continuously with the main control room, but maintenance team are working in compression plant for particular part time. Table [3.5] shows the existing operation and maintenance team for the whole plant:-

Table [3.5] Operation and maintenance team for the whole plant

No	**Disciplines**	**Position**	**No of position**	**Responsibility**
1	Operation	Operation superintendent	1	Overall plant operation lead focal
		Operation supervisor (Site)	1	Site operational activities

		Operation supervisor (Control room)	1	Control room monitoring
		Operators	20	Distributed at all areas
2	Maintenance (Plant Team)	Maintenance superintendent	1	Overall plant including external utilities
		Mechanical Engineer	1	Core person for all mechanical tasks
		Mechanical technicians	5	Execute mechanical tasks
		Electrical Engineer	1	Core person for all electrical tasks
		Electrical technicians	3	Execute electrical tasks
		Instrument Engineer	1	Core person for all instruments tasks
		Instrument technicians	4	Execute instrument tasks
		Control system engineer	1	Core person for all control tasks
3	Maintenance (Supporting team)	Senior planner	1	Maintenance plans and technical support provision
		Senior mechanical engineer	1	Spare parts and mechanical trouble shooting and causes analysis
		Senior Electrical engineer	1	Spare parts and electrical trouble shooting and causes analysis
		Senior Instrument engineer	1	Spare parts and instruments trouble shooting and causes analysis
		Corrosion and Inspection team	15	Corrosion prevention and inspection analysis mainly based on ASME B31
		Senior System and control engineer	1	Spare parts and electrical trouble shooting and causes analysis
		Senior Metrology engineer	1	For pressure safety valves, gas detectors, lifting equipment and gauges calibration

There is an existing outsourcing agreement for technical support with the manufacturer service engineer on call bases once needed. Mainly such calls will be only while emergencies and major overhauling. The main concern in such support is the delay in the response due to abroad mobilization till arrival at working site from another country. There is a check list formats used in maintenance tracking as record. Appendix I showed the used preventive maintenance check list for the 8,000 running hours.

CHAPTER FOUR

CHAPTER FOUR

PROBLEM's STATEMENT DETAILS AND IMPACT

4.1 About Gas Compression Unit (A)

The existing running hours (during the study) for the HP compressors packages are as in Table [4.1].

Table [4.1] Running hours for the HP compressors packages

HP Compression Unit	Running Hours (RH)
A	19,637
B	20,628
C	20,532

These three HP compression units are identical. Therefore, the study and analysis will be focused on the compression unit (A). From the running hours, it is clear that unit is almost new, but has a lot of unscheduled down time. Figure [4.1] shows the unit (A) up and down time (Time stamp date/time versus outlet pressure).

Figure [4.1] Compression unit (A) up and down time

From Figure [4.1], the down time (planned and unplanned non-working time) is high compared with the design mean time between failures which is eight (8) times.

The minor power dipping and the fluctuated trips are not considered in order to assess the main causes. Thus, Table [4.2] shows the recorded troubleshooting for the compression unit (A):-

Table [4.2]: Compression unit (A) troubleshooting

Fault	Cause	Corrective Action	Failure Date	Completion Date	Difference in days
Lube oil temperature high	Thermostat valve had stuck	Thermostat valve temperature element replaced	16/05/15	05/06/15	20
Pre-lube oil pump overload relay trip	The pre lube oil pump overload relay fault	The pre-lube oil pump overload relay replaced	22/07/15	29/07/15	7
Air Cooler motor vibration high	vibration switch set point not suitable	Adjust the vibration switch set point	06/08/15	07/08/15	1
2nd stage discharge scrubber cannot drain	condensate outlet pipeline blocked	the man-way for 2nd stage discharge scrubber condensate outlet pipeline opened and clean	26/08/15	30/09/15	35
LCP communication with DCS failure for short time, the data was not reachable to the CCR.	The fault was from the MOXA switch.	This MOXA switch Device already replaced by new type during plant shutdown plan.	17/10/15	25/10/15	8
Nitrogen regulator pressure gauge not reading	Found regulator isolation valve is block	Rectify the isolation valve and PM 2,000	05/11/15	12/11/15	7
Control room found gas flow rate is 0， but DCS display HP gas compressor status is normal,	Locally checked found the inlet and discharge SDV had closed, .Local control panel fault, fuse of the power supply of the IO module blown.	Investigated and replaced the fuse and failed card	10/12/15	11/12/15	1

Cylinders temperature found running with high temperature	Unloader valves and discharge valves were leaked	Unloader suction valves checked found no# 1 and # 3were leakage, as well no#4,5and 6 from discharge valves were leakage. Replaced by another unloader valves.	25/10/15	27/10/15	2
air cooler fan motor Over load relay trip frequently	Panel very hot	HP gas compressor P-23210A air cooler fan motor #1 Over load relay replaced from P-23610 LP gas compressor air cooler motor #1.	21/01/16	02/02/16	12
Compressor tripped due to high temperature	valve pin for divider block was stuck	Checked and clean the line goes to 1st suction pulsation cylinder#3 and the valve found ok ,vented the line and installed back. Also, checked the divider valve and the line goes to cylinder #4 for the discharge valves.	20/02/16	27/02/16	7
Compressor cannot start after normal shutdown	DNFT FS-23292A trip signal	Checked found loose connection in DNFT terminals due to vibration-re tightened	11/03/16	12/03/16	1
TIT-23221A 1st stage suction scrubber Temperature reading Zero	Analogy card problem	Analogy card problem, CPU power reset and card replaced,	23/03/16	04/04/16	12
The signal for the TT-23221A was not showing in the compressor HMI.	Two Channels in the AI Card were showing fault indication.	Power reset to the LCP.	14/04/16	15/04/16	1
Compressor tripped due to DNFT	DNFT trip signal	DNFT battery voltage 2.3V DC, replaced new one.PM 4,000	08/05/16	03/06/16	26
Cooling fan motor#3 running with abnormal noise	NDE side running with high noise	Replaced the DE bearing	04/08/16	11/08/16	7
Cylinder#4 running with high temperature	Two discharge valve and one unloader were leakage	Replaced the unloader and two discharge valve by new valves	30/08/16	04/09/16	5
PLC program crash notification.	Can cause by many reason	The logic uploaded	04/10/16	06/10/16	2

	like example power trip				
TT-23242 showing no reading in the Gas Compressor HMI.	The AI Card was showing fault indication.	Power reset to the LCP.	02/11/16	03/11/16	1
Air cooling fan #2 & #3 stopped	belts ruptured	Replaced by new ones	19/11/16	20/11/16	1
CYlinder#2 running with high temperature	Discharge valves #1 found leakage	Replaced by refurbished valve	02/02/17	15/02/17	13
Cylinder#3&4 high temperature.	Discharge valve#1,2 &# leakage for CY#1 discharge valve#1&&2 were leakage for CY#4	valve#1,2and3 replaced by new ones, valve1&2 replaced by refurbished ones	10/04/17	17/04/17	7
Compressor tripped due to DNFT	DNFT trip signal	battery connection wire damaged, replaced the wire and checked ok	25/05/17	29/05/17	4
Suction & Discharge Scrubbers TITs not giving correct reading	RTD length too short for sensing	Suction & Discharge Scrubbers TITs replaced with new ones with longer thermo-well. Design and engineering concerns	13/06/17	22/06/17	9
Compressor tripped due to DNFT	DNFT FSL-23292A trip signal	DNFT replaced from HPC-C	03/07/17	11/07/17	8
The time in the gas compressor HMI not matching with DCS System.	Time delay happening when the compressor LCP shutdown.	The time had been corrected in the compressor HMI.	31/08/17	18/09/17	18
Air cooling fan #2 stopped	belts raptured	Replaced the belt	06/10/17	07/10/17	1
Cylinder#4 due running with high temperature	Two discharge valve and one unloader were leakage	Replaced two discharge valve	18/10/17	19/10/17	1
M-23210 CM A Lube oil cooler fan motor MCB tripped	MCB tripped	Found bearing broken replaced a new motor	04/11/17	05/11/17	1
Compressor tripped due to alarm	PIT-23221A HH alarm signal	Checked and found Impulse line near valve broken due to high vibration, line modified and	02/12/17	21/04/18	140

		compressor started ok and PM 8,000			
The signal for the TT-23242 2 #CYLINDER TEMP showing wrong reading in the HMI.	The TT23242 has problem.	Internal repair fir the transmitter	22/05/18	30/05/18	8
Compressor tripped due to alarm in suction scrubber	suction scrubber(V-23220) Level Transmitter LT-23222A HH Alarm	Checked and found loose connection in Transmitter terminals tighten and get back normal	19/06/18	28/06/18	9
Cylinder#3&4 running with high temperature	Two discharge valve for cyl#4 and one discharge valve for cy#3 were leakage	Replaced two discharge valve for cyl#4 and one discharge valve for cy#3	01/08/18	02/08/18	1
1st cylinder#1 and 2nd cylinder#2&4 were running with high temperature.	1st one discharge valve was leakage and 2nd stage two discharge and suction valve were leakage	Replaced four valves as were found running with high temperature: 1st stage cylinder #3 one discharge valve, 2nd stage cylinder #2 one discharge vale and cylinder #4, one suction and one discharge valve.	19/09/18	02/10/18	13
Compressor tripped due to DNFT	weak lubrication feed, lead to DNFT trip signal	Line flushed by mechanical after that DNFT function checked ok and replace belts, replace power module LCP, replace all four discharge valves, PM 16,000	16/02/19	28/04/19	71

Table [4.3] shows the maximum estimated costs impact per year considering complete shutdown to oil and power plant , mobilization of manufacturer support for one month and in case of one fatality person (related to safety and insurance).

Table [4.3]: The estimated cost impacts for unplanned down time

No	Impact	Consequence Impact	Impact Estimated Cost
1	Safety impact	I. Lead of injury or death	0.5 M$USD/Year
		II. Firefighting and emergency response centre response	
		III. Reputation impact for working team	
		IV. Investigation and safety reports	
		V. Insurance impact	
2	OEM utilization	I. OEM cost (man day rates and mobilization)	0.3 M$USD/Year
		II. Long down time till OEM arrival	
3	Spare parts consumption	I. Affect Stock level (optimization) due to unplanned events and repair actions.	0.1 M$USD/Year
		II. Fast delivery cost for urgent requests.	
4	Plant power loss and use of back up diesel generator	I. Start-up procedure (manpower utilization)	1825M$USD /Year (100,000bopd for production deferment)
		II. Process plant impact	
		III. Fuel diesel and time loss	
5	Produced Gas Export impact	I. Loss of exported gas cost	54.8 M$USD/Year (0.15 M$USD/day for city power loss)
		II. Loss of two power generation plants for the city	
		III. Criticality of condensate in line	
Total Estimated maximum loss			**1880.7 M$USD/Year**

CHAPTER FIVE

CHAPTER FIVE

FRAME WORK PROPOSAL

5.1 Baseline Assessment of Compression Unit (A)

The current condition of the compression unit (A) is assessed as it is the area of the study in order to be as bench mark and baseline reference for results comparisons. A calculation of existing down time for compression unit (A) compared with the operating uptime is the core for the equipment condition assessment. Then, the reliability, availability and maintainability (RAM) will be verified as well for the overall equipment effectiveness (OEE %) calculation as first step.

The frequency is described in terms of mean time between failures (MTBF) of the unit. The total down time and operating uptime are sorted to determine the mean time between failures (MTBF) and mean time to repair (MTTR) for the production availability. Availability is the achievable proportion of the specified production demand over a specified period. So, based on the data collected from site as shown in Table [4.2], the production availability for the HP Compressor package (A) is calculated for the spent lifetime four years (1,460 days) from May 2015 to April end 2019 with loading time equal to 19,500 recorded running hours (812.5 days).

As the Availability is the amount of time in which the system is ready to use and able to carry out its function (Uptime/Total time), so it is calculated as follows using equation (2.9) and the gained result presented in Table [5.1] as in below:

$$Availability = \frac{(1460\ Days - 460\ days) * 100\%}{1460\ Days} = 68.5\%$$

Table [5.1]: HP Compression unit (A) Availability

ID	Description	Production Availability (%)	Total down time (Days)	No of outages	MTBF (hours)
PK-A	HP Gas Compressor Package A	68.5%	460	34	$(1{,}460 - 460)x\frac{24}{34} = 705.88$

The reliability of a system, $R_{(t)}$ is the probability that a system can perform a required function without failure under stated conditions for a given time .Reliability calculations for the HP Compression package (A) shows that the overall production availability of HP Compression unit is around 68.5%. It is low because of the huge downtime (460 days) compared with the four years total time for a single package A (1,460 days). The planned down time is obtained as per below equation (5.16) :-

$$planned\ down\ time = Total\ time - (downtime + loading\ time)$$
$$= 1460 - (460 + 812.5) = 187.5 days \tag{5.16}$$

Moreover, to obtain the overall reliability of the unit, it was essential to consider the total down time (TDT) importance. The TDT Importance is the contribution from each failure type to the overall system down time. This will give a better indication of the criticality and importance of the failure mode and component in the overall system. Therefore, the TDT Importance shows the failure mode that, if improved, would improve the overall TDT (total time the component is out-of-service). Table [5.2] presents the contributors to the TDT Importance expressed as total hours for HP compression package (A) as a percentage of the total downtime.

Table [5.2]: HP Compressor TDT Importance

ID	Description	TDT Importance Hours	TDT %
PK-23210A Vibration	Compressor trip due to HH alarm caused by impulse line	**3360**	**30.43%**

ID	Description	TDT Importance Hours	TDT %
	near valve broken due to high vibration		
PK-23210A DNFT	Compressor DNFT trips	**2640**	**23.91%**
PK-23210A Control	Control failure due to PLC/DCS/HMI issues	**1032**	**9.35%**
PK-23210A Cylinder High Temperature	Cylinder high temperature due to leakage of discharge valves	**1008**	**9.13%**
PK-23210A Blockage Drain	2nd stage discharge scrubber cannot drain	**840**	**7.61%**
PK-23210A Lube Oil	Main control board (MCB) /relay/ thermostat valve/Pump issue in Lube Oil system	**672**	**6.09%**
PK-23210A Auto and instrument	Incorrect/false reading due to instrumentation issues	**624**	**5.65%**
PK-23210A Motor	Air Cooler motor issues (vibration, trip and noise)	**480**	**4.35%**
PK-23210A Isolation Valve	Nitrogen regulator pressure gauge not reading due to blockage of regulator isolation block	**168**	**1.52%**
PK-23210A High temperature	Compressor high temperature trip	**168**	**1.52%**
PK-23210A Belt rupture	Air cooler belts ruptured	**48**	**0.43%**
Total		**11,040 hours**	**100%**

For the overall equipment effectiveness determination, the calculations as applied in equations (2.1), (2.15). So, performance (P) is calculated as equation (5.2):-

$$P = \frac{Load\ times}{Total\ Time\ - Downtimes} x\ capacity\ coefficient \qquad (5.2)$$

In our case, as it is heavy duty compressor, therefore the required load time is equal to 1,460 days.

$$Capacity\ coefficient = \frac{Actual\ capacity}{Nominal\ capacity} \qquad (5.3)$$

The compression is going through a loop where no gas leak. So, it flows in same system boundary, hence the value of quality (Q) will be equal to one (1) due to NO change in volumetric flow and No rejected gas. Therefore,

$$OEE\ \% = \frac{Capacity\ coefficient\ xload\ time}{Total\ Time} x100\% \qquad (5.4)$$

From Table [3.1], the design capacity =$100x10^4\ m^3$per day and actual capacity =$875x10^3\ m^3$per day. So, the capacity coefficient =0.875

$$OEE\% = \frac{0.875x812.5x100\%}{1{,}460} = 48.7\%$$

5.2 Existing Maintenance Strategies

5.2.1 Preventive, Corrective and Condition Monitoring Maintenance

There is an existing plan to perform the preventive maintenance as per the original equipment manufacturer (OEM) recommendations. These tasks are performed by the company personnel and sometimes with the support of OEM for major maintenance like 8,000 and 16,000 running hours, etc as well as when emergencies occurred.

The plant is monitored 24 hours by the operators and remotely from the main control room. So, in case of any abnormalities, a corrective maintenance notification will be launched immediately to the maintenance team.

Limited condition monitoring system is available and mainly to monitor the vibration and temperature limits. Major condition monitoring tools are:-

1) Visual inspection and unit survey.
2) Vibration meter and analyser.
3) Infra-red (IR) temperature gun.
4) Surface non-destructive tests (SNDT) using ultrasonic test (UT) and penetrant test (PT).

There is a technical report for every performed task either preventive or corrective maintenance contains all required information such as:-

1) Maintenance/problem statement and background.
2) Involved resources.
3) Task checklist and used spares.
4) Conclusion and next action and interval.

5.2.1.1 Gaps in Preventive, Corrective and Condition Monitoring Maintenance

Preventive maintenance is important and very useful for most of equipment either static, rotating or combine as it depends on time base factors (time frame or running hours), thus, most of manufacturer and practitioners use.

Preventive maintenance is easy to trace and flexible to be set in one master plan for follow up. The plan has resources dependant for the required manpower, materials, machine, tools and consumables. Maintenance tasks completion percent is also simple to be calculated in order to focus on areas with lower completion scores for more development. At present, the non-major preventive maintenance are executed by company team but major tasks require support and manufacturer supervision. Final execution reports are linked with computerized maintenance management system (CMMS-SAP R6) which reflect and save all the events for the scheduled maintenance plan. The role of CMMS is to auto issuance of the maintenance daily tasks. At present, it is not properly utilized. Currently, SAP R6 is used for daily plans, issue the operation's notifications as work requests and generate completion reports.

In general, preventive maintenance is affected by corrective maintenance as it will deviate the set plans, utilize resources and allocated budgets. Corrective maintenance is mainly un-planned maintenance due to sudden impact or while site monitoring and observation. There are several criticality level of the notifications, some are much important and require immediate action and some are minor which supposed to be performed by operators themselves as basic level of maintenance concepts. It is important to have report for the root causes in details contain one of suitable methods of root cause analysis. Also, main information are required to be considered for problem solving (what, when, where, and who). Generated reports are saved also in CMMS, but need dedicated competent team to do more analysis to ensure having more reliability and further improvement follow up.

Preventive and corrective maintenance tasks completion time are one of the major key performance indicators (KPI) of the maintenance execution performance. The KPIs for preventive and corrective maintenance score has direct correlation with the compliance to the schedule, quality, plan follow up and safe completion.

Condition monitoring is an effective tool to support planning of preventive maintenance for earlier predictions due to limited human senses and detections. Mainly, the condition monitoring depend on the skills of both operators and technicians as well for the used detection devices. Condition monitoring starts with visual survey and depends on sensing of any abnormal signs. Most of condition monitoring tasks are focused on equipment main parameters especially like pressure, temperature, vibration, level and noise. Collected condition monitoring records are usually compared with design allowable limits in order to detect any observation.

The summary of the major advantage of preventive, corrective and condition monitoring maintenance are as in below:-

I. Easy scheduling, monitoring and control.
II. Early flexible scheduled plans with costs and resources optimization.
III. Measurable outcomes through KPI targets, setting policies and procedures.
IV. Historical records.
V. Support for lowering the downtime.

The major gaps of preventive, corrective and condition monitoring maintenance execution in the gas plant unit (A) are:-

I. There is no dedicated maintenance team for the compression plant like operators. A lot of operation notifications can be performed by them directly and it does not require waiting for maintenance team response whom are engaged in other jobs.
II. Difficult to get the OEM when required for emergency conditions or while major activities.
III. Overdue in delivery of materials supplies.
IV. No proper assessment on the observed maintenance outcomes or recommendation (only basic reports and no failure modes or consequences impact analysis).
V. Limited improvement proposals and studies.

A general discussion was made with maintenance personnel at site to understand the frequency of these failures and the response repair time. The information gained is on the mean time to fail (MTTF) and the approach on resolving issues as well the mean time to repair (MTTR). The response or repair time is the mean time taken to perform all corrective or preventative maintenance repairs. Actually, it is described as:

Mean Time to Repair (MTTR) = Logistics Delay + Active Repair Time

Where:

1) Logistics delay is due to the followings:-

   I. Mobilization time: notification of the maintenance crew and response delay.

   II. Process related delay: this includes preparation of the system for example isolation, draining and purging by the Operations Team prior to maintenance handover for repair.

   III. Spares delivery time: this includes the time delay associated with ordering spare parts, tendering process and up to delivery to site.

   IV. Test and start-up time: this includes testing and preparation of the system before it can be brought back to operational readiness which need coordination with power system supply.

2) The Active Repair Time is the calendar time during which maintenance resources are being utilised either automatically or manually.

5.2.2 Gaps in Reliability Centred Maintenance (RCM) and Risk Based Inspection (RBI)

RCM is a modern system established from preventive maintenance programme which will allow achieving of the required improvement levels efficiently and effectively.

The main objectives of the RCM are:-

I. Maintain the equipment function at the required performance level.

II. Obtain the necessary information for further improvement studies.

III. Support in cost saving

IV. Assess the existing troubles and impact consequences

V. Monitor the condition of specific components.

Currently in the existing system, there is clear gap indicating that only root causes failure analysis reports (RCFA) are generally prepared, but not properly applied. RCFA is to support understanding the causes behind of the problems and prevent its occurrence. There are several tools which can be used to carry out the RCFA likes Fishbone Diagram, failure mode and effect analysis (FMEA), Pareto Analysis, Fault Tree Analysis and others. RCM which require essential information to obtain proper decision and improvement solution like (Failure Mode Effects and Criticality Analysis (FMECA), failure classification, failure frequency, etc).

For applied risk based inspection plans, it is done according the international standards mainly for American Petroleum institute (API). Most of the inspections practices are in line with (API 510 for vessels) and API570 for pipes as follow recommended practices. Through several conducted inspection, a lot of several findings were detected at earlier stages such as (cracks, pitting, corrosion monitoring system detection, etc) and repaired. These inspections are performed through dedicated specialized team (corrosion and inspection team). Therefore, results had positive and improvement, but still the final reports are Not Centralized with the rest of generated reports.

Package scrubber has a lot of influence for the occurred down time due to the condensate carryover impacts. Regular inspection, functional tests were carried out, but doesn't improve or mitigate neither the corrosion findings in the scrubber nor the causes of trips due to high condensate level alarm which occurred due to blockage of condensate drain line. The blockage reason is due to fallen parts from above installed demister into bottom drain.

Major observations of existing maintenance strategies and working conditions:-

1) The overall production availability is almost 90% which is still low, also the OEE% is 48.7% for studied package.
2) High No. of failures in several locations of the plant.
3) No clear KPIs to assess the gained targets versus the objectives.
4) Operators are not performing the minor noticed events. They just act to issue maintenance notification for corrective action due to limited awareness and given authorities for maintenance.
5) Non-sufficient improvement studies for compression plant to enhance current conditions especially for the scrubber vessel and instrument fittings.
6) No proper link of all these applied different strategies.

Therefore, a suitable integrated maintenance frame work is required to enhance the current conditions and minimize the existing problems causes. Proposal started with indemnity the merits and demerits of modern maintenance and best maintenance engineering practices.

5.3 Followed Steps to Develop the Integrated Proposed Frame Work

5.3.1 Set Key Performance Indicators (KPI's)

A Key Performance Indicator (KPI) is a measurable value that reflects how effectively the business objectives are achieved. Currently, most of the premises and organizations are using KPIs at several sectors in multiple levels to evaluate their positions compare to the set targets. Generally, the high-level KPIs may focus on the overall performance of the business, while low-level KPIs may focus on performed processes in departments such as production, sales, marketing, human resources, supporting team and others. KPIs provide a focus for strategic, operational improvement and offer an analytical basis for decision making and improvement.

Performance indicators measurement is a fundamental principle of management. The measurement of the performance is important because it identifies current performance gaps between current and desired performance and provides indication of progress towards closing the gaps. Proper selected key performance indicators identify where to take action to improve the performance.

All maintenance working team will deliver more efforts to ensure obtaining higher score points and achieved higher targets. These KPI indictors were set based on the common best practises for oil, gas natures and previous studies [75], [76] , but two additional points were added. The two additional KPIs were proposed are in below:-

1) KPI for main technical reports submission mainly for (RCFA and FMECA) to ensure all reports are completed within agreed time frame with clear indication either as closed case or with described next step. Usually, in the reports' recommendation or the next steps, there will be a further actions like modification, upgrades or more study.
2) KPI for evaluating the average of the overall related maintenance manpower annual performance. The working team has direct impact into the overall performance results, thus the average level is also need to be considered in order to know the working team competencies which will be subjected to management analysis and decisions like (set training, promotions, satisfaction, replacement, outsourcing, etc).

Table [5.3] shows the set KPIs considered for all the applied maintenance strategies.

Table [5.3]: KPIs for Maintenance

Cat.	Key Indicator	Scale	Target	Result
Maintenance and Inspection Execution	Compliance Safety: As per company HSE regulations (No of Major Incident due to lack of Maintenance)	No of Incidents	≤ 0	
	PM Completion %	%	≥ 97	
	CM Completion %	%	≥ 95	
	Unscheduled shut down due to maintenance/per plant	No of Shutdown	≤ 1	
	Inspection Plan completion%	%	≥ 95	
Reports	Completion of Reports (daily , weekly, monthly, annually)	days' timeline	≤ 5 days	
	RCFAs and FMECA	days' timeline	≤ 10 days	
Costs	Budget utilization (Budgeted costs versus actual costs)	Utilization %	≥ 95	
Critical cases and outstanding	Number of critical outstanding jobs have direct impact to	No of critical cases and outstanding	≤ 2	

	HSE/Production targets. (exclude delay due to delivery/visa/ security, etc)			
Reliability, Availability and OEE%	Reliability	%	≥ 95	
	Availability	%	≥ 94	
	OEE %	%	≥85	
Maintenance section Performance review (Average)	Review section performance as average against objectives contribution, performance standards (Know How) and personals' behaviour.	Outstanding Excellent Good Poor	Good as minimum average level for all team members.	

Maintenance staff are one of the core team to ensure having healthy systems, less down time and maximum overall efficiency. Thus, their KPI evaluation shall consider their contribution on the technical reporting submission (mainly for RCFA and FMECA) with specific time frame. Even if the report investigation need more time, so at least a preliminary version must be provided on particular time and to be followed till close out the report. Moreover, the overall maintenance team as one group shall be assessed as an average scale beside the detailed individual assessment for everyone.

This is to brief the higher management about all section assessment which lead to further decision like to increase the number of personals, trainings, outsourcing, replacement, etc. Once employees know about on time reporting submission and frequent assessment of their overall performance, logically they will increase their contribution, enhance their work quality and taking works execution properly and seriously.

5.3.2 Orientation and Training

Education and training programs shall be executed to ensure getting competent operators. Such educations will not be difficult as they already have the operation principles. Therefore, with limited efforts, their maintenance technical knowledge can be improved. Thus, establishing of training programs including training in maintenance concepts, tools and assessment will increase operators' morals, confidences and their self-completion for better success. The performed training session are listed in Table [5.4].

Table [5.4] : Performed training sessions

Course	**Attendees and outcomes**
Reliability Centre Maintenance	This training is provided for limited days though expert provider to engineers and supervisors for more understanding of RCM concept and its benefits. Similarly, RBI also conducted and covered in separate sessions and focused more with the corrosion and inspection team.
Risk Based Inspection	
Root Cause Failure Analysis	Education sessions were presented to supervisors, engineers, technicians and operators in order to make RCFA is responsibility of everyone for failures findings and predictions (developed RCFA template in appendix II)
Approach to Focused Improvement	This course was given to engineers and supervisors level and mainly was for engineers for further assessment and field improvement proposals (FIP).
LSV (Leadership site visit)	Mainly, this program covers the safety orientation related to working staff, site condition and their relationship. More elaboration was given by safety and risk specialists.

Understanding of TPM	This was short brief about TPM philosophy, concept and importance. All levels were attended and mainly for operators and technicians especially for the new assignments. Engineers were assigned to follow the improvement action and reports recommendation.
KPI measuring performance	Introduction to KPIs for all staff and focused on planners.

5.3.3 Integrate Maintenance Programs

The right step to build up a good system is to start with goals identifications. Goals can be defined as the measurable indicators to assess whether you have achieved the required objective. Therefore, the objective of proper optimum maintenance is to maximize the performance of equipment by attempting to prevent down time, minimizing the losses, save capital and costs. All that shall be in line with having a safe working conditions.

Each task of planned maintenance shall be executed by adopting particular Maintenance Procedures (MP). These MP shall demonstrate the steps of maintenance tasks. MP is set for compression unit (A) based on the recorded information from expert working team and OEM recommendation (Appendix III shows the developed MP for 8,000 RH).

5.3.4 Improve Computerized Management System (CMMS)

Basic step of maintenance plans depend on understanding of the organizational objectives, targets, resources, site and equipment nature. The steps of preparing a maintenance plan can vary and shall be customized based on the requirement. The key steps in preparing a typical maintenance plan are:-

1) Identify operation and maintenance goals in respect to the organizational goals and defining the type of maintenance tasks (activity), frequency of service and time required to complete the task within work schedule. Also, to build proper responsibility matrix and reporting delegation of authority.

2) Listing the physical assets which require maintenance, frequencies, tasks and bill of materials.
3) Prioritize assets by consequence / relative risk.
4) Establish targeted performance and maintenance cost centre (targeted performance level , manpower hours, material, equipment, allocated costs, etc)
5) Data uploading into a system (identifying what, when, where and by whom maintenance work is to be done, spare parts, tools , safety instruction and any other information).

5.3.4.1 Centralize Maintenance Planning and Feedback

CMMS software SAP R6 is one of modern systems which is not properly utilized at the moment. Only preventive and corrective maintenance orders are registered. But reporting systems, performance measurement and KPIs are not set properly. It could be fully utilized to generate all maintenance activities (planned and unplanned) and obtain all reports and equipment status compared related to the set KPI targets. So, centralization of planning office or planners is essential for the following duties control:-

1) Mange the issuance of planned and unplanned activities, determine the utilized resources and close out reports.
2) Measuring the performance in respect to targeted performance.
3) Centralize all reports feedback in addition to FMECA, RCFA, RBI inspection reports and to monitor the maintenance processes till completion.
4) Support improvement studies working team for required information and reports.

Maintenance processes main target is to convert maintenance activities from reactive to proactive maintenance. In such critical plant, planner shall be one of central custodian team for work requisitions, receiving of completion feedback and current status. Planners shall have an authority for spare parts issuance based on assigned work order with resources assessment. Later upon receiving any report, the gap versus targets will be close monitored and assessed. So, main point will be that all the executed reports shall be centralized, organized and archived for future needs, engineering review and further follow up till close out the case.

5.3.5 Developing RCM and RBI

To develop the RCM implementation, the below methodology were followed and customized:-

1) Define the Equipment Criticality Assessment which depends on the collected data and its classification.
2) Follow up and assess the Failure mode and effects criticality analysis (FMECA). Identify the Failure Cause and Detectability
3) Failure Classification (Hidden-evident) , Consequence Severity and Frequency (MTBF)

The Equipment Criticality Assessment (ECA) process provided the essential information and it is the starting point for the Reliability Centred Maintenance (RCM) analyses. The objective of ECA as known is to determine the relative criticality or the impact that the failure of equipment will have on Health, Safety, the Environment (HSE) or Production. The determination of those impacts is used as the basis for defining the criticality of the equipment and to determine the appropriate resources required to minimize those impacts. Thus, gas compression unit is considered as high critical equipment because in case of any failure it may has the potential to impact safety, health and environment beside the impact in case of production loss.

5.3.5.1 Failure Mode Effects and Criticality Analysis

The Failure Mode Effects and Criticality Analysis (FMECA) is performed in compliance with International Electro technical Commission

(IEC) Standard [77] as initial step of the RCM implementation. FMECA benefits are listed in below:-

1) Identify the significant failures which could affect safety, operation and/or economic.
2) Identify the failure modes and consequences impacts
3) Allow improvement of the system's maintainability (by highlighting areas of risk or nonconformity for maintainability).
4) Allow improvements of the system's reliability or safety (e.g. by design modifications or quality assurance actions).

The FMECA worksheets are presented in Table [5.5] with its approach as shown Figure [5.1]. The analysis identified the equipment package (A) into subsystems and components. Working engineers provided their input on the critical failures experienced at site in a constructed approach of using the proposed FMECA worksheet format. A short description of each field is presented in the legend below and further details regarding the key components of the worksheet are presented thereafter. Table [5.5] shows the FMEC worksheet for practical exercise.

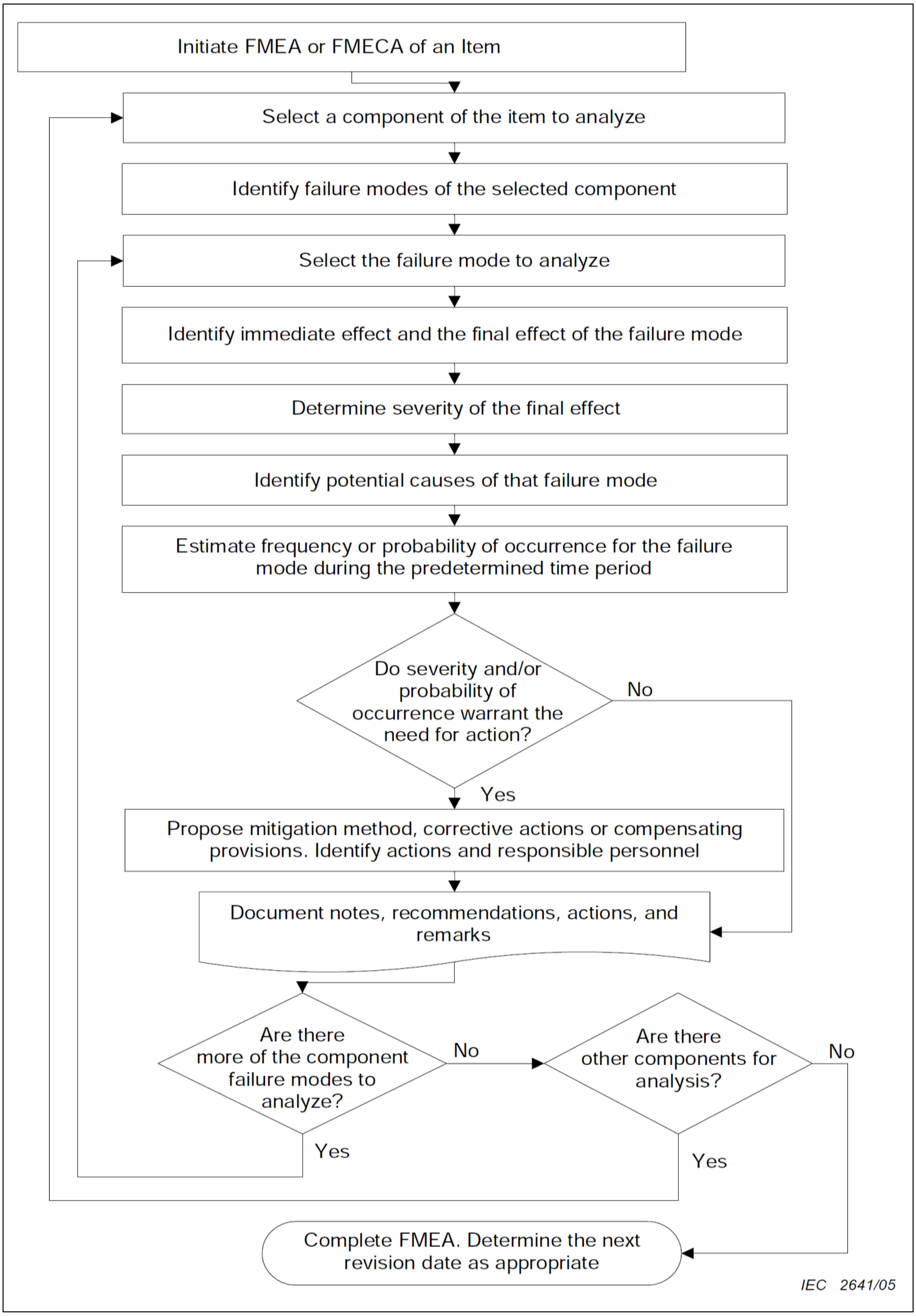

Figure [5.1] FMECA Approach (IEC 60812)

Table [5.5] FMECA Worksheet for Practical Exercise

Equipment Item(s)	Functionality	Failure Mode	Failure Cause	Failure Effect		Detectability	Reliability issues at site	Failure Classification	Risk			Criticality Score		Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
				Local	Global				Likelihood	Severity	Criticality	Detection	Risk Priority Number			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

Legend:

Lists the equipment items within the system

Provides the functionality of the system

Lists the expected failure modes (e.g. fail closed) for each item

Lists the possible causes of the failure

Describes the local effect (at the equipment/stream level)

Describes the global effects (at the plant level)

Describes the way in which a failure is detected (e.g. visual, alarm, troubleshooting etc.)

Defines the critical failure modes identified at site

Determines if a failure is Evident or Hidden in Safety, Operational and Economic terms

Provides the likelihood (probability of occurrence) of the failure mode

Provides the consequence severity level of the failure mode based on the ‘global’ effect

Provides the criticality level of the failure mode based on severity and likelihood

From the detection probability (detectability), a rating system to be applied

A rating system for detection probability (detectability), likelihood and severity to obtain a risk priority number (RPN)

Lists all the safeguards and mitigation factors in place

Details the current maintenance tasks performed for the equipment based on the Maintenance Procedures (MPs)

Enables identification of tasks that are most appropriate to prevent the failure mode or reduce its rate of failure

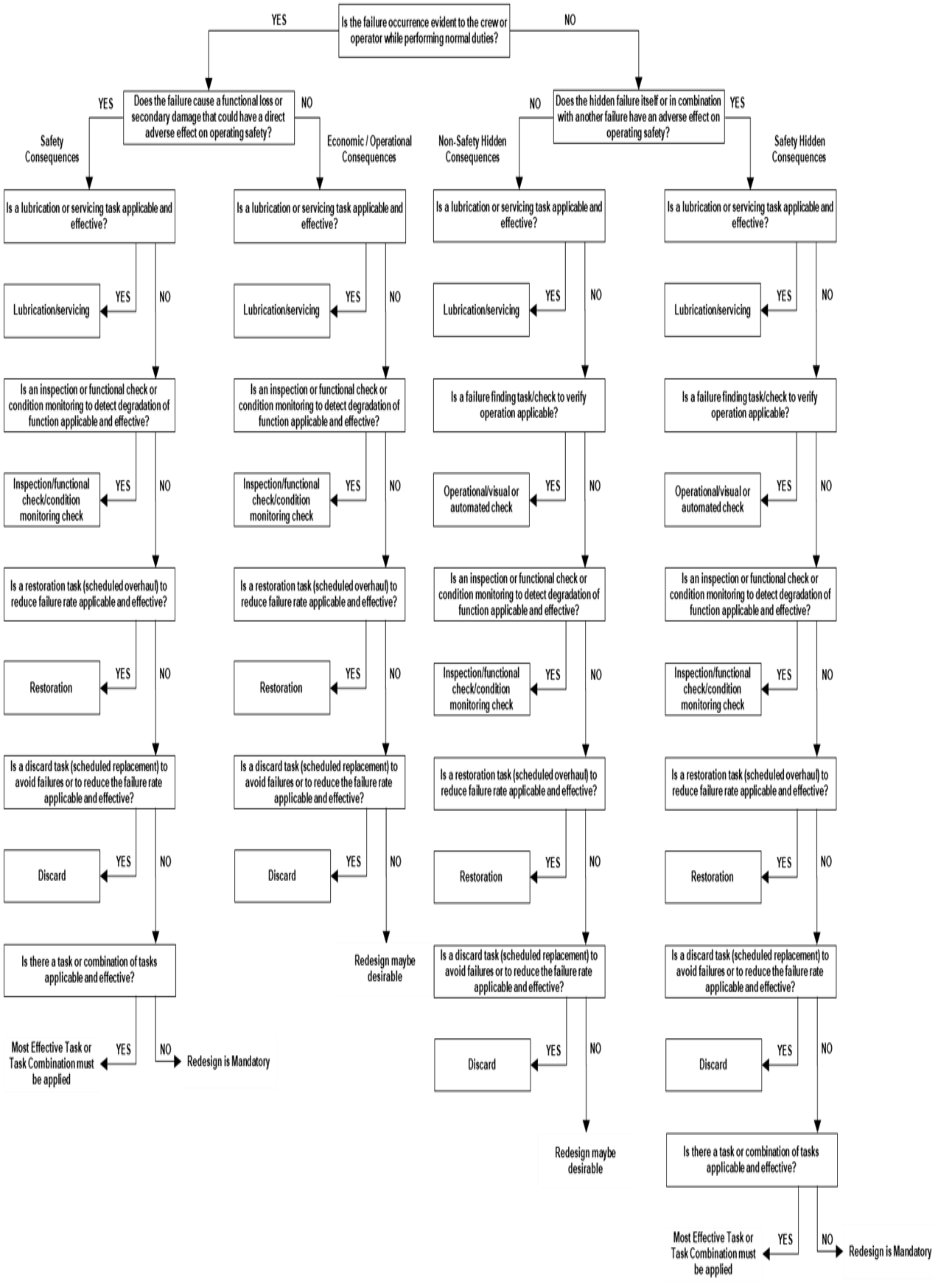

Figure [5.2] RCM decision logic

5.3.5.2 Failure Modes

A failure mode is a single event that causes a functional failure. Failure modes can occur at the system, subsystem or maintainable item level. They can be influenced by external factors arising both within and outside the boundaries of the asset under analysis. A preliminary list of failure modes is presented in Table [5.6].

Table [5.6]: Checklist of Failure Modes Used During Practical Exercise

Component	**Definition**	**Description**
Process Control Valves	Fail to close on demand	Actuator failure Valve body or closure member mechanical failure (valve stuck open)
	Fail to open on demand	Actuator failure Valve body or closure member mechanical failure (valve stuck close)
	Fail to regulate	Stuck valve (in position)
	Operates without demand	Undesired open/close (refer to above)
	Delayed operation	Opening/closure time different from specification
	External leakage	Seals failure Flange joints failure
	Leakage in closed position	Failure of the closure member
Shutdown valves	Fail to function on demand	Actuator failure Valve body or closure member mechanical failure (valve stuck open/close)
	Operates without demand	
Rotating Equipment	Fail to start on demand (backup pump)	Unable to activate the pump
	Fail to stop on demand (duty pump)	Unable to stop or incorrect shutdown process
	Spurious stop	Unexpected shutdown of pump (e.g. electrical failure)

Component	Definition	Description
	Breakdown	Serious damage (seizure, breakage, explosion, etc.)
	High output	Output pressure/flow above specification
	Low output	Output pressure/flow below specification
	Erratic output	Oscillating or unstable pressure/flow
	External leakage process medium	Corrosion, external impact, seal
	Vibration	Excessive vibration
	Noise	Excessive noise
	Overheating	Excessive Temperature (e.g. due to the motor)
Vessel	External leakage process medium	Corrosion Small bore fittings
	Partial flow restriction (plugged/choked)	Debris and/or deposition in the trap system
	Monitored parameter exceeding tolerances	Instrumentation failure (refer to the other equipment items)
	Abnormal instrument reading (e.g. false alarm, faulty reading)	Inability to detect and respond to process deviation

5.3.5.3 Failure Cause

The RCM process is guided by the correct identification of failure mode, so that it has been addressed proactively. The experience shows that, it is often the causes of the failure modes that are the targets of the RCM decisions. These causes are the combination of pre-existing conditions and triggering events leading to the failure mode event. Example of most common failure modes are addressed in below:

1) Failure mode Plugged/choked

I. Screws falling off inside scrubber and blocking the drain line causing high-high condensate trip.

2) Compressor Breakdown

I. Digital No Flow Timer (DNFT) spurious trips / incorrect signal

II. Shaft seal system and Gearbox

III. Mechanical issues in Compressor unit (e.g. packing, valves, bearing, piston, etc)

A single failure mode can have multiple root causes associated with it. While it is not necessary to classify them in the RCM. The following types are were listed based on Root Cause Analysis calculation:

1) Failure related to design

I. General: Inadequate equipment design (installation of control panel within the skid, long fittings)

II. Improper capacity: Inadequate dimensioning/capacity i.e. Suction Scrubber (1st Stage)

2) Failure related to operation/maintenance

I. General: Failure relate to operation/use or maintenance shortage.

II. Operator error: Mistake, misuse, negligence, oversight during operation

III. Maintenance error: Mistake, misuse, negligence, oversight during operation and maintenance.

3) Normal and Miscellaneous

I. General: Causes that do not fall into one if the categories above, or No cause found (Failure investigated but no specific cause found)

II. Combined causes: Several causes are acting simultaneously i.e. DFNT trip some cases spurious other real healthy signals.

III. General: Age and/or wear-out failures according to its inherent reliability characteristics

All potential failure effects are determined with consequences of a failure mode in terms of the operation, function or status of an element. The description of failure effects enables the team to justify the type of consequence management policy for risk elimination or reduction to a level that the can be tolerated. So, it is described as:

1) A local effect (at the equipment/stream level)
2) A global effect (at the plant level) which required higher management involvement

5.3.5.4 Delectability

Delectability is a change in behaviour of the asset prior to the failure. It comes from the general parameters conditions and sensing skills like Temperature, speed, vibration, noise. Such changes somehow notify the operator by an early alarm. Some failure modes are relatively easy to spot and others require diagnostic work.

The options of detections are as following:

1) Through sense: mostly visually, ear, smell and also touch.
2) Through alarm: audible alarms and warning lights

3) Operator/working team: the asset operator has the knowledge and skills to identify the failure mode root cause

5.3.5.5 Failure Classification

The next step of detailed maintenance analysis is Failure Classification which determines if a failure is Evident or Hidden in Safety, Operational (related to production) and Economic (cost for maintenance) terms. The definition is in below:-

5.3.5.5.1 Hidden Failure

A hidden failure is one that may not become evident to the operating crew under normal circumstances.

The only consequence of a hidden failure is the risk of multiple failures occurring. The main objective of a maintenance task for detecting hidden failures is to prevent or minimize the possibility of the associated risk. It should be noted that hidden failures are usually associated with protective devices which are not fail-safe. In the case of protective devices, a multiple failure occurs if the protected function fails while the protective device is in the failed state. Functions of protective devices include:

1) Alerting operators to abnormal conditions (alarms).
2) Shutdown equipment in the event of abnormal conditions.
3) Eliminating or relieving abnormal conditions which follow a failure like pressure safety valve (PSV).
4) Taking over from a function which has failed (redundant equipment).
5) Preventing a dangerous situation occurring (fire and gas detection).

An evident failure is one that becomes observable to the operating crew under normal circumstances, either through direct obvious effects on the process, off-line quality checks or long term degradation in performance of the equipment.

5.3.5.6 Consequence Severity

The consequence severity is an assessment of the significance of the failure mode's 'Global' effect on a system's operation with respect to production loss (downtime). Severity will be evaluated while taking mitigation factors into account. The severity levels are defined in Figure [5.3] (severity versus likehood).

5.3.5.7 Frequency

The frequency is the average number of occurrence of the failure mode per lifetime and will be evaluated whilst taking account of any detection in place and described in terms of (MTBF) of the equipment.

5.3.5.8 Criticality Scores

Criticality is a combination of the severity of a failure mode's 'global effect' and the frequency of the failure mode occurrence. The criticality analysis assigns a relative magnitude for each failure effect which can be used to screen out irrelevant failure modes and also to prioritise actions for mitigating or minimising effects of certain failures.

The area of study has its criticality and risk matrices. It is used in FMECA determination as presented in Figure [5.3] The process applies on a rating system 5x5 matrix for detection probability (delectability), likelihood and severity to obtain a risk priority number (RPN)[78].

Severity	Consequence				Probability									
					A	B	C	D	E					
Severity	Safety	Environmental	Production	Maintenance	Improbable MTBF = 10,000 years	Remote MTBF = 1,000 years	Occasional MTBF = 100 years	Probable MTBF = 10 years	Frequent MTBF = 1 year	Visual	Alarm	Troubleshooting	Senior Engineer	Vendor
1	*2.0 No effect	*1.5 No pollution	*1.0 No stop	*0.5 No cost	0	0.4	0.8	1.2	1.6	1	2	3	4	5
2	*4.0 Injuries not requiring medical treatment No effect on safety function	*3.5 Minor pollution (within the fence lines)	*3.0 Minor reduction of plant capacity X < 2%	*2.5 Low maintenance costs X < USD 25k	2	2.4	2.8	3.2	3.6	2	3	4	5	6
3	*6.0 Injuries requiring medical treatment Limited effect on safety function	*5.5 Some pollution (crosses fence)	*5.0 Moderate plant capacity reduction 2% < X < 20%	*4.5 Maintenance cost at or below normal acceptance $ 25k < X < USD 50k	4	4.4	4.8	5.2	5.6	3	4	5	6	7
4	*8.0 Serious personnel injury Potential for loss of safety functions	*7.5 Significant pollution affecting community	*7.0 Major reduction of plant capacity 20% < X < 50%	*6.5 Maintenance cost above normal acceptance $ 50k < X < USD 500k	6	6.4	6.8	7.2	7.6	4	5	6	7	8
5	*10.0 Loss of lives Vita safety-critical system inoperative	*9.5 Major pollution	*9.0 Plant capacity reduced by more than 50%	*8.5 Very high maintenance cost X > USD 500k	8	8.4	8.8	9.2	9.6	5	6	7	8	9

Figure [5.3] Criticality matrix

In other words, a failure mode with a high RPN number should be given the highest priority in the analysis and corrective action. To demonstrate more, appendix (IV) is showing the details of the developed FMECA worksheet with an example of the first raw of showing emergency shutdown valve (ESD) Loop initiating Transmitter Logic Solver at Inlet of HP Gas Compressor for Failure Mode “Operates Without Demand” ,the determination basis are as in blow:-

1) If Severity is 1 for Safety, 2 under Environmental, 3 under Production and 2 for Maintenance then the values to be used are 2, 3.5, 5 and 2.5 respectively. Now the maximum value will be considered which will be 5.
2) For probability, the number shall be taken based on the Risk Ranking, example if B3, as likelihood is B and the Severity worst case is 3 (as given above for Production). So, B3 value to be considered is 4.4.
3) For the Delectability , if the worst Severity number as 3 in our example, the corresponding maximum value is picked based on all the available Delectability in place (we have Visual as 3, Alarm as

4 and Troubleshooting as 5) so, Corresponding Delectability scores as also will be the maximum for the used calculation as 5. Hence ,

$$RPN = 5 \times 4.4 \times 5 = 110$$

Similarly, for all equipment failures list the RPN has been determined as shown in Table [5.7] below:-

Table [5.7]: HP Compressor Package Failures based on RPN

RPN	Equipment Item	Failure mode
828	K-23210 HP Gas Compressor	Vibration
756	K-23210 HP Gas Compressor	Compressor Overheat
588	ESD Loop PIT-23212A Initiating Transmitter PIA-23212A Logic Solver SDV-23211A Shutdown Valve at Inlet of HP Gas Compressor PK-23210	Failure to close on demand
588	ESD Loop PIT-23263A Initiating Transmitter PIA-23263A Logic Solver SDV-23213A Shutdown Valve at outlet of HP Gas Compressor PK-23210	Failure to close on demand
529.2	ESD Loop PIT-23263A Initiating Transmitter PIA-23263A Logic Solver SDV-23213A Shutdown Valve at outlet of HP Gas Compressor PK-23210	Operates without demand
528	ESD Loop PIT-23212A Initiating Transmitter PIA-23212A Logic Solver SDV-23211A Shutdown Valve at Inlet of HP Gas Compressor PK-23210	External leakage (PIT-23212A)
528	PV-23211A Pressure control valve & Pressure Control Loop for minimum circulation	External leakage (PIT-23211A)
528	ESD Loop LT-23222A Initiating Transmitter LIA-23222A Logic Solver SDV-23221A Shutdown Valve at outlet of 1st stage Suction Scrubber	External leakage (LT-23222A)

RPN	Equipment Item	Failure mode
	SDV-23211A Shutdown Valve at inlet of 1st stage Suction Scrubber	
528	LV-23222A Level control valve & Level Control Loop	External leakage (LT-23221A)
528	ESD Loop LT-23242A Initiating Transmitter LIA-23242A Logic Solver SDV-23241A Shutdown Valve at outlet of 2nd stage Suction Scrubber	External leakage (LIT-23242A)
528	LV-23242A Level control valve & Level Control Loop	External leakage (LIT-23241A)
528	ESD Loop LIT-23262A Initiating Transmitter LIA-23262A Logic Solver SDV-23261A Shutdown Valve at outlet of 2nd stage Discharge Scrubber	External leakage (LIT-23262A)
528	LV-23262A Level control valve & Level Control Loop	External leakage (LIT-23261A)
528	ESD Loop PIT-23263A Initiating Transmitter PIA-23263A Logic Solver SDV-23213A Shutdown Valve at outlet of HP Gas Compressor PK-23210	External leakage (PIT-23263A)
504	V-23220A Suction Scrubber (1st Stage)	External leakage
504	K-23210 HP Gas Compressor	Partial or total blockage of compressor suction
504	V-23240A Suction Scrubber (2nd Stage)	External leakage
504	V-23260A Discharge Scrubber (2nd Stage)	External leakage
425.6	V-23220A Suction Scrubber (1st Stage)	Plugged/choked
425.6	K-23210 HP Gas Compressor	Compressor Breakdown
409.6	E-23230A (Stage 1) After Cooler	Abnormal instrument reading
374.4	V-23240A Suction Scrubber (2nd Stage)	Plugged/choked
333.2	K-23210 HP Gas Compressor	Failure to start on demand
313.6	M-23210 HP Gas Compressor Motor	Failure to start on demand

RPN	Equipment Item	Failure mode
256	M-23210 HP Gas Compressor Motor	Overheating
256	M-23210 HP Gas Compressor Motor	Vibration
256	E-23230A (Stage 1) After Cooler	Insufficient heat transfer
182	V-23260A Discharge Scrubber (2nd Stage)	Plugged/choked
156	K-23210 HP Gas Compressor	Low Output
110	ESD Loop PIT-23212A Initiating Transmitter PIA-23212A Logic Solver SDV-23211A Shutdown Valve at Inlet of HP Gas Compressor PK-23210	Operates without demand
110	ESD Loop LT-23222A Initiating Transmitter LIA-23222A Logic Solver SDV-23221A Shutdown Valve at outlet of 1st stage Suction Scrubber SDV-23211A Shutdown Valve at inlet of 1st stage Suction Scrubber	Operates without demand
110	ESD Loop LT-23222A Initiating Transmitter LIA-23222A Logic Solver SDV-23221A Shutdown Valve at outlet of 1st stage Suction Scrubber SDV-23211A Shutdown Valve at inlet of 1st stage Suction Scrubber	Failure to close on demand
110	ESD Loop LIT-23262A Initiating Transmitter LIA-23262A Logic Solver SDV-23261A Shutdown Valve at outlet of 2nd stage Discharge Scrubber	Operates without demand
110	ESD Loop LIT-23262A Initiating Transmitter LIA-23262A Logic Solver SDV-23261A Shutdown Valve at outlet of 2nd stage Discharge Scrubber	Failure to close on demand
104	M-23210 HP Gas Compressor Motor	Low Output
96	M-23210 HP Gas Compressor Motor	Breakdown

RPN	Equipment Item	Failure mode
88	PV-23211A Pressure control valve & Pressure Control Loop for minimum circulation	Failure to open on demand
88	PV-23211A Pressure control valve & Pressure Control Loop for minimum circulation	Failure to close on demand
88	LV-23222A Level control valve & Level Control Loop	Failure to open on demand
88	LV-23222A Level control valve & Level Control Loop	Failure to close on demand
88	ESD Loop LT-23242A Initiating Transmitter LIA-23242A Logic Solver SDV-23241A Shutdown Valve at outlet of 2nd stage Suction Scrubber	Operates without demand
88	ESD Loop LT-23242A Initiating Transmitter LIA-23242A Logic Solver SDV-23241A Shutdown Valve at outlet of 2nd stage Suction Scrubber	Failure to close on demand
88	LV-23242A Level control valve & Level Control Loop	Failure to open on demand
88	LV-23242A Level control valve & Level Control Loop	Failure to close on demand
88	LV-23262A Level control valve & Level Control Loop	Failure to open on demand
88	LV-23262A Level control valve & Level Control Loop	Failure to close on demand
56	K-23210 HP Gas Compressor	Abnormal instrument reading
48	V-23220A Suction Scrubber (1st Stage)	Abnormal instrument reading
42	M-23210 HP Gas Compressor Motor	Abnormal instrument reading
36	E-23230A (Stage 2) After Cooler	Abnormal instrument reading
36	V-23260A Discharge Scrubber (2nd Stage)	Abnormal instrument reading
28.8	V-23240A Suction Scrubber (2nd Stage)	Abnormal instrument reading

RPN	Equipment Item	Failure mode
21.6	E-23230A (Stage 2) After Cooler	Insufficient heat transfer

5.3.6 Developing TPM

It is very clear and logical that human factors are playing main role for maintenance planning, execution and improvement based on their natures, cultures, knowledge and experience. The in complete implementation of tasks list will lead to have impact in equipment efficiency sooner or later. Therefore, set up of the TPM is also required by involving the working operators in the basic and first line maintenance executions with proper supervision. As, known, TPM implementation has eight pillars to obtain organized TPM system. Due to considering PM, CM, RCM and RBI in the plan, so the main pillars to be considered are:-

1) Operators' involvement in maintenance basic works and their development for such execution to obtain positive results by decreasing equipment downtime for minor failures as well by saving maintenance team working time schedule and increase level of operators competencies. The basic works are like cleaning, lubrication, general inspections and preventive first line maintenance. To achieve better results, close supervision and inspection programs will be essential for each level of the organization as leadership site visit (LSV).
2) Maintenance Continuous improvement will include the maintenance tracking and the execution for overall plans, reporting, KPI and also mainly will focus on the recommendations of RBI, RCM and inspection reports. Follow up is assigned to the engineering team especially. Moreover, after involving operators in the basic maintenance, now operators are providing good

improvement proposals based on the integration of operation and maintenance points of view.

3) Consideration of Spare Parts and consumables (spare parts management system) is important, mandatory and valuable to have optimum stock level for the planned activities. This is to ensure having the right spare part in the correct required moment with optimum cost. Such system requires to acquire the required materials at the required times. Price agreement for known consumables will be more useful either with a supplier or with the manufacturer directly for just in time spares (JIT). Also, ensure having an order level for other critical insurance spares that have no clear plan. Thus, a long term price agreement is established and focused on the delivery conditions.

4) Familiarization and experience will play significant role for such classification of method of spares and consumables requisitions. Lubricants consumption is huge for such compression plant, so continuous delivery is essential. The spare parts and consumables ordering are main assignment for engineers. Once received, issuance will be under custodian of planners for related work order. Based on actual consumption, planners will have proper cost estimation for required budget utilization and costs allocations. Proper systematic material ordering need a well-established system linked with the procurement sector (purchasing, logistic and warehouse).

The scheduled planned maintenance are sorted and considered in maintenance procedures. The proposed combined planned maintenance are listed in below Table [5.8].

Table [5.8] : the proposed combined planned maintenance

N	Planned Maintenance	Requirement	Responsibility
1	Service & Lubrication (Time Directed Preventive Maintenance)	Service and Lubrication tasks tend to focus on checking oil levels, changing complete oil containers and greasing. Such tasks is simple and can be addressed to the operators as first task to operators rather than maintenance team.	Site Operator
2	Basic Preventive maintenance (every 2,000 running Hours)	Preventive Maintenance is a basic maintenance performed on a schedule basis. It is part of first line maintenance, but with more knowledge in maintenance. Generally, the required tasks cover belts checking, piston valves lapping, piston rings, packing checking, etc.	Maintenance team
3	On-Condition Monitoring (Predictive Maintenance)	These tasks entail checking equipment or components for incipient conditions (potential failures), so that corrective actions can be planned to prevent or avoid the consequences of the functional failure. Typical On-Condition tasks include vibration and process parameter recording and trending, lube oil sampling and analysis managed through site operators' visual inspections.	Site Operator/ Maintenance team
4	Restoration Task and Major Maintenance (Time Directed Preventive and overhauling Maintenance)	Restoration is the work necessary to return the item to a specific standard. Since restoration may vary from cleaning or replacement of single parts up to a complete overhaul, the scope of each assigned restoration task has to be specified. These tasks entail overhauling or re-manufacturing a component or many components on a major plant item at or before a specified age limit, regardless of the condition of the item at that time. It will be more valuable if witnessed and supported by manufacturer technical member. Therefore, the restoration work is	Maintenance team / OEM

		planned along with the major overhauling for more cost saving in downtime and call out of OEM engineer. For major preventive maintenance, it is observed every 8,000 running hours if the required tasks are critical and have some speciality, thus OEM is recommended to attend.	
5	Discard (Time Directed Preventive Maintenance)	Discard is the removal from service of an item at a specified life limit. Discard tasks are normally applied to so-called single-cell parts such as cartridges, canisters, cylinders, turbine disks, safe-life structural members, etc. Discard tasks or Schedule Replacement (SR) tasks are considered technically feasible if there is an identifiable age at which the item shows a rapid increase in the probability of failure and if most items in a sample survive to that age.	Maintenance team
6	Default Maintenance Task (Detective Maintenance)	To be abnormal duty for the site working staff and to consider as Failure Finding Task for operational check as a task to determine that an item is fulfilling its intended purpose. It does not require quantitative checks, so it is a failure finding task visually and recorded in log sheets. Operators shall closely follow close out any detected points or at least converted to right way for further repair or study.	Site Operators / Maintenance team / Corrosion and inspection team

From above, the integration of comprehensive maintenance needs strong contribution from all organization levels to achieve the results. Figure [5.4] Proposed integrated maintenance frame work

demonstrates the summary of the proposed comprehensive maintenance strategy frame work which can call as the integrated maintenance system.

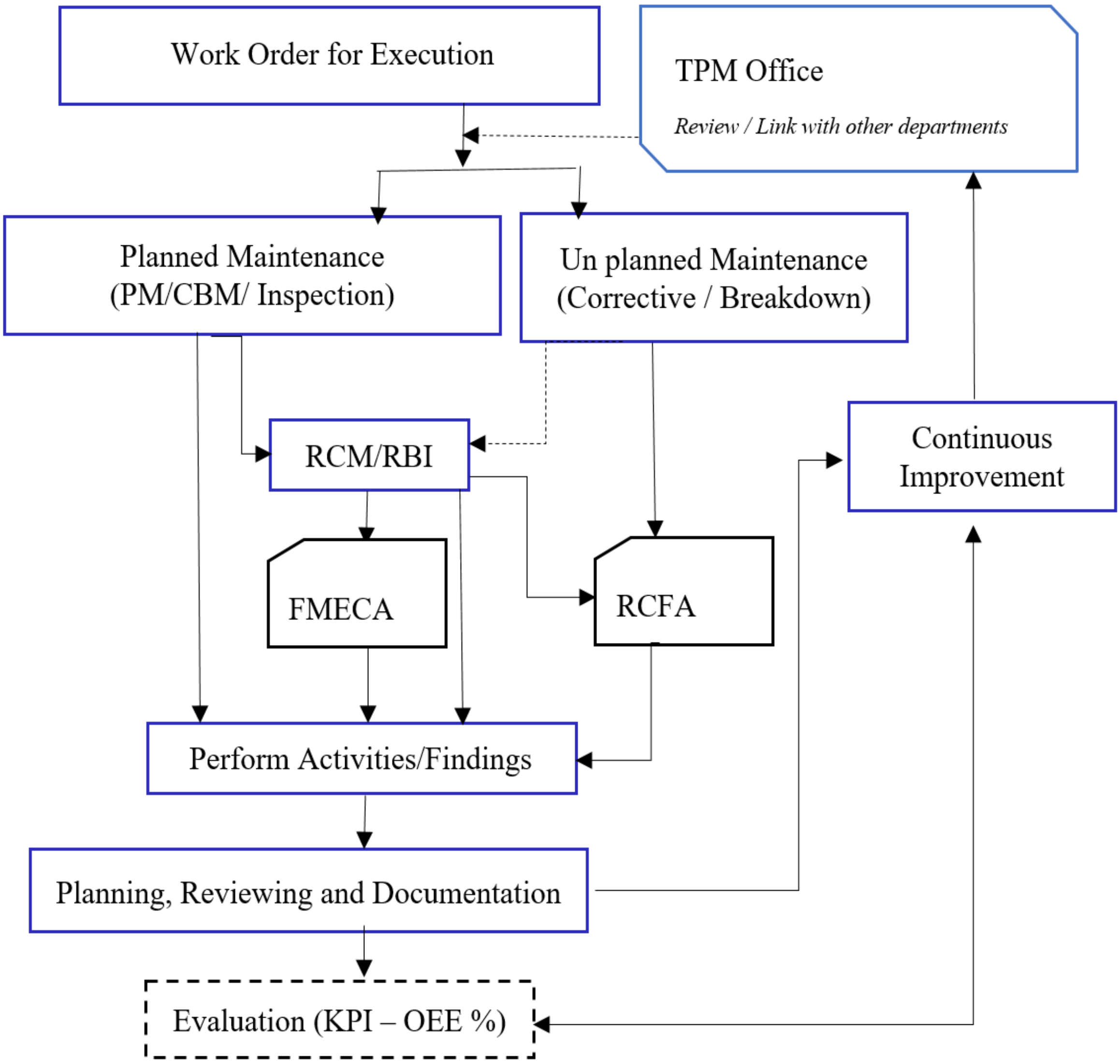

Figure [5.4] Proposed integrated maintenance frame work

CHAPTER SIX

CHAPTER SIX

RESULTS AND DISCUSSION

The above proposal is implemented from 1st of July 2019 up to the result generation in May 21st 2020 (326 days) for evaluation.

The records have been followed in terms of working team practise, familiarization and homogenies which mainly during the condition monitoring and first line maintenance execution by site operators as new assigned tasks. Moreover, the engineers were following up the planned maintenance sequence and execution from planner to working team unit final reporting closure. In addition, the findings reports (RCFA and FMECA) were in focus to be prepared well and on time as it will be reflected in final KPI achieved results. Monthly run of CMMS performance was under review of plant superintendent as higher level which will escalate the performance summary for further management endorsement.

The main assessment is determined for the same unit compression (A) to compare the initial conditions with the current obtained results. Thus, re assessment of RAM and OEE % is determined. Figure [6.1] shows the compression package (A) performance after framework implementation at the site. Compression unit (A) put in operation with standby time and had 45 days recorded as total down time in 13 failures. The total RH measured and found 24,907 hours which means the running hours after frame work implementation is 5,407 RH (225.3 days).

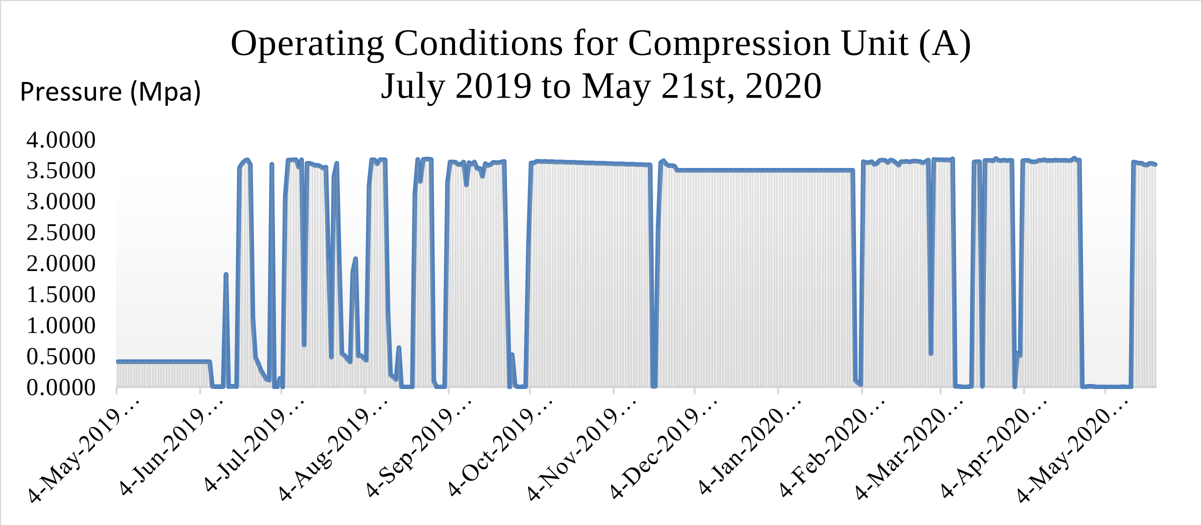

Figure [6.1] Compression package (A) performance after framework site implementation

Table [6.1] shows the details of faults description, causes and down time duration after frame work implementation.

Table [6.1]: Faults details after frame work implementation

Faults Description	**Cause**	**Failure Date**	**Rectification Date**	**Down time in days**
Soft starter alarm "under voltage" during starting	Power amplifier of protection relay on the Safety system panel was broken	09/07/2019	13/07/2019	4
Compressor tripped	DNFT signal tripped	21/07/2019	23/07/2019	2
Discharge valve of 2nd stage cylinder 2#	Two number discharge valves of 2nd stage	26/07/2019	28/07/2019	2

running with high temperature	cylinder was leaking			
AI (analogue input) module have fault alarm	unclear reason	01/08/2019	03/08/2019	2
Compressor oil pressure low alarm	Crankcase lube oil pump's relief valve was defective	13/08/2019	20/08/2019	7
Suction unloading valve of 2nd stage cylinder was running with high temperature	Suction valve retaining ring and retainer of 2nd stage cylinder was damaged	29/08/2019	02/09/2019	4
Three-way valve of lube oil filter have oil spilled	Dismantled the three-way valve and found the O-ring was damaged	26/09/2019	02/10/2019	6
Discharge valve of 2nd stage cylinder 4 was running with high temperature	Two discharge valves of 2nd stage cylinder was damaged	26/09/2019	02/10/2019	6
Discharge valve of 2nd stage	Two discharge valves of 2nd	26/09/2019	02/10/2019	6

cylinder had high temperature	stage cylinder were damaged			
Variable volume clearance pocket (VVCP) of 2nd stage cylinder #4 have gas leaking and display abnormally	VVCP gasket defected, Also Transmitter was defected	18/11/2019	21/11/2019	3
TIT display abnormally	Transmitter was defected	01/02/2020	02/02/2020	1
Suction valve of 2nd stage cylinder 2# running with high temperature	One suction valve and one retainer of 2nd stage cylinder 2# were damaged	28/02/2020	29/02/2020	1
3discharge valves of 1st stage cylinder 3# running with high temperature	Three discharge valves of 1st stage cylinder 3# were damaged	30/03/2020	31/03/2020	1

In general, the overall compression packages (A, B and C) are installed in parallel which will gain higher total availability and reliability. Re- assessment determinations are calculated by applying the recent results in equation (2.10) as in below:-

$$Availability = \frac{(326\ Days - 45\ Days) * 100\%}{326\ Days} = 86.2\%$$

Also, by using equation (5.4)

$$OEE\% = \frac{0.8758x225x100\%}{326} = 60.44\%$$

These achieved results shows the gained improvement on the compression unit (A) after the frame work implementation as indicated in figure [6.2].

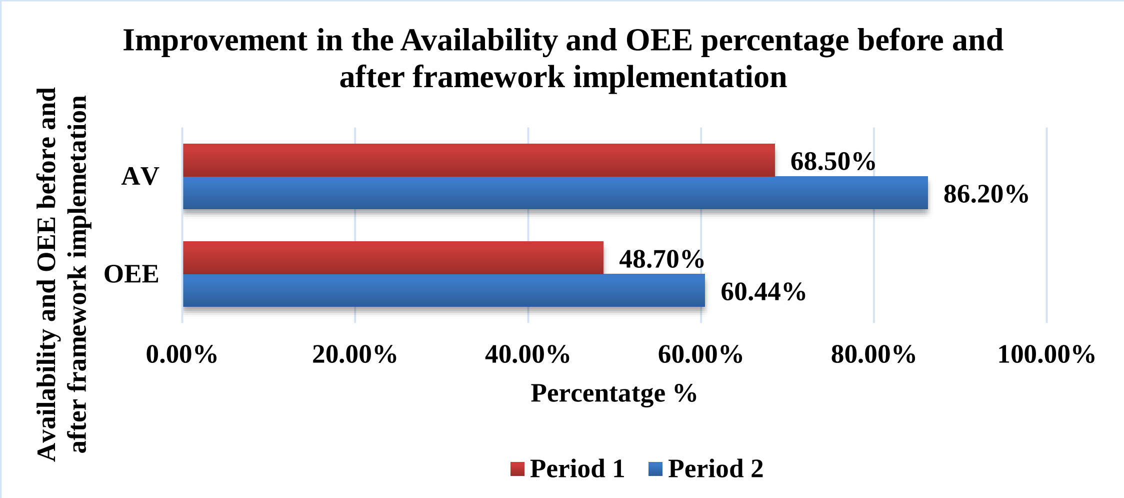

Figure [6.3] The Comparison before and after the frame work implementation.

Once, the availability increased means there is a reduction in the MTBF and number of failures in latest determined mean time. Therefore, all the studies and improvement trails are focusing to increase the availability percentage more. Similarly, from equation (18), OEE% depends on the up loading time which also related to the equipment availability when needed. Reference to Table [5.2], TDT importance as accumulative is calculated to determine the most contributed failures ranking in the compression unit as shown in Table [6.2]. Figure [6.4] shows clearly the root causes and failure data analysis which indicates the vibration and DNFT problems have the higher contribution into the failures occurrence (over 54% of the recorded failures).

Table [6.2]: TDT importance Grouping

ID	TDT Importance Hours	TDT Importance Accumulative	TDT Importance %	TDT Importance% Accumulative
Vibration	3360	3360	**30.43%**	**30.43%**
DNFT	2640	6000	**23.91%**	**54.34%**
Control Issue	1032	7032	**9.35%**	**63.69%**
Cylinder High Temperature	1008	8040	**9.13%**	**72.82%**
Blockage Drain	840	8880	**7.61%**	**80.43%**
Lube Oil	672	9552	**6.09%**	**86.53%**
Automation and Instrument	624	10176	**5.65%**	**92.17%**
Motor	480	10656	**4.35%**	**96.52%**
Isolation Valve	168	10824	**1.52%**	**98.04%**
High Temperature	168	10992	**1.52%**	**99.57%**
Belt Rupture	48	11040	**0.43%**	**100.00%**
Total	**11,040**	**96552**	**100%**	

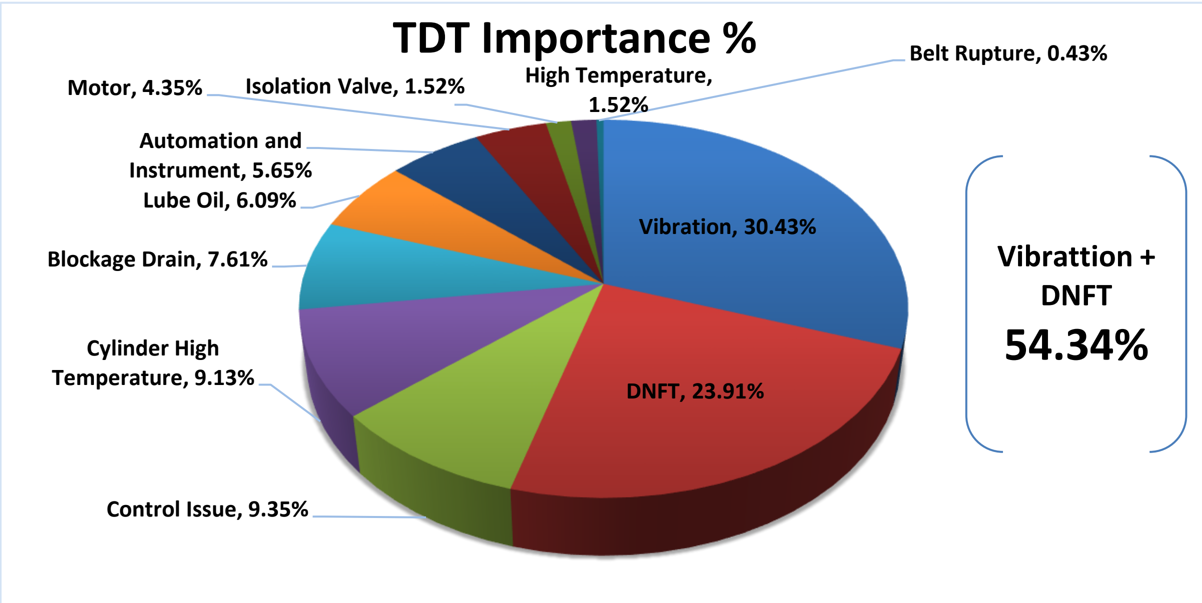

Figure [6.4] TDT Importance Contribution into Compression unit A

Thus, the focusing shall be increased on these major concerns as follows:-

1) Vibrational issues root-cause need more studies. Potential causes could be due to skid, structure and piping issues. This led to the change of piston

rods, collars and crank shaft as short term. However this was done after 16,000 hours while it should run for at least 30,000 hours. The repair time is almost 10-12 days for each compressor. Detailed analysis for vibrational assessment is required to prevent escalation and save component replacement costs.

2) Frequent trips due to digital no- flow timer (DNFT) trip signal. The major causes are due to weak lubrication feed and minor electrical issues which either need manufacturer's technical review or support with additional external lubrication system unit to resolve the issue. Performing lubrication/servicing can help to identify the issue based on the quality and output from the lubrication feed. Moreover, regular inspection / functional tests and conditional monitoring shall mitigate the issue. Since the DNFT issue has regular checks on cylinder lubrication to ensure continuous monitoring of the lubrication feed. Reducing the frequency of task from 4,000 hours to 2,000 hours checks will be more proactive approach. Also, as part of these inspections it must be ensured that the DNFT circuit is healthy and running to prevent unit trip.
3) Fallen of screws from the demister packing that blocks the drain line leading to condensate build-up in the scrubber which is eventually sent to the compressor and affect the valves. Increasing the size of the drain line can possibly eliminate this issue and enhance the way of bolts connections. Due to gas quality and specification, there is accumulation of moisture and condensate in the compressor. This leads to further issues in the HP gas compressor performance especially in piston, valves and scrubber. So, scrubber design and re-size is needed to ensure no more condensate drainage and lowering the build-up level in the scrubber and avoid the set alarms level. The recommended practise for scrubber inspection shall be updated into annual inspection instead of two years

CHAPTER SEVEN

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CONCLUSION AND RECOMMENDATION

Gas compression plants are unique plants in oil and gas industries which have high gas oil ratio. Such plants need professional operation and maintenance systems in place to minimize the down time and failures records to reduce the consequences impacts related to safety, production, costs, etc.

The study focused for compression plant newly commissioned in 2015, but 34 trips were recorded in the operational log sheets which it is high number of failures. Nevertheless, the manufacturer's recommendations were closely followed along with the basic maintenance types. But even though, more modern maintenance types and inspections programs are required to be implemented in such plant in order to fill the gaps of each maintenance programs to improve the whole maintenance system and have a controllable one integrated system.

In the research, the proposal framework is called "the integrated maintenance frame work" which applied for the compression plant unit (A) as a single unit out of three identical units by integrating the preventive, corrective, condition monitoring, RCM and RBI programs. All these maintenance types were also linked with TPM for operators' contribution and to ensure following the continuous improvement based on site requirement and to implement the failures reports recommendations for further enhancement. The idea of set a framework was initiated from sorting and ranking of the total down time (TDT) importance and risk priority ranking (RPN) which they are most useful to present a full overview of the failures ranking and to indicate which have major effect in the whole down time beside the comparison with the calculated RPN.

One maintenance and inspection system using multi strategies will also support in optimizing all the resources. Moreover, the maintenance programs were assessed and focused on filling the gaps of each type by including modern maintenance and inspection concepts. Therefore, there are additional practices are included to support improving the new framework as shown in below:-

1) Set of KPI.
2) Developed maintenance programs and implements RCM and RBI.
3) Centralized the reporting systems.
4) Considered operators' training and development.
5) Assigned support team for continuous improvement, evaluation and follow up.

The new frame work is applied, evaluated and compared with the initial operational log records. The gained results showed clear improvement in the compression unit (A) availability from 68.5% to 86.2% by reducing the MTBF as well the improvement of OEE% from 48.7% to 60.44%.

The prospect of this research is also shows how to integrate multi maintenance and inspection systems in one program and its effect. Such model has a significance of the possibility to implement the same concept of integrated maintenance system in different areas like factories, manufacturing premises, hospitals, etc with suitable customizations depend on working nature, business needs and its capacity.

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APPENDIX I: PM check list for 8,000 RH

Preventive Maintenance Checklist Form

Production Department

Originator section : Maintenance	Tag No.: K 23210 ( )
Superintendent:	Description: HP Gas Compressor
Supervisor:	Date:
8000 (9200)HOURS Service	

Item	Maintenance Task	Yes/No
Rotating Parts	- Remove and check the coupling cover;	Y
	- Check the electric motor NDE cover;	Y
Bolts and nuts loose	- Check the bolts & nuts tighten for gas comp & electric motor support and skid foundation;	Y
	- Check the bolts & nuts tighten for support-crosshead and cylinders;	Y
	- Check the bolts & nuts tighten for suction & discharge bottles gas compressor;	Y
Leakage	- Check force feed lubricator, lines connections and all connections to instruments;	Y
	- Check oil and water pipes, fittings and flanges connections;	Y
Cleaning	- Gas compressor, electric motor, oil cooler and base for electric motor, gas compressor;	Y
	- Gas compressor cylinders, support-crosshead & suction and discharge bottles;	Y
Action	- Replaced the oil: Shell Mysella S3N40 (stop the gas compressor, drain the gas compressor crankcase, and clean the gas compressor crankcase), replaced the lube oil filters, inspect gas compressor crankcase for bearing material, gear tooth condition, crosshead shoe and guide.	Y
	- Remove from each cylinder one suction and one discharge valves, inspect the valves and replaced the damage parts (springs, plates)	Y
	-Measure gas compressor pistons end clearance; normal (crank end) for 1st is CE =1.4mm, (head end) HE = 2.4--3.9mm and for 2st HE=2.3.6mm CE=1mm	Y
	- Remove the cover doors from the crosshead guide and inspect the packing area on Cylinder #1,2,3 & 4 piston rod, inspect crosshead guide for wear metals, check crosshead clearances (0.18-0.3mm);	Y
	-check piston rod RUNOUT clearance: horizontal V=0.064 H=0.025mm, (if necessary re-tighten the cylinder to the crosshead guide);	Y
	Replaced rupture disks of force feed lubricator pump.	Y
	-1st Stage and 2nd Stage Cylinder #1,2,3,4 ,the each piston removed out and replaced piston rings and wear band with new, rebuilt the road packing and replaced the oil wiper by new	Y
	- Measure compressor Piston Bottom clearance.	Y
	- Inspect gas compressor auto-drain system; greased the electric motor bearings;	Y
Smooth running	- check for any abnormal or excessive noise from the gas compressor/electric motor;	Y
	- Measure and record vibration for gas compressor and el. motor; grease the DE and NDE bearings.	Y
	- measure and record temperature for gas compressor and el. motor;	Y
Note	- in cause the maintenance task don't match with the equipment job you will mark **N/A** (not applicable)	
	- for torque values see the torque recommendations;	
	- available for HP gas compressor tag no: K-23210 A/B/C;	

COMPRESSOR						ELECTRIC MOTOR					
DE			NDE			DE			NDE		
V mm/s	H mm/s	T °C	V mm/s	H mm/s	T °C	V mm/s	H mm/s	T °C	V mm/s	H mm/s	T° C

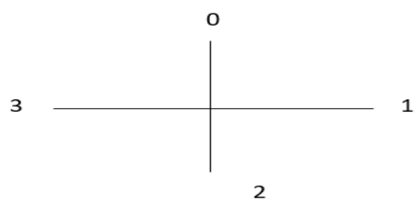
Job done by :

Date :

	Assemblies		*K 23210 A*		*Acceptable limit*
1	Piston Bottom Clearance	Cylinder # 1			> 0.40 mm
		Cylinder # 2			
		Cylinder # 3			
		Cylinder # 4			
			CE	HE	
2	Piston end clearance	Cylinder # 1			HE=2.4-3.9mm CE=1.4 mm
		Cylinder # 2			CE=1mm , HE=2-3.6mm
		Cylinder # 3			HE=2.4-3.9mm CE=1.4 mm
		Cylinder # 4			CE=1mm , HE=2-3.6mm
3	Crank shaft End Play				0.34-0.76mm
4	Crosshead shoe clearance	Cylinder # 1			0.18-0.3mm
		Cylinder # 2			
		Cylinder # 3			
		Cylinder # 4			
5	Crankshaft pin to connecting rod bearing	Cylinder # 1			0.10-0.23mm
		Cylinder # 2			
		Cylinder # 3			
		Cylinder # 4			
6	Connection rod thrust	Cylinder # 1			0.38-0.84mm
		Cylinder # 2			
		Cylinder # 3			
		Cylinder # 4			
7	Crank shaft journal bearing	Cylinder #1			0.10-0.18mm
		Cylinder # 2			
		Cylinder # 3			
		Cylinder # 4			

			H	V	
8	Piston rod run out	Cylinder # 1			V=0.064mm H=0.025mm
		Cylinder # 2			
		Cylinder # 3			
		Cylinder # 4			

Alignment check value



position	Position0	Position1	Position2	Position3
Angular				
Parallel				
Allowed limit	<0.13mm			

Recommended torques

FASTENER	NOMINAL SIZE INCH - TPI	TYPE	TORQUE, LB X FT (N·m)
Main Bearing Cap - Cap Screw	1-1/8 - 7	12 Point - Gr 8	540 (732)
Connecting Rod - Cap Screw	1-1/8 - 12	12 Point - Gr 8	See Table 1-12 on page 1-22
Torsional Vibration Detuner Donut - Cap Screw	1 - 14	12 Point - Gr 8	530 (715)
Crosshead Pin Through Cap Screw - Lock Nut	5/8 - 18	Hex - Prevailing	125 (170)
Spacer Bar - Cap Screw	1-3/8 - 12	12 Point - Gr 8	1060 (1435)
Crosshead Guide to Frame - Cap Screw	1 - 8	12 Point - Grade 8	420 (570)
Crosshead Guide to Cylinder - Cap Screw	7/8 - 9	12 Point - Gr 8	280 (380)
	7/8 - 14	Hex Stud - Nut	315 (425)
Crosshead Guide Support - Cap Screw	1-1/4 - 7	Hex - Grade 8 or 9	770 (1045)
Head End Cylinder Support to Cylinder	1/2 - 13	Hex - Grade 8	44 (60)
	5/8 - 11		88 (120)
	3/4 - 10		160 (215)
	7/8 - 9		255 (345)
Eccentric Vernier Cap - Cap Screw	3/8 - 16	Hex - Grade 8	Hand Wrench Tight
Idler Sprocket Through Cap Screw - Lock Nut	1/2 - 20	Hex - Prevailing	41 (55)
	5/8 - 18		82 (110)
Sprocket or /Flywheel to Crankshaft - Cap Screw	3/4 - 16	Hex - Grade 9	215 (290)
Rod Packing - Cap Screw	7/8 - 9	12 Point - Grade 8 or 17-4PH	205 (280)
	7/8 - 14		230 (310)
	1-1/4 - 12		700 (950)
Rod Catcher to Packing	5/8 - 18	12Pt-Gr8/17-4PH	105 (142)
Piston Nut	2 - 12	Ariel Design	3970 (5380)[a]
Crosshead-Balance Nut	2-1/4 - 8	Ariel Design	3120 (4230)[b]
Lifting Bracket to Frame	1-1/2 - 6	12 Point - Gr 8	1200 (1630)
Rupture Disk - Blow-Out Fitting Cap	1/4 Nom. Tube	Hex - Tube Fitting	40 lb x in. (4.5)
Piston Rod Oil Slinger Lock Nut	1/4-28	Hex - Jam	95 lb x in. (11)

Spare parts used for 8000 RH PM

No.	Assembly	Description	Part No.	QTY use
1	1st Stage suction valve with unloader	Unloader valve	B-5720-JJ	3
2	1st Stage suction valve	Suction valve	B-2704-Z	1
		Valve plate	A-8524	1
		Wafer spring	A-2165	1
3	1st Stage discharge valve	Discharge valve	B-2620-CC	1
		Valve plate	A-8189	7
		Springs	A-1344	170
		Wafer spring	A-2165	7
4	2nd Stage suction valve with unloader	Unloader valve	B-5733-QQ	2
		Valve seat	A-7865	1
		Valve plate	A-15670	2
		Wafer plate	A-2858	2
		Spring	A-1346	32
5	2nd Stage suction valve	Valve plate	A-5506	3
		Wafer spring	A-2183	3
		Spring	A-15151	48
6	2nd Stage discharge valve	Valve plate	A-8178	1
		Spring	A-1344	32
		Wafer spring	A-2183	1
7	1st stage gasket	Steel gasket	A-1889	24
8	1st O-ring	O-ring valve cover	A-0032	24
9	2nd gasket	Steel gasket	A-2079	16
10	2nd O-ring	O-ring valve cover	A-0724	16
11	Piston rod packing	Repair kits	B-6408	4
12	Wiper ring	Repair kits	B-5847	4
13	gasket	Crank case top cover gasket	C-6197	1
14	Gasket	Cover guide gasket	B-1430	1
15	Gasket	Cover Cross head guide gasket	B-1429	1
16	Gasket	1st VVCP gasket	A-2839	2
17	Gasket	2nd VVCP gasket	A-2080	2
18	1st Stage piston compression ring	Piston ring	A-2835	4
19	1st Stage wear band	Piston wear band ring	A-4360	2
20	2nd Stage piston compression ring	Piston ring	A-4008	8
21	2nd Stage wear band	Piston wear band ring	A-4738	2
22	2nd stage Cylinder #4 piston rod packing	Aluminum gasket	As part of repair kit B-6408	1

APPENDIX II: Developed RCFA Template

Maintenance Section

ROOT CAUSE FAILURE ANALYSIS REPORT

Equipment Failure Description

Report Date: **Work Order No:**

Report No.:xx-RCFA-Plant-Motn/Year/ Serial No.

A. Equipment/ System Details.

Facility/Plant	HP Gas Compressor System/ xx
Equipment Tag, Make, Model	
Equipment/System/Sub system	
Date and time of abnormality	

B. Brief Description of Failure

Description: (Briefly mention-What Happened? / Where Happened? / When Happened? / Why Happened? / Who is Responsible for corrective action?)	
➢ ➢	
Criticality:	
Level (High/Medium/Low):	
Justification	

C. Background/Problem Statement:

(List down briefly the previous history / problems faced during maintenance, since inception)
➢ ➢

D. Likely Root Cause:

Briefly mention about probable root causes and way forward	
Description:	
Likelihood (High/Medium/Low):	
Information: (i). Check (ii)/Tests to Clarify	

E. Analysis of Basic Root Cause

Analysis of Basic Root Cause / Distribution of Responsibility	1- 2-

Page **1** of **2**

Corrective Action to Eliminate Basic Root Cause	1- 2-
Implementation of Corrective Action	
Verification of Corrective Action and Effectiveness	1- 2-
Follow up of Corrective Action Effectiveness (by Origination/Planner)	1- 2-
Recommendations	1- 2-
Remarks (if any)	
Next Date to Update Team Members	

Team Members:

S.	Name	Position	Signature
01	Prepared by:		
02	Revised by:		
03	Approved By:	Maintenance Section Head	

Photos:

APPENDIX III: Prepared Maintenance Procedure-8,000 RH

	COMPANY NAME MAINTENANCE PROCUDURE **8000Rh PM -HP Gas Compressor** K-23210 A/B/C	Date : Rev.

1.0 SUMMARY:

This document prepared for one year 8000RH preventive maintenance to be a reference for how to check this equipment to ensure all the procedure to be done as per the manual and vendor recommendation, this will prevent the equipment from breaking down also to take active steps to keep the equipment in good condition, preventive maintenance usually more efficient than repairing or replacing equipment after break it or fail.

Equipment Type : xxxxx
Equipment model: xxxxx
Equipment ID : **K-23210 A/B/C**
Manufacture : xxxxx

Description of the Product: -Heavy duty balanced opposed compressor. The major components of the frame assembly are the crankcase, crankshaft and bearings, connecting rods, chain drive system, crossheads and guides, and distance pieces.
Lubrication System: There are two independent systems for lubricating the compressor; the frame oil system and the force feed system. The frame oil system is a pressurized circulating system that supplies constant pressurized supply of oil to the crankshaft, connecting rods and crossheads, the force feed system is a low volume high pressure injection system that supplies small quantities of oil at regular intervals to lubricate the piston rod packing and the piston rings, In many applications these two systems can use the same lubricant

2.0 SAFETY, HEALTH & ENVIRONMENT:

3.1 All work must be coordinated through Area Supervisor.
3.2 Fulfill all the points of JHA and obtain Work Permit before starting the work.
3.3 Ensure that the Compressor is purged by nitrogen properly vented and isolated.
3.4 Ensure that all power energy sources are isolated, Lock Out and Tag Out procedures are followed properly.
3.5 Ensure that relieve all pressure from the compressor cylinder
3.6 Ensure normal ambient temperature before disassembly.
3.7 During dismantling pay attention to the stability of the Dismantled components, if necessary, use supporting devices.

Rev. : 0 Date:	Page 3 of 13

	COMPANY NAME MAINTENANCE PROCUDURE **8000Rh PM -HP Gas Compressor** K-23210 A/B/C	Date : Rev.

3.8 Make sure that all lifting equipment is in good condition and a suitable type / capacity for the task. Only use approved safe methods of handling heavy equipment.
3.9 Ensure proper House Keeping all the times.
3.10 Make sure that all special hand tools is in good condition.
3.11 Use proper PPE all the times of work.
3.12 Block the flywheel to prevent rotation of the compressor and driver,

3.13 Pay attention to hazardous situations during dismantling, take care to stand firm, secure assembly parts against dropping, support or prop loose parts, hang on crane etc.
3.14 After completing maintenance remove any locking or blocking devices before attempting to rotate equipment.

3.0 SPECIAL TOOL LIST & PART LIST

4.1 Hand Measurement Tool Kit

a) General engineering hand tools
b) General measuring tools including Vernier caliper, dial gauge etc.
c) Tarpaulin sheet and diesel, WD-40 and grease.
d) Alignment Device & shims

4.0 PROCEDURE:

SR #	Activity Description	Responsible	Sign-off
5.1	**The following procedure to be perform as per the manual and vendor recommendation during running**		
	1. Verify the high and low pressure are within the acceptable limit.		
	2. Bearing temperature to be checked		
	3. Oil temperature and pressure to be checked.		
	4. Valve temperature survey to be checked.		
	5. Verify the high discharge gas temperature shutdown is set to within 10% or as close as practical above the normal operating discharge temperature. Do not exceed the maximum discharge temperature shutdown setting for the application		

Rev. : 0 Date:	Page 4 of 13

	COMPANY NAME MAINTENANCE PROCEDURE 8000Rh PM -HP Gas Compressor K-23210 A/B/C	Date : Rev.

SR #	Activity Description	Responsible	Sign-off
	6. Condition monitoring to be checked for compressor frame, supports, piping and cylinders.		
5.2	**a.crank case lube oil**		
	1. Blind the suction and discharge pipes.		
	2. Drain the lube oil from the compressor frame, associated piping and lube oil cooler.		
	3. Removed the old oil filter should be after completely drained the oil from the filter housing.		
	4. Dismantled the main lube oil pump strainer to inspect and clean it with proper solvent		
	5. Assembled back the strainer and install new oil filters.		
	6. Refill the compressor frame with new oil shell Mysella (LAS3N40)		
	b. force feed lubricator pump.		
	1- Drain and replace the lube oil with fresh (Dacnis LPG 150)		
	2- Removed the sintered element and clean or replaced, replacement the sintered element dependent on the filter condition.		
	3- Cam shaft and gear should inspected for wear before refilling oil.		
5.3	**VVCP (variable volume clearance pocket)**		
	1. VVCP to be creased 2 or 3 pumps with multi-purpose grease using a standard hand pump grease gun		
	2. The VVCP handle to be turned for fully close and open to grease the VVCP thread stem and should measure or count turns to return handle to original position		
5.4	**Pressure test distribution block**		
	1. Test each divider block assembly complete with pin indicators installed and the test only one divider valve at a time.		
	2. Place the divider block assembly in an open container with all base outlets open.		
	3. Operate the purge pump to divider block assembly and complete cycle time several time to ensure all air coming out		
	4. Verify that oil will flow freely from all divider outlet, the divider block should cycle at less than 300psig (21bar).		
	5. Divider valves stamped with a "T" are to have only one outlet on the base plugged during testing of that side of the piston		
	1. Each base outlet of the divider valves stamped with a "T" must be plugged and tested one side at a time. "Testing "T" Divider Valve". Individual testing of each outlet ensures both sides of the piston will build adequate pressure.		

	COMPANY NAME MAINTENANCE PROCEDURE 8000Rh PM -HP Gas Compressor K-23210 A/B/C	Date : Rev.

SR #	Activity Description	Responsible	Sign-off
	2. All divider valves stamped with an "S" on the front are to have both outlets on the base plugged to test for by-passing. "Testing "S" Divider Valve". This will test both sides of the piston at the same time.		
	3. Plug the outlet on the base behind the divider valve being tested with a 1/8 inch pipe plug. If a tubing fitting is installed in the base, plug the fitting with a tubing plug and leave all other outlets lets open.		
	4. Operate the purge gun until the pressure gauge indicates 3000 psig (207 bar) the block may cycle once or twice, but should pressurize to 3500 psig (241bar) immediately Stop pumping oil into the divider block at 3500 psig (241 bar).		
	5. If the pressure gauge on the purge gun drops suddenly and oil squirts from the other outlets the piston is worn and is allowing oil to by-pass		
	6. The pressure should not lose more than (69bar) during 30 second otherwise piston is worn need to be replaced.		
5.5	**The following clearances to be checked and if the below point is abnormal please check the(Maintenance and Repair Manual) to replace or repair any affected parts**		
	1. Piston to cylinder clearance		
	2. Crank end and head end clearance.		
	7. Crosshead to guide clearance.		
	8. Main bearing, connecting rod bearing, and crankshaft jack and thrust clearances.		
	9. Piston rod run out.		
5.6	**Removed all valve and gaskets for more details check the Suction and Discharge valves Change out - HP Gas Compressor CPF 2 K-23210 ABC) for more details.**		
	1. Remove valves cover.		
	2. Use special polar to remove the valves.		
	3. Remove all valves steel gasket.		
	4. Visual inspection for valves pocket.		
	5. Checked the valves for testing leakage.		
	6. Dismantled the valve if leakage, inspect the valve seat, valve guarder, wafer spring, valve plate and springs.		
	7. In case the valve seat has scratched, should be lapped and tested again otherwise need to be replaced.		

SR #	Activity Description	Responsible	Sign-off
	8. Check all valve cover O-ring and valves steel gasket, replace which one needed.		
	9. Visually inspect suction valve unloader actuator stems for damage or wear. Visually inspect stem seals for damage or wear and confirm that the actuator moves freely.		
5.7	**Inspection for Cylinder bore, piston rings and wear band**		
	1. Check the cylinder bore for blemishes or gouges.		
	2. Bore out of round more than 0.001 inch per inch of bore diameter (0.001 mm/mm) or tapered.		
	3. Check the piston ring end gap clearance, normal gap clearance dependent on the cylinder size, check the manual Table 1-10: PISTON, PISTON RING AND WEARBAND CLEARANCES.		
	4. Piston ring end clearance as per manufacturer recommendation to be replaced when increase three times the new dimension, check table 1-10		
	5. For determine the wear band to be replace or not, should know that wear band doesn't working as a seal ring so the end ring gap not a critical issue.		
	6. The amount of wear band projection beyond the outer diameter of the piston is important.		
	7. To determine the amount of wear band radial projection clearance you can check the clearance between the cylinder and the piston.		
	8. Replace the wear band before it has worn enough to allow the piston to touch the cylinder bore.		
5.8	**Piston rod inspection**		
	1. Check the piston rod for excessive wear and replace it if any condition exist:- a. Gouges or scratches on the rod. b. Under size more than 0.005 inch (0.13 mm). c. Out of round more than 0.001 inch (0.03 mm) per inch of rod diameter. d. Tapered more than 0.002 inch (0.05 mm) per inch of rod diameter.		
5.9	**Re-assembling**		
	1. Re- install the piston rod packing, for more information check Gas Compressor Stuffing Box Packing Replacement		

SR #	Activity Description	Responsible	Sign-off
	2. Re-install the piston and rod into the cylinder bore if was removing, check the manual for piston and rod installation**),** also check piston and rod installation – typical		
	3. Re-tighten the cross head balance nut then tighten the lock nut using new one.		
	4. Check fastener torques of gas nozzle flange, valve cap, piston rod packing, crosshead pin through bolt , crosshead guide to frame, crosshead guide to cylinder, cylinder mounting flange to forged steel cylinder, distance piece to cylinder, distance piece to crosshead guide, and tandem cylinder to cylinder, check table 1-11 Torque value of fasteners		

5.0 ATTACHMENTS:

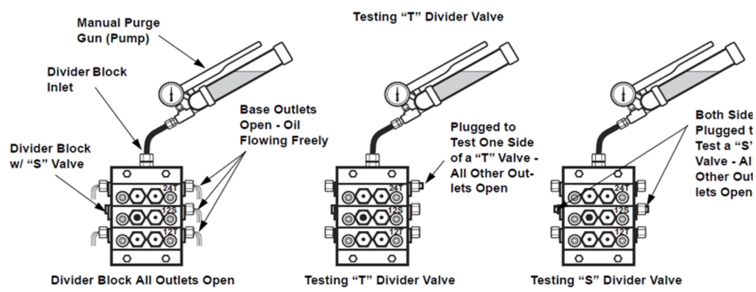


FIGURE 4-15: PRESSURE TESTING DIVIDER BLOCKS

Table 1-10: Piston, Piston Ring and Wearband Clearances, (Millimeters)

PISTON TO CYLINDER CLEARANCE		PISTON RING END GAPS - FILLED TEFLON[a]		WEAR BANDS NEW		
BORE (mm) INCHES	CLEARANCE	NEW	MAXIMUM	MINIMUM END GAP		RADIAL PROJECTION
				45°	70°	
(63.5) 2.5	(1.40 to 1.60)	(0.38 to 0.64)	(1.91)	(2.03)	(2.69)	(0.46 to 0.64)
(66.7) 2.625	(1.40 to 1.60)	(0.38 to 0.64)	(1.91)	(2.13)	(2.82)	(0.46 to 0.64)
(76.2) 3	(1.40 to 1.60)	(0.43 to 0.69)	(2.06)	(2.44)	(3.25)	(0.46 to 0.64)
(88.9) 3.5	(1.52 to 173)	(0.28 to 0.46)	(1.37)	---	(3.00)	(0.46 to 0.66
(98.4) 3.875	(1.52 to 173)	(0.30 to 0.48)	(1.45)	---	(3.33)	(0.46 to 0.66)
(108) 4.25	(1.80 to 2.01)	(1.30 to 1.55)	(4.65)	---	(3.45)	(0.58 to 0.79)
(111) 4.375	(1.80 to 2.01)	(1.35 to 1.60)	(4.80)	---	(3.56)	(0.66 to 0.84)
(117) 4.625	(1.80 to 2.01)	(1.42 to 1.68)	(5.03)	---	(5.00)	(0.58 to 0.79)
(127) 5	(2.06 to 2.26)	(1.27 to 1.52)	(4.57)	(4.06)	(5.41)	(0.69 to 0.89)
(137) 5.375	(2.06 to 2.26)	(1.65 to 1.96)	(4.88)	(4.37)	(5.82)	(0.69 to 0.89)
(149) 5.875	(2.06 to 2.26)	(1.50 to 1.80)	(5.41)	(4.78)	(6.35)	(0.69 to 0.89)
(159) 6.25	(2.06 to 2.26)	(1.60 to 3.50)	(10.52)	(5.08)	(6.76)	(0.69 to 0.89)
(171) 6.75	(2.21 to 2.44)	(1.73 to 2.06)	(6.17)	(5.49)	(7.29)	(0.74 to 0.94)
(178) 7	(2.21 to 2.44)	(1.78 to 2.13)	(6.40)	(5.69)	(7.57)	(0.74 to 0.94)
(184) 7.25	(2.21 to 2.44)	(1.83 to 2.21)	(6.63)	(5.89)	(7.82)	(0.74 to 0.94)
(200) 7.875	(2.34 to 2.57)	(2.00 to 2.41)	(7.24)	(6.40)	(8.51)	(0.79 to 1.02)
(213) 8.375	(2.34 to 2.57)	(2.13 to 2.54)	(7.62)	(6.81)	(9.04)	(0.79 to 1.02)
(222) 8.75	(2.29 to 2.51)	(2.67 to 3.18	(9.53)	---	(7.11)	(0.76 to 0.99)
(232) 9.125	(2.44 to 2.67)	(2.31 to 2.79)	(8.38)	(7.42)	(9.86)	(0.84 to 1.07)
(235) 9.25	(2.29 to 2.51)	(2.82 to 3.33)	(9.98)	---	(7.52)	(0.76 to 0.99)
(244) 9.625	(2.44 to 2.67)	(2.44 to 2.95)	(8.79)	(7.82)	(10.41)	(0.84 to 1.07)
(248) 9.75	(2.29 to 2.51)	(2.97 to 3.49)	(10.44)	---	(7.92)	(0.76 to 0.99)
(251) 9.875	(2.77 to 3.00)	(2.51 to 3.02)	(9.07)	(8.03)	(10.67)	(0.94 to 1.19)
(260) 10.25	(2.29 to 2.51)	(2.79 to 3.35)	(10.06)	---	(11.89)	(0.84 to 1.02)
(264) 10.375	(2.77 to 3.00)	(2.64 to 3.18)	(9.53)	(8.43)	(11.23)	(0.94 to 1.19)
(267) 10.5	(2.90 to 3.12)	(2.67 to 3.20)	(9.60)	(8.53)	(11.35)	(0.99 to 1.24)
(273) 10.75	(2.29 to 2.51)	(2.79 to 3.35)	(10.06)	---	(11.89)	(0.84 to 1.02)
(276) 10.875	(2.90 to 3.12)	(2.74 to 3.30)	(9.98)	(8.84)	(11.76)	(0.99 to 1.24)
(279) 11	(2.90 to 3.12)	(2.79 to 3.35)	(10.06)	(8.94)	(11.89)	(0.99 to 1.24)
(279) 11L & M	(2.29 to 2.51)	(2.79 to 3.35)	(10.06)	---	(11.89)	(0.84 to 1.02)
(286) 11.25	(2.54 to 2.74)	(3.42 to 4.04)	(12.12)	---	(9.14)	(0.91 to 1.07)
(289) 11.375	(2.90 to 3.12)	(2.90 to 3.48)	(10.44)	(9.25)	(12.29)	(0.99 to 1.24)
(298) 11.75	(2.54 to 2.74)	(3.58 to 4.19)	(12.57)	---	(9.55)	(0.91 to 1.07)
(305) 12	(2.97 to 3.24)	(3.05 to 3.66)	(10.97)	(9.75)	(12.98)	(0.99 to 1.27)
(311) 12.25	(2.97 to 3.23)	(3.12 to 3.73)	(11.20)	(9.96)	(13.23)	(0.99 to 1.27)
(314) 12.375	(2.54 to 2.74)	(3.76 to 4.37)	(12.95)	---	(9.55)	(0.91 to 1.07)
(318) 12.5	(2.97 to 3.24)	(3.18 to 3.81)	(11.43)	(10.16)	(13.51)	(0.99 to 1.27)
(333) 13.125	(3.20 to 3.48)	(3.33 to 4.01)	(12.04)	(10.67)	(14.17)	(1.09 to 1.35)

COMPANY NAME
MAINTENANCE PROCUDURE
8000Rh PM -HP Gas Compressor K-23210 A/B/C | Date : Rev.

Table 1-10: Piston, Piston Ring and Wearband Clearances, (Millimeters)

PISTON TO CYLINDER CLEARANCE		PISTON RING END GAPS - FILLED TEFLON[a]		WEAR BANDS NEW		
BORE (mm) INCHES	CLEARANCE	NEW	MAXIMUM	MINIMUM END GAP		RADIAL PROJECTION
				45°	70°	
(346) 13.625	(3.20 to 3.48)	(3.45 to 4.17)	(12.45)	(11.07)	(14.73)	(1.09 to 1.35)
(359) 14.125	(3.20 to 3.48)	(3.58 to 4.32)	(12.90)	(11.48)	(15.27)	(1.09 to 1.35)
(362) 14.25	(3.20 to 3.48)	(4.34 to 4.95)	(14.86)	(11.58)	(15.39)	(1.07 to 1.32)
(375) 14.75	(3.20 to 3.48)	(4.50 to 5.11)	(15.32)	(11.99)	(15.93)	(1.07 to 1.32)
(391) 15.375	(3.23 to 3.50)	(3.91 to 4.70)	(14.10)	(12.50)	(16.61)	(0.97 to 1.27)
(403) 15.875	(3.23 to 3.50)	(4.04 to 4.85)	(14.55)	(12.90)	(17.15)	(0.97 to 1.27)
(441) 17.375	(4.55 to 4.85)	(4.42 to 5.31)	(15.93)	(14.12)	(18.80)	(1.12 to 1.45)
(454) 17.875	(4.60 to 4.90)	(4.55 to 5.46)	(16.38)	(14.53)	(19.33)	(1.12 to 1.45)
(498) 19.625	(4.75 to 5.05)	(5.99 to 6.81)	(20.42)	(15.95)	(21.21)	(1.27 to 1.60)
(511) 20.125	(4.70 to 5.00)	(6.15 to 6.96)	(20.88)	(16.36)	(21.77)	(1.27 to 1.60)
(559) 22	(5.41 to 5.72)	(6.71 to 7.72)	(23.16)	(17.88)	(23.77)	(1.50 to 1.83)
(613) 24.125	(5.44 to 5.74)	(7.36 to 8.38)	(25.15)	(19.61)	(26.09)	(1.42 to 1.75)
(673) 26.5	(5.74 to 6.05)	(8.13 to 9.14)	(27.43)	(21.54)	(28.65)	(1.47 to 1.80)

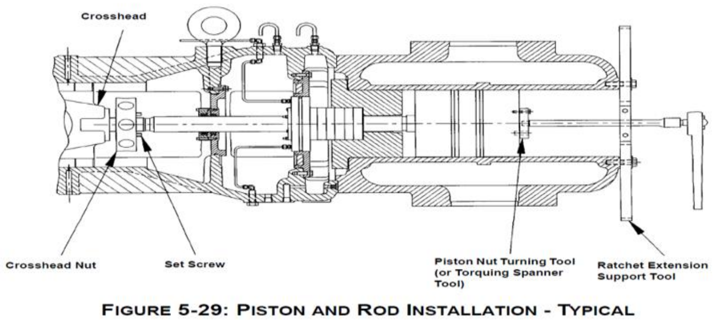


Figure 5-29: Piston and Rod Installation - Typical

TORQUE VALUES OF FASTNERS

TABLE 1-11: FASTENER TIGHTENING VALUES

FASTENER	NOMINAL SIZE INCH - TPI	TYPE	TORQUE, LB X FT (N·m)
Main Bearing Cap - Cap Screw	1-1/8 - 7	12 Point - Gr 8	540 (732)
Connecting Rod - Cap Screw	1-1/8 - 12	12 Point - Gr 8	See Table 1-12 on page 1-22
Torsional Vibration Detuner Donut - Cap Screw	1 - 14	12 Point - Gr 8	530 (715)
Crosshead Pin Through Cap Screw - Lock Nut	5/8 - 18	Hex - Prevailing	125 (170)
Spacer Bar - Cap Screw	1-3/8 - 12	12 Point - Gr 8	1060 (1435)
Crosshead Guide to Frame - Cap Screw	1 - 8	12 Point - Grade 8	420 (570)
Crosshead Guide to Cylinder - Cap Screw	7/8 - 9	12 Point - Gr 8	280 (380)
	7/8 - 14	Hex Stud - Nut	315 (425)
Crosshead Guide Support - Cap Screw	1-1/4 - 7	Hex - Grade 8 or 9	770 (1045)
Head End Cylinder Support to Cylinder	1/2 - 13	Hex - Grade 8	44 (60)
	5/8 - 11		88 (120)
	3/4 - 10		160 (215)
	7/8 - 9		255 (345)
Eccentric Vernier Cap - Cap Screw	3/8 - 16	Hex - Grade 8	Hand Wrench Tight
Idler Sprocket Through Cap Screw - Lock Nut	1/2 - 20	Hex - Prevailing	41 (55)
	5/8 - 18		82 (110)
Sprocket or /Flywheel to Crankshaft - Cap Screw	3/4 - 16	Hex - Grade 9	215 (290)
Rod Packing - Cap Screw	7/8 - 9	12 Point - Grade 8 or 17-4PH	205 (280)
	7/8 - 14		230 (310)
	1-1/4 - 12		700 (950)
Rod Catcher to Packing	5/8 - 18	12Pt-Gr8/17-4PH	105 (142)
Piston Nut	2 - 12	Ariel Design	3970 (5380)[a]
Crosshead-Balance Nut	2-1/4 - 8	Ariel Design	3120 (4230)[b]
Lifting Bracket to Frame	1-1/2 - 6	12 Point - Gr 8	1200 (1630)
Rupture Disk - Blow-Out Fitting Cap	1/4 Nom. Tube	Hex - Tube Fitting	40 lb x in. (4.5)
Piston Rod Oil Slinger Lock Nut	1/4-28	Hex - Jam	95 lb x in. (11)

TABLE 1-11: FASTENER TIGHTENING VALUES

FASTENER	NOMINAL SIZE INCH - TPI	TYPE	TORQUE, LB X FT (N·m)
Cylinder Mounting Flange to Forged Steel Cylinder	1-14	12 Point - Grade 8 or 17-4PH	485 (655)
	1-1/4-12	12 Point - Grade 8 or 17-4PH	955 (1290)
Hold Down - Stud Nut	1-3/8 - 6	Hex Stud - Nut	1100[c](1500)
Valve Cap/Cylinder Head/Unloader/ VVCP/Gas Passage Cap/Ariel Supplied Companion Flange to Cylinder - Cap Screw[d], Except “Peanut” Dual Nozzle Companion Flanges	1/2 - 13	Hex - Grade 8/9 or 12 Point - Grade 8 or 17-4PH	40 (54)
	5/8 -11		79 (105)
	3/4 - 10		140 (190)
	3/4 - 16		160 (215)
	7/8 - 9		230 (310)
	7/8 -14		260 (355)
	1 - 8		345 (470)
	1 - 14		395 (535)
	1-1/8 - 12		560 (760)
“Peanut” Dual Nozzle Companion Flanges	1/2-13	12 Point - Grade 8 or 17-4PH	53 (71)
Tandem Cylinder to Cylinder - Cap Screw [d]	1/2 - 13	Hex - Grade 8/9 or 12 Point - Grade 8 or 17-4PH	44 (60)
	5/8 - 11		88 (120)
	3/4 - 10		160 (215)
	3/4 - 16		180 (245)
Seating Studs in Cylinder	1/2 - 13	Dog Point	22 (30)
	5/8 - 11		44 (60)
	3/4 - 10		79 (105)
	3/4 - 16		90/120
	7/8 - 9		130 (170)
	7/8 - 14		145 (195)
	1 - 8		190 (260)
	1 -14		220 (300)
	1-1/8 - 12		310 (420)
	1-1/4 - 12		435 (590)
Distribution Block Tie Rod - Nut	1/4 - 28	Hex	68 lb x in. (7.7)
Distribution Block Divider Valve - Cap Screw	1/4 - 28	Socket Head	75 lb x in. (8.5)

PART LIST – FOR ONE COMPRESSOR

Part No.	Description	Qty
KB-2704-Z	Kit, Valve, 158ct, NYX	6
KB-2620-CC	Kit, Valve, 158ct, MTX	12
KB-5720-JJ	Rebuild Kit, Suction Valve W/Unloader, 158ct, Pc	6
KB-2230-WX	Kit, Valve, 148ct, NYX	4
KB-2231-DD	Kit, Valve, 148ct, MTX	8
KB-5733-QQ	Rebuild Kit, Suction Valve W/Unloader, 147ct, Pc	4
A-8723-K	Rebuild Kit, Piston Actuator, Pa88m	6
A-17399-K	Rebuild Kit, Piston Actuator, Pa88m	4
A-4360	Wear Band,17-7/8t:D:U, 3.000 Groove Width	2
A-4738	WEAR BAND,12-1/2TDU:TDU/LM3.0W	2
A-2835	Piston Ring,17-7/8k:C:Z	4
A-4008	piston ringG,12-1/2C:D:Z:U	8
B-6408-K	Rebuild Kit, 2.500 Piston Rod Packing	4
B-5847-K	Rebuild Kit, 2.500 Oil Wiper Packing, Wat, 3rws	4
A-3166	Lube Oil Filter Element Kit, JGC:D & Z:U/2	3
A-8723-K	Filter Kit, Force Feed Lubricator, 150 Micron	1

ATTACHMENTS:
This procedure is applicable for the Tag Nos. mentioned in Annexure-7.7
ANNEXURE – 7.7
K-23210 A
K-23210 B
K-23210 C
K-23610

Procedure End Date: ________________ Time: ____________

- - -End of Procedure -

APPENDIX IV: FMECA Worksheets

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
ESD Loop PIT-23212A Initiating Transmitter PIA-23212A Logic Solver SDV-23211A Shutdown Valve at Inlet of HP Gas Compressor PK-23210	ESD function to trip the compressor and close SDV-23211A/13A to protection against low suction pressure or blocked outlet	Operates without demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Low suction pressure of compressor (operating off the curve and starve)	Potential impact to CPF2 Power Plant. Compressors B will maintain the supply of gas to the raw gas export pipeline. Potential impact to CPF2 process for low supply of gas to CPF2 Power Plant.	PIA-23212A will alarm low pressure at the inlet of the Suction Scrubber .PIA-23241A will alarm low pressure at the inlet of the Suction Scrubber (2nd stage). PIA-23261A will alarm low pressure in the Discharge Scrubber. PIA-22612 will alarm low pressure at the 16" HP gas header. PIALL-23212A will trip the compressor	Hidden	Hidden Economic and/or Operational	Yes	Yes	Yes	N/A	N/A	B	1	2	3	2	B3	Troubleshooting	**110**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	6 monthly: • External visual inspection (valve and actuator) • Internal visual inspection (valve and actuator) • Valve diagnostic checks (Calibration, Bench Set, Friction, Travel, Dynamic Error, Resolution, Sensitivity) • Function test – input loops • Function test – leak rate • Function test – stroke time • Function test – position verification • Function test - opening and closing times • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.) Opportunistic: • Scheduled overhaul / refurbishment	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Failure to close on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Potential high pressure gas in the line. This could be required to be closed in an emergency event to isolate the HP Compressor Package	Potential damage to the compressor if the pressure goes beyond the design intent in case of an emergency leading to a major release from the casing	PIA-23212A will alarm high pressure at the inlet of the Suction Scrubber PIA-23241A will alarm high pressure at the inlet of the Suction Scrubber (2nd stage) PIA-23261A will alarm high pressure in the Discharge Scrubber PIA-22612 will alarm high pressure at the 16" HP gas header PIAHH-23212A will trip the compressor	Hidden	Hidden Safety	Yes	Yes	Yes	N/A	N/A	B	5	5	4	4	B5	Troubleshooting	**588**	On loss of signal, the SDV fails close Basic Process Control System to regulate the pressure to HP Flare and alarm high pressure upstream		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		External leakage (PIT-23212A)	Excessive vibration	Projectile impact on adjacent equipment or people. Loss of containment of gas inside the Compressor Package Building	Confirmed gas case require Global Shutdown	Fire and Gas System	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	C	5	2	5	2	C5	Alarm	**528**	Shutdown on Confirmed Gas by Control Room Operator Intervention		Refer to K-23210A
PV-23211A Pressure control valve & Pressure Control Loop for minimum circulation	Compressor recycle pressure control loop	Failure to open on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	HP Gas Compressor Package fails to recycle with potential to pressurize the Discharge Scrubber	Potential damage to the HP Gas Compressor due to pressure build up on the second stage compressor	PIA-23261A will alarm high pressure in the Discharge Scrubber PIALL-23212A will trip the compressor and close SDV-23211A	Non-critical	Evident Economic	Yes	Yes	N/A	N/A	N/A	B	2	2	3	2	B3	Alarm	**88**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) PSV-23213A at the discharge of 2nd stage bottle will open to HP Flare	6 monthly: • External visual inspection (valve and actuator) • Internal visual inspection (valve and actuator) • Valve diagnostic checks (Calibration, Bench Set, Friction, Travel, Dynamic Error, Resolution, Sensitivity) • Function test – input loops • Function test – leak rate • Function test – stroke time • Function test – position verification • Function test - opening and closing times • Instrument checklist	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Failure to close on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling,	Potential high pressure gas in the line during recycle	Continuous recycle leading to reduced send out of gas from the compressor. Potential damage to the 1st stage compressor if the pressure increases	PIA-23212A will alarm high pressure at the inlet of the Suction Scrubber PIA-23241A will alarm high pressure at the inlet of the Suction Scrubber (2nd stage) PIA-23261A will alarm high pressure in the Discharge Scrubber PIA-22612 will alarm	Non-critical	Evident Economic	Yes	Yes	N/A	N/A	N/A	B	1	2	3	2	B3	Alarm	**88**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) PSV-23211A at the inlet of the Suction Scrubber (1st stage) will open to HP Flare		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
			instrumentation, pressure sensors)			high pressure at the 16" HP gas header PIAHH-23212A will trip the compressor																in case of high pressure On loss of signal, the PV fails close	(condition, instrument loop test, cable and gland installation, terminations etc.) Opportunistic: • Scheduled overhaul / refurbishment	
		External leakage (PIT-23211A)	Excessive vibration	Projectile impact on adjacent equipment or people. Loss of containment of gas inside the Compressor Package Building	Confirmed gas case require Global Shutdown	Fire and Gas System	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	C	5	2	5	2	C5	Alarm	**528**			Refer to K-23210A
V-23220A Suction Scrubber (1st Stage)	1st Stage Suction Scrubber to knock out any droplet and separate condensate from gas before sending the gas to the compressors	Abnormal instrument reading	False alarm Faulty Readings	Could potentially lead to incorrect gas and condensate send out, e.g. incorrect readings of level on Suction Scrubber will lead to incorrect opening of the LV-23222A	Potential disruption in gas send out. Time for detecting and troubleshooting based on detection available downstream and upstream of the process	Multiple alarms available on equipment upstream and downstream for check and confirmation on the process parameters PIA-23212A at the inlet of the Suction Scrubber PIA-23241A at the inlet of the Suction Scrubber (2nd stage) PIA-23261A at the Discharge Scrubber LIA-23242A at the Suction Scrubber (2nd Stage) LIA-23262A at the Discharge Scrubber (2nd Stage)	Non-critical	Hidden Economic and/or Operational	No	Yes	Yes	Yes	N/A	D	1	1	2	2	D2	Senior Engineer	**48**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) Multiple transmitters on the Suction Scrubber to provide correct process parameter reading in case of failure of one (TT-23221A, LT-23222A, LT-23221A)	6 monthly: • External visual inspections • External close inspection including NDT • Internal inspections with representative thickness measurements • Hydrostatic test • Instrumentation calibration Opportunistic: • Scheduled overhaul / refurbishment	Subject to RBI for detailed assessment However since it is a hidden failure, a Failure Finding Task/Troubleshooting is required to identify the failure.
		External leakage	Corrosion issues	Gas/condensate release in the area	Global Shutdown on Confirmed Gas Case. Potential for small fire and disruption to gas supply	LIA-23222A will alarm low level on 1st stage Suction Scrubber, trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) LIA-23221A will alarm low level on 1st stage Suction Scrubber and close condensate drainaget	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	B	5	2	5	2	B5	Alarm	**504**	LIA-23222A will alarm low level on 1st stage Suction Scrubber, trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) F&G Detectors in the area 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		Subject to RBI for detailed assessment
		Plugged/choked	Deterioration in demister packing material. This leads to plastic screw falling off and blocking the drain line	Lead to level build-up in the 1st Stage Suction Scrubber	Potential damage to the HP Gas Compressor due to liquid carry over.	LIAHH-23222A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge)	Critical	Evident Economic	Yes	Yes	Yes	Yes	Yes	E	2	2	4	1	E4	Senior Engineer	**425.6**	LIAHH-23222A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		Plugging/choked is identified as critical. This has consequences on the compressor performance. Hence the RCM decision matrix is followed for the Scrubber to improve the reliability of the HP Compressor due to condensate carryover issues. • Even with lubrication/servicing task of the HP Compressors the failure persists. • Regular inspection/functional tests and conditional monitoring of the HP Compressors

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
																								doesn't improve or mitigate the issue. • Restoration tasks could be performed on the Scrubber to reduce the failure rate, where in increasing the size of the drain line can possibly eliminate blockage of drain line. This will ensure more condensate drainage and result in slower level build-up in the Scrubber. • The effectiveness of the above task needs to be assessed. The next task of discarding or Scrubber replacement will be expensive and not effective. • The root cause issue is the quality of the process gas which is not adequately handled by the Scrubber. Hence the Scrubber design and size needs to be revisited to be able to handle the incoming gas or installing a Filter Coalescer/Treatment package upstream of the Compressors
ESD Loop LT-23222A Initiating Transmitter LIA-23222A Logic Solver SDV-23221A Shutdown Valve at outlet of 1st stage Suction Scrubber SDV-23211A Shutdown Valve at inlet of 1st stage Suction Scrubber	Liquid carryover protection whereby shutdown valve shall close at the inlet of 1st stage Suction Scrubber	Operates without demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Lead to level build-up in the 1st Stage Suction Scrubber	Potential damage to the HP Gas Compressor due to liquid carry over.	LIAHH-23222A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge)	Hidden	Hidden Economic and/or Operational	Yes	Yes	Yes	N/A	N/A	B	2	2	3	3	B3	Troubleshooting	**110**	LIAHH-23222A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	6 monthly: • External visual inspection (valve and actuator) • Internal visual inspection (valve and actuator) • Valve diagnostic checks (Calibration, Bench Set, Friction, Travel, Dynamic Error, Resolution, Sensitivity) • Function test – input loops • Function test – leak rate • Function test – stroke time • Function test – position verification • Function test - opening and closing times • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.) Opportunistic: • Scheduled overhaul / refurbishment	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
	Gas blowby protection whereby shutdown valve shall close at the outlet of 1st stage Suction Scrubber for condensate sendout	Failure to close on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Loss of level in the Suction Scrubber 1st Stage and gas blow by to the Condensate Separator	Potential low suction pressure at the HP Gas Compressor and high pressure at the Condensate Separator	PIA-22651 will alarm high pressure in the Condensate Separator	Hidden	Hidden Safety	Yes	Yes	Yes	N/A	N/A	B	2	2	3	2	B3	Troubleshooting	**110**	LIALL-23222A will close LV-23222A 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) On loss of signal, the SDV fails close		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		External leakage (LT-23222A)	Excessive vibration	Projectile impact on adjacent equipment or people. Loss of containment of gas inside the Compressor Package Building	Confirmed gas case require Global Shutdown	Fire and Gas System	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	C	5	2	5	2	C5	Alarm	**528**	Shutdown on Confirmed Gas by Control Room Operator Intervention		Refer to K-23210A
LV-23222A Level control valve &	Level control valve at the outlet of 1st		Valve mechanical failures (e.g. sticking, degradation		Potential damage to the HP Gas	LIAHH-23222A will trip the compressor and close SDV-23211A	Non-critical	Evident Economic	Yes	Yes	N/A	N/A	N/A	B	2	2	3	3	B3	Alarm	**88**	LIAHH-23222A will trip the compressor and close SDV-	6 monthly: • External visual inspection (valve	• The regular lubrication/servicing task is effective.

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
Level Control Loop	stage Suction Scrubber for condensate send out to ensure minimum level in the vessel	Failure to open on demand	to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Lead to level build-up in the 1st Stage Suction Scrubber	Compressor due to liquid carry over.	(suction) and SDV-23213A (discharge)																23211A (suction) and SDV-23213A (discharge) 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	and actuator) • Internal visual inspection (valve and actuator) • Valve diagnostic checks (Calibration, Bench Set, Friction, Travel, Dynamic Error, Resolution, Sensitivity) • Function test – input loops • Function test – leak rate • Function test – stroke time • Function test – position verification • Function test - opening and closing times • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.) Opportunistic: • Scheduled overhaul / refurbishment	• Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Failure to close on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Loss of level in the Suction Scrubber 1st Stage and gas blow by to the Condensate Separator	Potential low suction pressure at the HP Gas Compressor and high pressure at the Condensate Separator	PIA-22651 will alarm high pressure in the Condensate Separator LIALL-23222A will close SDV-23221A	Non-critical	Evident Economic	Yes	Yes	N/A	N/A	N/A	B	2	2	3	2	B3	Alarm	**88**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) On loss of signal, the LV fails close		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		External leakage (LT-23221A)	Excessive vibration	Projectile impact on adjacent equipment or people. Loss of containment of gas inside the Compressor Package Building	Confirmed gas case require Global Shutdown	Fire and Gas System	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	C	5	2	5	2	C5	Alarm	**528**	Shutdown on Confirmed Gas by Control Room Operator Intervention		Refer to K-23210A
K-23210 HP Gas Compressor	Pressurize and discharge gas, part to power plant close to CPF2 (non-H2S) and part to export pipeline	Partial or total blockage of compressor suction	Suction valve closed	Due to insufficient gas flow to the compressor suction to overcome the pressure in the discharge, process gas in the cylinder will heat up, leading to destruction of soft members, for example piston rings. This will eventually cause piston loss support, metal contact between piston and cylinder, leading to vibration and loss of integrity. This could possibly cause catastrophic failure with fracture of the casing and loss of containment of process gas.	Major release from the casing is likely.	PIA-23212A will alarm low pressure at the inlet of the Suction Scrubber PIA-23241A will alarm low pressure at the inlet of the Suction Scrubber (2nd stage) PIA-23261A will alarm low pressure in the Discharge Scrubber PIA-22612 will alarm low pressure at the 16" HP gas header PIALL-22614 will close SDV-22613 to raw gas export pipeline	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	B	5	5	4	4	B5	Alarm	**504**	PIALL-23212A will trip the compressor close SDV-23211A 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	Daily: • Checks for unusual noise, vibration, bearing temperature, frame oil pressure/temperature, RPM, lubrication • Checks for leakages (gas, oil, coolant) Checks vents for leakage (crosshead guide vents, actuator vents of the suction valve, clearance pocket vents) Monthly: • All daily checks • Safety shutdown functionality • Vibration monitoring • Temperature monitoring • Oil analysis 4000 hours: • All monthly checks • Unit shutdown • Service & lubrication (Lubrication	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Compressor Breakdown	Shaft seal system Gearbox Mechanical issues in Compressor unit (e.g. bearing, rotor/impeller) DNFT trips	Loss of Compressor function	Impact to CPF2 Power Plant operations during switch over to diesel. Compressors B will maintain the supply of gas to the raw gas export. Potential impact to CPF2 process for low supply	Compressor running indication Compressor shutdown indication	Critical	Evident Economic	Yes	Yes	Yes	Yes	Yes	E	1	2	4	4	E4	Vendor	**425.6**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		Breakdown due to vibrational issues is identified as critical. Vibrational issues root-cause unknown. • Even with lubrication/servicing task the failure persists. • Regular inspection/functional tests and conditional monitoring doesn't improve or mitigate the issue. • Restoration tasks have been performed to reduce

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability: Visual	Detectability: Alarm	Detectability: Troubleshooting	Detectability: Senior Engineer	Detectability: Vendor	Criticality Score: Likelihood	Severity: Safety	Severity: Environmental	Severity: Production	Severity: Maintenance	Risk	Detection	RPN	Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
					of gas to CPF2 Power Plant.																		Management Program) • Coupling alignment 8000 hours: • All checks as per 4000 hours • Inspect (measure log, trend) and repair (if required) main bearing, connecting rod bearing and bushing, crankshaft jack and thrust clearances, crosshead to guide clearances, piston rod, rod bearings, cylinder bores, drive belt • Compressor valve monitoring (remove and refurbish if required including gaskets, cap O-rings/seals) • Inlet air filter inspection	the failure rate, where in change of piston rods, collars and crank shaft has reduced the vibrations slightly to an acceptable level but not to the optimum level. • The effectiveness of the above task needs to be assessed. The next task of Compressor replacement is not feasible. • The root cause issue is not clearly know. Given the soil conditions, the structure condition is a potential issue and hence reinforcements might be required. However it is recommended to have a detailed Vibrational Analysis/assessment by vendor to be able to resolve the issue
		Low Output	Shaft seal system Gearbox Mechanical issues in Compressor unit (e.g. bearing, rotor/impeller) Blocked filter	Reduced send out from the compressor	Compressors B will maintain the supply of gas to the raw gas export. Potential impact to CPF2 process for low supply of gas to CPF2 Power Plant.	PIA-23241A will alarm low pressure at the inlet of the Suction Scrubber (2nd stage) PIA-23261A will alarm low pressure in the Discharge Scrubber PIA-22612 will alarm low pressure at the 16" HP gas header PIALL-22614 will close SDV-22613 to raw gas export pipeline LIA-23242A will alarm low level at the Suction Scrubber (2nd Stage) LIA-23262A will alarm low level at the Discharge Scrubber (2nd Stage)	Critical	Evident Economic	No	Yes	Yes	Yes	N/A	D	1	1	3	2	D3	Senior Engineer	**156**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		Low output due to vibrational issues is identified as critical. Vibrational issues root-cause unknown. • Even with lubrication/servicing task the failure persists. • Regular inspection/functional tests and conditional monitoring doesn't improve or mitigate the issue. • Restoration tasks have been performed to reduce the failure rate, where in change of piston rods, collars and crank shaft has reduced the vibrations slightly to an acceptable level but not to the optimum level. • The effectiveness of the above task needs to be assessed. The next task of Compressor replacement is not feasible. • The root cause issue is not clearly know. Given the soil conditions, the structure condition is a potential issue and hence reinforcements might be required. However it is recommended to have a detailed Vibrational Analysis/assessment by vendor to be able to resolve the issue
		Compressor Overheat	Main lubrication pump failure Blocked lube oil filter Low level in crank case	Bearing failure	Major release from the casing is likely.	TIA-23222A will alarm high temperature in the First Stage Compressor TIA-23223A will alarm high temperature in	Critical	Evident Safety	Yes	Yes	Yes	Yes	Yes	B	5	5	4	4	B5	Vendor	**756**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor		Overheating due to vibrational issues is identified as critical. Vibrational issues root-cause unknown. • Even with

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability: Visual	Detectability: Alarm	Detectability: Troubleshooting	Detectability: Senior Engineer	Detectability: Vendor	Criticality Score: Likelihood	Severity: Safety	Severity: Environmental	Severity: Production	Severity: Maintenance	Risk	Detection	RPN	Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
			Temperature control loop failure Interstage cooling failure Inlet cooler malfunction Blocked discharge			the First Stage Compressor TIA-23242A will alarm high temperature in the Second Stage Compressor TIA-23243A will alarm high temperature in the Second Stage Compressor																may be out for maintenance) High Bearing Temperature trip on Compressor High High Bearing Temperature trip on Compressor		lubrication/servicing task the failure persists. • Regular inspection/functional tests and conditional monitoring doesn't improve or mitigate the issue. • Restoration tasks have been performed to reduce the failure rate, where in change of piston rods, collars and crank shaft has reduced the vibrations slightly to an acceptable level but not to the optimum level. • The effectiveness of the above task needs to be assessed. The next task of Compressor replacement is not feasible. • The root cause issue is not clearly know. Given the soil conditions, the structure condition is a potential issue and hence reinforcements might be required. However it is recommended to have a detailed Vibrational Analysis/assessment by vendor to be able to resolve the issue
		Vibration	Routing Supporting Shaft alignment Piston rods Breakage in impulse line	Vibration could potentially result in seal failure	Major release from the casing is likely.	Vibrational Monitoring on Compressor	Critical	Evident Safety	Yes	Yes	Yes	Yes	Yes	D	5	5	4	4	D5	Vendor	828	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) High High Vibration trip on Compressor		Vibrational issues is identified as critical. Vibrational issues root-cause unknown. • Even with lubrication/servicing task the failure persists. • Regular inspection/functional tests and conditional monitoring doesn't improve or mitigate the issue. • Restoration tasks have been performed to reduce the failure rate, where in change of piston rods, collars and crank shaft has reduced the vibrations slightly to an acceptable level but not to the optimum level. • The effectiveness of the above task needs to be assessed. The next task of Compressor replacement is not feasible. • The root cause issue is not clearly know. Given the soil conditions, the structure condition is a potential issue and hence reinforcements might be required. However it is recommended to have a detailed Vibrational Analysis/assessment by

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
																								vendor to be able to resolve the issue
		Abnormal instrument reading	False alarm Faulty reading Control unit failure Issues in cabling, junction box	Inability to detect and respond to process deviation	Potential to operate outside of the safe envelope of level and pressure. Loss of gas export production until repair is complete. No impact to crude oil export.	Multiple alarms available on equipment upstream and downstream for check and confirmation on the process parameters PIA-23212A at the inlet of the Suction Scrubber PIA-23241A at the inlet of the Suction Scrubber (2nd stage) PIA-23261A at the Discharge Scrubber LIA-23222A at the Suction Bottle (1st Stage) LIA-23242A at the Suction Scrubber (2nd Stage) LIA-23262A at the Discharge Scrubber (2nd Stage)	Non-critical	Hidden Economic and/or Operational	No	Yes	Yes	Yes	N/A	C	2	1	2	2	C2	Senior Engineer	**56**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		• The regular lubrication/servicing task is required to be performed. • However since it is a hidden failure, a Failure Finding Task/Troubleshooting is required to identify the failure. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Failure to start on demand	Shaft seal system Gearbox Mechanical issues in Compressor unit (e.g. bearing, rotor/impeller) Blocked filter Suction valve closed	Applicable for the compressor on Standby. No flow of gas to consumers downstream	Impact to CPF2 Power Plant operations during switch over to diesel. Loss of gas export production until repair or maintenance on the third one is complete	Failed state not evident during normal operation. Multiple Pressure and Level alarms shall indicate no flow PIA-23212A will alarm low pressure at the inlet of the Suction Scrubber PIA-23241A will alarm low pressure at the inlet of the Suction Scrubber (2nd stage) PIA-23261A will alarm low pressure in the Discharge Scrubber LIA-23222A will alarm low level at the Suction Bottle (1st Stage) LIA-23242A will alarm low level at the Suction Scrubber (2nd Stage) LIA-23262A will alarm low level at the Discharge Scrubber (2nd Stage) Compressor running indication Compressor shutdown indication	Non-critical	Hidden Economic and/or Operational	No	Yes	Yes	Yes	N/A	C	1	1	4	2	C4	Senior Engineer	**333.2**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		• The regular lubrication/servicing task is required to be performed. • However since it is a hidden failure, a Failure Finding Task/Troubleshooting is required to identify the failure. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
M-23210 HP Gas Compressor Motor	To drive the HP Compressor so that the gas can be sent to the consumers downstream	Breakdown	Mechanical issues in pump unit (e.g. bearing, stator, rotor, shaft etc.) Circuit breaker Loss of power supply	Loss of Compressor due to motor failure	Impact to CPF2 Power Plant operations during switch over to diesel. Compressors B will maintain the supply of gas to the raw gas export.	Running status on Motor Trip status on Motor Fault status on Motor Stop status on Motor	Non-critical	Evident Operational	Yes	Yes	N/A	N/A	N/A	C	1	2	3	2	C3	Alarm	**96**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	8000 hours: • Visual Inspection (corrosion, paint, cracks & chips, grounding connections, grounding conductors, mountings) • Sealing gasket	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
					Potential impact to CPF2 process for low supply of gas to CPF2 Power Plant.																		checks • Service & lubrication (Lubrication Management Program) • Vibration condition monitoring • Thermography condition monitoring • Acoustic monitoring • Oil condition monitoring • Cooling system and filter inspection • Visual inspection of connections (for spark, insulation damage, heat de-colorization, moisture, corrosion) • Electrical checks (contactors, overload relays, breakers, cables, Insulation Resistance tests) • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.)	
		Low Output	Mechanical issues in pump unit (e.g. bearing, stator, rotor, shaft etc.) Blocked filter in lubrication system Malfunction in cooling system	Reduced send out from the compressor	Compressors B will maintain the supply of gas to the raw gas export. Potential impact to CPF2 process for low supply of gas to CPF2 Power Plant.	PIA-23241A will alarm low pressure at the inlet of the Suction Scrubber (2nd stage) PIA-23261A will alarm low pressure in the Discharge Scrubber PIA-22612 will alarm low pressure at the 16" HP gas header PIALL-22614 will close SDV-22613 to raw gas export pipeline LIA-23242A will alarm low level at the Suction Scrubber (2nd Stage) LIA-23262A will alarm low level at the Discharge Scrubber (2nd Stage)	Non-critical	Evident Operational	No	Yes	N/A	N/A	N/A	D	1	1	3	2	D3	Alarm	**104**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Overheating	Main lubrication pump failure Blocked filter in lubrication system Temperature control loop failure Inlet cooler malfunction	Potentially lead to stopping of the motor and hence leading to loss of compressor	Potential oil leakage at the bearing causing fire. Impact to CPF2 Power Plant operations during switch over to diesel. Compressors B will maintain the supply of gas to the raw gas export. Potential impact to CPF2 process for low supply of gas to CPF2 Power Plant.	High Temperature alarm on Motor High High Temperature alarm on Motor Winding High High Temperature alarm on Motor Bearing	Critical	Evident Safety	No	Yes	N/A	N/A	N/A	B	4	2	3	2	B4	Alarm	**256**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) High High Bearing Temperature trip on Compressor motor		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Vibration	Mechanical issues in pump unit (e.g. bearing, stator, rotor, shaft etc.) Supporting Rotor imbalance	Potentially lead to stopping of the motor and hence leading to loss of compressor	Potential oil leakage at the bearing causing fire. Impact to CPF2 Power Plant operations during switch over to diesel. Compressors B will maintain the supply of gas to the raw gas export. Potential impact to CPF2 process for low supply of gas to CPF2 Power Plant.	Vibrational Monitoring on Motor	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	B	4	2	3	2	B4	Alarm	**256**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) High High Vibration trip on Compressor motor		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Abnormal instrument reading	False alarm Faulty reading Control unit failure	Inability to detect and respond to faulty signals, hence leading to stopping the motor	Impact to CPF2 Power Plant operations during switch	Multiple alarms available on equipment upstream and downstream for	Non-critical	Hidden Economic and/or Operational	No	Yes	Yes	Yes	N/A	C	1	1	2	2	C2	Senior Engineer	**42**	3 x 50% HP Compressor. Stand-by compressor maintain production		• The regular lubrication/servicing task is required to be performed. • However since it is a

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
			Issues in cabling, junction box	and losing the compressor	over to diesel. Compressors B will maintain the supply of gas to the raw gas export. Potential impact to CPF2 process for low supply of gas to CPF2 Power Plant.	check and confirmation on the process parameters PIA-23212A at the inlet of the Suction Scrubber PIA-23241A at the inlet of the Suction Scrubber (2nd stage) PIA-23261A at the Discharge Scrubber LIA-23222A at the Suction Bottle (1st Stage) LIA-23242A at the Suction Scrubber (2nd Stage) LIA-23262A at the Discharge Scrubber (2nd Stage)																(however the standby compressor may be out for maintenance)		hidden failure, a Failure Finding Task/Troubleshooting is required to identify the failure. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Failure to start on demand	Mechanical issues in motor unit (e.g. bearing, rotor, stator) Blocked filter in lubrication system Malfunction in cooling system Circuit breaker Loss of power supply	Applicable for the compressor motor on Standby. No flow of gas to consumers downstream as the compressor won't be able to start	Impact to CPF2 Power Plant operations during switch over to diesel. Loss of gas export production until repair or maintenance on the third one is complete	Failed state not evident during normal operation. Multiple Pressure and Level alarms in compressor skid shall indicate no flow PIA-23212A will alarm low pressure at the inlet of the Suction Scrubber PIA-23241A will alarm low pressure at the inlet of the Suction Scrubber (2nd stage) PIA-23261A will alarm low pressure in the Discharge Scrubber LIA-23222A will alarm low level at the Suction Bottle (1st Stage) LIA-23242A will alarm low level at the Suction Scrubber (2nd Stage) LIA-23262A will alarm low level at the Discharge Scrubber (2nd Stage) Running status on Motor Trip status on Motor Fault status on Motor Stop status on Motor	Non-critical	Hidden Economic and/or Operational	No	Yes	Yes	Yes	N/A	B	1	1	4	2	B4	Senior Engineer	**313.6**	Single compressor maintains 50% gas sendout if one duty has failed		• The regular lubrication/servicing task is required to be performed. • However since it is a hidden failure, a Failure Finding Task/Troubleshooting is required to identify the failure. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
E-23230A (Stage 1) After Cooler	To cool the gas post compression	Abnormal instrument reading	False alarm Faulty reading Control unit failure	Insufficient cooling of the compressed gas leading to sendout of high temperature compressed gas to the second stage compression	Potential for damage in the bearings and seals at the 2nd stage which could result in release of fuel gas from the shaft system. If ignited fire/explosion in the compressors areas	TIA-23241A will alarm high temperature in the Suction Scrubber (2nd Stage)	Non-critical	Hidden Economic and/or Operational	No	Yes	Yes	Yes	Yes	B	4	4	4	4	B4	Vendor	**409.6**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	6 monthly: • External visual inspections for fan blades • External close inspection including NDT • Internal inspections with representative thickness measurements (including tube) 8000 hours:	Aftercooler is subject to RBI for detailed assessment. However since it is a hidden failure, a Failure Finding Task/Troubleshooting is required to identify the failure. As for the motor: • The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Severity				Risk	Detection	RPN			
															Safety	Environmental	Production	Maintenance						
																							• Visual Inspection (corrosion, paint, cracks & chips, grounding connections, grounding conductors, mountings) • Sealing gasket checks • Service & lubrication (Lubrication Management Program) • Vibration condition monitoring • Thermography condition monitoring • Acoustic monitoring • Oil condition monitoring • Cooling system and filter inspection • Fan and motor alignment checks • Visual inspection of connections (for spark, insulation damage, heat de-colorization, moisture, corrosion) • Electrical checks (contactors, overload relays, breakers, cables, Insulation Resistance tests) • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.)	and conditional monitoring shall ensure high reliability of the equipment
		Insufficient heat transfer	Mechanical issues in motor unit (e.g. drive belts, bearing, rotor, stator) Lack of aerodynamic blade shape Clogging of tube bundles	Less or no cooling of the compressed gas leading to sendout of high temperature compressed gas to the second stage compression	Potential for damage in the bearings and seals at the 2nd stage which could result in release of fuel gas from the shaft system. If ignited fire/explosion in the compressors area	TIA-23241A will alarm high temperature in the Suction Scrubber (2nd Stage)	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	B	4	4	4	4	B4	Alarm	**256**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		Aftercooler is subject to RBI for detailed assessment. As for the motor: • The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
V-23240A Suction Scrubber (2nd Stage)	2nd Stage Suction Scrubber to separate condensate from gas at 1st stage discharge pressure and temperature before sending the gas the second stage compressors	Abnormal instrument reading	False alarm Faulty Readings	Could potentially lead to incorrect gas and condensate send out, e.g. incorrect readings of level on Suction Scrubber will lead to incorrect opening of the LV-23242A	Potential disruption in gas send out. Time for detecting and troubleshooting based on detection available downstream and upstream of the process	Multiple alarms available on equipment upstream and downstream for check and confirmation on the process parameters PIA-23212A at the inlet of the Suction Scrubber PIA-23241A at the inlet of the Suction Scrubber (2nd stage) PIA-23261A at the Discharge Scrubber LIA-23242A at the Suction Scrubber (2nd Stage) LIA-23262A at the Discharge Scrubber (2nd Stage)	Non-critical	Hidden Economic and/or Operational	No	Yes	Yes	N/A	N/A	B	1	1	2	2	B2	Troubleshooting	**28.8**	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) Multiple transmitters on the Suction Scrubber to provide correct process parameter reading in case of failure of one (TT-23241A, LT-23242A, LT-23241A)	6 monthly: • External visual inspections • External close inspection including NDT • Internal inspections with representative thickness measurements • Hydrostatic test • Instrumentation calibration Opportunistic: • Scheduled overhaul / refurbishment	Subject to RBI for detailed assessment However since it is a hidden failure, a Failure Finding Task/Troubleshooting is required to identify the failure.

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
		External leakage	Corrosion issues	Gas/condensate release in the area	Global Shutdown on Confirmed Gas Case. Potential for small fire and disruption to gas supply	LIA-23242A will alarm low level on 2nd stage Suction Scrubber, trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) LIA-23241A will alarm low level on 1st stage Suction Scrubber and close condensate sendout	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	B	5	2	5	2	B5	Alarm	**504**	LIA-23242A will alarm low level on 2nd stage Suction Scrubber, trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) F&G Detectors in the area 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		Subject to RBI for detailed assessment
		Plugged/choked	Deterioration in demister packing material. This leads to plastic screw falling off and blocking the drain line	Lead to level build-up in the 1st Stage Suction Scrubber	Potential damage to the HP Gas Compressor due to liquid carry over.	LIAHH-23242A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge)	Non-critical	Evident Economic	Yes	Yes	Yes	Yes	Yes	D	2	2	3	4	D4	Alarm	**374.4**	LIAHH-23242A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		Plugging/choked is identified as critical. This has consequences on the compressor performance. Hence the RCM decision matrix is followed for the Scrubber to improve the reliability of the HP Compressor due to condensate carryover issues. • Even with lubrication/servicing task of the HP Compressors the failure persists. • Regular inspection/functional tests and conditional monitoring of the HP Compressors doesn't improve or mitigate the issue. • Restoration tasks could be performed on the Scrubber to reduce the failure rate, where in increasing the size of the drain line can possibly eliminate blockage of drain line. This will ensure more condensate sendout and result in slower level build-up in the Scrubber. • The effectiveness of the above task needs to be assessed. The next task of discarding or Scrubber replacement will be expensive and not effective. • The root cause issue is the quality of the process gas which is not adequately handled by the Scrubber. Hence the Scrubber design and size needs to be revisited to be able to handle the incoming gas or installing a Filter Coalescer/Treatment package upstream of the Compressors

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
ESD Loop LT-23242A Initiating Transmitter LIA-23242A Logic Solver SDV-23241A Shutdown Valve at outlet of 2nd stage Suction Scrubber	Liquid carryover protection whereby shutdown valve shall close at the inlet of 1st stage Suction Scrubber	Operates without demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Lead to level build-up in the 2nd Stage Suction Scrubber	Potential damage to the HP Gas Compressor due to liquid carry over.	LIAHH-23242A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge)	Non-critical	Evident Economic	Yes	Yes	N/A	N/A	N/A	B	2	2	3	3	B3	Alarm	88	LIAHH-23242A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	6 monthly: • External visual inspection (valve and actuator) • Internal visual inspection (valve and actuator) • Valve diagnostic checks (Calibration, Bench Set, Friction, Travel, Dynamic Error, Resolution, Sensitivity) • Function test – input loops • Function test – leak rate • Function test – stroke time • Function test – position verification • Function test - opening and closing times • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.) Opportunistic: • Scheduled overhaul / refurbishment	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
	Gas blowby protection whereby shutdown valve shall close at the outlet of 1st stage Suction Scrubber for condensate send out	Failure to close on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Loss of level in the Suction Scrubber 2nd Stage and gas blow by to the Condensate Separator	Potential low suction pressure at the HP Gas Compressor and high pressure at the Condensate Separator	PIA-22651 will alarm high pressure in the Condensate Separator	Non-critical	Evident Operational	Yes	Yes	N/A	N/A	N/A	B	2	2	3	2	B3	Alarm	88	LIALL-23242A will close LV-23222A 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) On loss of signal, the SDV fails close		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		External leakage (LIT-23242A)	Excessive vibration	Projectile impact on adjacent equipment or people. Loss of containment of gas inside the Compressor Package Building	Confirmed gas case require Global Shutdown	Fire and Gas System	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	C	5	2	5	2	C5	Alarm	528	Shutdown on Confirmed Gas by Control Room Operator Intervention		Refer to K-23210A
LV-23242A Level control valve & Level Control Loop	Level control valve at the outlet of 2nd stage Suction Scrubber for condensate send out	Failure to open on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Lead to level build-up in the 2nd Stage Suction Scrubber	Potential damage to the HP Gas Compressor due to liquid carry over.	LIAHH-23242A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge)	Non-critical	Evident Economic	Yes	Yes	N/A	N/A	N/A	B	2	2	3	3	B3	Alarm	88	LIAHH-23242A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	6 monthly: • External visual inspection (valve and actuator) • Internal visual inspection (valve and actuator) • Valve diagnostic checks (Calibration, Bench Set, Friction, Travel, Dynamic Error, Resolution, Sensitivity) • Function test – input loops • Function test – leak rate • Function test – stroke time • Function test – position verification • Function test - opening and closing times • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.) Opportunistic: • Scheduled	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Failure to close on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Loss of level in the Suction Scrubber 2nd Stage and gas blow by to the Condensate Separator	Potential low suction pressure at the HP Gas Compressor and high pressure at the Condensate Separator	PIA-22651 will alarm high pressure in the Condensate Separator LIALL-23242A will close SDV-23241A	Non-critical	Evident Economic	Yes	Yes	N/A	N/A	N/A	B	2	2	3	2	B3	Alarm	88	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) On loss of signal, the LV fails close		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		External leakage (LIT-23241A)	Excessive vibration	Projectile impact on adjacent equipment or people. Loss of containment of gas	Confirmed gas case require Global Shutdown	Fire and Gas System	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	C	5	2	5	2	C5	Alarm	528	Shutdown on Confirmed Gas by Control Room		Refer to K-23210A

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Severity				Risk	Detection	RPN			
															Safety	Environmental	Production	Maintenance						
				inside the Compressor Package Building																		Operator Intervention	overhaul / refurbishment	
E-23230A (Stage 2) After Cooler	To cool the compressed gas before send out	Abnormal instrument reading	False alarm Faulty reading Control unit failure	Insufficient cooling of the compressed gas leading to send out of high temperature compressed gas for export	No further consequences as the HP gas will mix with the other HP Gas Compressor Packages.	TIA-23261A will alarm high temperature in the Discharge Scrubber (2nd Stage)	Non-critical	Hidden Economic and/or Operational	No	Yes	Yes	Yes	N/A	B	1	1	2	2	B2	Senior Engineer	36	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	6 monthly: • External visual inspections for fan blades • External close inspection including NDT • Internal inspections with representative thickness measurements (including tube) E-2001 8000 hours: • Visual Inspection (corrosion, paint, cracks & chips, grounding connections, grounding conductors, mountings) • Sealing gasket checks • Service & lubrication (Lubrication Management Program) • Vibration condition monitoring • Thermography condition monitoring • Acoustic monitoring • Oil condition monitoring • Cooling system and filter inspection • Fan and motor alignment checks • Visual inspection of connections (for spark, insulation damage, heat de-colorization, moisture, corrosion) • Electrical checks (contactors, overload relays, breakers, cables, Insulation Resistance tests) • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.)	Aftercooler is subject to RBI for detailed assessment. However since it is a hidden failure, a Failure Finding Task/Troubleshooting is required to identify the failure. As for the motor: • The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Insufficient heat transfer	Mechanical issues in motor unit (e.g. bearing, rotor, stator) Lack of aerodynamic blade shape Clogging of tube bundles	Less or no cooling of the compressed gas leading to send out of high temperature compressed gas for export	No further consequences as the HP gas will mix with the other HP Gas Compressor Packages.	TIA-23261A will alarm high temperature in the Discharge Scrubber (2nd Stage)	Non-critical	Evident Operational	Yes	Yes	N/A	N/A	N/A	B	1	1	2	2	B2	Alarm	21.6	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)		Aftercooler is subject to RBI for detailed assessment. As for the motor: • The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
			False alarm				Non-critical		No	Yes	Yes	Yes	N/A	B	1	1	2	2	B2	Senior Engineer	36			

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
V-23260A Discharge Scrubber (2nd Stage)	2nd Stage Discharge Scrubber to separate condensate from gas before exporting	Abnormal instrument reading	Faulty Readings	Could potentially lead to incorrect gas and condensate send out, e.g. incorrect readings of level on Suction Scrubber will lead to incorrect opening of the LV-23262A	Potential disruption in gas send out. Time for detecting and troubleshooting based on detection available downstream and upstream of the process	Multiple alarms available on equipment upstream and downstream for check and confirmation on the process parameters PIA-23212A at the inlet of the Suction Scrubber PIA-23241A at the inlet of the Suction Scrubber (2nd stage) PIA-23261A at the Discharge Scrubber LIA-23242A at the Suction Scrubber (2nd Stage) LIA-23262A at the Discharge Scrubber (2nd Stage)		Hidden Economic and/or Operational														3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) Multiple transmitters on the Suction Scrubber to provide correct process parameter reading in case of failure of one (TT-23261A, LT-23262A, LT-23261A)		Subject to RBI for detailed assessment However since it is a hidden failure, a Failure Finding Task/Troubleshooting is required to identify the failure.
		External leakage	Corrosion issues	Gas/condensate release in the area	Global Shutdown on Confirmed Gas Case. Potential for small fire and disruption to gas supply	LIA-23262A will alarm low level on 2nd stage Discharge Scrubber, trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) LIA-23261A will alarm low level on 2nd stage Discharge Scrubber and close condensate send out	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	B	5	2	5	2	B5	Alarm	**504**	LIA-23262A will alarm low level on 2nd stage Discharge Scrubber, trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) F&G Detectors in the area 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	6 monthly: • External visual inspections • External close inspection including NDT • Internal inspections with representative thickness measurements • Hydrostatic test • Instrumentation calibration	Subject to RBI for detailed assessment
		Plugged/choked	Deterioration in demister packing material. This leads to plastic screw falling off and blocking the drain line	Lead to level build-up in the 2nd stage Discharge Scrubber	Liquid carry over to the gas export pipeline and CPF2 Power Plant	LIAHH-23262A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge)	Non-critical	Evident Economic	Yes	Yes	Yes	Yes	Yes	D	2	2	3	2	D3	Alarm	**182**	LIAHH-23262A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	Opportunistic: • Scheduled overhaul / refurbishment	Plugging/choked is identified as critical. This has consequences on the compressor performance. Hence the RCM decision matrix is followed for the Scrubber to improve the reliability of the HP Compressor due to condensate carryover issues. • Even with lubrication/servicing task of the HP Compressors the failure persists. • Regular inspection/functional tests and conditional monitoring of the HP Compressors doesn't improve or mitigate the issue. • Restoration tasks could be performed on the Scrubber to reduce the failure rate, where in increasing the size of the drain line can possibly eliminate blockage of drain line. This will ensure more condensate sendout and result in

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
															Severity									
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Safety	Environmental	Production	Maintenance	Risk	Detection	RPN			
																								slower level build-up in the Scrubber. • The effectiveness of the above task needs to be assessed. The next task of discarding or Scrubber replacement will be expensive and not effective. • The root cause issue is the quality of the process gas which is not adequately handled by the Scrubber. Hence the Scrubber design and size needs to be revisited to be able to handle the incoming gas or installing a Filter Coalescer/Treatment package upstream of the Compressors
ESD Loop LIT-23262A Initiating Transmitter LIA-23262A Logic Solver SDV-23261A Shutdown Valve at outlet of 2nd stage Discharge Scrubber	Liquid carryover protection	Operates without demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets)	Lead to level build-up in the 2nd Stage Discharge Scrubber	Liquid carry over to the gas export pipeline and CPF2 Power Plant	LIAHH-23262A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge)	Hidden	Hidden Economic and/or Operational	Yes	Yes	Yes	N/A	N/A	B	2	2	3	3	B3	Troubleshooting	**110**	LIAHH-23262A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	6 monthly: • External visual inspection (valve and actuator) • Internal visual inspection (valve and actuator) • Valve diagnostic checks (Calibration, Bench Set, Friction, Travel, Dynamic Error, Resolution, Sensitivity) • Function test – input loops • Function test – leak rate • Function test – stroke time • Function test – position verification • Function test - opening and closing times • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.) Opportunistic: • Scheduled overhaul / refurbishment	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
			Actuator mechanical failures																					
			Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)																					
	Gas blowby protection whereby shutdown valve shall close at the outlet of 2nd stage Suction Scrubber for condensate sendout	Failure to close on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets)	Loss of level in the 2nd Stage Discharge Scrubber and gas blow by to the Condensate Separator	Potential low pressure for gas export and high pressure at the Condensate Separator	PIA-22651 will alarm high pressure in the Condensate Separator	Hidden	Hidden Safety	Yes	Yes	Yes	N/A	N/A	B	2	2	3	2	B3	Troubleshooting	**110**	LIALL-23262A will close LV-23222A and SDV-23241A 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) On loss of signal, the SDV fails close		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
			Actuator mechanical failures																					
			Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)																					
		External leakage (LIT-23262A)	Excessive vibration	Projectile impact on adjacent equipment or people. Loss of containment of gas inside the Compressor Package Building	Confirmed gas case require Global Shutdown	Fire and Gas System	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	C	5	2	5	2	C5	Alarm	**528**	Shutdown on Confirmed Gas by Control Room Operator Intervention		Refer to K-23210A
LV-23262A Level control valve & Level Control Loop	Level control valve at the outlet of 2nd stage Discharge Scrubber for condensate sendout	Failure to open on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets)	Lead to level build-up in the 2nd Stage Discharge Scrubber	Liquid carry over to the gas export pipeline and CPF2 Power Plant	LIAHH-23222A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge)	Non-critical	Evident Economic	Yes	Yes	N/A	N/A	N/A	B	2	2	3	3	B3	Alarm	**88**	LIAHH-23262A will trip the compressor and close SDV-23211A (suction) and SDV-23213A (discharge) 3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor	6 monthly: • External visual inspection (valve and actuator) • Internal visual inspection (valve and actuator) • Valve diagnostic checks (Calibration, Bench Set, Friction, Travel, Dynamic Error, Resolution,	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
			Actuator mechanical failures																					
			Valve control and instrumentation failure (e.g. cabling,																					

Equipment Item	Functionality	Failure Mode	Failure Causes	Failure Effects (Local)	Failure Effects (System Level)	Detection	Reliability Issues identified at site	Failure Classification	Detectability					Criticality Score								Safeguards / Mitigating Factors	Maintenance Tasks	RCM Decision Logic
									Visual	Alarm	Troubleshooting	Senior Engineer	Vendor	Likelihood	Severity				Risk	Detection	RPN			
															Safety	Environmental	Production	Maintenance						
			instrumentation, pressure sensors)																			may be out for maintenance)	Sensitivity) • Function test – input loops • Function test – leak rate • Function test – stroke time • Function test – position verification • Function test - opening and closing times • Instrument checklist (condition, instrument loop test, cable and gland installation, terminations etc.) Opportunistic: • Scheduled overhaul / refurbishment	
		Failure to close on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Loss of level in the 2nd Stage Discharge Scrubber and gas blow by to the Condensate Separator	Potential low pressure for gas export and high pressure at the Condensate Separator	PIA-22651 will alarm high pressure in the Condensate Separator LIALL-23262A will close SDV-23261A	Non-critical	Evident Economic	Yes	Yes	N/A	N/A	N/A	B	2	2	3	2	B3	Alarm	88	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance) On loss of signal, the LV fails close		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		External leakage (LIT-23261A)	Excessive vibration	Projectile impact on adjacent equipment or people. Loss of containment of gas inside the Compressor Package Building	Confirmed gas case require Global Shutdown	Fire and Gas System	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	C	5	2	5	2	C5	Alarm	528	Shutdown on Confirmed Gas by Control Room Operator Intervention		Refer to K-23210A
ESD Loop PIT-23263A Initiating Transmitter PIA-23263A Logic Solver SDV-23213A Shutdown Valve at outlet of HP Gas Compressor PK-23210	ESD function to trip the compressor and close SDV-23211A/13A in case of blocked outlet protection or low suction pressure	Operates without demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Low pressure of the raw gas export pipeline	Compressor packages A would be line up to CPF2 Power Plant, B to gas export pipeline and C standby. CPF2 production loss and damage to the reputation due to the impact on the raw gas export pipeline.	PIA-23261A will alarm high pressure in the Discharge Scrubber PIA-22612 will alarm low pressure at the 16" HP gas header PIAHH-23261A will trip the compressor	Hidden	Hidden Economic and/or Operational	Yes	Yes	Yes	N/A	N/A	B	1	1	5	2	B5	Troubleshooting	529.2	3 x 50% HP Compressor. Stand-by compressor maintain production (however the standby compressor may be out for maintenance)	6 monthly: • External visual inspection (valve and actuator) • Internal visual inspection (valve and actuator) • Valve diagnostic checks (Calibration, Bench Set, Friction, Travel, Dynamic Error, Resolution, Sensitivity) • Function test – input loops • Function test – leak rate • Function test – stroke time • Function test – position verification • Function test - opening & closing times • Instrument checklist (condition , instrument loop test, cable and gland installation, terminations etc.) Opportunistic: • Scheduled overhaul / refurbishment	• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		Failure to close on demand	Valve mechanical failures (e.g. sticking, degradation to closure member, degraded seals / seats, gaskets) Actuator mechanical failures Valve control and instrumentation failure (e.g. cabling, instrumentation, pressure sensors)	Potential high pressure gas in the line. This could be required to be closed in an emergency event to isolate the HP Compressor Package	Potential damage to the compressor if the pressure goes beyond the design intent in case of an emergency leading to a major release from the casing	PIA-23212A will alarm high pressure at the inlet of the Suction Scrubber .PIA-23241A will alarm high pressure at the inlet of the Suction Scrubber (2nd stage).PIA-23261A will alarm high pressure in the Discharge Scrubber PIA-22612 will alarm high pressure at the 16" HP gas header PIAHH-23261A will trip the compressor	Hidden	Hidden Safety	Yes	Yes	Yes	N/A	N/A	B	5	5	4	4	B5	Troubleshooting	588	On loss of signal, the SDV fails close BDV-23212A at the outlet of the Discharge Scrubber (2nd stage) will open to HP Flare		• The regular lubrication/servicing task is effective. • Since it's not a Functionally Significant Failure item, the regular inspection/functional checks and conditional monitoring shall ensure high reliability of the equipment
		External leakage (PIT-23263A)	Excessive vibration	Projectile impact on adjacent equipment or people. Loss of containment of gas inside the Compressor Package Building	Confirmed gas case require Global Shutdown	Fire and Gas System	Critical	Evident Safety	Yes	Yes	N/A	N/A	N/A	C	5	2	5	2	C5		528	Shutdown on Confirmed Gas by Control Room Operator Intervention		Refer to K-23210A