Consultancy Services for the Plant Audit in various Pump Stations and Reservoirs (OP18REFCS03)

Preliminary

Technical Report for PAGCOR Pump Station

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Preliminary Report for Pagcor Pump Station

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Executive Summary

PAGCOR Pump Station has 8 numbers of pumps (6 booster pumps and 2 storage pumps). Based on preliminary assessment on historical corrective and preventive intervention records, significant degradation has been observed for pumps, which experienced high frequency of failure on bearing and coupling components. Statistically, it is evident from the time series data in the period from 2014 to 2016 on power consumption and production that more power has been incurred while the availability of the pump system is less.
Based on the results of testing, reliability, and life cycle cost analysis, GHD recommends to execute a set of preventive intervention program that involves periodic replacement of pump components and frequent inspection/testing to collect historical data sufficient to estimate the reliability of pumps and the system. The intervention program can be done in the first year of the next 5 years preventive intervention plan that are reflected in the optimal time window shown along with the impact curves.
Furthermore, GHD recommends Maynilad that optimal time window to execute the intervention program shall take into consideration of network analysis which will enable Maynilad to set priorities to perform intervention program not only for Pagcor station but also for other stations. In addition, Maynilad might consider to combine intervention programs of a group of stations as it will be also optimal when preparing the bid.

Contents

Chapter 1

Introduction

1.1 General introduction

Pagcor PS is located in Pasay area (refer to Figure 1.1). It has a total capacity of 1,387,813 m^3/day and pumps the treated water to a discharge line serving the an area in Pasay, Metro Manila. The schematic diagram showing its connectivity is in Figure 1.3.

Figure 1.1: Pagcor PS [$14°31'9.60''N, 120°59'6.78''E$]

Figure 1.2: Pump gallery

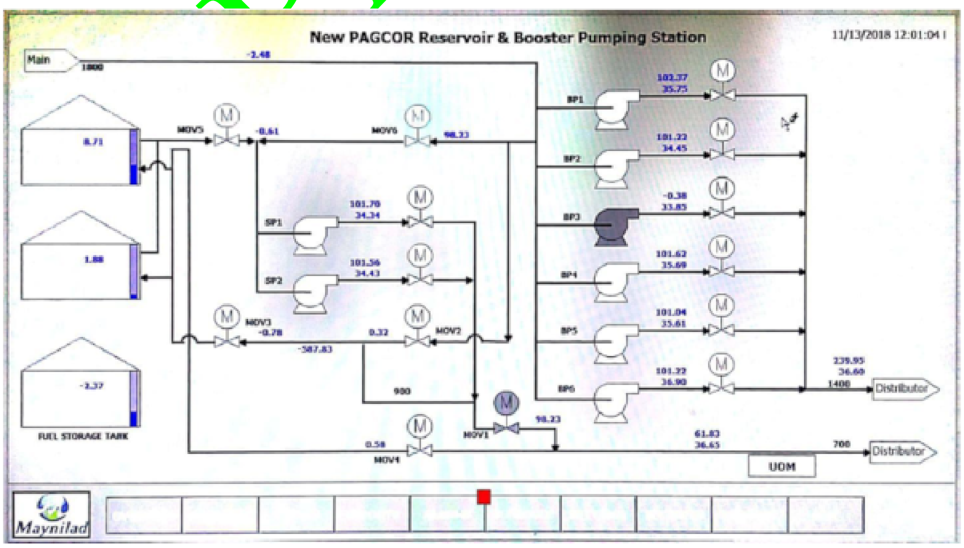


Figure 1.3: Schematic diagram

This PS has been reported by the Client to experience considerable degradation with regard to inefficiency of operation, higher power consumption, and more frequent breakdowns of assets leading to the increase in maintainability and decrease in availability.

The Client has therefore awarded GHD and its sub-consultants (RB Sanchez and APSI) to conduct a plant audit project with an expectation to establish rigorous asset management framework based on reliability study and to determine optimal intervention program for the next five (5) years.

1.2 Objectives

The objectives of this work are as follows

- To evaluate the current operating condition of PS as compared to the original design intent and to provide recommendations for improving the operational efficiency and lowering operating cost;
- To be able to determine an optimal intervention program for the PS in the next 5 years with reference to the recommendations from the assessment and audit based on life cycle cost; and equipment efficiency study whether the equipment is subjected to replacement or repair. These equipment are:
    - Pumps;
    - Motors;
    - Generators;
    - Motorize Valves.

1.3 Scope of Work

Scope of Work (SOW) has been defined in the Contract Agreement and be in compliance with the GHD technical and financial proposal and the agreements made during a number of project meetings (refer to minutes of meeting of the project). It is important to note that the electrical audit and analysis is not part of the scope for this station as the work was conducted by Maynilad prior to the bid of this project.

1.4 Limitations

Results of the study with analysis, conclusion, and recommendations are only within the scope of work and agreements, and particularly under the following major constraints:

- Operational constraint: It was not possible to shutdown the entire PS for visual inspection of assets, particularly mechanical assets;
- Incomplete historical data: It was a matter of fact that Maynilad has not established an asset management system, thus data regarding historical intervention is limited and incomplete, leading to non-optimal reliability analysis;

1.5 Glossaries

Following glossaries are defined and used in the report:

Level of Services (LOS)

A Level of Services (LOS) is any value or expectation of asset managers and beneficiers regarding the functionality and serviability of an asset of a system of assets.

Intervention

Intervention is a generic and global term used to refer to non-physical and physical activities on assets. It encompasses do-nothing, or do somethings like repair, maintenance, rehabilitation, renewal, investment, and inspection and testing.

Corrective Intervention (CI)

A Corrective Intervention (CI) is an intervention executed without proper and systematic plan. An CI is often incurred by failure/breakdown of assets. In most of cases, it incurs significant negative impacts (e.g. cost to repair, disruption of service, loss in revenue).

Preventive Intervention (PI)

A Preventive Intervention (PI) is an intervention executed with proper and systematic plan. Note that an PI is executed on asset that is still working but not provide adequate level of services.

Intervention Type

An Intervention Type (IT) is a specific and well-defined type of work/task that can be executed on/for an asset (e.g. replacement of a bearing for a pump).

Intervention Strategy (IS)

An Intervention Strategy (IS) is a set/collection of intervention types.

Intervention Program (IP)

An Intervention Program (IP) is a set/collection of intervention strategies for one asset or more than one assets of the same system.

Work Program (WP)

A Work Program (WP) is an execution program consisting of Intervention Program and management program (e.g. project management, procurement) that shall be implemented in order to realize/actualize the Intervention Program.

Chapter 2

Preliminary Assessment and Data Gathering

GHD did conduct preliminary assessment on a set of data provided by Maynilad. The data set includes a number of records on daily production and power consumption and intervention reports issued after Maynilad experienced failure/breakdown of assets.

The assessment provided a base for GHD to generate the Inspection Testing Plan (ITP) [9] aiming to gather necessary data for conducting reliability study. The ITP has been reviewed by Maynilad, together with the Work Safety Permit (WSP), prior to execution of visual inspections and testings at the site [6].

2.1 Maynilad's data

Maynilad provided a set of data as shown in Table 2.1

Table 2.1: Data provided by Client.

No.	Data	Remarks
1	Production and power consumption from 2012 to 2018	Recorded in excel fiels. Data set is incomplete but can be considered acceptable for the study
2	As-built drawings	Both in CAD and PDF format
3	Intervention records	Refer as activity, preventive and corrective maintanance reports. Note that the numbers of records are limited.
4	Asset registry	Asset registry was incompleted as confirmed by the IAM team of Maynilad.
5	Specifications and technical manuals	Includes pressure graph, bearing information

2.1.1 Intervention records

The provided data set includes 29 intervention records and 1 major inspection activity (refer to Table 2.2).

As can be seen from the table, no PI has been executed. This was due to a matter of fact that Maynilad still has not come up with preventive maintenance program within the overall asset management framework. The IAM team has recently established with expectation to generate short-term, medium-term, and long-term preventive intervention program. In close discussion with Maynilad, GHD learns that Maynilad has a regular/frequent activities for check-up (e.g. monthly and quarterly), however, recorded data has not been digitalized and the data itself has not aligned well with the asset registry. Aside from the above data, there is an additional excel file with records on both CI (23) and PI (18), particularly for only the year of 2018.

Table 2.3 presents highlights on intervention data on pumps.

Table 2.2: Data provided by Client.

Year	Numbers of		Major	References
	CI	PI	Inspection	
2012	4	0	0	[50, 49, 48, 51]
2013	0	0	0	
2014	5	0	0	[32, 22, 33, 23, 26]
2015	2	0	0	[29, 27]
2016	12	0	0	[45, 24, 47, 31, 28, 30, 43, 44, 46, 36, 25, 34]
2017	7	0	0	[38, 39, 42, 35, 37, 41, 40]
2018	0	0	1	

Table 2.3: Highlight of intervention data on pumps.

Pumps	Description of CI	Date
BP1	Replacement of pump coupling	1/11/2017
BP1	Replacement of pump outer bearing	5/3/2017
BP2	Replacement of mechanical seal	9/10/2017
BP3	Replacement of pump inner and outer bearing	2/9/2017
BP3	Replacement of pump outer mechanical seal and bearing	4/22/2017
BP3	Replacement of pump inner bearing and mechanical seal	7/7/2017
BP5	Replacement of defective mov (5) butterfly valve	1/13/2016
BP5	Alignment of pump and motor	7/4/2016
BP5	Replacement of pump coupling	5/13/2017
SP1	Dismantling SP1 because of foreign material that causes strong vibration and noise	2/5/2016
SP1	Replacement of pump outer bearing and mechanical seal and Alignment of pump and motor	7/29/2016
SP1	Replacement of mechanical seal	8/16/2016
SP2	Replacement of pump inner and outer mechanical seals and bearings	8/1/2016
SP2	Replacement of mechanical seal	5/18/2017

2.1.2 Interview data

GHD conducted an interview session on 07/12/2018. Results of the interview are summarized in the minutes [7], with the following highlights.

- No further data is available aside from the provided set presented in earlier section
- There is an existing regular check-up for assets but data is not digitalized and the information is only generic
- Spare parts are not stocked for most of components, except for bearing. Regarding service delivery, the required discharge pressure remains the top priority in pump operation modulation and sequencing. Critical parts and components for VFD and bearing are usually stacked to have spared in case of emergency repair and replacements. The consumables on the other hand, are not stacked but ordered in advance for use in maintenance activities
- No visual bank of assets
- No standard testing regime that follows a regular scheme based on optimality
- Pumps are operated based on pressure and not manual
- No existing PI/CI procedure to be followed
- No expansion plan is forecasted
- There is a problem with the inflow of incoming water, leading to lower level of reservoir chambers that has affected pump operations occasionally
- no historical data on pump efficiency, which is a simple yet useful value in determining pump performance. The main impediment in the individual pump efficiency is the measurement of flow produced by each pump. The existing configuration of the pump-motor and piping system do not cater to conventional methods of flow determination

- No intervention records for FDAS. It was revealed that different version on operation and functionality of the FDAS was reported by both guard and site operators.

2.1.3 Asset hierarchy

During the bidding phase, Maynilad did provide the first draft of the Asset Registry (AR) that describes a hierarchy of eight (8) levels. Figure 2.1 visualizes the hierarchy with brief description presented in Table 2.4.

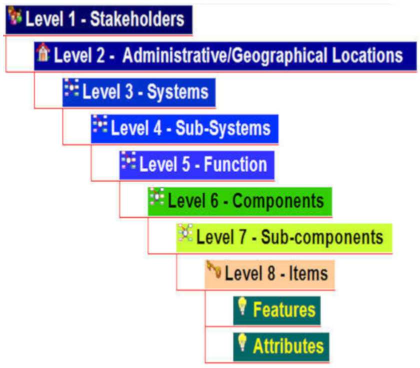


Figure 2.1: Asset Hierarchy

Table 2.4: Condition state definition - Multiple.

Asset hierarchy	Description
Level 1	Stakeholder level. For example, an pump station belongs to MWSI
Level 2	Geographical locations/ or administrative zone (e.g. a pump station belong to Quezon city or Makati)
Level 3	System (e.g. the entire pump stations and reservoir system)
Level 4	Sub-system (e.g. one specific pump station and reservoir such as the Lamesa PSR)
Level 5	Functional system (e.g. booster system or storage system)
Level 6	Component (e.g. Suction line, Reservoir line and Tank)
Level 7	Sub-component (e.g. Suction pipe and fittings, Concrete reservoir, pump)
Level 8	Items (e.g. valve, bearing, motor)

GHD received the latest version of the AR with 227 assets for this PS. The full list of assets is given in the excel file provided by Maynilad in 2018. GHD has developed a MS Access program to convert the data in the excel file to a relational database structure. Per agreement with Maynilad, GHD will only verify level 7 of the AR with the actual site condition for the study [8].

2.2 Preliminary assessment

Assessment on the lastest provided intervention records reveals that the provided pertinent data is incomplete and cannot be used as representative data for a complete reliability study. However, the behaviour of the data can give a glim on the reliability of the PS. This glim can be seen in Figure 2.2

The statistics infers that there are numerous major CIs that did incurred in just one year. CI also infers that there are loss in Revenue, Reputation, and Regulatory (3Rs) that Maynilad could have been suffered. This 3Rs has not been addressed in the historical data.

Further table study indicates that the pump system fails due to a number of failures of its items, which are shown in Table 2.5.

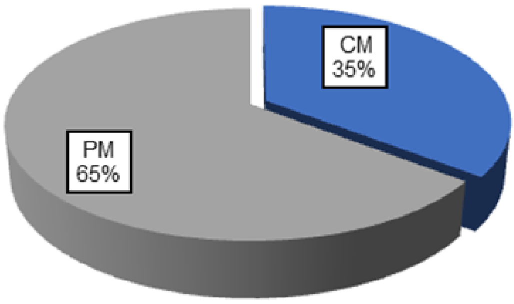


Figure 2.2: PI and CI – 2017

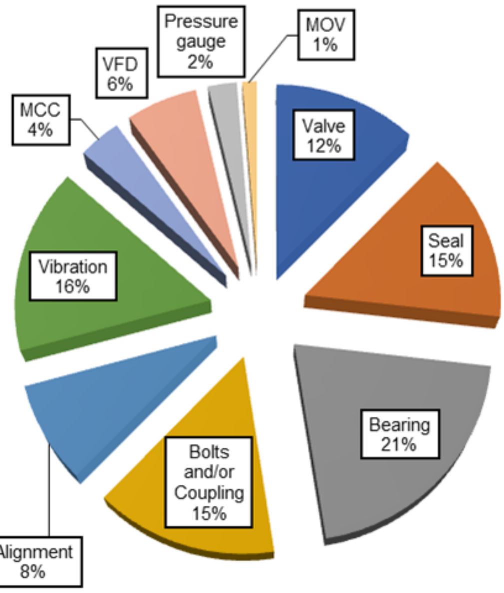


Figure 2.3: Manhour spent on interventions – 2017

Table 2.5: Summary of breakdown of items.

Category	Items	Numbers
Pump system		82
	Valve	10
	Seal	12
	Bearing	17
	Bolts and/or Coupling	12
	Alignment	7
	Vibration	13
	MCC	3
	VFD	5
	Pressure gauge	2
	Impeller	0
	MOV	1
Other Assets		
	Lighting	4
	Ventilation	0
	Lifting	0

It is also noted from the provided data that the Client has done regularly check-up on GENSETs to ensure that it provides adequate level of services in case of emergency. The statistic on check-up and routine cleaning and inspection of the GENSETs is shown in Table 2.6

As can be seen from Table 2.5, majority of pump maintenance involves vibration both as a source and/or a result. Problems with alignment, bearings and couplings make up more than half of the maintenance work and are mostly associated with vibration (Figure 2.3). Minimizing vibration will lead to less damage to components and better maintenance of components will reduce unwanted vibrations during pump operation. A thought to be noted is the association of failures between pump parts in that failure in one promotes succeeding failures of the others.

From reliability point of view, having frequency CIs indicates a level of uncertainty that the PS does not provide adequate level of services (LOS).

Further evaluations and tests have to be conducted to identify the areas for improvement of preventive measures in mitigating corrective measures and study the ways to strengthen preventive measures to improve operating conditions and life of pump components.

Improving the reliability of the pump stations for the next coming years require evaluation of the existing pump station conditions and maintenance practices, particularly assessment of the pump and its components. With that, areas for improvement of operation and maintenance

Table 2.6: Summary of 2017 GENSETS routine cleaning and check-up.

Category	Items	Numbers
Genset		39
	Oil	10
	Coolant	10
	Battery	10
	Filters	10
	Belt	4
	Electrical connections	4
	Hoses	4

be addressed through action items that come from the resulting recommendations.

In order to capture a relatively good picture on the reliability of the pump system and its associated assets, a number of tests shall be conducted.

2.3 Summary of the inspection test plan (ITP)

A complete write-up on testing shall be referred to the ITP [9], which has been submitted, reviewed, and approved by the Client. This section only provides highlights to help readers keeping abread of the flow of the report.

2.3.1 Mechanical Audit

The Mechanical Tests to be conducted are enumerated and discussed hereunder including their background and applications, standards used if applicable, and the equipment to be used. During testing, the following are the assumptions and considerations:

- The operation of the pumps cannot be interrupted (at day time when demand is high).
- The valve settings then cannot be adjusted to produce different flow rates.

2.3.1.1 Structural Inspection for Pump Discharge and Suction Line

This activity measures the current thickness of the existing pipelines at the pump vicinity using ultrasonic thickness gauging. The flow regime especially around the elbow and possibly corrosion and scaling conditions are to be predicted from the measurements of this test.

Following procedures will be executed

Step 1: Locate and mark testing points

At a minimum of two (2) meters away from the pump intake/discharge flange, the test points shall be marked at 3, 6, 9 and 12 o'clock positions and at one (1) meter interval along the pipes, additional test sections with same set points shall be added as long as available beneath the immediate ground level (Figure 2.4 and Figure 2.5). Note that there will be no testing at section 4 as indicated in the figure as it falls on the control valve. The next 1 meter away from the pump flange will be considered instead.

Another set of test points shall be for the elbows and will be determined from the flow direction considering the probable points of most thinning from turbulent water flow (Figure 2.6).

Step 2: Prepare test point surfaces

- Wipe the surface free of dirt (no need to remove paint)
- Using a chalkstone (erasable), mark x on the test point

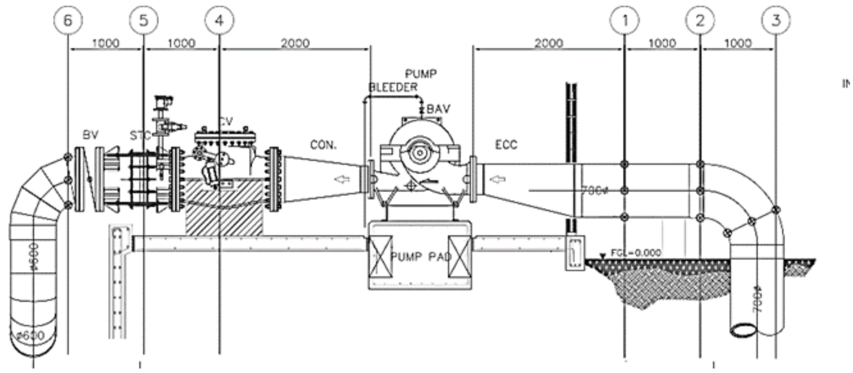


Figure 2.4: Sample pump layout and testing points

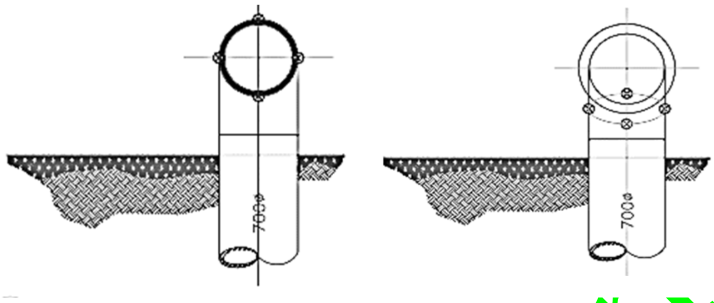


Figure 2.5: Test Points - Cross sectional view of Section 1 and Section 3

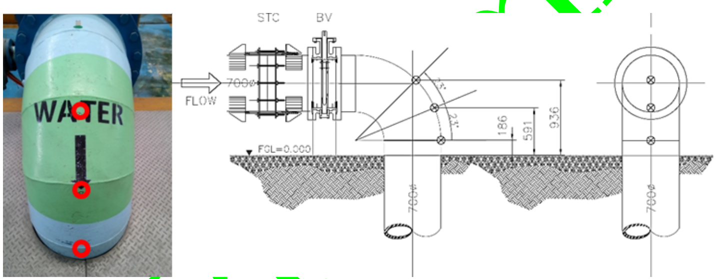


Figure 2.6: Sample test points for elbow

Step 3: Apply sufficient couplant on test point surface

- Use petroleum jelly/Vaseline as couplant

Step 4: Set transducer probe on test point

Step 5: Read and record value as indicated on module display

Record values shown on the screen (Figure 2.7).

Step 6: Clean test point after reading

2.3.1.2 Unit Flow Measurement

The activity measures pump capacities. Pump efficiency is then calculated using the measured values.

Figure 2.7: UTG reading

Step 1: Locate Sensor Position Point Area and mark all points to be taken.

- Observe required offset distance from fittings/pump to consider the fully developed flow. At least 10 times the diameter distance away from the suction/discharge of the pump if applicable, otherwise consider at least 2D distance away from the fittings. This is to ensure the flow will be stable and fully developed for flow measurement accuracy (Figure 2.8).
- Otherwise, test at near turbulent zones and consider normalizing the flow. Refer to Figure 2.9:

Figure 2.8: Set points for straight pipe with developed flow

Figure 2.9: Set points for straight pipe with flow turbulence

Step 2: Pipe Specification Input on the Flow Meter.

- Identify nominal pipe size with equivalent parameters such as schedule designation, equivalent thickness, OD, and etc.
- Input outside diameter.
- Input pipe thickness.
- Input pipe material (carbon steel).
- Input pipe medium (water).

Step 3: Prepare test point surfaces

- Clean the surface of pipe with a sandpaper and steel brush or any suitable abrasive materials, exposing the base metal.

Step 4: Install transducers at set points

- Apply enough couplant that it covers transducers sensors to ensure an acoustically conductive connection to the pipe. Also apply couplant on the test point surface (Figure 2.10).
- Clamp the transducers at the side of pipe using metal chains, straps or mounting rails Observing proper spacing and alignment. Note flow direction and install transducers at either 0 or 45 degrees, whichever would give more stable reading (Figure 2.11, Figure 2.12, Figure 2.13)
- Wait for the module to display "System Normal" before reading. Inspect set-up for any fault and properly reinstall if signal is poor/low (no reading)

Figure 2.10: Applying couplant

Figure 2.11: Clamping the transducers

Figure 2.12: Transducer installation on straight pipe with developed flow

Figure 2.13: Transducer installation on straight pipe with flow turbulence

Step 5: Data gathering

Read and record all necessary data measurement by the equipment, (i.e. flow, fluid velocity, sound velocity, Reynolds number, etc.)

Figure 2.14: UFM Measurement Display

Step 6: Remove transducers and restore paints

Remove the transducers and restore the surface of pipe after measurement.

2.3.1.3 Suction and Discharge Pressure Measurement

The activity measures each pump suction and discharge pressure. The pump efficiency is then calculated using the measured values.

Step 1: Disassembly of existing Pressure Gauge

- Inspect for any leaks or unusual noise before proceeding: If anything is detected, report immediately to the operator;
- Close gate valve located before the pressure gauge and wait for the pressure reading to drop;
- Remove the pressure gauge: (1) Hold the adapter steady with one wrench and the grip the stationary socket of the pressure gauge with another; (2) Loosen the pressure gauge then remove it.

Step 2: Installing the Pressure Gauge

- Prepare the connections: (1) Clean the connections before installing; (2) Put Teflon tape on the pressure connection of the gauge;
- Install the pressure gauge: (1) Mount the pressure gauge on the adapter then hand tighten the arrangement; (2) Further tighten the assembly using a pair of wrenches: hold the adapter steady with one wrench and the grip the stationary socket of the pressure gauge with another; (3) Tighten the assembly;
- Inspect the assembly again.

Step 3: Reading the pressure

- Slowly open the gate valve: Observe any leaks or unusual noise;
- Measurement: (1) Wait until reading is stable; (2) Record the pressure as indicated.

Step 4: Restoring the earlier gauge

- Inspect for any leaks or unusual noise before proceeding: If anything is detected, report immediately to the operator;
- Close gate valve located before the pressure gauge and wait for the pressure reading to drop;
- Remove the pressure gauge: (1) Hold the adapter steady with one wrench and the grip the stationary socket of the pressure gauge with another; (2) Loosen the pressure gauge then remove it;
- Prepare the connections: (1) Clean the connections before installing; (2) Put Teflon tape on the pressure connection of the gauge;
- Install the pressure gauge;
- Mount the pressure gauge on the adapter then hand tighten the arrangement;
- Further tighten the assembly using a pair of wrenches: hold the adapter steady with one wrench and the grip the stationary socket of the pressure gauge with another;
- Tighten the assembly.

2.3.1.4 Parameters

Parameters was recorded using visual inspection form, interview questionnaire, and testing results. Main parameters are listed, but not limited to, in the Table 2.7. Raw data is enclosed in the Appendix.

Table 2.7: Main parameters to be collected.

Parameters	Symbol	Remarks
Pipe thickness Gauge	t	mm
Pump Capacity	Q	Gpm/cmh
Suction Pressure	Ps	mH2O
Discharge Pressure	Pd	mH2O
Vibration Data	-	-
Head	H	mH2O
Efficiency	e	%

2.3.2 Fire protection and safety (FDAS) audit

It was confirmed at site that the FDAS brand is Cooper System (FACP)Firedex 2202. This is a conventional alarm system acting as an early warning system design that could detect a fire occurred within a zone/area. However, its limitation is that it cannot specify exact location of fire. Table 2.8 lists assets of the FDAS.

Table 2.8: Main parameters to be collected.

Assets	Quantity	Unit
Smoke detectors	6	pcs
Call points	2	pcs
Strobe light w/sounder	2	pcs

The Emergency and fire fighting equipment consists of the following :

- Fire extinguishers Dry Chemical (Red color)
- Fire extinguishers HCFC (Green color)
- Emergency lighting
- Exit signages
- Exit Doors
- PPE cabinet
- Fire hose cabinet
- Evacuation plan for every floor

Audit on FDAS has been conducted following sequences

Step 1: Assign (1) one person on the Fire Alarm Control Panel to operate / accept the fire alarm activation and another group/person to conduct spraying on the device, communicate using two way radio.

Step 2: Conduct spray of smoke detector tester (SOLO brand or any) directly on the smoke detector device for not more than 1 sec, repeat action until detector is activated. Note : If detector fails to respond after 3 tries, device will declared faulty (Figure 2.15-a).

Step 3: Hear and visually check strobe light and sounder every time you activated the smoke detectors.

Step 4: Remove device and clean, allow particles to disperse. Then return to socket (Figure 2.15-b).

Step 5: Check that strobe light is functioning/ blinking after returning. Note original status if no light is visible. Check that the control panel breaker feeding the device is reset (Figure 2.15-c).

Step 6: Repeat steps 2, 3, and 4 on different locations until all the devices are tested.

Step 7: Conduct testing for manual call point /manual pull station by pressing the device, hear if the alarm bell / buzzer is activate after you trigger the device (Figure 2.15-d).

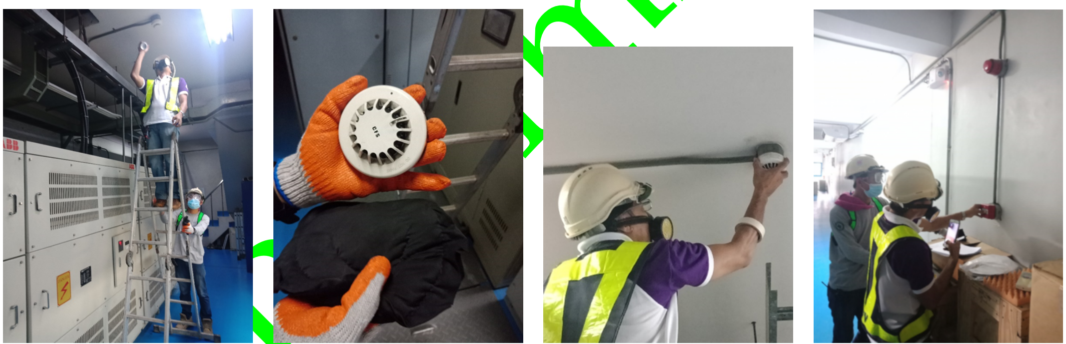
Step 8: Check bells and buzzer audibility.

Step 9: Return Manual Call Point /Manual Pull Station on stand by position. Repeat it on all device.

Step 10: Make a record for the fault device.

Step 11: Record the status of FACP and reset the panel until the fault clear on trouble.

Step 12: Conduct closing of activities to all concerned .



(a) (b) (c) (d)

Figure 2.15: FDAS testing

2.3.3 Vibration and structural assessment

This activity measures the vibrations of the pump and motor at the drive and non-drive ends. The data will be used to address pump vibration problems such as cavitation, pump flow pulsation, bent pump shaft, pump impeller imbalance, shaft misalignment and bearing problems.

Following procedures will be executed

Step 1: Test location identification

Locate the testing points on drive and non-drive ends of pump and motor (Figure 2.16).

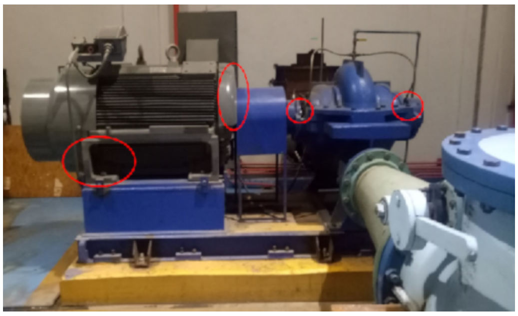


Figure 2.16: Drive and Non-Drive Testing Areas for Vibration

Step 2: Set transducer probe on test point. Observe HIRAC for access to elevated positions

Step 3: Read and record value as indicated on module display

Figure 2.17: Vibration Reading using Analyser (Left – vertical mount, Right – horizontal mount)

2.3.4 Workplace environment management

Maynilad provided WEM service reports for 2015 [2] and 2016 [3]. Tests conducted for WEM are air quality, general ventilation, illumination level, air temperature, percent relative humidity, and noise level. These tests were determined at workplace stations inside the pump station.

Testing results show that the work places were satisfied with air quality criteria as compared to the standard maximum levels of gases and particulates. The standards were met for the other succeeding parameters. The lighting provides adequate illumination above the minimum recommended lighting requirement. The noise as within the pumping house and vicinity are near below the permissible noise level as required by the Occupational Safety and Health Standards of DOLE.

GHD/RBSanchez conducted WEM tests at designated locations (Figure 2.18) to record values of parameters presented in Table 2.9.

Table 2.9: WEM Parameters.

Parameters	Symbol	Units
Dry Bulb Temperature	tdb	oF/oC
Relative Humidity	RH	%
Sound Intensity	-	dB
PM 2.5 Count	PM2.5	ug/m^3
Visible useful light	-	Lux

2.4 Database

GHD developed an MS Access program that functions as a database used to record data collected from visual inspections and testings. The database has been developed using the concept of Relational Database Management System (RDMS), which is a must to record data systematically. The benefits of using the database are

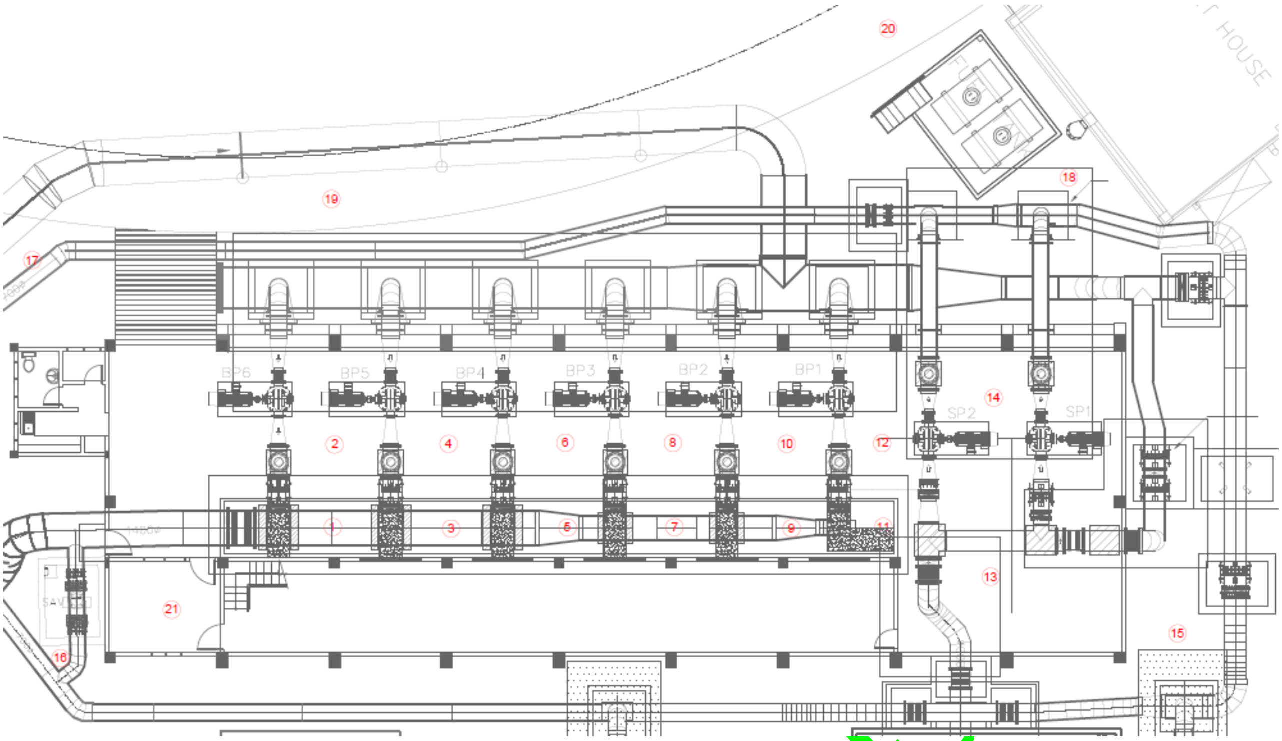


Figure 2.18: Testing locations

- Eliminate redundancy and repeatition of same data
- Eliminate incorrect data entry that is often found when working with excel files
- Provide linkages among asset hierarchy
- Provide ease for programing (e.g. reliability modeling and life cycle cost analysis)
- Support Maynilad AIM team to learn the benefits of using RDMS in developing an integrated Asset Management System for now and future
- Provide compatibility with any CMMS that is often using other RDMS such as Microsoft SQL Server, Oracle SQL server, or MySQL platform
- Provide ease for compilation of desire tables for further analysis using SQL (Structure Query Language)
- Provide ease for importing/exporting to different extension formats (e.g. flat, csv, xlsx)
- Provide a strong background for Maynilad team to migrate recording practices to Web-based that will be part of GHD's recommendation for future usage.

The MS Access database is then migrated into MySQL server, which is far more powerful database system that is used also to migrate, compile, and store all production and power consumption data into a single table. Main reasons behind the development of the MySQL server are for statistical computing with R and for faster compilation of queries.

GHD will provide these two sets of database as part of our deliverable and will provide training for Maynilad team to learn how to use the database in an efficient approach.

Chapter 3

Methodology

3.1 The Integrated Asset Management Approach (IAM)

We proposes an Integrated Asset Management (IAM) approach with its framework shown in Figure 3.1 for executing this project. The IAM approach will eventually be beneficial to Clients as it will lay a foundation to build up a systematic asset management plan for the future.

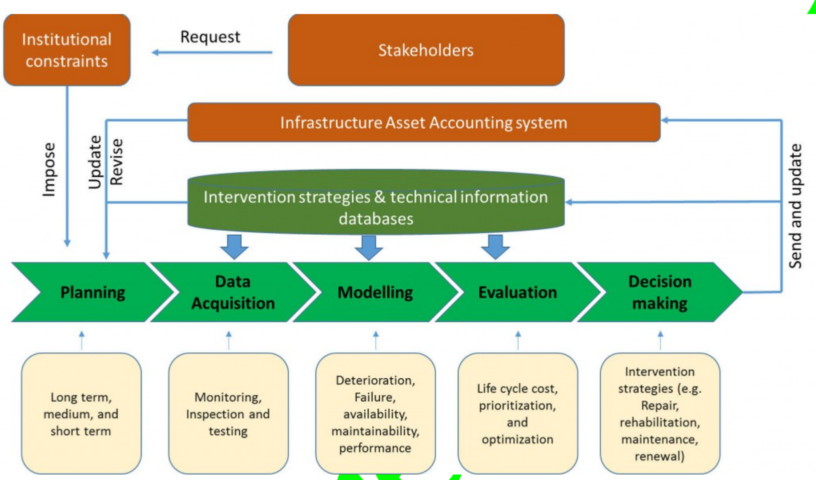


Figure 3.1: Integrated asset management approach (adopted from POM+ http://www.pomplus.vn)

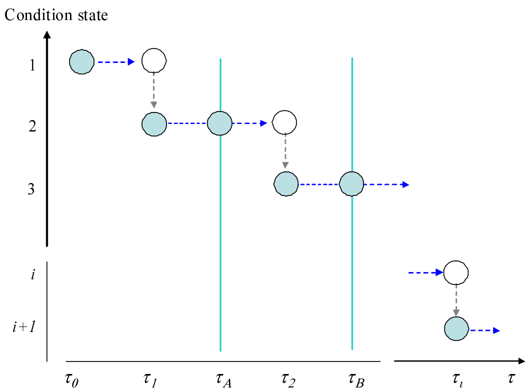
As can be seen in Figure 3.1, we sees the overall picture of works that should be executed in close connection to each other in order to make a full cycle of asset management effectively.

Works associated with auditing equipment and facilities of pump stations and reservoirs, coming up with a preventive maintenance program, tendering, and detailed design can be described explicitly using the framework in Figure 3.1. For example, various type of data concerning physical and operational condition and performance of equipment and facilities will be collected, filtered, and analyzed (Data Acquisition); the data will be further used for modeling purposes (e.g. prediction of failure rate, draw deterioration curve, reliability and efficiency); life cycle cost analysis will be then performed for each equipment and for its system. In this process, either prioritization or optimization technique can be used; finally a set of preventive maintenance intervention strategies will be generated for decision making purposes.

3.2 Deterioration process and rating index

In order to analyze and forecast the deterioration of assets, it is necessary to accumulate time series data on the CS of the assets. The historical deterioration process of an asset is described in Figure 3.2. This figure shows the deterioration progress of a component that has not been repaired. In reality, there exists uncertainty in the deterioration progress of the asset, and moreover, the CS at each point in the time axis is restricted by the time, at which, visual inspection is carried out.

In this figure, τ represents real calendar time (the expression "time" will be used instead throughout this paper). The deterioration of the asset starts immediately after it begins to operate at time τ_0. The CS of an asset is expressed by a rank J representing a state variable i $(i = 1, \cdots, J)$. For a component in the good or new situation, its condition state is given as $i = 1$, and increasing of CS i describes progressing deterioration. A value of $i = J$ indicates that an asset has reached its service limit. In Figure 3.2, for each discrete time τ_i $(i = 1, \cdots, J-1)$ on the time-axis, the corresponding CS has increased from i to $i+1$. Hereinafter τ_i is referred to the time a transition from a CS i to $i+1$ occurs.



Note) In this example, the deterioration process of a infrastructure component if expressed in terms of calendar time $\tau_1, \tau_2, ..., \tau_i$, and condition state of the section is increased in unitary units.

Figure 3.2: Transition Time of Condition State (adopted from [21]).

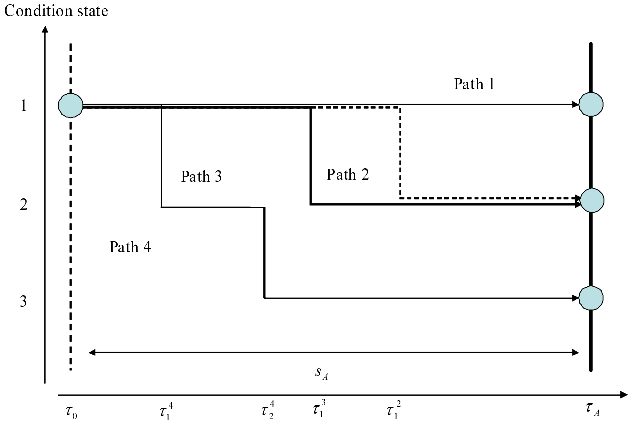
Information regarding the deterioration process of an asset can be acquired through periodical visual inspections. However, information on the CS based on continuous visual inspection is difficult to obtain. In this case, the initial inspections is carried out at times τ_A on the time-axis. It is supposed that at time τ_A the CS observed by inspection is i $(i = 1, \cdots, J-1)$. The deterioration progress in future times is uncertain. Among the infinite set of possible scenarios describing the deterioration process only one path is finally realized.

Figure 3.3 shows four possible sample paths. Path 1 shows no transition in the CS 1 from initial time τ_0 to first inspection time τ_A. In paths 2 and 3, CS has advanced to one upper CS at the calendar times τ_1^2 and τ_1^3 respectively. The CS of these two paths observed at time τ_A become 2. In a periodical inspection scheme, the point times τ_1^2 and τ_1^3 in which the CS has changed from 1 to 2 are not determined. In addition, path 4 shows transitions in the CS at times τ_i^4 and τ_{i+1}^4 during the inspection interval. The CS observed at time τ_A becomes 3. That is, in spite of the transitions in the CS are observable at the time of periodical inspection, it is not possible to obtain information about the times in which those transitions occur.

Figure 3.4 further describes the deterioration process inferring the inspection approach and how the CS is assumed. In this figure, it is assumed that the CS at the calendar time τ_{i-1} has changed from $i-1$ to i. The calendar time τ_{i-1} is assumed to be equivalent to $y_i = 0$. The time represented by the sample time-axis is referred from now on as a "time point", and differs from "time" on the calendar time axis. The times τ_A and τ_B correspond to the time points y_A and y_B on the sample axis. It can be seen that $y_A = \tau_A - \tau_{i-1}$, $y_B = \tau_B - \tau_{i-1}$.

Information on the CS i at the beginning of the calendar time τ_{i-1} cannot be obtained in a periodical inspection scheme. Therefore, time points y_A and y_B on the sample time-axis cannot be correctly obtained either. For convenience of description, it is assumed that the information at the time a point is known in order to develop the model, despite this assumption is not necessarily essential. The following paragraph discusses that even without information at time points y_A and y_B an exponential hazard model can be estimated.

In the case the CS of an asset at time τ_i (time point y_C) is assumed to change from i to $i+1$, the period length in which the CS has remained at i (referred as the life expectancy of a CS i) is represented by $\zeta_i = \tau_i - \tau_{i-1} = y_C$. The life expectancy of a CS i is assumed to be a stochastic

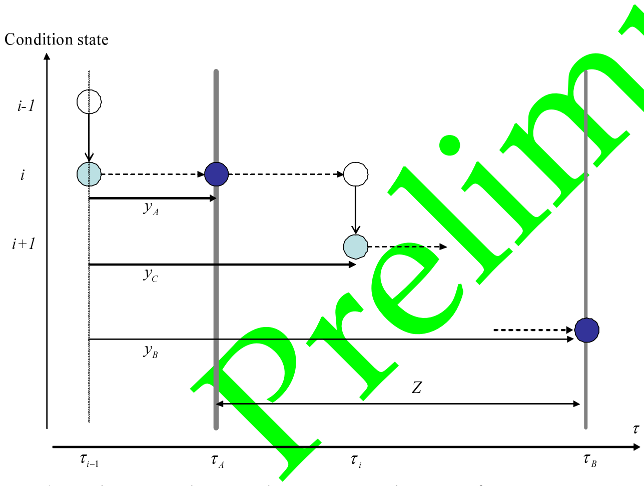


Note) In this example, the deterioration process of an asset is expressed in terms of four different sample paths. In paths 2 and 3 the CS has advanced to one upper CS at the calendar times τ_1^2 and τ_1^3 respectively. In path 4, the CS has increased one state at each time τ_1^4 and τ_2^4. However, in the case of a periodical inspection carried out at times τ_A the CS at any point in time between inspections cannot be observed.

Figure 3.3: Transition Pattern of Condition State.

variable ζ_i with probability density function $f_i(\zeta_i)$ and distribution function $F_i(\zeta_i)$. Random variable ζ_i is defined in the domain $[0, \infty]$. The distribution function is defined as

$$F_i(y_i) = \int_0^{y_i} f_i(\zeta_i) d\zeta_i. \tag{3.1}$$



Note) In the case the condition state changes from $i-1$ to i at the calendar time τ_{i-1} the inspections carried out at times τ_A and τ_B will also correspond to the points in time y_A and y_B when using τ_{i-1} as the time origin. The figure shows a sample deterioration path in which the condition state has advanced in one unit to y_c in the interval time $\tau_{i-1} - y_C$. However, observations at time τ_{i-1} are not possible in a periodical inspection scheme, so there is no way to obtain observation at y_A, y_B and y_C. Nevertheless, it is possible to use the information contained in $z = y_C - y_A \in [0, Z]$.

Figure 3.4: Model of Deterioration Process.

The distribution function $F_i(y_i)$ represents the cumulative probability of the transition in the CS from i to $i+1$. CS i is assumed to be observed at initial time $y_i = 0$(time τ_A). The time interval measured along the sample time-axis until the time point y_i is $\tau_{i-1} + y_i$. Therefore, using the cumulative probability $F_i(y_i)$, the probability $\tilde{F}_i(y_i)$ of a transition in the CS i during the time points interval $y_i = 0$ to $y_i \in [0, \infty]$ is defined by $\tilde{F}_i(y_i)$:

$$\text{Prob}\{\zeta_i \geq y_i\} = \tilde{F}_i(y_i) = 1 - F_i(y_i). \tag{3.2}$$

The conditional probability that the CS of an asset at time y_i advances from i to $i+1$ during the time interval $[y_i, y_i + \Delta y_i]$ is defined as

$$\lambda_i(y_i)\Delta y_i = \frac{f_i(y_i)\Delta y_i}{\tilde{F}_i(y_i)}, \tag{3.3}$$

where the probability density $\lambda_i(y_i)$ is referred as the hazard function.

3.3 Condition State (CS) definition

Condition of an asset can be described either by a range of discrete condition state (CS) or by continuous values of one or more than one parameters such as cracking, thickness, and corrosion. In asset management practice, discrete range of CS is often for the following reasons:

- It can be converted/mapped from continuous value of monitoring data;
- It is convenient for non-technical persons and managers;
- It is suitable for determination of intervention strategy and thus for life cycle cost modeling.

Assets in pump stations are different in category and functionality, thus it is not easy to define a universal range of CSs. However, it is possible that a generic range of CSs can be used to map appropriately different type of assets. In this project, following definitions are used for multiple CSs (Table 3.1) and binary state (Table 3.2) systems.

Table 3.1: Condition state definition - Multiple.

CS i	Definition	Require Intervention	Remarks
1	New/likely new and provide adequate LOS	No	Good (None/Insignificant)
2	Install <=5 years, provide adequate LOS	No	Acceptable (Minor)
3	Moderate aging, not provide adequate LOS, observed moderate breakdown	Yes	Damaged (Significant)
4	Moderate aging, not provide adequate LOS, require frequent CI and PI	Yes	Poor (Extensive)
5	Aging and not provide adequate LOS	Yes	Safety is endangered

Table 3.2: Condition state definition - Binary.

CS i	Definition	Require Intervention	Remarks
0	Not provide adequate LOS	No	
1	Provide adequate LOS	Yes	

3.4 Technical efficiency

Technical efficiency is a coefficient measured as the ratio of actual parameter value and expected/design parameter value. In case of PSs, TE is often discussed around the value of pump efficiency (η), which is a factor that accounts for the kinetic energy lost during the operation [10]. The PE is a product of the followings:

- Hydraulic efficiency (primarily, disk friction against the liquid with impeller shrouds). This efficiency is contributed by the speed and impeller geometry. Shock losses during rapid changes in direction along the impeller and volute can also resulted in additional shock losses;
- Volumetric efficiency (recirculation losses at wear rings, interstage bushes and other);
- Mechanical efficiency (friction at seals or gland packing and bearings)

Hydraulic efficiency and volumetric efficiency are used at the design stage of PS when there is a need to determine suitable pump or group of pumps that satisfies the designed LOS. Whilst, mechanical efficiency is used to determine operational efficiency once pumps are in used.

The mechanical efficiency (η_m) is estimated based on the equation 3.4

$$\eta_p = \frac{P_W}{P_B} \tag{3.4}$$

Where P_W and P_B are water power and brake power, respectively.

Following equations are used to calculated the P_W and P_B:

$$P_{W(kW)} = \gamma \times H \times Q \tag{3.5}$$

$$P_{B(kW)} = P_E \times e_m \tag{3.6}$$

where

P_W	*Water power (kW);*
P_B	*Brake power (kW);*
P_E	*Electric power (kW);*
Q	*Water flow rate (m^3/s);*
H	*Head produced by pump (m_{H_2O});*
η_e	*Motor efficiency (%);*
γ	*specific weight of fluid (water) (kN/m^3).*

3.5 Reliability

3.5.1 Qualitative and Operational Analysis

3.5.1.1 Failure Mode and Effects Analysis (FMEA)

An FMEA is often the first step of a system reliability study. It involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, and their causes and effects. FMEA is an inductive reasoning (forward logic) single point of failure analysis and is a core task in reliability engineering, safety engineering and quality engineering.

A successful FMEA activity helps identify potential failure modes based on experience with similar products and processes—or based on common physics of failure logic. It is widely used in development and manufacturing industries in various phases of the product life cycle.

Functional analyses are needed as an input to determine correct failure modes, at all system levels. The FMEA is in principle a full inductive (forward logic) analysis, however the failure probability can only be estimated or reduced by understanding the failure mechanism. Hence, FMEA may include information on causes of failure (deductive analysis) to reduce the possibility of occurrence by eliminating identified (root) causes.

3.5.1.2 Reliability Centered Maintenance (RCM)

Reliability-centered maintenance (RCM) is a process to ensure that systems continue to do what their user require in their present operating context. It is generally used to achieve improvements in fields such as the establishment of safe minimum levels of maintenance. Successful implementation of RCM will lead to increase in cost effectiveness, reliability, machine uptime, and a greater understanding of the level of risk that the organization is managing. It is defined by the technical standard SAE JA1011, Evaluation Criteria for RCM Processes.

Reliability centered maintenance is an engineering framework that enables the definition of a complete maintenance regimen. It regards maintenance as the means to maintain the functions a user may require of machinery in a defined operating context. As a discipline it enables machinery stakeholders to monitor, assess, predict and generally understand the working of their physical assets. This is embodied in the initial part of the RCM process which is to identify the operating context of the machinery, and write a Failure Mode Effects Analysis (FMEA). The second part of the analysis is to apply the "RCM logic", which helps determine the appropriate maintenance tasks for the identified failure modes in the FMEA. Once the logic is complete for all elements in the FMEA, the resulting list of maintenance is "packaged", so that the periodicities of the tasks are rationalised to be called up in work packages; it is important not to destroy the applicability of maintenance in this phase. Lastly, RCM is kept live throughout the "in-service" life of machinery, where the effectiveness of the maintenance is kept under constant review and adjusted in light of the experience gained.

RCM can be used to create a cost-effective maintenance strategy to address dominant causes of equipment failure. It is a systematic approach to defining a routine maintenance program composed of cost-effective tasks that preserve important functions.

3.5.2 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a logical and graphical method to represent the chain of events leading to failure of system [20, 52]. The method has been used widely for assessment of reliability of industrial and nuclear power plants. It has been proved to be a suitable approach to identify critical assets of a plant that require special attention.

A set of representative FTA graphs for a typical pump station is illustrated in this subsection.

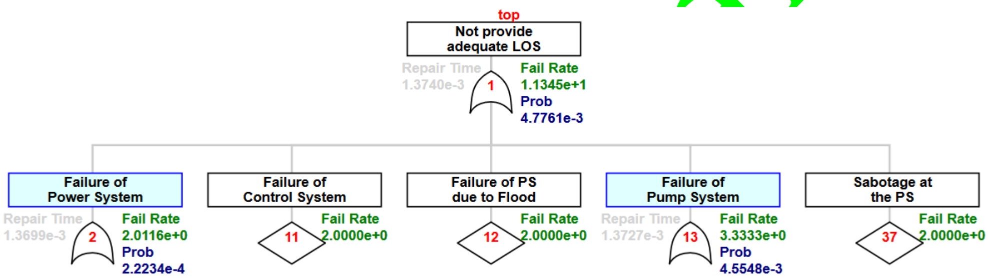


Figure 3.5: Fault Tree - Causes of Failure

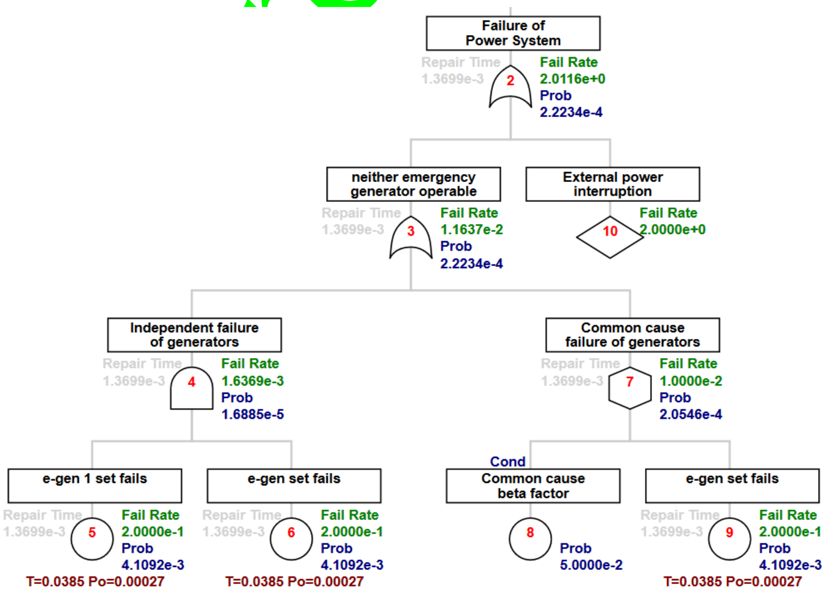


Figure 3.6: Fault Tree - Failure of Power System

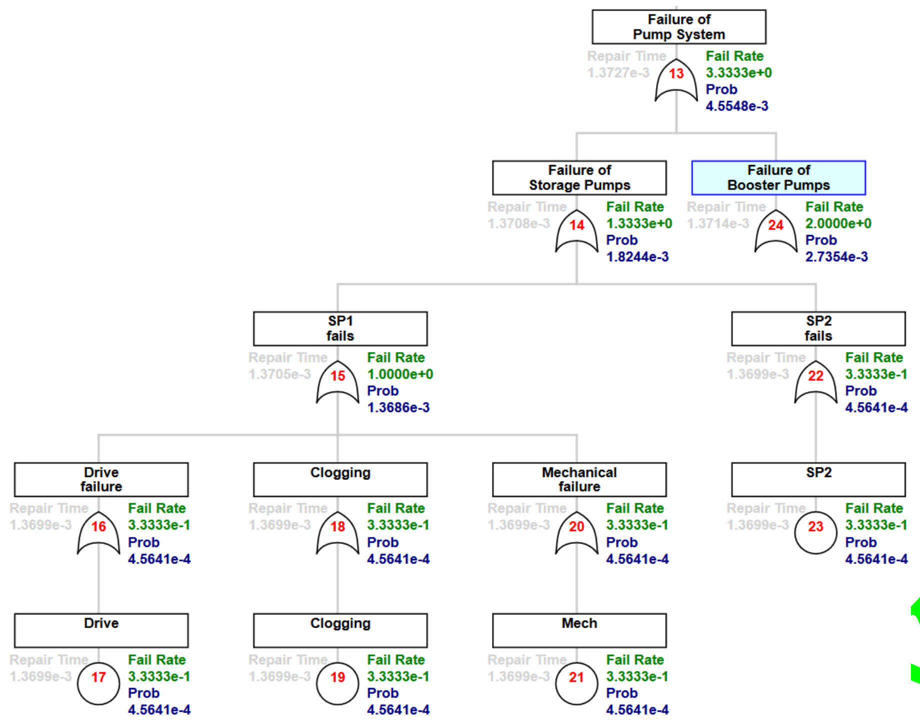


Figure 3.7: Fault Tree - Failure of Pump System

3.5.3 Herz model

Herz model is a semi-probabilistic model that has been used widely in deterioration prediction of water pipe [12, 11, 13]. Following formula describes formula to estimate the proportion or percentage of pipe (y_i) that remain in CS i at time x.

$$y_i(x) = \begin{cases} \frac{a+1}{a+e^{b(x-c)}} & x \geq c \\ 1,0 & \text{Otherwise} \end{cases} \tag{3.7}$$

where

- a *Deterioration factor;*
- b *Transition parameter;*
- c *Resistance period.*

The percentage of CS i remains within a period x is analogy to reliability of the pipe staying in respective CS. The parameters a, b, and c are calibrated based on historical monitoring data. Thus, having historical data is pre-requisite for applying the model.

3.5.4 Weibull model

In hazard analysis, the deterioration of element is subjected to follow a stochastic process [19]. For binary state system, two condition level $0, 1$ are often used. When receiving a PI or CI, the CS from 1 must be changed into 0. In reliability study, this process is often regarded as renewal process. The renewal is carried out at alternative time t_k $(k = 0, 1, 2, ...)$. In this way, the next renewal time is denoted as $t = t_0 + \tau$, where τ indicating the elapsed time. The life span of an asset is expressed by a random variable ζ. The probability distribution and probability density function of the failure occurrence are $F(\zeta)$ and $f(\zeta)$ respectively. The domain of the random variable ζ is $[0, \infty]$. The living probability (hereafter named as survival probability) expressed by survival function $\tilde{F}(\tau)$ can be defined according to the value of failure probability $F(\tau)$ in the following equation:

$$\tilde{F}(\tau) = 1 - F(\tau). \tag{3.8}$$

The probability, at which the asset performs in good shape until time τ and break down for the first time during an interval of $\tau + \Delta\tau$ can be regarded as hazard rate and expressed in the following equation:

$$\lambda_i(\tau)\Delta\tau = \frac{f(\tau)\Delta\tau}{\tilde{F}(\tau)}, \tag{3.9}$$

where $\lambda(\tau)$ is the hazard function of the asset. In reality, the breakdown probability depends largely on the elapsed time of the asset since its beginning of operation. Thus, the hazard function should take into account the working duration of the asset (time-dependent). In another word, the memory of the system should be inherited. Weibull hazard function is satisfied in addressing the deterioration process [4, 17]:

$$\lambda(\tau) = \alpha m \tau^{m-1}, \tag{3.10}$$

where α is the parameter expressing the arrival density of the asset, and m is the acceleration or shape parameter. The probability density function $f(\tau)$ and survival function $\tilde{F}(\tau)$ in the form of Weibull hazard function can be further expressed in equation (3.11) and (3.12):

$$f(\tau) = \alpha m \tau^{m-1} \exp(-\alpha\tau^m), \tag{3.11}$$
$$\tilde{F}(\tau) = \exp(-\alpha\tau^m). \tag{3.12}$$

Estimation for Weibull's parameter is often with Maximum Likelihood Estimation (MLE) approach on historical data. Thus, the model's parameter is sensitive to how data behaves. We recommend to use this model only when there is sufficient data to be used.

An example of source code for education purpose is given in Github site of Nam Le [1]. The complete program is a copyright of Nam Le.

3.5.5 Markov model

The transition process among the condition states of an infrastructure component is uncertain. Therefore, future condition states cannot be forecasted deterministically. In this situation, Markov transition probability is employed to represent the uncertain transition pattern of the condition states during two time points. Markov transition probabilities can be defined for arbitrary time intervals.

For simplification, Markov transition probabilities can be defined and used to forecast the deterioration of a infrastructure component based on the information from periodical inspection scheme shown in Figure 3.4. The observed condition state of the component at time τ_A is expressed by using the state variable $h(\tau_A)$. If the condition state observed at time τ_A is i, then the state variable $h(\tau_A) = i$. A Markov transition probability, given a condition state $h(\tau_A) = i$ observed at time τ_A, defines the probability that the condition state at a future time (τ_B for example) will change to $h(\tau_B) = j$:

$$\text{Prob}[h(\tau_B) = j | h(\tau_A) = i] = \pi_{ij}. \tag{3.13}$$

The Markov transition probability matrix can be defined and rearranged by using the transition probabilities between each pair of condition states (i, j) as

$$\mathbf{\Pi} = \begin{pmatrix} \pi_{11} & \cdots & \pi_{1J} \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \pi_{JJ} \end{pmatrix}. \tag{3.14}$$

The Markov transition probability (3.13) shows the transition probability between the condition states at two given times τ_A and τ_B, therefore, it is straightforward that the values of a transition

[1] https://github.com/namkyodai/Models

probability will differ for different time intervals. Since deterioration continues as long as no repair is carried out $\pi_{ij} = 0$ $(i > j)$. From the definition of transition probability $\sum_{j=1}^{J} \pi_{ij} = 1$. Following conditions must be satisfied:

$$\left.\begin{array}{l} \pi_{ij} \geq 0 \\ \pi_{ij} = 0 \quad (\text{when} \quad i > j) \\ \sum_{j=1}^{J} \pi_{ij} = 1 \end{array}\right\}. \tag{3.15}$$

The worse level of deterioration is expressed by the condition state J, which remains as an absorbing state in the Markov chain as long as no repair is carried out. In this case $\pi_{JJ} = 1$.

Markov transition probabilities are defined independently from the deterioration history. As shown in Figure 3.4, the condition state at the inspection time τ_A is i, however, the time, at which, condition state changed from $i-1$ to i is unobservable. In a Markov chain model, it is assumed that the transition probability between the inspection times τ_A and τ_B is only dependent on the condition state at time τ_A.

The Markov chain model is operative and widely applied in management of infrastructure system. Particularly, at management of network level, Markov chain model is used to define the average transition probability of the entire system, or a group of infrastructure components given two periodical inspection data.

Estimation for the Markov transition probability can be done by the MLE approach [19, 21] or Bayesian Estimation approach [14, 16] based on historical data. One advance of using the Markov model is that one time monitoring data can be used. A generic formula to estimate the transition probability is given in following Equations:

$$\pi_{ii} = \exp(-\theta_i Z), \tag{3.16-a}$$

$$\pi_{ii+1} = \frac{\theta_i}{\theta_i - \theta_{i+1}}\{-\exp(-\theta_i Z) + \exp(-\theta_{i+1} Z)\}, \tag{3.16-b}$$

$$\pi_{ij} = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} \exp(-\theta_k Z), \tag{3.16-c}$$

$$\pi_{iJ} = 1 - \sum_{j=i}^{J-1} \pi_{ij}, \tag{3.16-d}$$

$$(i = 1, \cdots, J-1) \qquad (j = i, \cdots, J).$$

An example of source code for education purpose is given in Github site of Nam Le [2]. The complete program is a copyright of Nam Le.

3.6 Intervention Strategy (IS)

Intervention Strategy (IS) is at asset level (level 7). It is a collection of intervention type for component level (level 8). A collection of ISs will form an Intervention Program for (IP) the station. A collection of IPs will form a Work Program (WP) for network level intervention (e.g. a bid awarded for a designer/contractor can be a WP that consists of intervention program for one or more than one pump stations). Following generic IS is defined to guide the selection of IPs that will be details in the later part of the report.

For each type of asset, IS will be selected based on reliability study and consideration of cost. Further more, Employers inputs and requirements are also taken into account.

3.7 Determination of optimal intervention strategy

Following subsections briefly describe the model that can be used to determine optimal intervention strategy.

[2]https://github.com/namkyodai/Models

Table 3.3: Generic intervention strategy (IS).

IS	Definition	Remarks
1	Do Nothing	
2	Minor repair	Require minimal effort and can be done only for certain asset type
3	Major repair	Require extensive efforts to return the asset to likely new condition
4	Replacement/Renewal	Replacing assets or components of asset with identical one or with new model

3.7.1 Block Replacement Model

It is assumed that a PI is executed after a pre-defined time $n \cdot T$ $(n = 0, 1, 2, \cdots, N)$. Once the PI is executed, the functionality and serviceability of the asset could be the same or different from that of the asset before the intervention. In between the time Δt ($[0 \leq \Delta t \leq T]$), hazards could occur and cause the asset in worse CSs (hereafter denoted as i $(i = 1, \cdots, I)$), in which the asset is no longer providing an adequate level of services (LOS). In both cases, when the PI or CI is executed, there are impacts incurred by stakeholders s (e.g. the owner, the users, the public).

Following notations are used to describe the formulation of the model.

$\theta(\Delta t \mid t)$	Conditional failure rate i $(i = 1, \cdots, I)$ when the asset has been in service in an interval t after the PI
$\Psi(\cdot \mid t)$	Any conditional function Ψ given that a PI is executed by a unit of age t, where t is a random variable
$F(t)$	Cumulative distribution function (cdf) of age t of a unit for a PI at execution time
$w_p^s(t)$	Impacts incurred by stakeholder s due to the execution of PI
$w_c^s(t)$	Impacts incurred by stakeholder s due to the execution of CI
$w_o^s(\Delta t \mid t)$	Conditional impacts incurred by stakeholder s when the structure is remains in normal operation (*i.e.* providing an adequate LOS) during time interval Δt after a PI has been carried out and the asset has not entered failure state
ρ	discount factor
$p_l^k(t)$	probability of failure at time t of the affecting other assets k
$C_c^{s,k}$	Impacts incurred by stakeholder s due to the execution of an CI on other assets k
T	interval between the PIs
$T^\star$	Optimal interval time between PIs, which is the variable of the model
$\Omega_p(T, t)$	minimum expected total discounted impact for an infinite time span when the asset has been in service during an interval t after the execution of the PI and the asset has not entered failure state
$\Omega_c(T, t)$	minimum expected total discounted impact for an infinite time span when a CI has been executed, of the asset that has been in service during a time interval t after the execution of the PI and the asset has entered failure state

In the model, it is assumed that at each damage level i, there exists a corresponding well defined CI. Within an increment of time Δt, after the asset has been under the PI after time t, the total expected impacts due to the execution of CIs are:

$$v_c(\Delta t \mid t) = \sum_{s=1}^{S} \left[w_c^s(\Delta t) + \sum_{k=1}^{K} p_l^k \cdot C_c^{s,k} \right] \cdot \theta(\Delta t \mid t). \tag{3.17}$$

The total impacts due to the execution of PIs and the total impacts incurred by stakeholders during the service time of the asset are defined in Eq. (3.18) and Eq. (3.19), respectively.

$$v_p(t) = \sum_{s=1}^{S} w_p^s(t). \tag{3.18}$$

$$v_o(t) = \sum_{s=1}^{S} w_o^s(t). \tag{3.19}$$

According to the principle of optimality, which is described in [1, p. 15], the minimum expected total discounted impact $\Omega_c(T,t)$ for infinite time is formulated in following equation.

$$\Omega_c(T,t) = \int_0^\infty \left[v_c(\Delta t|t) + \Omega_p(T,\Delta t|t)\right] dF(t). \tag{3.20}$$

The minimum expected total discounted impact $\Omega_p(T,\Delta t|t)$, which appears inside Eq. (3.17), is obtained as follows

$$\Omega_p(T,\Delta t) = min\Gamma(\Delta t). \tag{3.21}$$

where $\Gamma(\Delta t)$ is defined as

$$\begin{aligned}\Gamma(\Delta t) = \int_0^\infty \Bigg[v_o \int_0^{dt} exp(-\rho\tau)d\tau + \{1-\theta(\Delta t|t)dt\} \cdot \Omega_p(T,\Delta t + dt|t) exp(-\rho dt) \\ +\theta(\Delta t|t)dt \cdot \Omega_c(T,\Delta t+dt|t)exp(-\rho dt) \Bigg] dF(t).\end{aligned} \tag{3.22}$$

According to [15], Eq. (3.22) is rewritten in following form

$$\begin{aligned}\Gamma(\Delta t) = \Omega_p(T,\Delta t) + \left[-\rho\Omega_p(T,\Delta t) + d\Omega_p(T,\Delta t)/dt\right] dt \\ + \int_0^\infty \left[v_o + v_c(\Delta t|t)\right] dF(t)dt.\end{aligned} \tag{3.23}$$

Thus, from $\Omega_p(T,\Delta t) = \Gamma(\Delta t)$ (Eq. (3.21)), the following equation can be derived:

$$\Omega_p(T,\Delta t) = exp(\rho\Delta t)\left[\Omega_p(T,0) - \int_0^\infty \int_0^t exp(-\rho\tau)\{v_o + v_c(\tau|t)\}\right] d\tau dF(t). \tag{3.24}$$

where,

$$\begin{aligned}\Omega_p(T,0) = \{1-exp(-\rho T)\}^{-1} \int_0^\infty \Bigg[exp(-\rho T)\{v_p(T,t)\} \\ + \int_0^T exp(-\rho\Delta t)\{v_o(\Delta t|t) + v_c(\Delta t|t)\} dt \Bigg] dF(t).\end{aligned} \tag{3.25}$$

when T tends to infinity $T \to \infty$, Eq. (3.25) becomes

$$\Omega_p(\infty,0) = \int_0^\infty \int_0^\infty exp(-\rho t)\left[v_o + v_c(\Delta t|t)\right] dt dF(t). \tag{3.26}$$

Eqs. (3.25) and (3.26) are the explicit forms of the expected total discounted impact in infinite time horizon. This is the classical optimization problem. By differentiating the expected total discounted impact $\Omega_p(T,0)$ and $\Omega_p(\infty,0)$ and setting it equal to zero, the optimal time $T^\star$ can be obtained. The optimal time $T^\star$ for PI is the solution of the following system of equations:

$$\begin{cases} T^\star = \arg \min\limits_{T^\star \in [0,T]} \Theta_p(T,0) \\ T^\star = \arg \min\limits_{T^\star \in [0,\infty]} \Theta_p(\infty,0) \end{cases} \tag{3.27}$$

in which the differentiates of $\Theta_p(T,0)$ and $\Theta_p(\infty,0)$ are respectively:

$$\begin{aligned}\Theta_p(T,0) &= \frac{\delta(\Omega_p(T,0))}{\delta T} \\ &= [1-exp(-\rho T)] \int_0^\infty \Bigg[-\rho v_p(T,t) \\ &\quad +d(v_p(T,t))/dT + v_o(T,t) + v_p(T,t) \Bigg] dF(t) \\ &\quad -\rho \int_0^\infty \Bigg[exp(-\rho T)\{v_p(T,t)\} \\ &\quad + \int_0^T exp(-\rho\Delta t)\{v_o(\Delta t|t) + v_c(\Delta t|t)\} dt \Bigg] dF(t).\end{aligned} \tag{3.28}$$

and

$$\Theta_p(\infty,0) = \frac{\delta(\Omega_p(\infty,0))}{\delta T}$$
$$= \int_0^\infty \left[-\rho \left\{ v_p(\infty|t) + \int_0^\infty exp(-\rho t) \left\{ v_o(\Delta t|t) + v_p(\Delta t|t) \right\} \right\} \right.$$
$$\left. + \lim_{T\to\infty} d(v_p(T,t))/dT + v_o(\infty|t) + v_p(\infty|t) \right] dF(t) \tag{3.29}$$

3.7.2 Time-dependent replacement model

Time-dependent replacement model (or Age replacement model) are the ones where the following conditions apply:

- the asset starts operating at $t = 0$, i.e. it is newly built or newly restored to a like new condition following an intervention;
- the probability of failure is described with $f(t)$ and $F(t)$, i.e. the lifetime density and the lifetime;
- if the asset fails on the interval $(0, T]$ a CI is executed;
- if the object does not fail on the interval $(0, T]$ the object is replaced at T, i.e. the PI replacement is executed, regardless if the object has failed and been restored in the time interval $(0, T]$;
- the execution of a PI restores the object to a like new condition;
- the execution of a CI restores the object to a like new condition.

3.7.2.1 Minimize impact

If an age replacement IS is followed the time to the first intervention, Z, is the minimum amount of the time to failure of the length of the renewal period:

$$Z = min(\tau, T) \tag{3.30}$$

The expected, or mean, time to the first intervention is then determined by

$$E[Z = \int_0^T (1 - F(x))dx] \tag{3.31}$$

The mean impact in one renewal period then equals the probability of failure on T multiplied by the impacts associated with the CI plus the probability that no failure occurs on T multiplied by the impacts associated with the PI:

$$F(T) \times I^{CI} + (1 - F(T)) \times I^{PI} \tag{3.32}$$

The mean impacts per unit time, therefore, equal the mean cost in one renewal period divided by the length of the renewal period, i.e. the time to the first intervention.

$$\eta_{AC} = \frac{F(T) \times I^{CI} + (1 - F(T)) \times I^{PI}}{\int_0^T (1 - F(x))dx]} \tag{3.33}$$

3.7.2.2 Maximize availability

If it is desired to determine the age replacement IS that maximizes availability the following is often assumed, additionally that:

- the PI replacement takes t^{PI};
- the PI takes t^{CI};

If the asset fails before T then the length of the renewal period will, therefore, be $X = t + t^{CI}$, which has the probability $f(t)dt$ of occurring, and if the object does not fail before T then the length of the renewal period will be $X = t + t^{PI}$, which has the probability $1 - F(T)$ of occurring.

In this case, the expected, or mean, renewal period length is:

$$E[X] = \int_0^T (1 - F(x))dx + t^{CI}F(T) + t^{PI}(1 - F(T)) \tag{3.34}$$

As the asset is operational on average $\int_0^T (1 - F(x))dx$ then the availability is given by:

$$\eta_{AA} = \frac{\int_0^T (1 - F(x))dx}{\int_0^T (1 - F(x))dx + t^{CI}F(T) + t^{PI}(1 - F(T))} \tag{3.35}$$

3.8 Return on Investment (ROI)

Return on Investment (ROI) is a simple way to determine if the investment is worth to be executed. The ROI is defined using the ratio between the Net Profit and the Total Investment.

$$ROI = \frac{\text{Net Profit}}{\text{Total Investment}} \times 100 \tag{3.36}$$

The Total Investment is referred as CAPEX or ballpark estimate, which can be spent when the IS is executed. In this case, we can assume that the IS will be executed at time 0. This does not mean that the execution falls exactly this year but can be in any year within the planning horizon (e.g. 5 years).

Net Profit is calculated based on Cash Flow Analysis (CFA) that will incorporate the yearly production and resource consumption of the PS (e.g. power, lubricant, chemical). The conventional CFA is done with Net Present Value (NPV)

$$NPV = \sum_{t=0}^{T} [B(t) - C(t)] \times \frac{1}{(1 + \rho^t)} \tag{3.37}$$

Where $B(t)$ and $C(t)$ are benefit and cost, respectively. The benefit can be a sum of revenue, profit, and added value for stakeholers, whilst the cost is a sum of CAPEX, operational cost, and other impacts incurred to stakeholders that can be quantified as monetary units.

We suggests the WSPs to consider the 3Rs in applying the above formulas. The 3Rs are revenue, reputation, and regulatory. Revenue can be conveniently estimated. However, reputation and regulatory are hard to quantify.

Chapter 4

Data and Analysis

4.1 Qualitative and Operational Analysis

4.1.1 Facts and Data

Summary of facts and data concerning operational and overall plan reliability is presented in this subsection.

4.1.1.1 Normal Operation Scenario

- 6 booster pumps are available but only 5 are in operation. The booster pumps deliver to the Cavite side of the distribution system including parts of Pasay. Distribution pipe size is 1400mm.
- A separate system for the Reclamation Area is supplied by the storage pumps. The line size is 700mm. Only one storage pump is required for the Reclamation Area distribution system. The other pump serves as standby.
- At 10pm-12mn, the MOV to the Reclamation Area distribution system is closed and the 2 storage pumps are used to refill the 2 storage tanks. During this period, the individual consumers are using their own stored water supply for internal use. Normal operations resumes at 12mn.

4.1.1.2 High Demand Scenario

- all 6 booster pumps are in operation

4.1.1.3 Low Demand Scenario

- only 5 booster pumps are running

4.1.1.4 Spares Policy

- The booster pumps do not have a spare during high demand scenario. If 1 pump will be under maintenance during this period, there will be a drop in pressure and some of the consumers in the outermost section of the distribution system will experience low pressure or will not get any water.
- The storage pumps also do not have a spare during the refilling phase. If a failure of one of the storage pumps occurs, the refilling duration will be much longer to complete.

4.1.1.5 Emergency Situation (loss of electrical power from Meralco)

- Immediately after the power is cut, one of the 2 gensets automatically start and makes electric power available for the booster and/or supply pumps. The operator resets all the pumps before restarting each manually. This may take between 60 seconds to 5 minutes before all the pumps provide enough pressure/flow to the system.

4.1.1.6 Maintenance

- There is no structured maintenance program in the facilities. The operator makes rounds of the pumps and if something unusual is observed, a text or email is sent to the Control Center for scheduling of maintenance check and repairs.
- There is also a maintenance team visiting the site regularly with specific lists of tasks and responsibilities.

4.1.1.7 Others

- Water Leakages are found in the engineering room during rains.

4.1.2 Recommendations

In order to ensure the PS to provide adequate level of services around the clock, it is important to establish a good operational scheme that allows optimization of utilization of pumps to reduce breakdown and conserve energy. A summary of major recommendations to be considered are

- Adding an additional booster pump to improve the overall reliability, particularly for the major distribution line (1’400mm). This additional pump will allows switching of pump usage, for instance, with one pump undergoing major repairs, the arrangement will not allow for another pump to fail, otherwise, there will be a major in pressure with only 5 booster pumps running during peak demands;
- Adding an additional storage pump to increase the reliability of the reclamation area distribution system (700 mm line);
- Establish a scheme to consider a dedicated duty and a dedicated spare set-up for the pumps. If this is not acceptable, then consider doing a much longer switch of the storage pumps. Currently, it is being switched daily to supply 700mm distribution system. This allows for almost an equal rate of deterioration between the two pumps and if one pump fails due to age-related component failure, the other one is close to a similar failure which may occur before the first pump is fully repaired. It is suggested that the switch happen once a month or even every 3 months;
- In place of the longer switching cycle (e.g. every 3 months), there should be a corresponding maintenance program for the standby pump for both booster and storage;
- Develop a more structured discipline in applying routine maintenance work process to ensure that maintenance tasks are given the proper priority in terms of mitigation measures and avoid unplanned shutdown of critical pumps in operation.

Aside from the above recommendations, we also generate a list of recommendations based on the RCM methodology. The list shall be considered as a living program, which requires continuously improvement as part of the total quality management system (refer to Deming cycle presented in GHD’s technical proposal).

4.2 Pump discharge and suction pipe - thickness

4.2.1 Data and measurement

Thickness data on discharge and suction pipes of pumps is presented in Table 4.1 and Table 4.2 .

In the table, the positions and the distances for the Ultrasonic Thickness Gauging (UTG) are referred to Figure 4.1 and Figure 4.2.

Table 4.1: Thickness data - Booster Pumps (mm).

Asset	Position	Distance						
		Suction				Discharge		
		2.5m	3.5m	4.5m	Elbow	4m	5m	Elbow
BP1	12	4.68	4.68	4.66	4.59	4.60	4.63	3.94
	3	4.62	4.75	4.79	4.48	4.69	4.67	3.92
	6	4.69	4.74	4.69	4.63	4.73	4.60	4.64
	9	4.71	4.74	4.71	-	4.71	4.72	-
BP2	12	4.68	4.41	4.69	4.66	4.73	4.92	4.93
	3	4.76	4.67	4.80	4.32	4.91	4.22	4.98
	6	4.69	4.46	4.76	4.69	4.70	4.94	4.62
	9	4.65	4.78	4.69	-	4.88	4.90	-
BP3	12	4.61	4.67	4.65	4.69	4.71	4.69	4.62
	3	4.66	4.69	4.75	4.72	4.76	4.79	4.73
	6	4.68	4.63	4.66	4.67	4.68	4.70	4.61
	9	4.65	4.69	4.64	-	4.67	4.74	-
BP4	12	4.63	4.77	4.75	4.67	4.91	4.98	4.37
	3	4.65	4.75	4.70	4.69	4.90	4.92	4.97
	6	4.75	4.54	4.71	4.83	4.93	4.95	4.75
	9	4.62	4.67	4.58	-	4.98	4.92	-
BP5	12	4.80	4.69	4.49	4.73	4.72	4.68	4.76
	3	4.71	4.56	4.71	4.67	4.86	4.65	4.76
	6	4.75	4.75	4.60	4.67	4.75	4.64	4.86
	9	4.66	4.65	4.67	-	4.67	4.74	-
BP6	12	4.64	4.66	4.77	4.09	4.95	4.96	4.92
	3	4.65	4.74	4.72	4.46	4.93	4.87	4.98
	6	4.66	4.77	4.71	4.69	4.86	4.88	4.60
	9	4.75	4.63	4.70	-	4.81	4.79	-

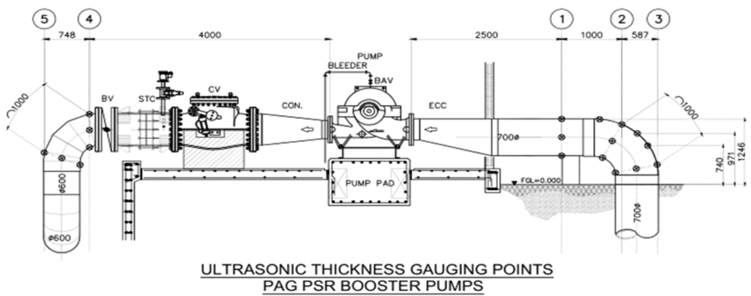


Figure 4.1: Positions and distances of UTG - Booster Pump

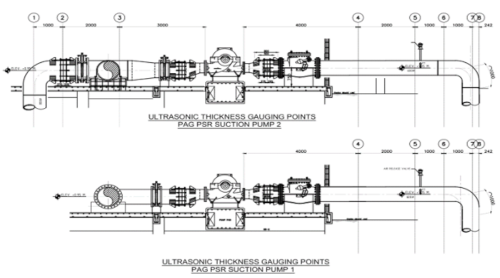


Figure 4.2: Positions and distances of UTG - Storage Pump

4.2.2 Analysis

This section provides analysis/discussion on estimation of minimum allowable thickness of pipes and statistics around the measured data collected during inspection and testings.

Table 4.2: Thickness data - Storage Pumps (mm).

Asset	Position	Distance								
		Suction				Discharge				
		3m	5m	6m	Elbow	4m	6m	8m	9m	Elbow
SP1	12				4.84	4.78	4.76	4.74	4.77	4.61
	3				4.54	4.61	4.78	4.64	4.72	4.77
	6				4.4	4.25	4.81	4.8	4.64	4.66
	9					4.73	4.88	4.65	4.72	-
SP2	12	5.4	5.11	5.35	5.43	4.6	4.75	4.97	4.74	4.91
	3	5.28	5.12	5.3	5.41	4.62	4.78	4.78	4.66	4.64
	6	-	5.09	5.45	5.4	4.43	4.18	4.73	4.75	4.51
	9	-	5.2	5.22	-	4.4	4.75	4.45	4.58	-

4.2.2.1 Statistics

A summary on statistics regarding the measured thickness for booster pumps and storage pumps is presented in Table 4.3.

Table 4.3: Summary of statistics - thickness.

Statistics	Booster suction		Booster discharge		Storage suction		Storage discharge	
	Straight	Elbow	Straight	Elbow	Straight	Elbow	Straight	Elbow
Min	4.410	4.090	4.220	3.920	5.090	4.400	4.180	4.510
1st Qua.	4.650	4.600	4.690	4.612	5.140	4.615	4.617	4.617
Median	4.690	4.670	4.755	4.740	5.250	5.120	4.730	4.650
Mean	4.681	4.608	4.782	4.664	5.252	5.003	4.670	4.683
3rd Qua.	4.740	4.690	4.910	4.905	5.338	5.407	4.772	4.742
Max	4.800	4.830	4.980	4.980	5.450	5.430	4.970	4.910

Table 4.4 shows the summary of statistics for individual pump with extrados thickness calculated.

Table 4.4: Summary of statistics - thickness (individual pump).

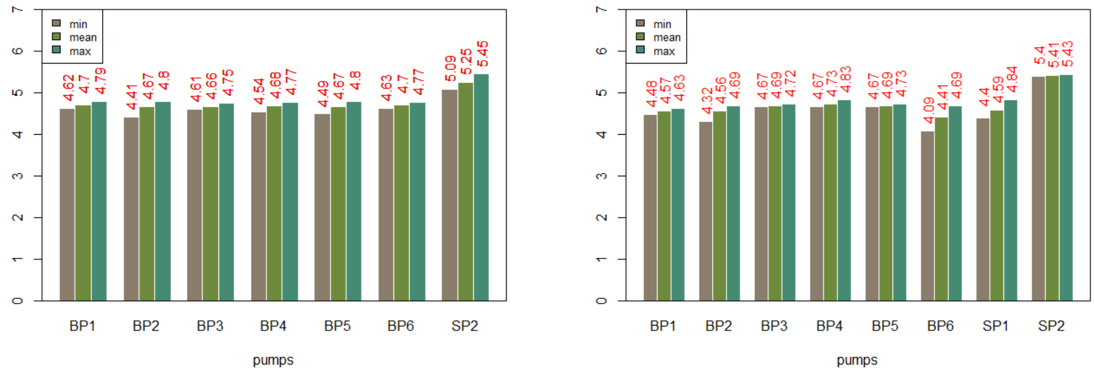
Assets	Suction (mm)				Discharge (mm)			
	Min	Mean	Extrados	Max	Min	Mean	Extrados	Max
BP1	4.480	4.677	4.608	4.790	3.920	4.532	4.346	4.730
BP2	4.320	4.647	4.554	4.800	4.220	4.794	4.836	4.980
BP3	4.610	4.671	4.680	4.750	4.610	4.700	4.672	4.790
BP4	4.540	4.742	4.742	4.830	4.370	4.871	4.796	4.980
BP5	4.490	4.650	4.674	4.800	4.640	4.735	4.756	4.860
BP6	4.090	4.534	4.643	4.770	4.600	4.868	4.882	4.980
SP1	4.400	4.593	4.593	4.840	4.250	4.701	4.710	4.880
SP2	5.090	5.289	5.398	5.450	4.180	4.644	4.754	4.970

Figures 4.3 and 4.4 show comparative graphs of min, mean, and max values of thickness. Followings are generic interpretation by examining the tables and graphs

- Mean value of thickness is above 4.6 mm;
- Mean and median values are close, inferring a confidence on having less heterogeneity, i.e. distribution of thickness around the pipe is more or less homogeneous;
- Thickness at elbow is less than that of the straight line;
- THickness of storage line is likely to be higher than that of the discharge line;
- BP1 has a value of 3.92 as min at the elbow, which requires attention from time to time.

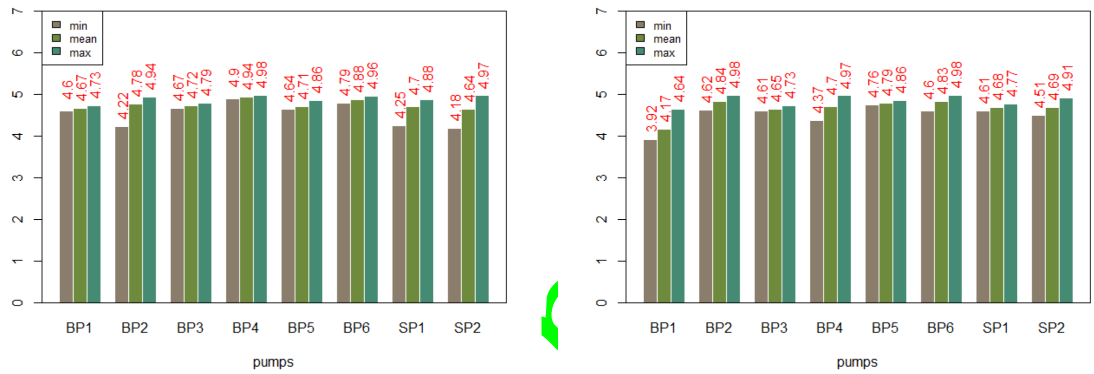
<u>BP1</u>

- Suction Piping System - The extrados thickness is less than the remaining thickness values measured.



a - Straight b - Elbow

Figure 4.3: Suction line



a - Straight b - Elbow

Figure 4.4: Discharge line

- Discharge Piping System - The average extrados thickness is 4.346 mm, with a minimum of 3.94 at the entry area to the center of the extrados. Localized thinning is observed to be higher at the upper half of the discharge line (as seen in 4m mark, 12-3-9 o'clock position). Then extends to the elbow entry up to the center of extrados. This may be caused by possible cavitation carried over from the pump to the discharge side and then amplified by the backflows in the elbow.

<u>BP2</u>

- Suction Piping System - The extrados thickness is less than the remaining thickness values measured. The 6-o'clock value at 3.5 meter is the backflow/eddie zone of the elbow, thus assuming to have high backflow rate in the suction.
- Discharge Piping System - The flow from the pump enters the elbow at the lower half (6 o'clock of 4m mark) and swirls to the 3 o'clock position reference to the pump flange. It continued swirling to the sides and the exit extrados of the elbow. This is caused by the disturbance caused by the fittings in between.

<u>BP3</u>

- Suction Piping System - The extrados thickness is approximately equal to all measured thickness. Also, it is seen in the 6-o'clock of 3.5 and 4.5m mark that it is slightly thinner that of its 12-o'clock positions. This may indicate a high backflow of water thus creating higher turbulency as a result. The high turbulency of water causes the coverage of the localized thinning larger extending up to the 2.5m mark from the pump flange.

- Discharge Piping System - The flow enters the lower half of the intrados entry. The flow then continued at the extrados area with a considerate backflow at the intrados. The average extrados thickness indicates also that the extrados is thinner when compared to the rest of the elbow thickness.

BP4

- Suction Piping System - The extrados thickness is slightly higher to all measured thickness. This indicates the flow of water in this pipe enters the elbow at between 9-o'clock position and 12-o'clock position with high backflow rate and eddies forming at the intrados area (6-o'clock of elbows). This pattern creates a swirling turbulent flow that results to larger localized wall thinning coverage extending to the upper portion of the pipe.
- Discharge Piping System - The data indicates that the flow through the elbow based on thinning is that the flow enters the elbow entry and extending to the intrados area of the elbow, with small backflow rate (as seen in 3-6-9 o'clock position at 5m mark). It is then flows through the extrados exit again resulting to thinning with 4.75 mm thickness measured.

BP5

- Suction Piping System - The extrados thickness is less than the remaining thickness values measured. The 3-o'clock thinning at 3.5m mark may indicate that the water flows from extrados to the sides, that causes water swirling entering the diffusers and pumps.
- Discharge Piping System - The elbow middle extrados is where the localized thinning area occur at this pipe section. However, the average extrados thickness is almost the same compared to the rest of pipe measurements.

BP6

- Suction Piping System - The extrados thickness is less than the remaining thickness values measured. The 4.09 mm thickness reading may indicate that the water flows faster in the upper section of the elbow exit and partially swirls extending to the 2.5m mark, thus having a uniform localized wall thinning at the right-half of the straight pipe.
- Discharge Piping System - The thinnest part of the discharge pipeline is at the exit elbow extrados. However, the thickness is not critical compared to the other elbows. The component to be monitored is the elbow, yet is not critical.

SP1

- Suction Piping System - The thickness data for suction is only at the extrados zone of the elbow. However, this shows the common thinning effect at elbows. The thinning measurement show that the flow inside the pipe is high that the water makes contact between the central extrados area extending to the exit extrados of the pipe. Noting that the points are of the same central angles, the thinning difference between the points, 0.30 mm and 0.10 mm shows faster thinning at the exit extrados of the elbow.
- Discharge Piping System - This pipe is long enough to make the flow developed and not too turbulent before entering the elbow. However, the bottom (6 o'clock position) the 4m mark from the pipe flange has considerable localized thinning and is extended to the sides of the pipe. The thinning continued at the sides of the elbow entry (3-6 o'clock) of the 8 and upper half of the 9m mark. The thinning also indicates a backflow in the elbow's intrados extending to the elbow exit.

SP2

- Suction Piping System - This pipe line as seen in the actual and in the plan is a larger pipe compared to that of the previous pipes. This pipe is not critical in terms of the current thickness.
- Discharge Piping System - The discharge side of the pipe indicates possible cavitation is carried over. It is observed from the data having a uniform thinning at the pipe circumference. It shows that the water flows more at the left side (6-9 o'clock position reference to the pipe flange), then continued to the bottom of the pipe at 6m mark. The flow enters the elbow at the sides with considerable thinning due to backflow (as seen in the 3-9 o'clock at 9m mark). The thinning greatly eroded the exit part of the elbow.

4.2.2.2 Assumptions

Following assumptions are used in calculating the required thickness of pipe

- Maximum Working Head – based on the design drawings and pump nameplate;
- Pipe Material – assume pipe material is ASTM A570 Grade 33 (market available material for spiral welded pipe);
- Design Guide – basis used for the simulated calculation is AWWA Manual M11 – Steel Pipe, A Guide for Design and Installation, 4th Edition. Statement for corrosion allowance is located at Chapter 4, which states *"At one time, it was a general practice to add a fixed, rule-of-thumb thickness to the pipe wall as a corrosion allowance. This was not an applicable solution in the water work field, where standard for coating and lining materials and procedures exists. The design shall be made for the required wall-thickness pipe as determined by the loads imposed, then linings, coatings, and cathodic protection selected to provide the necessary corrosion protection"*;
- Thickness calculation will be based on the internal pressure. External pressure will not be considered because much of the discharge line is not buried.
- Surge Pressure was not considered since there are surge protection along the line.
- This document will only consider the calculation of the minimum thickness along the discharge line since this is the part of the system where maximum pressure is experience.

4.2.2.3 Limitations

As confirmed by Maynilad, there is no available data regarding the design report. Design assumptions herein may be different from what was used by the designer/contractor of this station.

This document will not be able to provide the corrosion/degradation factor of the pipe since there is no available historical data on the thickness of the pipe.

4.2.2.4 Parameter values for thickness estimation

In order to estimate the minimum allowance thickness for pipes in straight line considering material handling (t_{mh}) and maximum internal pressure based on AWWA M11 (t_{sph}), following equations are used, respectively:

$$t_{mh} = \frac{\Phi}{\delta} \tag{4.1}$$

$$t_{sp} = \frac{\epsilon \times P_{max} \times \Phi}{2 \times S_e} \tag{4.2}$$

where P_{max} is maximum internal pressure

$$P_{max} = \frac{\rho_{H_2O} \times g \times H_{max}}{1000} \tag{4.3}$$

In order to estimate the minimum allowance thickness for pipes at elbows (Miter Bend), only maximum internal pressure is considered:

$$t_{mb} = \frac{P_{max} \times \Phi}{2 \times S_e} \times \left[1 + \frac{\Phi}{(3 \times R) - (1.5 \times \Phi_d)}\right] \times \epsilon \tag{4.4}$$

Paramater values used for computation are given in Table 4.5

Table 4.5: Parameter values for thickness estimation.

Parameters	Symbol	Unit	Pumps		Remarks
			Booster	Storage	
Discharge diameter	Φ	mm	600	600	
Max flow rate	Q_{max}	m^3/s	0.64	0.53	
Max pump head	H_{max}	m	40	50	based on name plate
Yield strength of material	S_y	MPa	227.5	227.5	ASTM A570 Grade 33, spiral welded pipe based on AWWA C200
Allowable stress	S_e	MPa	113.75	113.75	
Density of water	ρ_{H_2O}	kg/m^3	1000	1000	
Gravity constant	g	m/s^2	9.81	9.81	
Safety factor	ϵ		2	2	
Bulk modulus of compressibility of liquid	k	Pa	2.1E+09	2.1E+09	
Young's modulus of elasticity of pipe wall	E	Pa	2.1E+11	2.1E+11	
Radius of Elbow	R	mm	800	800	
Empirical constant	δ		288	288	

4.2.2.5 Required thickness

Results of computation for minimum allowable thickness for booster pumps and storage pumps are given in Table 4.6.

Table 4.6: Minimum thickness allowance.

Pumps	Internal pressure (Mpa)	Minimum allowable thickness (mm)		
	P_{max}	t_{mh}	t_{sp}	t_{mb}
Booster	0.392	2.080	2.070	2.900
Storage	0.491	2.080	2.590	3.620

If comparing these values with the measured values of thickness shown in subsection 4.2.2.1, it can be concluded that current thickness of pipes at both suction and discharge still provide adequate level of services as the measured value is about 4.60 mm on average while the required values for booster pumps are less than 3 mm and for storage pump is less than 3.62 mm.

However, it is important to note that required thickness at the elbow of storage pumps is 3.62 mm, which is not so far off from measured value of 4.60 mm. Especially, elbow section is significant important and shall not be at risk.

4.2.2.6 Deterioration

Given the lack of design data, precise design thickness is unknown, following assumptions are made

- Maximum measured thickness is considered to be the design thickness;

- Pipe has been in operation for 9 years since 2010;
- Deterioration rate is to follow linear function.

A simplest way to predict the remaining duration till thickness of pipe reaching alarming level (minimum allowable thickness). This prediction is shown in Table 4.5

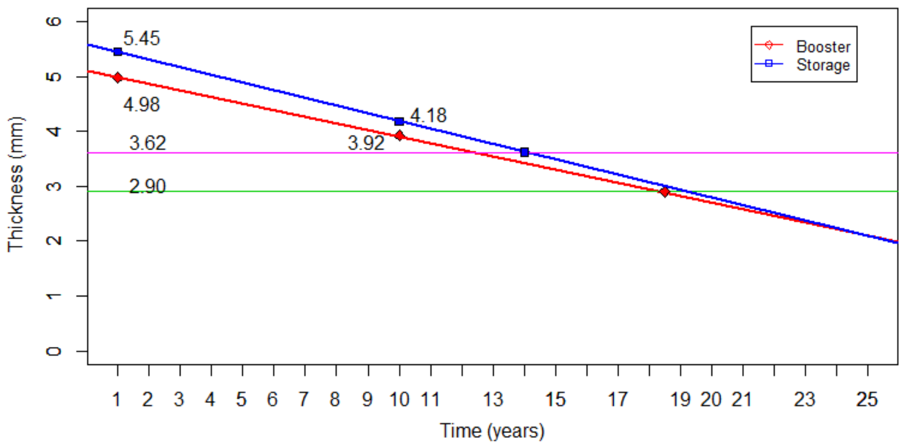


Figure 4.5: Thickness prediction

Inferences from reading the figure are

- thickness of booster pipes, particularly at the elbow, will reach its minimum allowable thickness at years 18 (or in 2027);
- thickness of storage pipes, particularly at the elbow, will reach its minimum allowable thickness at years 14 (or in 2023).

4.2.2.7 Recommendations

Given the current thickness of pipe the lack of design information, it is advisable to

- Not perform any major intervention on the pipes;
- Keep regular testing on exact locations using the same type of UTG devices. It is important for Maynilad to establish a testing regime for obtaining thickness at exact same location over time (e.g. every year). Information obtained from testing will be then used to compute deterioration rate based on thickness value;
- Establish an approach to inspect/test the thickness of underground pipe, which is considered to be more vulnerable to leakage and corrosion on external wall;
- The elbows in the suction and the discharge piping systems must be monitored regularly especially BP1, BP2, BP5 and BP6.
- It is recommended to have a profiling of the piping systems above and below the ground in order to have a baseline in the analysis of the Maynilad Piping System. In order to have a profiling of pipe thickness at differential time T, additional measurement at similar locations shall be conducted periodically, behavior can then be monitored.
- Perform coating regularly the pipe to prevent possible corrosion/errosion and damage that cause by external factors and surrounding condition;
- Since the location is reclaimed area, it is advisable to set up a regime to regular inspection for the use of cathodic protection for all underground piping lines.

4.3 Visual Inspection on Pipe, valves, fittings, supports, expansions, and appurtenances

4.3.1 Highlights

Visual inspection data on pipes, valves, fittings, supports, expansions, and appurtenances is highlighted in Table 4.7.

Table 4.7: Highlights of visual inspection

No.	Items	CS	Remarks	Ref
1	Valve Leaks		Water leakages for moving parts of checked valves of pumps. Evident of prolonged leaks are shown by local corrosion and accumulation of water pools around valves's vicinity	
2	Pressure gauges		Discrepancy in reading between the dial and digital gauges Defective bourdon (dial) pressure gauges were found at suction side. No pressure gauses installed near pump suction nozzle and discharge flange inferring no ability to immediately read the head pressure. Excessive deterioration/fading of tags making them unreadable Some tags have been superimposed with recent data written by inappropriate markers that cause difficulty in reading. Some tags found with inconsistency of data	
3	Alignment bolts		without washers	
4	Grounding cables		Not found for any motor	
5	Vibration monitoring probes		Some were found disconnected or/and untended	
6	Spare pumps		Susceptible to false brinelling (e.g. The spare pump located near BP1 may experience minor vibrations due to its location near the almost continuously operating pumps. There is no observed intermittent rotating of the pump shaft by the operators during the visit)	
7	Piping stability/settlement		Possible execcisve level of movement leading to weakness of tensile/compressive strength of materials/fixtures. The entire pump house is suffering from ground settlement and that the alignments of the pumps and the corresponding fittings have been compromised. Mitigating supports have been installed but their functions are doubtful due to observed obscurities. Interviews with operators also confirm serious damages to pumps and increased vibration during operation because of the significant piping movements Wall opening provisions for pipe movement due to ground settlement. These local tear downs leave the wall unaesthetic and inconsistently enclosed as some are covered with deteriorating plywood. Some round bars are left protruding and can pause danger Crooked and/or drawn concrete saddle strap bolts. Some of the fastening area on the concrete saddle display small to large cracks Evidences of axial suction piping movements Space gap between saddle arc and pipe Doubtful piping supports. The counter action of the U supports (both round and flat type) are doubtful. The U supports function to counter the water thrust on the elbow as immense water volumes pass thru it. The bolts are not turned to tighten the flat bar U support. Space between the U supports and the pipes are observed	
8	Motion actuated lighting		Interview with the maintenance team revealed that the motion actuated lighting sometimes causes slight nausea due to dim lighting when repair. The minute motions of repair are sometimes not enough to actuate the lights and thus interrupt the work	

Visual inspections are supported with the photos taken at particular locations/positions in questions.

It was realized that the entire pump house is suffering from ground settlement and that the alignments of pumps and corresponding fittings have been compromised. For example, as can be shown in Figure 4.6-a, the portion of wall through which the pipe passes thru has been torn down partially to provide allowance for settlement as the pipe levels going down.

Damages to the concrete saddle supports appearing as cracks and crooked or completely drawn bolts have been observed as shown in Figure 4.6-b. Furthermore, gaps are also observed

a - wall opening

b - Support damage

c - Gap between saddle support and pipe

d - common leakage

Figure 4.6: Ground settlement impacts and leakages

between the concrete saddle supports and the straight pipe beneath as shown in 4.6-c.

For the booster pumps, there are two saddle supports located near to each other and are positioned just outside the pump house after the suction elbows as shown in Figure 4.7-a. For the storage pumps, the three saddles are located farther, one before the discharge elbow and the other still outside the pump house and just after the check valve.

Piping movements parallel to the central axis also have been observed. As shown in Figure 4.7-b, a gap has been observed between several counter supports and the elbow. The counter supports are supposed to handle elbow thrust as immense water volumes pass thru the elbow.

a - Piping supports

b - Piping counter supports

Figure 4.7: Impacts from supporting system

A common observation is that corrosion appears where there are leaks exist. Figure 4.6-d shows water leakage of BP6 check valve and surrounding and SP1 check valve.

Several dial pressure gauges were not functioning (Figure 4.8-a). Also it was observed that some suction pressure gauges do not have a vacuum range and are only able to measure positive pressures. Moreover, it was observed that the readings of dial gauges and digital pressure gauges do not match with differences up to 10 psi as shown in Figure 4.8-b.

The component tags were also inspected during the visits. As observed, some of the tags are unprotected and erased. Further, some tags are inconsistent in content. Different brands of pressure gauges were installed at similar corresponding tapping points. It was observed that the alignment bolts for the pumps are washerless and that nuts are used instead, as shown in Figure 4.9-a. Also, there were no frame grounding found for all the pumps as seen in Figure 4.9-b.

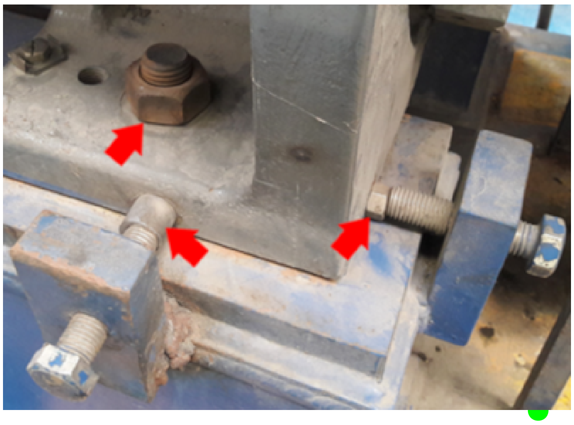
4.3.2 Visual inspection data

Visual inspection data on assets are summarized in tables of this section.

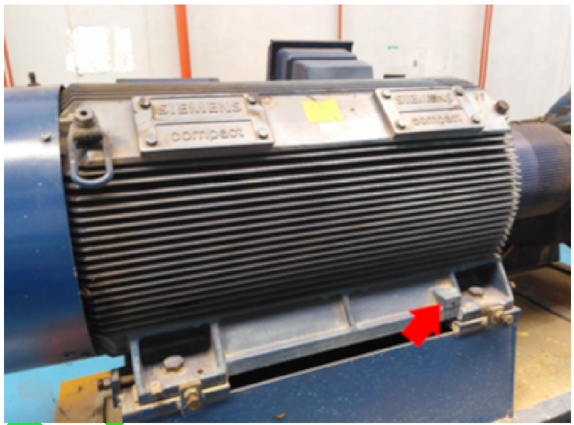
a - Defective

b - Digital and dial pressure gause discrepancy

Figure 4.8: Defective/discrepancy pressure gauges



a - Motor alignment bolts



b - Motor alignment supportsy

Figure 4.9: Alignment impacts

Table 4.8: Visual inspection data - BP1

No.	Items	CS	Remarks
1	SBV	-	Below ground; not inspected,
2	FJ	-	Below ground; not inspected,
3	SE	1	Mitered elbows were used (not radius elbows)
4	PIPE1	2	Pipe not consistently cylindrical; Pipe made from very short pieces of pipes welded diagonally and circumferentially. Slump areas due to counteraction of steel strap when pipe imbalance during ground settlement develop slump areas.
5	ECR	1	Eccentric reducers used appropriately
6	FJ	3	Flexible joint adjusts to ground settlement for pump and casing, Joint statues need be checked
7	CS1	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and crook fastening bolts. Space/gap between saddle seat and pipe exist.
8	CS2	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and crook fastening bolts. Space/gap between saddle seat and pipe exist. U counter supports faultily installed. Fastening bolts are not tighten/used at all.
9	CCR	1	Concentric reducers were used appropriately
10	CV	2	Water leakage and corrosion observed at the shaft of the balancer
11	EJ	3	Outer stud rods may short circuit expansion action of the inner joint
12	DBV	1	Valve and actuator working properly
13	DE	1	Thickness is acceptable and no sign of corrosion or paint deterioration
14	PAD	1	No crack propagation observed
15	CS3	1	No crack propagation observed; CV sits well on the support

4.3.3 Observation and recommendations

- Pumps were installed with poorly fabricated and/or fitted pipe concrete saddles and steel straps, which provide insufficient support. These flaws, along with the natural reaction forces between the pipe sections and said supports, possibly aggravated by soil settlement,

Table 4.9: Visual inspection data - BP2

No.	Items	CS	Remarks
1	SBV	-	Below ground; not inspected,
2	FJ	-	Below ground; not inspected,
3	SE	1	Mitered elbows were used (not radius elbows)
4	PIPE1	2	Pipe not consistently cylindrical; Pipe made from very short pieces of pipes welded diagonally and circumferentially. Slump areas due to counteraction of steel strap when pipe imbalance during ground settlement develop slump areas.
5	ECR	1	Eccentric reducers used appropriately
6	FJ	4	Flexible joint adjusts to ground settlement for pump and casing, Joint statues need be checked
7	CS1	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist.
8	CS2	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist. U counter supports faultily installed. Fastening bolts are not tighten/used at all.
9	CCR	1	Concentric reducers were used appropriately
10	CV	1	No water leakage and local corrosion is minimal
11	EJ	4	Outer stud rods short circuit expansion action of the inner joint
12	DBV	1	Valve and actuator working properly
13	DE	1	Thickness is acceptable and no sign of corrosion or paint deterioration
14	PAD	1	No crack propagation observed
15	CS3	1	No crack propagation observed; CV sits well on the support

Table 4.10: Visual inspection data - BP3

No.	Items	CS	Remarks
1	SBV	-	Below ground; not inspected,
2	FJ	-	Below ground; not inspected,
3	SE	1	Mitered elbows were used (not radius elbows)
4	PIPE1	2	Pipe not consistently cylindrical; Pipe made from very short pieces of pipes welded diagonally and circumferentially. Slump areas due to counteraction of steel strap when pipe imbalance during ground settlement develop slump areas.
5	ECR	1	Eccentric reducers used appropriately
6	FJ	4	Flexible joint adjusts to ground settlement for pump and casing, Joint statues need be checked
7	CS1	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist.
8	CS2	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist. U counter supports faultily installed. Fastening bolts are not tighten/used at all.
9	CCR	1	Concentric reducers were used appropriately
10	CV	1	No water leakage and local corrosion is minimal
11	EJ	4	Outer stud rods short circuit expansion action of the inner joint
12	DBV	1	Valve and actuator working properly
13	DE	1	Thickness is acceptable and no sign of corrosion or paint deterioration
14	PAD	1	No crack propagation observed
15	CS3	1	No crack propagation observed; CV sits well on the support

have created obvious visible gaps within the load bearing areas, as well as fractures in the concrete saddles and the steel anchor bolts. Instances of crevice corrosion were found in some contact areas.

Recommendations

✓ Short term: clear away oxide scales, especially among crevices, and recoat affected areas;

✓ Medium term: install properly engineered piping supports, equipped with anti-corrosion shields; install cathodic protection on the pipelines.

- Station designers relied on foam inserts along penetrations in the front concrete wall to provide flexible piping support, which resulted in numerous wall cracks that are currently

Table 4.11: Visual inspection data - BP4

No.	Items	CS	Remarks
1	SBV	-	Below ground; not inspected,
2	FJ	-	Below ground; not inspected,
3	SE	1	Mitered elbows were used (not radius elbows)
4	PIPE1	2	Pipe not consistently cylindrical; Pipe made from very short pieces of pipes welded diagonally and circumferentially. Slump areas due to counteraction of steel strap when pipe imbalance during ground settlement develop slump areas.
5	ECR	1	Eccentric reducers used appropriately
6	FJ	4	Flexible joint adjusts to ground settlement for pump and casing, Joint statues need be checked
7	CS1	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist.
8	CS2	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist. U counter supports faultily installed. Fastening bolts are not tighten/used at all.
9	CCR	1	Concentric reducers were used appropriately
10	CV	2	Water leakage and corrosion observed at the shaft of the balancer
11	EJ	4	Outer stud rods short circuit expansion action of the inner joint
12	DBV	1	Valve and actuator working properly
13	DE	1	Thickness is acceptable and no sign of corrosion or paint deterioration
14	PAD	1	No crack propagation observed
15	CS3	1	No crack propagation observed; CV sits well on the support

Table 4.12: Visual inspection data - BP5

No.	Items	CS	Remarks
1	SBV	-	Below ground; not inspected,
2	FJ	-	Below ground; not inspected,
3	SE	1	Mitered elbows were used (not radius elbows)
4	PIPE1	2	Pipe not consistently cylindrical; Pipe made from very short pieces of pipes welded diagonally and circumferentially. Slump areas due to counteraction of steel strap when pipe imbalance during ground settlement develop slump areas.
5	ECR	1	Eccentric reducers used appropriately
6	FJ	4	Flexible joint adjusts to ground settlement for pump and casing, Joint statues need be checked
7	CS1	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist.
8	CS2	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist. U counter supports faultily installed. Fastening bolts are not tighten/used at all.
9	CCR	1	Concentric reducers were used appropriately
10	CV	1	No water leakage and local corrosion is minimal
11	EJ	4	Outer stud rods short circuit expansion action of the inner joint
12	DBV	1	Valve and actuator working properly
13	DE	1	Thickness is acceptable and no sign of corrosion or paint deterioration
14	PAD	1	No crack propagation observed
15	CS3	1	No crack propagation observed; CV sits well on the support

being repaired. Even if repairs on the said wall are completed, support for the affected piping is insufficient because wall penetrations are not designed for such a purpose.

<u>Recommendations</u>

✓ Isolate piping from the concrete wall.

- Pumps have little to no isolation from hydrodynamic forces. Strain caused by movement at the inlet and outlet pipe sections are transmitted to pump casings. Moreover, hydrodynamic forces, along with the static weight of said pipe sections, including the flexible coupling and the water contained therein, are transmitted to the casing due to lack of proper piping support upstream or downstream of the pump.

Table 4.13: Visual inspection data - BP6

No.	Items	CS	Remarks
1	SBV	-	Below ground; not inspected,
2	FJ	-	Below ground; not inspected,
3	SE	1	Mitered elbows were used (not radius elbows)
4	PIPE1	2	Pipe not consistently cylindrical; Pipe made from very short pieces of pipes welded diagonally and circumferentially. Slump areas due to counteraction of steel strap when pipe imbalance during ground settlement develop slump areas.
5	ECR	1	Eccentric reducers used appropriately
6	FJ	4	Flexible joint adjusts to ground settlement for pump and casing, Joint statues need be checked
7	CS1	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist.
8	CS2	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist. U counter supports faultily installed. Fastening bolts are not tighten/used at all.
9	CCR	1	Concentric reducers were used appropriately
10	CV	2	Water leakage and corrosion observed at the shaft of the balancer
11	EJ	4	Outer stud rods short circuit expansion action of the inner joint
12	DBV	1	Valve and actuator working properly
13	DE	1	Thickness is acceptable and no sign of corrosion or paint deterioration
14	PAD	1	No crack propagation observed
15	CS3	1	No crack propagation observed; CV sits well on the support

Table 4.14: Visual inspection data - SP1

No.	Items	CS	Remarks
1	SBV	1	Valve working properly
2	EJ	4	Outer stud rods short circuit expansion action of the inner joint
3	ECR	1	Eccentric reducers used appropriately
4	PAD	1	No crack propagation observed; Base is dirty and lubricating sludge drops from the drive end of the motor
5	FJ	3	Flexible joint adjusts to ground settlement for pump and casing, however misalignment between suction nozzle and pipe centerline needs to be checked.
6	CCR		Concentric reducers were used appropriately
7	CV	2	Water leakage and corrosion observed at the shaft of the balancer
8	PIPE2	2	Pipe shape is good; Corrosion and paint removal at pipe portion that seats with saddle show accelerated deterioration comapred to other portions.
9	DE	1	No disfigurement or paint deterioration
10	FJ	-	Below ground; not inspected,
11	DBV	-	Below ground; not inspected,
12	CS3	1	No crack propagation observed; CV sits well on the support; Refurbishing needed on portion that catches the water leakage from CV
13	CS4	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist. Counter supports not properly installed with either no fasteners or nut-tightened bolts
14	CS5	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist.

Recommendations

✓ Install proper isolation and support upstream and downstream of the pumps.

- Poor installation and/or alignment practices allowed the use of spacer-nuts to compensate for short jack screws and washerless anchor bolts in BP6.

Recommendations

✓ Implement proper quality control of shaft alignment jobs, whether done in-house or outsourced.

- All motors lack frame grounding. Assuming the motor power supplies were grounded at the motor control center (MCC), an assumptions that still needs to be verified, current may

Table 4.15: Visual inspection data - SP2

No.	Items	CS	Remarks
1	SBV	1	Valve working properly
2	EJ	4	Outer stud rods short circuit expansion action of the inner joint
3	ECR	1	Eccentric reducers used appropriately
4	PAD	1	No crack propagation observed; Base is dirty and lubricating sludge drops from the drive end of the motor
5	FJ	3	Flexible joint adjusts to ground settlement for pump and casing, however misalignment between suction nozzle and pipe centerline needs to be checked.
6	CCR		Concentric reducers were used appropriately
7	CV	2	Water leakage and corrosion observed at the shaft of the balancer
8	PIPE2	2	Pipe shape is good; Corrosion and paint removal at pipe portion that seats with saddle show accelerated deterioration comapred to other portions.
9	DE	1	No disfigurement or paint deterioration
10	FJ	-	Below ground; not inspected
11	DBV	-	Below ground; not inspected,
12	CS3	1	No crack propagation observed; CV sits well on the support; Refurbishing needed on portion that catches the water leakage from CV
13	CS4	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist. Counter supports not properly installed with either no fasteners or nut-tightened bolts
14	CS5	4	Concrete saddles display crack propagations. Rigid steel straps resist pipe movement during ground settlement because of misalignment and so uproot and/or crook fastening bolts. Space/gap between saddle seat and pipe exist.

pass through the bearings should the motor shaft be grounded whilst the motor frame is ungrounded, which may lead to bearing damage, especially among variable speed drive (VFD) units. Bonding of non-current carrying metal components (e.g., motor frames) to the ground system is necessary to create an equipotential plane between the concrete floor and plant personnel who may risk electrocution should said parts become energized.

Recommendations

✓ Bond motor frames to the ground system; review present grounding policies/procedures.

- Possible inner cavitation/corrosion: inner parts of pipes, particularly at the elbow sections, might have already been sufferred from cavitation/corrosion.

Recommendations

✓ Develop a long term testing regime that allows partial shutdown to conduct visual inspection inside (e.g. by CCTV) for checking cavitation/corrosion, manufacturing defects for steel plat or during spiral welded pipe fabrication.

4.4 Pump efficiency

Data on flow and head were measured for each pump. However, there was no measured data of motor/pump assembly regarding power ratings of all pumps. This was due to the fact that electrical audit is not part of the scope of work.

GHD/RBSanchez did verify on the provided electrical audit to see if there is available power rating for individual motor/pump assembly. However, the electrical audit does not include measured data for individual pump. Thus, cannot be used as a reference to more or less correlate with measured flow and head for computation of pump efficiency as desired.

4.4.1 Unit flow measurement

Data on measured flow (Q) was recorded with min and max values is shown in Table 4.16 for each pumps.

Table 4.16: Unit flow measurement (cubic meter per second - cms).

Assets	Φ (mm)	Flow Q (cms)				Remarks
		Design	Measure			
			Min	Max	Ave.	
BP1	700	0.6365	0.3407	0.3533	0.3470	
BP2	700	0.6365	0.3028	0.3343	0.3186	
BP3	700	0.6365	0.5930	0.6119	0.6024	
BP4	700	0.6365	0.5110	0.5614	0.5362	
BP5	700	0.6365	0.6939	0.7128	0.7034	
BP6	700	0.6365	0.6119	0.6561	0.6340	
SP1	600	0.5324	0.3583	0.3659	0.3621	
SP2	600	0.5324	0.3785	0.3848	0.3817	

4.4.2 Pressure measurement

Data on measured flow (Q) was recorded with min and max values is shown in Table 4.17 for each pumps.

Table 4.17: Head (mH_2O).

Assets	Head (H - mH_2O)			Remarks
	Design	Discharge	Suction	
BP1	40	42.1581	2.4592	
BP2	40	42.1581	2.7403	
BP3	40	42.1581	2.4592	
BP4	40	40.7529	2.7403	
BP5	40	42.1581	2.9511	
BP6	40	40.7529	2.8105	
SP1	50	37.8088	0.7026	
SP2	50	36.5371	0.7026	

4.4.3 Efficiency

Pump efficiency is computed based on the flow/head measurement and the assumed value of power rating (Table 4.18).

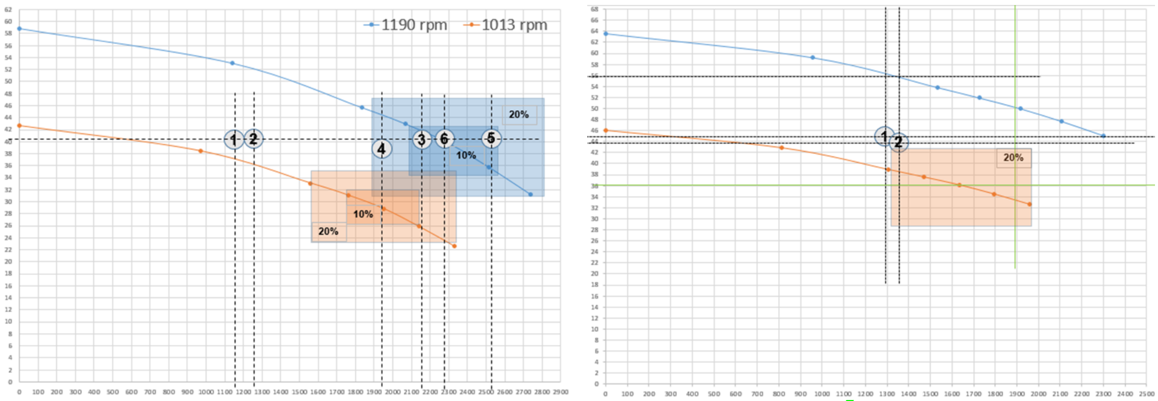
Table 4.18: Pump efficiency (%).

Assets	Flow m^3/s	Head mH_2O	Input Power kW	Water Power kW	Efficiency (%)		
					Tested	Design	Diff.
BP1	0.347	41.68	181	142	78.60	85.67	-7.07
BP2	0.319	41.4	181	129	71.70	85.67	-13.97
BP3	0.602	41.68	283	246	86.90	85.67	1.23
BP4	0.536	40	283	210	74.20	85.67	-11.47
BP5	0.703	41.19	283	242	-	85.67	
BP6	0.634	39.93	283	248	87.60	85.67	1.93
SP1	0.362	45.33	185	161	87.00	86.89	0.11
SP2	0.382	44.06	185	165	89.10	86.89	2.21

It is important to note that the values of input power is an assumed values which might not perfectly reflect the actual value in actual situation. This assumption is a limitation of the study, particularly for this station, since the electrical audit was carried out without actual records on power for individual pump. The design pump efficiencies are taken from the test report of the KSB [18].

In Table 4.18, efficiency for BP5 is not estimated due to the fact that the measured flow is beyond the maximum allowable flow of the pump. This infers that the pump has been operated inappropriately pursuant to its design specification. As a consequence, the operation of the pump might have already incurred more power than it should be. If this scheme of operation is continues, highly likely that the failure probability will increase.

Figure 4.10-a, and 4.10-b presents the efficiency curves for booster pumps and storage pumps, respectively. The curves are created based on the recorded data provided in the test record of KSB [18].



a - Booster pumps b -Storage Pumps

Figure 4.10: Efficiency curves

Figure 4.10-a shows that BP1 and BP2 deviates away from the curve. In this case, BP1 and BP2 possibly operates at underflow condition, and at higher friction loss. The pump operates at lower efficiency based on the plot curve, and backed up to have an efficiency of 78.6% and 71.7%, respectively. This also constitutes to the "fair" condition of the pump with possible cavitation at the suction head. Moreover, BP3, BP5, and BP6 have efficiencies higher than 85%. As shown at the shaded region, these pumps operate under the 10% tolerance BEP range, thereby operating at considerably good operation point although BP5 has overflow-measured flow. In the contrary, these pumps were diagnosed to have a "fair" pump condition state. This is due to pump possible cavitation from the suction and carried throughout the discharged side of the pumps. In the other hand, BP4 has an efficiency of 74.2% and deviates slightly away to the curve with the operating point of BP4 is under the 20% tolerance BEP range. The pump operates at lower head and possibly in underflow condition. The pump have a diagnosis of having a good pump health that means lower vibration and possible cavitation occurred / occurring within pump impellers.

Figure 4.10-b shows that the operating point of SP1 and SP2 deviates away from the pump curve. This may possibly means that the pump is operating at higher friction head, and either overflow and underflow. Operating points of both pumps are within the 20% tolerance range (shaded region) based on the GPM* (best GPM point), and has slight increase in pressure head. This can be associated in why is their efficiency is still above 80% even operating at deviated operation conditions. In the other hand, it would affect the system performance when operated over time, thereby having an initial diagnosis of "fair" pump health based on the vibration analysis standpoint.

Generally, VFD controlled-pumps deviates greatly away to the curve than the fixed-speed pumps (BP3 to BP6). This could possibly means that the operating duty points of the pumps when controlled by VFD is out of the best efficiency range of the pumps, thereby may incur higher power consumptions.

<u>Recommendations</u>

- Proper operating condition shall be established for the VFD Pumps in a given time to avoid them operating beyond their BEP for a long period of time. Also include the proper combinations of running pumps in a given time.
- Multiple tests and conditions is still recommended to have a holistic approach on the pump assessment.

- Measurement of important pump performance parameters shall also be included in the modifications (refer to the conceptual design in Chapter 5).

4.5 Vibration and structural assessment

4.5.1 Measurement and spectrum reading

Rotating equipment generate vibration waveforms that are mathematical functions of machine dynamics, such as speed, alignment, and rotor balance, among others. Vibration analysis entails measurement and analysis of the amplitude of vibration at certain frequencies to gather useful information relating to the accuracy of shaft alignment and balance, the physical condition of bearings, and the possible effects of structural issues; in the case of Maynilad, the problem of impeller possible cavitation is an added and serious concern.

Three main parameters are measured to determine the severity or amplitude of vibration; namely: displacement, velocity and acceleration. Along with temperature, the vibration level is a primary indicator of the physical condition of a machine. As a generally rule, higher vibration levels indicate greater defects.

Rotating speeds below 600 rpm (10 Hz) generate minimal acceleration, moderate velocity, but relatively high displacement. Hence, shaft displacement is a critical parameter for slow speed rotors, such as steam turbines. Between 600 – 60000 rpm (10 - 1000 Hz) velocity and acceleration levels provide useful indications of the severity of defects. While velocity as a parameter may indicate the presence or relative magnitude of a problem, it makes no distinction as to the source or cause. This is where an FFT vibration analyzer comes in. A fast Fourier transform algorithm converts acceleration waveforms into functions of frequency in a way suitable-trained humans can distinguish the component sources or causes of the vibration.

By means of a OneProd Falcon high-resolution FFT analyzer equipped with tri-axial accelerometer with a linear frequency range of 2Hz-30kHz, vibration spectral readings were taken from four bearing locations in each motor-pump unit. Analysis and results are summarized as follows:

4.5.2 Data and analysis

Raw data of vibration measurement is provided in separately digital format. The raw data of each pump is used to generate a set of graphs provided in Appendix A.

Analytical results on vibration are with the Appendix A. A summary of grading for each pump is given in Table 4.19.

Table 4.19: Pump vibration condition state.

Assets	Operational issues detected	Condition	
		Motor	Pump
BP1	shaft misalignment impeller possible cavitation low lubrication at pump inboard (IB) bearing	2	3
BP2	early stage fault low lubrication at pump outboard (OB) bearing	2	3
BP3	misalignment impeller possible cavitation	2	3
BP4	vibration in all bearings were within acceptable levels	2	2
BP5	impeller possible cavitation low lubrication at pump outboard (OB) bearing	2	3
BP6	impeller possible cavitation low lubrication at pump outboard (OB) bearing	2	3
SP1	shaft misalignment impeller possible cavitation	2	3
SP2	impeller possible cavitation	2	3

It is note that the CS 2, and 3 shown in Table 4.19 infers good and fair, respectively [1].

It can be seen from Table 4.19, vibration on motor is with CS 2 inferring that they are still operating in acceptance level of vibration (good). However, vibration on pump is mostly with CS 3 (fair), except for BP4. Problems found from observation and vibration analysis are mainly due to shaft misalignment, impeller possible cavitation, and low lubrication at pump inboard (IB) and outboard (OB) bearing.

4.5.3 Recommendations

Recommendations are shown in Table 4.20

Table 4.20: Recommendation to reduce vibration.

Assets	Condition		Recommendations	IT
	Motor	Pump		
BP1	2	3	Align motor and pump shafts per manufacturer specifications Monitor and/or mitigate possible cavitation progress Follow manufacturer prescribed dynamic operation to prevent impeller damage Regrease pump IB bearing	2
BP2	2	3	Regrease pump OB bearing Monitor vibration regularly to assess trend	2
BP3	2	3	Align motor and pump shafts per manufacturer's specifications Monitor and/or mitigate possible cavitation progress Follow manufacturer prescribed dynamic operation to prevent impeller damage Monitor vibration regularly to assess trend	
BP4	2	2	Monitor vibrations regularly	2
BP5	2	3	Monitor and/or mitigate possible cavitation progress Follow manufacturer prescribed dynamic operation to prevent impeller damage Regrease pump bearings	
BP6	2	3	Monitor and/or mitigate possible cavitation progress Follow manufacturer prescribed dynamic operation to prevent impeller damage Regrease pump bearings	2
SP1	2	3	Align motor and pump shafts per manufacturer's specifications Monitor and/or mitigate possible cavitation progress Follow manufacturer prescribed dynamic operation to prevent impeller damage	2
SP2	2	3	Monitor and/or mitigate possible cavitation progress Follow manufacturer prescribed dynamic operation to prevent impeller damage	2

A common problem that occurs to all pumps are issues concerning possible misalignment that can affect the vibration of pumps now and in the future. Some proof of issues are with figures shown in subsection 4.3.1.

4.6 Energy management audit

4.6.1 Production and power data

Production data for this station has been recorded in excel files. Each file represents a month with 24 hours of daily records. Maynilad provided this set of data from 2012 to 2018 per GHD' request. Initial verification on this set was conducted with following conclusions

- Data of 2012 and 2013 is not usable due to its incompatibility to the later data. Fundamentally, we found a great number of errors on this data. In addition, the data itself is incomplete and only reflects aggregate value, which makes impossible to compare with the later set;
- The structure of data is not homogeneous with many numerical errors. This problem is due to the fact that excel file is not suitable for recording a large volume of data, partic-

[1]The CS is slightly different from that defines in Table 3.1

ularly cells are not set up to reject string and value outside the lower and upper bounds. content.

When excluding the data of 2012 and 2013, the set used for compilation has following statistics

In order to compile such a huge data set, it is not possible with manual inputting, instead, GHD has developed a hybrid program consisting of Visual Basic (VBA) Code and MySQL code for fast compilation. VBA code is used to add header, fill up missing information in excel file, and ignore rows and columns that should not exist with regard to database structure. MySQL codes are used to eliminate measurement errors and bring together all individual files to one file that allows statistical analysis with R.

4.6.2 Measurement errors

Following measurement errors are with the provided excel files

- String/text values are found numerous in columns that shall be only numerical values;
- Extreme values are found numerous;
- Negative values are found in many places that shall only be positive

4.6.3 Data compilation for analysis

Out of all recorded attributes, useful attributes that can be used for energy audit are total production per hour and total power consumption per hour. There is no record on production and power consumption for individual pump.

After data filtering, data correction, and compilation, the obtained set of data includes 27,625 records. Final data set is saved in MySQL server.

4.6.4 Analysis

As a matter of fact, power consumption of a PS is mostly contributed by the operation of pumps. Thus, the audit has been centralized on

- Analyzing given production and power consumption data to understand the trend and establish a benchmark ratio of production vs power for future audit and management;
- Evaluating other part of the audit such as pump efficiency and reliability in order to derive better intervention program that will eventually beneficial to the Client to maintain a benchmark level of power consumption against the production.

Figure 4.11 shows the statistical correlation between production and power. It can be seen from the correlation graph and correlation value that there is little correlation among these two values. This is against the hypothesis that when production increase, power consumption shall also increase. However, it is not the case as observed from the graph. This infers that the pump system might have incurred a certain level of deterioration leading to its low reliability over time.

Figure 4.12 shows a trend in time series production since 2014. It can be seen from the graph that the production has kept decreasing slightly over the year.

Figure 4.13 shows a trend in time series power consumption since 2014. It can be seen from the graph that the power has kept increasing over the year.

Figure 4.14 shows time series of ratio between power and production. As the production decreases and power increase, the ratio keeps increasing over time.

Interpretation from these graphs can be summarized as follows

- Efficiency of the pump system has decreased due to more frequent breakdown of pumps;
- Pumps might have been operated in a non-optimal operational scheme/sequence;

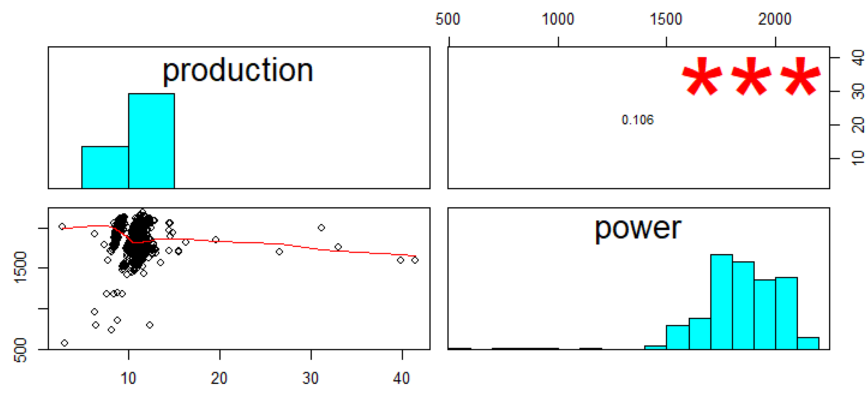


Figure 4.11: Correlation between production and power consumption

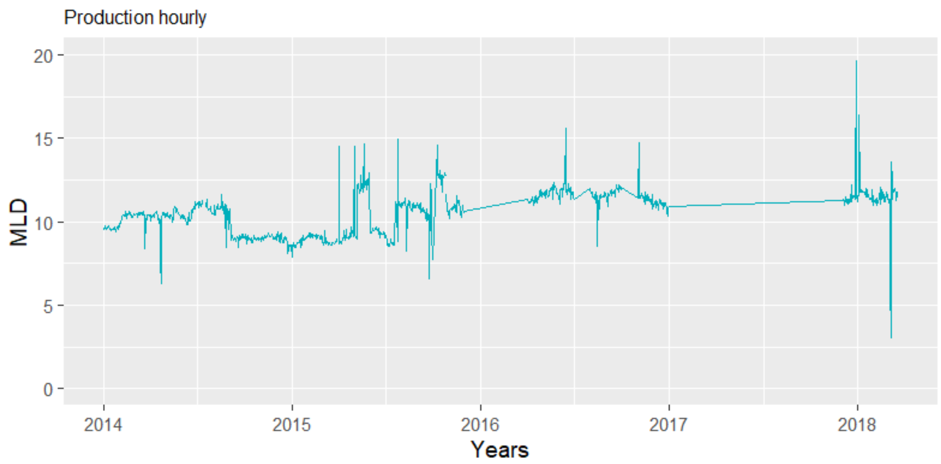


Figure 4.12: Time series production/hour

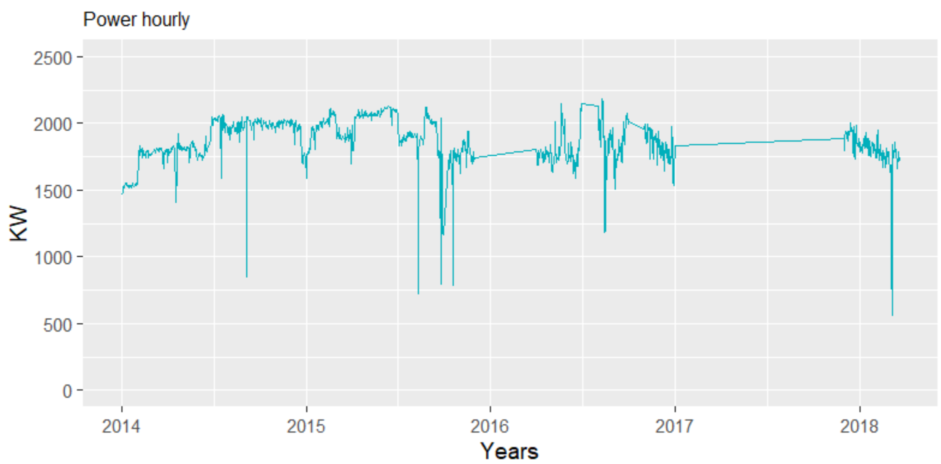


Figure 4.13: Time series power/hour

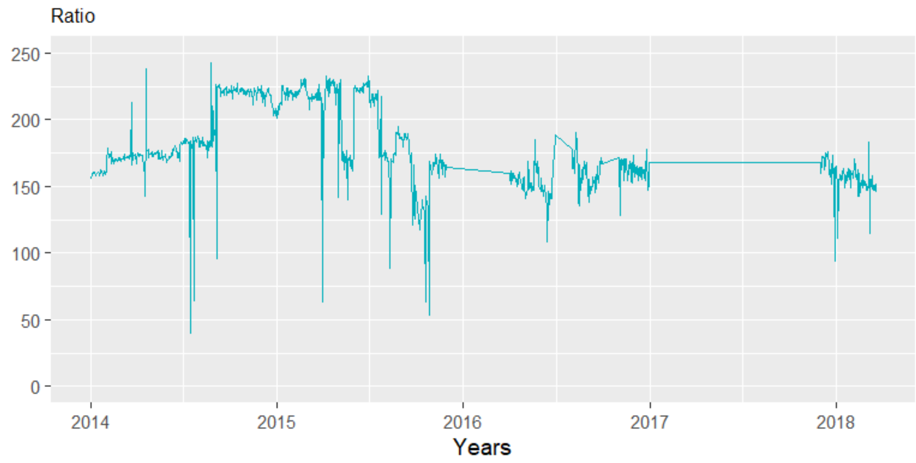


Figure 4.14: Time series ratio between production and power

4.6.5 Recommendation

In order to operate the PS in a manner that is energy efficient, it is advisable to

- Establish an optimal operation scheme;
- Establish a benchmark energy efficiency ratio for continuous monitoring and reporting. This ratio shall become a Key Performance Indicator (KPI) used for managerial purpose.

4.7 Workplace environment management

4.7.1 Temperature and relative humidity

4.7.1.1 Data

Data concerning the temperature and relative humidity is presented in Table 4.21. Data was measured at targeted points shown in Figure 2.18. Raw data is with the site inspection reports, which will be provided to the Client separately. Persuant to ASHRAE standard, the recommended ranges for temperature and humidity are [72 - 80 $^\circ F$] and [45 - 60 %], respectively.

4.7.1.2 Analysis

As can be seen from Table 4.21, it is obvious that the temperatures inside the pump house at every measurement points are significant higher than the maximum value of the recommended range (80 F). The average value is 94.16 F. The higher values of temperature compared to the range have also been observed for points outside the pump house, in the vicinity, and even inside the office.

Regarding the relative humidity, recorded data was within the recommended range inside the pump house and in the office (54.55 % and 48.80 %, respectively). The humidity value outside the pump house (61.36%) is slighly higher than the maximum value in the recommended range (60.00%). However, it can be understandable given the the fact that it is directly affected by the ambient temperature.

As a matter of fact, temperature and humidity is highly correlated and as per XXX, the recommended combination of temperature and humidity shall be within the comfortable zone as shown in Figure 4.15.

4.7.1.3 Recommendations

In order to reduce the negative impacts from high temperature, particularly inside the pump house, the Client shall consider

Table 4.21: Temperature and relative humidity.

Points	Description of points	Temperature ($^\circ F$)		Humidity (%)	
		Actual	Range	Actual	Range
	A. Inside pump house (outside the office)				
1	Between BP5 and BP6 away from pump	91.04	72 - 80	59.80	45 - 60
2	Between BP5 and BP6	95.72	72 - 80	53.30	45 - 60
3	Between BP5 and BP4 away from pump	92.12	72 - 80	53.40	45 - 60
4	Between BP5 and BP4	93.38	72 - 80	52.70	45 - 60
5	Between BP4 and BP3 away from pump	93.20	72 - 80	56.30	45 - 60
6	Between BP4 and BP3	96.26	72 - 80	52.30	45 - 60
7	Between BP3 and BP2 away from pump	94.28	72 - 80	53.30	45 - 60
8	Between BP3 and BP2	95.00	72 - 80	52.40	45 - 60
9	Between BP2 and BP1 away from pump	93.74	72 - 80	56.90	45 - 60
10	Between BP2 and BP1	96.08	72 - 80	53.40	45 - 60
11	Between SP2 and BP1 away from pump	93.38	72 - 80	53.90	45 - 60
12	Between SP2 and BP1	96.44	72 - 80	52.40	45 - 60
13	Between SP2 and SP1 away from pump	93.56	72 - 80	56.90	45 - 60
14	Between SP2 and SP1	94.10	72 - 80	56.70	45 - 60
	Average	94.16		54.55	
	B. Outside pump house				
15	Near Reservoir	84.44	72 - 80	64.73	45 - 60
16	Back of the Office	89.42	72 - 80	58.97	45 - 60
17	Near Guard House	88.46	72 - 80	59.40	45 - 60
18	Near Diesel Tank	86.66	72 - 80	62.33	45 - 60
	Average	87.25		61.36	
	C. Vicinity				
19	Near Diesel Tank, outside vicinity	91.28	72 - 80	56.57	45 - 60
20	Near Guard House, outside vicinity	90.56	72 - 80	56.47	45 - 60
	Average	90.92		56.52	
21	D. Office	82.16	72 - 80	48.80	45 - 60

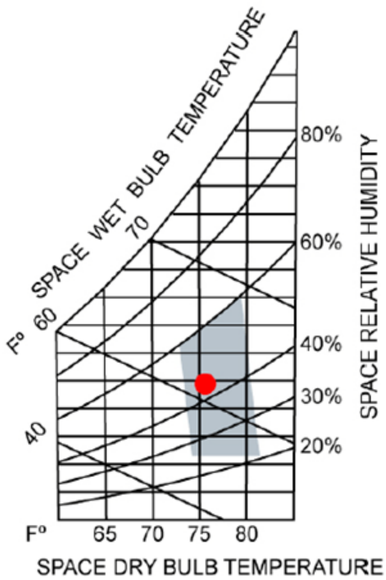


Figure 4.15: ASHRAE standard 55 : Summer Comfort Zone

- To establish a good daily monitoring, exercise, and management considering ergonomic and health and occupational activities (e.g. appropriate time window for break in designated resting area);
- To execute physical intervention to reduce temperature can be with improving ventila-

tion system by natural mean (e.g. installation of weather proofed louvers). This will be reflected in the conceptual design in Chapter 5.

4.7.2 Air quality

4.7.2.1 Data and analysis

Data concerning the air quality is presented in Table 4.22 with value of PM2.5 measured in ppm. Data was measured at targeted points shown in Figure 2.18. Raw data is with the site inspection reports, which will be provided to the Client separately. Persuant to currently applied standard, the recommended safe ranges for PM2.5 is in [0-35].

Table 4.22: Air quality - PM2.5 (ppm).

Point	Description of the Point Location	PM2.5
	A. Inside pump house (outside the office)	
1	Between BP5 and BP6 away from pump	16.00
2	Between BP5 and BP6	16.00
3	Between BP5 and BP4 away from pump	12.00
4	Between BP5 and BP4	15.00
5	Between BP4 and BP3 away from pump	12.00
6	Between BP4 and BP3	15.00
7	Between BP3 and BP2 away from pump	13.00
8	Between BP3 and BP2	15.00
9	Between BP2 and BP1 away from pump	14.00
10	Between BP2 and BP1	14.00
11	Between SP2 and BP1 away from pump	12.00
12	Between SP2 and BP1	14.00
13	Between SP2 and SP1 away from pump	15.00
14	Between SP2 and SP1	14.00
	Average	14.07
	B. Outside pump house	
15	Near Reservoir	11.00
16	Back of the Office	12.00
17	Near Guard House	12.00
18	Near Diesel Tank	13.00
	Average	12.00
	C. Vicinity	
19	Near Diesel Tank, outside vicinity	14.00
20	Near Guard House, outside vicinity	14.00
	Average	14.00
21	Office	11.00

Values of PM2.5 are all within the range of acceptance, inferring no issue with the quality of air.

4.7.2.2 Recommendations

Though there is no issue with the air quality, it is anticipated that future problem can incur with a certain low probability, a better management approach is to ensure that all activities/tasks to be executed within the premise of the PS to follow strictly safety and environmental regulation. For example, all employees and staff to wear appropriate dust-proofed masks when working with activities that potentially incurs dusts or other harmful particles.

4.7.3 Illumination

4.7.3.1 Data and analysis

Data concerning the illumination is presented in Table 4.23 with the LUX value. Data was measured at targeted points shown in Figure 2.18. Raw data is with the site inspection reports, which will be provided to the Client separately. Persuant to RULE 1075.4 of DOLE-OSH standard [5], the recommended minimum for LUX is in 100.

Table 4.23: Illumination (x 100 LUX).

Point	Description of the points	Trials			Ave.
		1	2	3	
	A. Inside pump house (outside the office)				
1	Between BP5 and BP6 away from pump	15.02	12.67	15.50	14.40
2	Between BP5 and BP6	13.89	12.64	11.74	12.76
3	Between BP5 and BP4 away from pump	8.86	9.37	9.21	9.15
4	Between BP5 and BP4	10.79	10.50	10.40	10.56
5	Between BP4 and BP3 away from pump	9.43	10.21	10.09	9.91
6	Between BP4 and BP3	10.45	10.50	9.84	10.26
7	Between BP3 and BP2 away from pump	10.73	10.62	9.96	10.44
8	Between BP3 and BP2	11.15	10.50	10.37	10.67
9	Between BP2 and BP1 away from pump	9.48	9.60	9.76	9.61
10	Between BP2 and BP1	10.52	11.13	10.51	10.72
11	Between SP2 and BP1 away from pump	8.97	7.98	8.01	8.32
12	Between SP2 and BP1	10.57	10.78	10.41	10.59
13	Between SP2 and SP1 away from pump	6.43	5.43	5.83	5.90
14	Between SP2 and SP1	5.66	5.44	5.34	5.48
	Average	10.14	9.81	9.78	9.91
	B. Outside pump house				
15	Near Reservoir	135.70	154.10	160.20	150.00
16	Back of the Office	259.00	263.00	264.00	262.00
17	Near Guard House	170.60	164.40	163.90	166.30
18	Near Diesel Tank	145.70	132.70	124.00	134.13
	Average	177.75	178.55	178.03	178.11
	C. Vicinity				
19	Near Diesel Tank, outside vicinity	268.00	260.00	274.00	267.33
20	Near Guard House, outside vicinity	259.00	269.00	263.00	263.67
	Average	263.50	264.50	268.50	265.50
21	D. Office	321.00	326.00	339.00	328.67

The average lightings inside the Pump House (1,000 Lux) where activities are being conducted are 10x higher than the minimum Illumination Level Acceptable Value (100 Lux).

Illumination is provided by natural means through the Skylights and is augmented by Motion-activated Lighting Systems. At night time, the light provided by Lighting System is for a particular zone only or place where there are motions.

4.7.3.2 Recommendations

- Use artificial lighting equipment when accessing and conducting activities requiring detailed output at darker specific areas especially at night because the existing lighting systems cannot provide adequate lighting or when deemed necessary.
- Such artificial supplementary lightings shall be especially designed for the specific tasks and provided with shading or diffusing devices to prevent glare.
- Periodic cleaning of Skylights and glass windows should be implemented to ensure they are kept clean at all times

4.7.4 Industrial ventilation

4.7.4.1 Data and analysis

There are two ways of ventilation available, natural and mechanical. Natural ventilation is possible through the entrance door in front of Guard House (Door 1) and the other one beside the office (Door 2) which are both always open. Other door, situated at the farthest side of SP1 (Door 3) can also be used as a means of natural ventilation but it is normally closed and not utilized (Figure 4.16). Thus, mechanical ventilation is the main option as the plant installed supply and exhaust fan for the pump house running most of the time, specifically during hot dry days and when there are on-going maintenance activities. An air conditioned office is also available for the operator monitoring the plant daily operation.

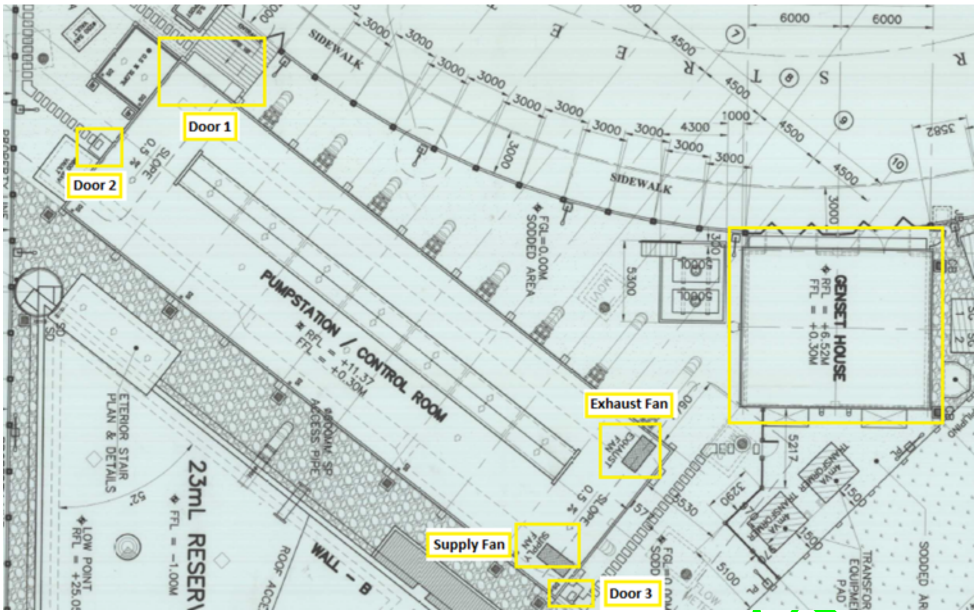


Figure 4.16: Existing ventilation layout

It was realized that natural ventilation through Door 1 and Door 2 is not sufficient to attain the minimum air changes requirement of the Pump House and so mechanical ventilation is utilized most of the time.

4.7.4.2 Recommendations

- Install weather-proof louver at the Pump House. This is to increase the air change inside the pump house by natural ventilation. The purpose is to utilize the Natural wind around the area and at the same time, lessen the Power Consumption of the Supply and Exhaust Fan.

If the PS is rehabilitated with the recommendation, eventually, it will contribute to the reduction of hazards associated with air quality and energy/heat. The recommendation is also reflected in the conceptual design provided in later chapter.

4.7.5 Housekeeping

4.7.5.1 Documentation

Following problems are the facts:

- Current documentation practice is heavily dominated with paper based system, which follows the current practice in Maynilad. There is a large amount/collection of papers that recorded past activities but is of no use and beneficial if data cannot be transformed into digital format for time series analysis, which is an essential part of asset management practice;
- No proper filing/library system with standardized coding rule that will provide convenience for operators/users to timely find appropriate documents;
- Daily operation data is crucial information for future analysis but it is recorded in excel based file without relational tables, which makes it from hard to impossible for data

compilation, filtering, and mining. Many past data has been recorded with outliers and incorrect data types.

4.7.5.2 Waste management and environmental control

There is no issue with regard to waste management and environmental control as confirmed by the checklist shown in Table 4.24

Table 4.24: Waste management.

Description	Status	CS	IT	Remarks
- Sufficient waste segregation assets	yes	1	1	
- waste segregation policy	yes	1	1	
- Signage	yes	1	1	
- Genset emission control	yes		1	

4.7.5.3 Office arrangement and ergonomic

Table 4.25 shows the data concerning parameters associated with office arrangement and ergonomic.

4.7.5.4 Recommendations

Followings are recommendations

- Development of a web-based database management system, with appropriate set of relational data tables to record operational data, power consumption data, and intervention data;
- Development of documentation code and naming for appropriate filing and library/referencing;
- Applying best practices with regard to ergonomic in combination with interior design and arrangement of office space.

4.7.6 Noise

4.7.6.1 Data and analysis

Data concerning the noise is presented in Table 4.26. Data was measured at targeted points shown in Figure 2.18. Raw data is with the site inspection reports, which will be provided to the Client separately. Persuant to

All pumps (6 Booster and 2 Storage Pumps) are running during the Sound Level Testing and so the reading closely represents the normal daily noise level inside the Plant. The average sound level inside the Pump House is 93 dBA, beyond the standard of less than 90 dbA.

On the other hand, the sound level at locations – Inside Pump Station and Reservoir, Outside the Vicinity of Pump Station and inside the office are from 69 – 70 dBA, an acceptable value.

4.7.6.2 Recommendations

- Use protective hearing equipment when working inside the Pump House and have a scheduled break/rest at designated location. Shall not be exposed at such noise beyond 5 hours in a day.
- Designate location inside the Plant with the minimum noise level - can be the Office, Inside Pump Station and Reservoir, and Outside the Vicinity of Pump Station, if below is not possible.
- Install Sound Attenuation Device (such as sound-absorbing wall panels and door seals) at the Office to reduce the current 69 dBA to ideal Office level of 50-55 dBA.
- Purchase a sufficient numbers of electronic noise canceling earphones.

Table 4.25: Ergonomic.

Parameters	Sub-parameters	Status	Remarks
Posture	Head	1	Ceiling height is high enough to cause head injury while sitting or when standing.
	Neck	1	Neck posture is in good ergonomic condition. Consider having an interval for fit-break to avoid neck muscles stiffening.
	Back	1	Back posture while sitting is in good posture. Consider standing and doing fit-break exercises to relax spine.
	Hands/Wrist	0	Proper hand positioning in the keyboard is not observed. Wrist bending is seldom.
	Feet	1	Feet position is in good posture. Good clearance below worktables.
	Eyes	0	The computer monitor is on eyelevel in a certain operator only. Consider adjusting the monitor level comfortable to every operator. Look away into distance in order to rest the eyes for every 10 minutes or so.
Equipment / Tool			
	Computer display	0	Not adjusted and the operator get used to its current setting. Display brightness must be adjustable in the comfortability of the operator-in-charge. Consider the use of anti-glare and blue light to reduce the possibility of eyestrain.
	Keyboard	1	Keyboard position causes poor hand posture that can lead to injury at long exposure.
	Mouse	1	Mouse usage is average due to monitoring. Prolong usage may cause reduced blood flow leading to muscular injury.
	Chair	0	Consider using ergonomic chair that is capable of back support, height, armrest adjustments.
	Table	0	Consider use of ergonomic tables to adjust the height of the table in desired position easily without exerting much effort to adjust manually.
	Files	1	Hard copy file system and location is well observed. Too high or too low file location may require a person to bend his body or force his hand to grip a file in an awkward posture. Frequent situation may lead to MSD.
Operations / Maintenance	Illumination	0	According to the maintenance team, the motion-activated light is not bright enough to complete their task efficiently at night. Moreover, the light has short on-off delay operation that means that the team must move more often to avoid the light to dim. Consider having a manual switch option to by-pass the motion sensors and le the light on while doing maintenance.
	Noise Exposure	1	Noise emitted by the machines in the pump station is high. Consider the use of proper ear protections to reduce the sound intensity. In offices, the sound intensity is acceptable.
	Temperature	1	Temperature in the pump station is not acceptable at long exposure. Consider cooling down the body temperature at the designated area (i.e. outside, office).
Facility / General Workplace	Layout	1	Layout of the pump station is well observed. Distance between pumps is acceptable for well maintenance movement.
	Height clearances	1	Height clearances from ceiling to head is very high. Chance of getting head injury is very low.

4.8 Fire protection and safety (FDAS) audit

4.8.1 Fire alarm and detection system

4.8.1.1 Data and analysis

Summary of data and information from FDAS audit is presented in Table 4.27 with visual images on as-found devices and panels (Figure 4.17).

Table 4.26: Noise (dBA)

Point	Description of the Point Location	Trials									
		1			2			3			
		Min	Ave.	max	Min	Ave.	Max	Min	Ave.	Max	Ave.
	A. Inside pump house (outside the office)										
1	Between BP5 and BP6 away from pump	91.30	94.40	97.50	91.50	93.55	95.60	91.30	93.15	95.00	93.70
2	Between BP5 and BP6	90.00	92.10	94.20	90.50	92.85	95.20	90.20	92.80	95.40	92.58
3	Between BP5 and BP4 away from pump	91.30	93.30	95.30	91.90	93.60	95.30	90.50	92.45	94.40	93.12
4	Between BP5 and BP4	90.60	93.00	95.40	90.80	93.25	95.70	90.60	93.00	95.40	93.08
5	Between BP4 and BP3 away from pump	91.60	93.25	94.90	91.80	93.55	95.30	91.30	93.30	95.30	93.37
6	Between BP4 and BP3	91.10	93.20	95.30	91.50	93.35	95.20	91.90	93.50	95.10	93.35
7	Between BP3 and BP2 away from pump	92.20	93.90	95.60	92.50	93.90	95.30	92.10	94.05	96.00	93.95
8	Between BP3 and BP2	91.20	92.60	94.00	90.70	92.35	94.00	90.80	92.40	94.00	92.45
9	Between BP2 and BP1 away from pump	91.70	93.65	95.60	91.70	93.45	95.20	92.10	93.45	94.80	93.52
10	Between BP2 and BP1	90.40	92.70	95.00	90.20	92.55	94.90	90.90	93.00	95.10	92.75
11	Between SP2 and BP1 away from pump	93.50	94.85	96.20	92.40	94.55	96.70	92.00	94.10	96.20	94.50
12	Between SP2 and BP1	90.70	92.95	95.20	90.60	92.85	95.10	90.60	92.70	94.80	92.83
13	Between SP2 and SP1 away from pump	92.10	94.30	96.50	91.90	93.85	95.80	92.20	94.00	95.80	94.05
14	Between SP2 and SP1	91.20	93.35	95.50	90.80	92.95	95.10	90.80	91.95	93.10	92.75
	Average		93.40			93.33			93.13		93.29
	B. Outside pump house										
15	Near Reservoir	64.70	71.70	78.70	64.20	65.80	67.40	64.20	65.60	67.00	67.70
16	Back of the Office	71.50	77.25	83.00	71.40	74.90	78.40	71.80	72.60	73.40	74.92
17	Near Guard House	65.40	66.30	67.20	64.60	65.65	66.70	64.80	66.35	67.90	66.10
18	Near Diesel Tank	65.10	72.70	80.30	65.70	69.75	73.80	65.40	69.35	73.30	70.60
	Average		71.99			69.03			68.48		69.83
	C. Vicinity										
19	Near Diesel Tank, outside vicinity	65.70	69.50	73.30	66.00	68.35	70.70	65.50	72.35	79.20	70.07
20	Near Guard House, outside vicinity	66.80	71.75	76.70	67.00	71.75	71.00	66.90	71.75	76.00	71.07
	Average		70.63			70.05			72.05		70.91
21	Office	66.70	68.10	69.50	68.00	68.40	68.80	68.60	69.35	70.10	68.62

4.8.1.2 Recommendations

The findings/facts and results of the audit are presented in Table 4.29. Visual images of assets are shown in Figure 4.20.

Highlights are

- **Smoke Detector 01:** Red indicator light should be visible after spraying of smoke tester. Removal of device from base to Reset contact point and cleaning did not show any improvement on the device. Hence device is declared not functioning and there is communication failure between device and FACP panel;
- **Smoke Detector 02:** Smoke detector is still functioning but there a is communication failure between device and FACP panel since the FACP did not detect the change of status of the device during testing;
- **Smoke Detector 03:** Red indicator light should be visible after spraying of smoke tester. Removal of device from base to Reset contact point and cleaning did not show any improvement on the device. Hence device is declared not functioning and there is communication failure between device and FACP panel;
- **Smoke Detector 04:** Red indicator light should be visible after spraying of smoke tester. Removal of device from base to Reset contact point and cleaning did not show any improvement on the device. Hence device is declared not functioning and there is communication failure between device and FACP panel;

Table 4.27: FDAS data highlights.

No.	Assets	Status	Remarks
A	Visual check of the fire alarm control panel		
1	Panel Status, installed and location area	1	Power up, located near Engineering office with light indicator
2	Power indicator lamp operational	1	Operational
3	Devices properly indicated and marked	1	Device installed motor control room and 2nd floor, 3 meters in height
4	Panel clear from trouble indicators	0	For verification of fault
5	Lamp test indicator operational	0	For verification of fault
6	Zones properly indicated and marked	1	Conventional system
7	Check if it's connected to sprinkler system	0	For verification on testing
B	Checking of installed devices		
1	Check floor plan lay-out and location of the device if accessible/easy to access	1	No FDAS lay-out but devices are accessible
2	Heat detectors and / or smoke detectors indicator lamp functioning	1	For verification
3	Heat detectors and / or smoke detectors indicator lamp functioning	0	Not all indicator lamp the device are functioning
4	Pull station locations acceptable	0	For Verification
5	Bells and buzzers operated correctly	0	For verification
6	Bells and buzzers audibility	0	For verification
7	Strobe lights locations are acceptable	0	Lacking devices at rooms
8	Strobe light operated correctly	0	For verification during testing
9	Are Fire alarm zones (areas) clearly marked	0	
10	Is there a maintenance and service contract for the fire alarm system	1	None as per interview with the maintenance
	Does the Fire Alarm System smoke detector, heat detector, manual call point , horn and strobe light working and have a current inspection tag	0	None
	Is the fire alarm system if full working order	0	For verification

Table 4.28: FDAS data highlights.

No.	Assets/Description	Status	CS	Remarks
1	Evacuation plan	1		
2	Fire extinguishers	1		Green (HCFC)
				FEX signage without physical Fire Extingushers
				As per plan, there should be 6 FEX
3	Fire exits	1		With exit indication
4	Fire hose cabine	1		With inspection tag 8/30/18
5	Fire sprinkler system	1		No sprinkler system
6	Emergency exit signages	1		BIGLITE Brand
				Exit signage do no have power supply
7	Emergency lights	1		Firefly brand. Last Inspection 8/30/18
				All emergency lights are with light indicator
8	PPE cabinet	1		with latest tag inspection as of 8/30/18

- **Smoke Detector 05:** Smoke detector is still functioning but there is a communication failure between device and FACP panel since the FACP did not detect the change of status of the device during testing;
- **Smoke Detector 06:** Red indicator light should be visible after spraying of smoke tester. Removal of device from base to Reset contact point and cleaning did not show any improvement on the device. Hence device is declared not functioning and there is communication failure between device and FACP;
- **Manual Call Point 01:** Communication failure between Manual call point 01 and FACP;
- **Manual Call Point 02:** Communication failure between Manual call point 02 and FACP;
- **Buzzer with strobe light 01:** Communication failure between Buzzer 01 and FACP;
- **Buzzer with strobe light 02:** Communication failure between Buzzer 02 and FACP;
- **Fire Alarm control Panel (FACP):** System failure of FDAS and devices due to communication failure and not functioning devices installed within the system.

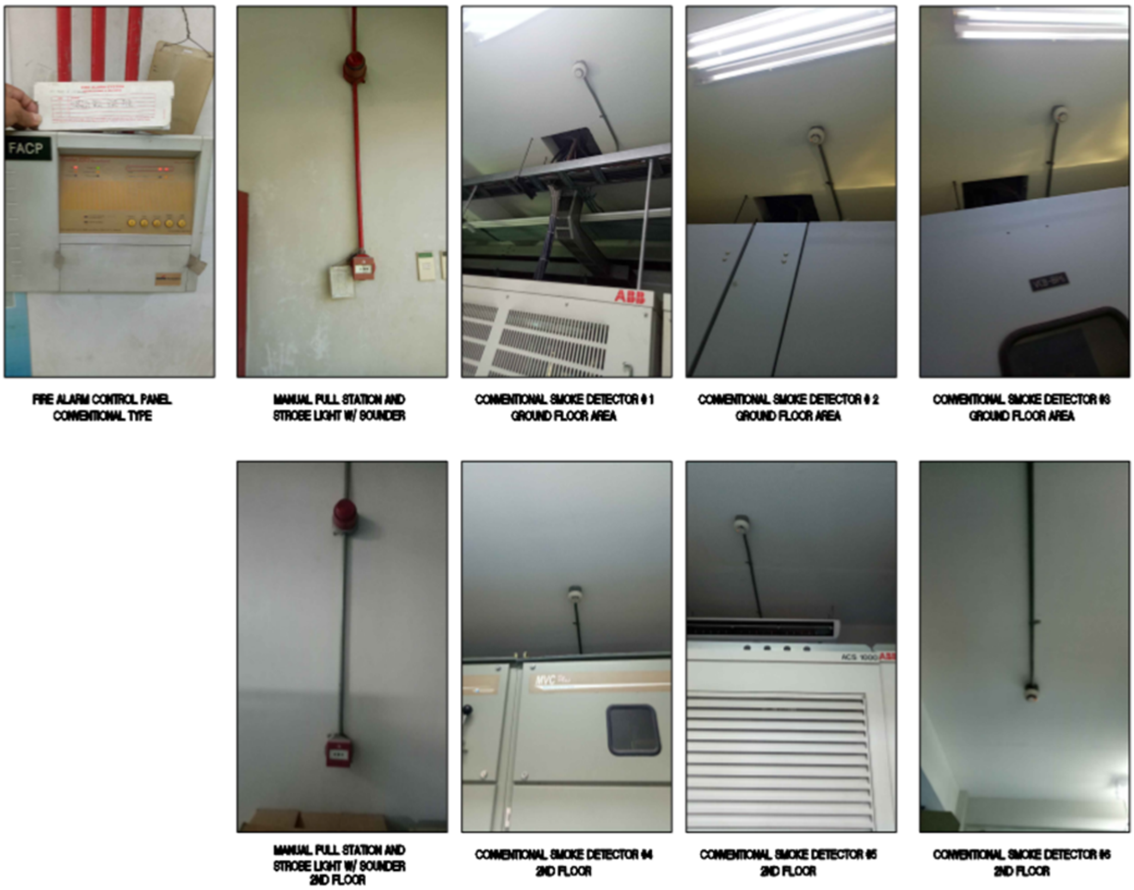
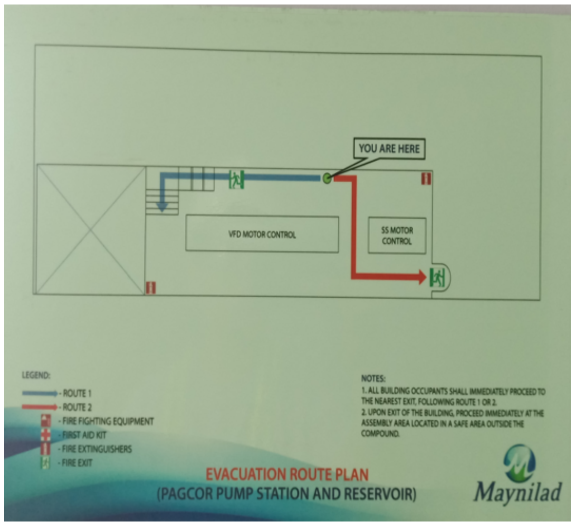


Figure 4.17: As-found devices and panels

(a - 1st floor)



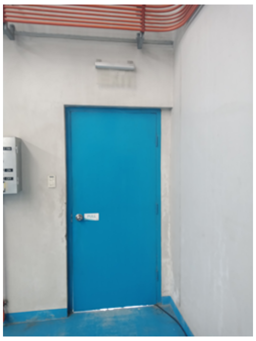
(b -2nd floor)

Figure 4.18: Existing evacuation plan

In brief, FDAS of the station is not provide adequate level of services mainly due to:

- Most of the smoke detector devices, manual call point, buzzer and the FACP were not functioning. These were established during the conducted testing of FDAS and devices;
- Lacking smoke / heat detector devices at substation room and genset room, engineer's office, pantry and guardhouse. In every close room there should be a device installed to


(a - Emergency light)


(b-Exit door)


(c- Cabinet)


(d - Fire hose)


(e - HFCF FEX)

(f-Dry chemical FEX)

(g - Exit signage)

Figure 4.19: Existing safety devices

detect heat or smoke.

Short term recommendations

- Troubleshoot wiring for output voltage signal and check fuse of panel to determine if FACP if is still functioning completely and working in coordination with the devices;
- Troubleshoot wiring outside the panel to determine if there is non-continuity and check end of line resistor if it is still functioning;
- Troubleshoot devices declared as non-functioning. Follow manufacturers procedure on troubleshooting.

Short term recommendations

✓ Troubleshoot wiring for output voltage signal and check fuse of panel to determine if FACP if is still functioning completely and working in coordination with the devices;

✓ Troubleshoot wiring outside the panel to determine if there is non-continuity and check end of line resistor if it is still functioning;

✓ Troubleshoot devices declared as non-functioning. Follow manufacturers procedure on troubleshooting.

Long term recommendations

✓ Replace the system with newer and addressable type FACP to determine exact location of fire as it happens;

✓ Additional smoke detector devices are required in engineer's office, guardhouse, pump area;

✓ Additional heat detector devices are required in pantry, genset room, substation room;

Table 4.29: FDAS analysis.

No.	Assets	CS	IT	Facts	Remarks
1	SM 01	0	4	dust inside and outside no light indication broken base Spray Max 3 times	no response after repeat sprays Repeat clean After 3x sprays, still no response
2	SM 02	1	4	dust inside and outside With light indication (orange color maintained light) Spray Max 3 times	no response after repeat sprays Repeat clean After 2x spray, light turned red but without response on the alarm panel Removed and cleaned dirt and smoke particles No light indicator after cleaning
3	SM 03	0	4	dust inside and outside With light indicator (orange color maintained light) Spray Max 3 times	no response after repeat sprays Repeat clean After 3x sprays, still no response Removed and cleaned dirt and smoke particles No light indicator after cleaning (reset)
4	SM 04	0	4	dust inside and outside With light indicator (orange color maintained light) Spray Max 3 times	Same as SM 03
5	SM 05	0	4	Same as SM 04	Same as SM 04
6	SM 06	0	4	Same as SM 04	Same as SM 04
7	MCP 01	0	4	No response after pushing	
8	MCP 02	0	4	No response after pushing	
9	Buzzer 01	0	4	Spray SD /push MCP	No response/audible sound/ smoke
10	Buzzer 02	0	4	Spray SD /push MCP	No response/audible sound/ smoke
11	FACP	0	4	Spray SD /push MCP	No response No response on pushbutton, reset, evacuation, silence, mute buzzer or disabled/enabled Remain light signal indicator for fire, power charger/fault. Fault zone 1&3

- ✓ Additional strobe with sounder and call point at the genset and substation room since these rooms are located in separate buildings and for safety reasons for sounding alarm at the instant that there is fire;
- ✓ Annual Inspection, Testing and Maintenance

System Testing

FDAS shall be subjected to the following tests conforming to the Philippine Electronics Code of 2014 and Philippine Electrical Code of 2017

- ✓ Testing of insulation resistance and continuity of wires;
- ✓ Verification of installed devices;
- ✓ Operation and response of FDAS;
- ✓ Testing the operation of initiating devices;
- ✓ Measuring sound pressure level generated by notification devices;

Records

Every FDAS system shall keep the following documentations

- ✓ A complete set of operation and maintenance manuals of the manufacturer covering all equipment used in the system;
- ✓ A complete set of as-built drawings;

a - Smoker detector 01

b - Smoker detector 02

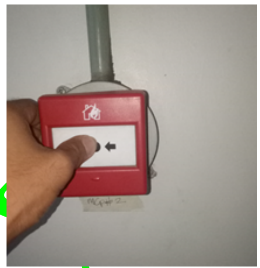
c - Smoker detector 03

d - Smoker detector 04

e - Smoker detector 05

f - Smoker detector 06

g - Manual call point 01



h - Manual call point 02

i - buzzer 01

j - buzzer 01

k - FACP

Figure 4.20: FDAS assets

- ✓ A written sequence of operation;
- ✓ Record of completion and results of every inspection, testing and maintenance;
- ✓ Record of components within the database.

4.8.2 Lighting protection system

4.8.2.1 Data and analysis

No lightning protection was installed for this PS.

4.8.2.2 Recommendations

Refer to the conceptual design in Chapter 5

Short term Recommendations

Plan for the installation of a new lightning protection system

- ✓ the LPS conforms to the design and is based on the standard;

- ✓ all components of the LPS are in good condition and capable of performing their designed functions, and that there is no corrosion.

Long term Recommendations

Plan for the installation of a new lightning protection system

- ✓ According to the standard, an inspection should be undertaken during the construction of the structure, after the installation, after alterations or repairs, and when it is known that the structure has been struck by lightning;
- ✓ It is also recommended that inspections take place "periodically at such intervals as determined with regard to the nature of the structure to be protected", taking into account the local environment, such as corrosive soils and corrosive atmospheric conditions and the type of protection measures employed;
- ✓ The inspection comprises checking the technical documentation, visual inspections and test measurements;
- ✓ Prepare an inspection guide to facilitate the inspection process containing sufficient information on the installation and its components, tests methods and previous inspection/test data;
- ✓ During the visual inspection, the following should be checked;
  - the deterioration and corrosion of air-termination elements, conductors and connections
  - the corrosion of earth electrodes
  - the earthing resistance value for the earth-termination system
  - the condition of connections, equipotential bonding and fixings.
- ✓ For those parts of an earthing system and bonding network not visible for inspection, tests of electrical continuity should be performed;
- ✓ An inspection report should be prepared detailing the status of the system, any deviations from the technical documentation and the results of any measurements undertaken. Any obvious faults should also be reported.

No lightning protection system is 100% effective. A system designed in compliance with the standard does not guarantee immunity from damage. Lightning protection is an issue of statistical probabilities and risk management. A system designed in compliance with the standard should statistically reduce the risk to below a pre-determined threshold. The IEC 62305-2 risk management process provides a framework for this analysis. An effective lightning protection system needs to control a variety of risks. While the current of the lightning flash creates a number of electrical hazards, thermal and mechanical hazards also need to be addressed.

Risk to persons (and animals) include:

- Direct flash;
- Step potential ;
- Touch potential ;
- Side flash ;
- Secondary effects
  - asphyxiation from smoke or injury due to fire
  - structural dangers such as falling masonry from point of strike
  - unsafe conditions such as water ingress from roof penetrations causing electrical or other hazards, failure or malfunction of processes, equipment and safety systems

Risk to structures & internal equipment include:

- Fire and/or explosion triggered by heat of lightning flash, its attachment point or electrical arcing of lightning current within structures ;
- Fire and/or explosion triggered by ohmic heating of conductors or arcing due to melted conductors;
- Punctures of structure roofing due to plasma heat at lightning point of strike ;
- Failure of internal electrical and electronic systems ;
- Mechanical damage including dislodged materials at point of strike.

4.8.3 Ground-Fault circuit interrupter (GFCI) or electric leakage circuit breaker (ELCB) or Residual circuit devices (RCD)

4.8.3.1 Data and analysis

No ground fault circuit interrupter (GFCI) or earth leakage Circuit breaker (ELCB) protection was installed in the panel for FDAS for this PS.

4.8.3.2 Recommendations

Refer to the conceptual design in Chapter 5

4.8.4 Electrical safety and protective devices

4.8.4.1 Data and analysis

Facts obtained from inspection are presented in Table 4.30 with indicative figures for each devices presented in Figure 4.21.

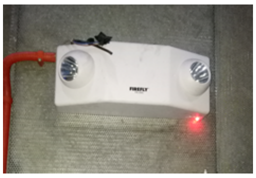
4.8.4.2 Recommendations

Based on the status of devices, recommendations are with intervention types shown in Table 4.30. Chapter 5 further illustrates the recommendation with the conceptual design.

4.8.5 Recommendations

Table 4.30: Protective devices.

No.	Assets	CS	IT	Facts	Remarks
1	Exit light 01 (Fig. 4.19-g)	0	4	Not function No light indication	Unsafe risk to the safety of people in the event of power a power outage
2	Exit light 02 (Fig. 4.21-h)	0	4	Not function No light indication	Unsafe risk to the safety of people in the event of power a power outage
3	Exit light 03 (Fig. 4.19-b)	0	4		Unsafe risk to the safety of people in the event of power a power outage
4	Exit light 04 (Fig. 4.21-i)	0	4		Unsafe risk to the safety of people in the event of power a power outage
5	Exit light 05 (Fig. 4.21-j)	0	4		Unsafe risk to the safety of people in the event of power a power outage
6	Emergency light tag 01 (Fig. 4.19-a)	0	4	No updated Last update is 30/Aug/2018	Unsafe Failure to inspect emergency light can make it ineffective
7	Emergency light tag 02 (Fig. 4.21-a)	0	4	No tag	Unsafe Failure to inspect emergency light can make it ineffective
8	Emergency light tag 03 (Fig. 4.21-b)	0	4	No tag	Unsafe Failure to inspect emergency light can make it ineffective
9	MCP#1 (Fig. 4.20-g)	0	4	No updated	Unsafe Failure to inspect manual call point can make it ineffective in case of fire
10	Fire extinguisher 01 (Fig. 4.21-c)	0	4	Missing	Unsafe Failure to replace or locate fire extinguisher can delay response to
11	Fire extinguisher 02 (Fig. 4.21-d)	0	4	Missing	Unsafe Failure to replace or locate fire extinguisher can delay response to
12	Fire extinguisher 03 (Fig. 4.21-e)	0	4	Missing	Unsafe Failure to replace or locate fire extinguisher can delay response to
13	Fire extinguisher 04 (Fig. 4.21-f)	0	4	No inspection tag	Unsafe Failure to inspect fire extinguisher can make it ineffective in case of fire.
14	PPE cabinet tag (Fig. 4.21-g)	0	4	Not updated Last update is 7-30-2018	Unsafe Failure to inspect PPE cabinet may not ensure completeness of content and PPE may have damage that can make these equipment ineffective



a - Emergency light 2

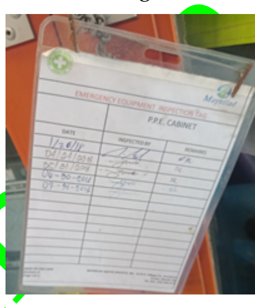
b - Emergency light 3

c - Fire extinguisher 1

d - Fire extinguisher 2

e - Fire extinguisher 3

f - Fire extinguisher 4



g - PPE cabinet

h - Exit light 02

i - Exit light 04

j - Exit light 05

Figure 4.21: Protective devices.

Chapter 5

Conceptual Design and Reliability Study

5.1 Basis of Design

5.1.1 As-built drawings

A collection of as-built drawings are given in A3 print out with electronic files saved both in PDF and CAD formats.

5.1.2 Mechanical design

As set of conceptual drawings is given in Appendix C.1.

5.1.3 FDAS design

5.1.3.1 Fire alarm and detection system

Design criteria

The conceptual design for FDAS has been developed based on findings/results of the audit (refer to subsections 4.8, design criteria including required code of practice, and the required level of services.

- Individual components shall be compatible with each other and shall be approved and listed by institutions recognized by the relevant authority
- The FDAS designer shall have the experience in the proper design, application, installation and testing of FDAS
- If the total floor area is more than 8000m2, a semi-addressible system shall be used, otherwise, a conventional system maybe used.
- Automatic detection shall have a complete indoor coverage of building or facilities including all rooms, halls, etc.
- For smoke detectors, the performance characteristics of the detector and the area shall be taken into account when selecting smoke detectors. Smoke detectors shall not be installed in rooms with temperature below 5 degree centigrade, above 45 degree centigrade and with relative humidity above 93
- For heat detectors, temperature rating shall be set at least 11 degree centigrade above maximum expected temperature and is spaces not more than 7.5meters. It shall not be installed in locations where relative humidity is above 93 % and if the ceiling is more than 4 meters.
- Beam-type smoke detector shall be used if ceilings are more than 6m in height and shall be kept clear of opaque obstacles at all times

- Manual detection is achieved through the manual activation of fire push or pull stations installed at a height of 1.4meters above floor and shall be easily seen and is accessible. It is usually colored red.
- Alarm shall be clearly audible throughout the floor and or/or building where they are installed. It shall have a minimum of 65 dbA or 10db higher than ambient room noise and a maximum of 115 dbA.
- Visual notification shall be used along with audible notification for areas where hearing protection is worn.

Design

5.1.3.2 Lighting protection system

Requirements

The design of a lightning protection system needs to: Intercept lightning flash (i.e. create a preferred point of strike) Conduct the lightning current to earth Dissipate current into the earth Create an equipotential bond to prevent hazardous potential differences between LPS, structure and internal elements/circuits

Following points shall be considered

- The lightning protection design shall be in accordance with the requirements of Article 2.90 Protection against Lightning , Philippine Electrical Code 2017 and NFPA 780, standard for the installation of lightning protection systems;
- The building lightning protection system shall include
  - Roof mounted copper air terminals;
  - Ground rods of lightning protection shall shall be metal clad steel with a diameter of 20mm by 3 meters long connected triangularly with equal distances of 3 meters between two ground rods;
  - Down conductor, 50mm2 Bare copper wire and shall be placed in protective conduit (PVC);
  - Lightning protection shall have electronically controlled mechanical register which activates registration for every discharge;
  - clamps, conduits and auxiliary equipment as required for complete and operational lightning protection system. Materials shall be resistant or protected against corrosion.
- The company providing the design should have a minimum of 5 years experience and be well versed with Article 2.90 Protection against Lightning , Philippine Electrical Code 2017 and NFPA 780;
- Lightning protection systems are designed specifically for the building or structures they are intended to protect;
- The design is not only impacted by the shape and size, but also by building systems and structural components.

Installation

The installation shall be in accordance with the requirements set forth in Article 2.90 Protection against Lightning and NFPA 780 and installed in a neat and workmanlike manner

5.1.3.3 Ground Electrode Installation and Common Bonding

Ground electrode installation and common building

- Ground electrodes shall be installed in accordance with NFPA 780 and Article 2.90 of PEC 2017.
- Common bonding between all building electrode systems shall be installed in accordance with NFPA 780 and PEC 2017
- Maintain horizontal or vertical runs of ground wires and ensures that all bends have at least 200 mm radius and angle of any bend shall not be less than 90 degrees.
- Lightning carrier cable and down conductor shall be supported every 1.50 meters on center using fabricated copper clamps, bolted to roof slab with plastic expansion sleeves.
- Ground rods should be driven far enough away from the footing and drain tile and also past the roof's drip edge.
- Ground rods shall be installed into undisturbed soil.
- If it is not practical to install ground rods outside of the building, the ground rods should be installed as close to the building's walls as practical without damaging the footing.
- The correct ground rod driver adapter should be used to avoid mushrooming or damaging the end of the ground rod.
- If the damage to the ground rod is to severe, the top of the rod may need to be cut off so that the ground rod clamp or exothermic connection can be properly made
- For testing and maintenance, access of each ground electrode should be available.

Ground ring electrode installation

- If required, a ground ring electrode for the lightning protection system shall be installed at least 460mm (18 inches) below earth unless prohibited by ground conditions;
- A ground ring electrode installed for the purposes of electrical grounding shall be installed to a depth of at least 765 mm (30 inches);
- Ground ring electrodes shall be continuous around the structure and connected to all down conductors. The ground ring electrode shall be installed below the line.

field test

Test the grounding system to assure the continuity and that the resistance to ground is not excessive.

5.1.4 WEM design

5.2 Bill of Materials

Based on the recommendations and conceptual design, a high level Bill of Quantity (BOQ) can be generated . The BOQ table includes the condition states and intervention types respectively.

5.3 Determination of optimal intervention strategies

This section focuses on determination of intervention strategies for pumps of the PS. Other assets such as electrical assets and assets belong to FDAS system are not part of the analysis because they are utmost critical assets that require to provide adequate level of services at all time. Intervention strategies for electrical assets and FDAS assets are suggested to follow replacement schedule defined by the manufacturers.

5.3.1 Reliability

With the historical data given (refer to Table 2.2), it is not possible to precisely quantify the reliability for each pump. Thus, In order to more or less estimate the reliability, obtaining knowledge and experience of the end-users becomes important.

In reviewing the activity reports, mostly in 2016, following facts are revealed

- Pumps fail to provide adequate level of services due to aging/wear out of bearing, coupling, and mechanical seals both inside and outside;
- Defective and aging check valves from time to time caused the disruption of normal operation;
- Strong vibration was observed also due to possible misalignment and experienced of foreign objects.

We assume reliability of a pump to follow a Weibull function. The Weibull function is suitable function to be used in survival/reliability analysis since it considers the memory of assets, i.e. past failure probability will be considered with duration of failure (refer to subsection 3.5.4 for further description on Weibull model).

Table 5.1 shows the assumed values used for model's parameters.

Table 5.1: Weibull parameters.

Assets	Weibull parameters		MTTF	Remarks
	α	m	(hours)	
BP1	0.052	1.752	5,000	
BP2	0.052	2.190	4,000	
BP3	0.052	1.947	4,500	
BP4	0.052	2.086	4,200	
BP5	0.052	1.460	6,000	
BP6	0.052	1.593	5,500	
SP1	0.052	1.348	6,500	
SP2	0.052	1.348	6,500	

Using the parameter values in Table 5.1, reliability curves for respective pumps can be drawn (Figure 5.1. Figure 5.2) presents a snapshot of reliability of pumps within 5 years.

5.3.2 Impacts

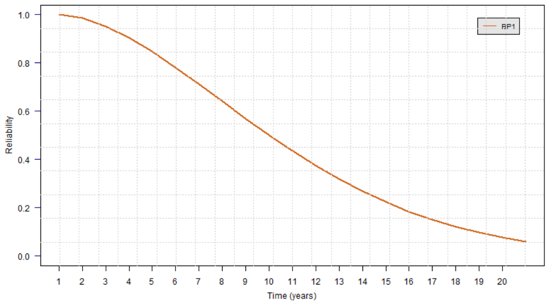
Impacts are costs or loss of benefits incurred to the Client and users. Impacts are incurred by execution of PI or CI and by disruption to the operation of the PS.

Impacts incurred by execution of PI can be estimated based on, for example, conceptual design with the ballpark estimate. However, impacts incurred by execution of a CI is not easy to obtain due to lack of historical data. This is similar to the estimation of impacts such as loss in revenue, reputation, and regulatory.

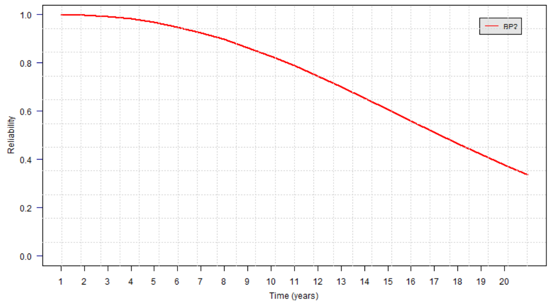
Fortunately, from mathematical view point, the optimization model presented in subsection 3.7.1 will be only dependent on the ratio between CI and PI. This means that we can make assumption on the ratio between CI and PI based on holistic approach. For example, if the PI is 10 millions PHP and CI is 20 million, the ratio would be CI/PI =2, and the model will determine the optimal time window (T) to execute the PI. This time window T will not change as long as the ratio between CI/PI is the same.

Table 5.3 shows the assumption on impacts incurred by execution of PI and CI as well the the impacts incurred considering the 3Rs (revenue, reputation, and regulatory).

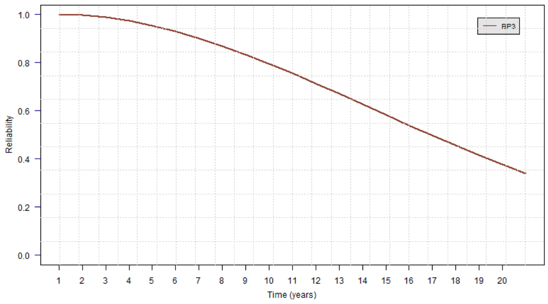
Values of revenues incurred by execution on respective pumps shall be calculated based on assumption on maintainability (e.g. duration of CI execution to fix the pump). Reputation and regulatory are not straightforward to estimate in monetary units, however, they can be assumed to be measured by "Willingness to Pay".



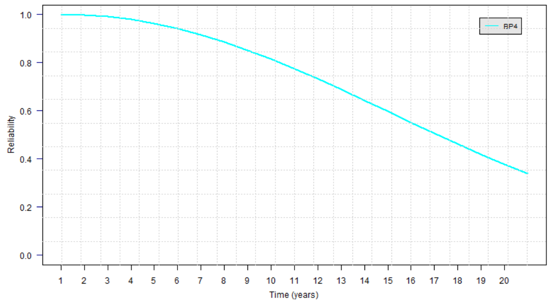
a - BP#1



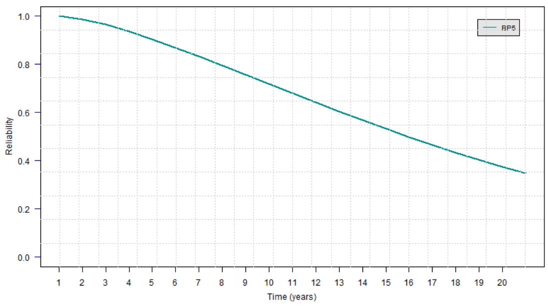
b - BP#2



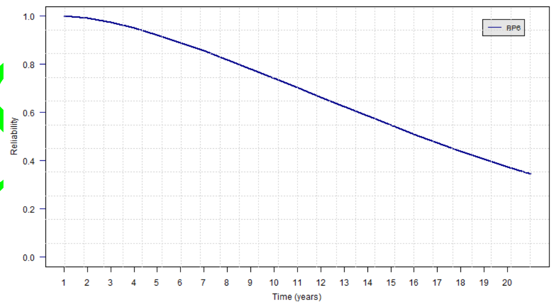
c - BP#3



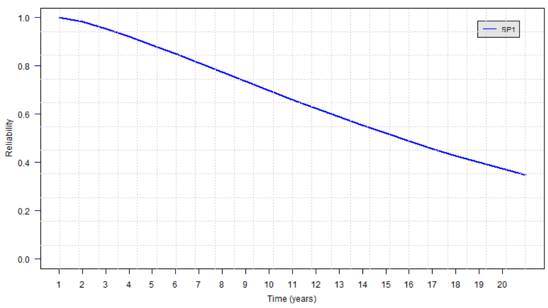
d - BP#4



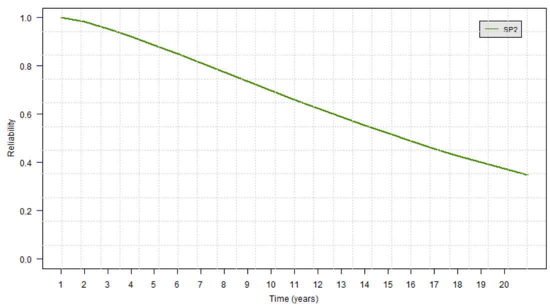
e - BP#5



f - BP#6



g - SP#1



h - SP#2

Figure 5.1: Reliability

5.3.3 Optimal Time Window and Impacts

Figure 5.3 presents a collection of curves representing Optimal Time Window (OTW) and impacts incurred by executing PIs on respective pumps.

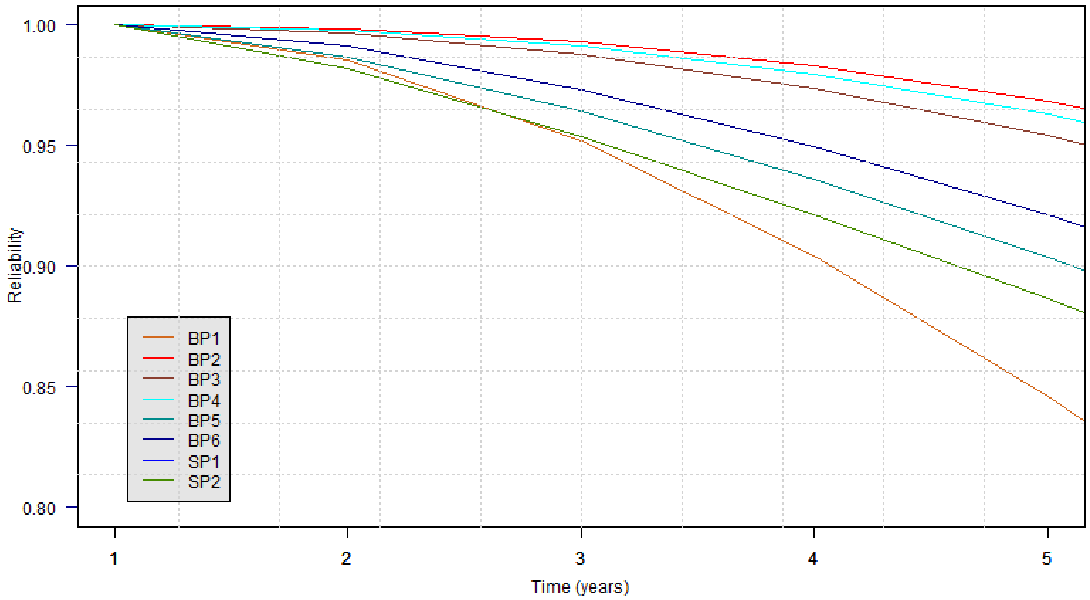


Figure 5.2: Reliability curves

Table 5.2: Impact values (mus).

Assets	Impacts (mus)					Discount
	PI	CI	R1	R2	R3	ρ
BP1	1	3	2	2	2	0.085
BP2	1	3	2	2	2	0.085
BP3	1	3	2	2	2	0.085
BP4	1	3	2	2	2	0.085
BP5	1	3	2	2	2	0.085
BP6	1	3	2	2	2	0.085
SP1	1	3	2	2	2	0.085
SP2	1	3	2	2	2	0.085

Note: R1, R2, R3 are revenue, reputation and regulatory, respectively.

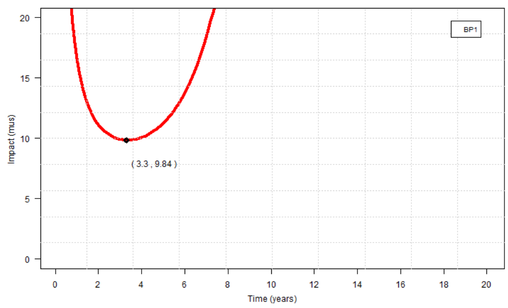
The curves are with parabolic shapes, with a minimal point representing the optimal point obtained by the model. Shapes of the curves prove following important conclusions

- If a PI is executed too often, the failure probability will be decreased, however, at the same time, more money is to spend on intervention activities. It will be a waste of resources to follow a program that triggers PIs;
- The impact will decrease as the OTW increases to the optimal point and then go upward indicating that if a PI is executed beyond a certain reliability threshold, failure probability will increase, leading to more sudden failures that require to execute CIs and higher loss (e.g. the 3 Rs).

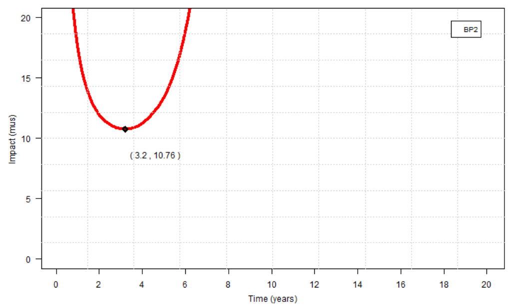
5.3.4 Sensitivity analysis

As a matter of fact, results of the optimization model are subjected to uncertainties with model's parameters and variables. Model's parameters are deterioration parameters α and m and impacts that should be obtained from historical data.

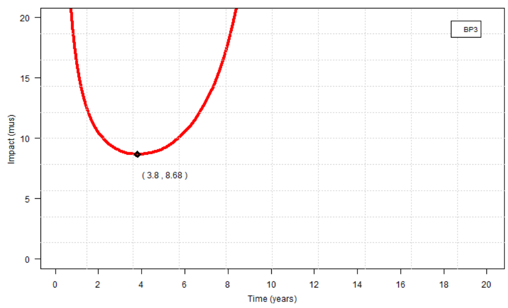
This subsection provides results of sensitivity analysis (SA) conducted on Weibull parameters α and m and the ratio between CI and PI. A SA was conducted by running the targeted parameter



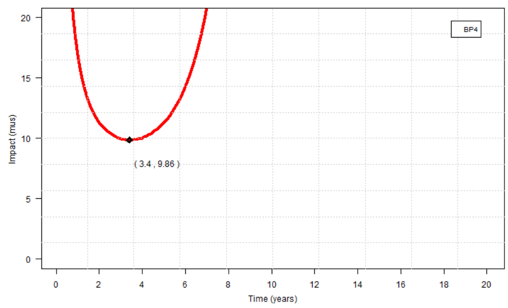
a - BP#1



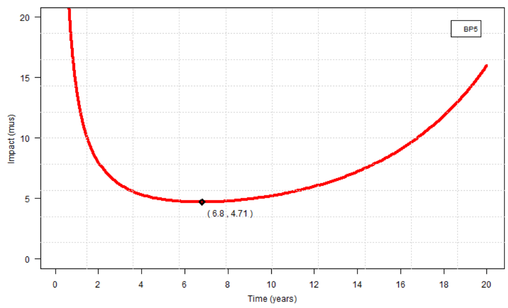
b - BP#2



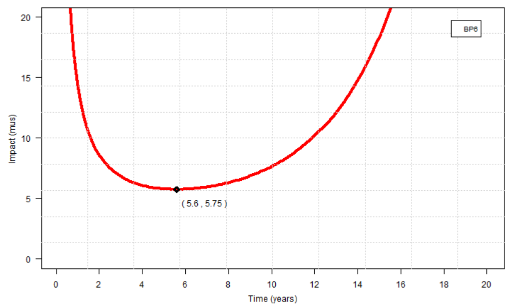
c - BP#3



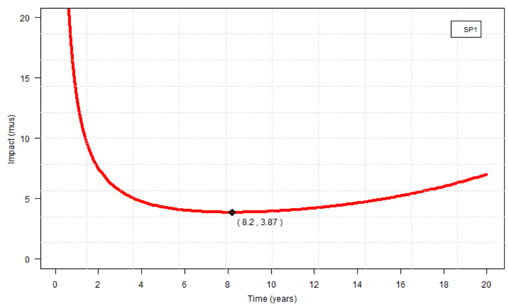
d - BP#4



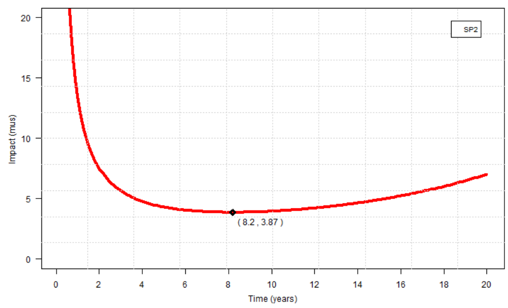
e - BP#5



f - BP#6



g - SP#1



h - SP#2

Figure 5.3: Impact curves

in a pre-defined range while keeping other parameters constant.

Results of the SA on parameter α are shown in Figure 5.4, with following discussion points.

- Values of OTW follow either exponential function or log-normal function with decreasing

Table 5.3: Impact values (mus).

Assets	OTW (years)	Minimum Impact (mus)
BP1	4.60	7.043
BP2	3.20	10.757
BP3	3.80	8.676
BP4	3.40	9.862
BP5	6.80	4.709
BP6	5.60	5.750
SP1	8.20	3.869
SP2	8.20	3.869

Note: OTW stands for Optimal Time Window to execute an PI.

trend and be converged to a minimum year. This is logic as the smaller value of α is, the less failure probability, and therefore the OTW will be deferred longer;

- Values of impact follow a monotonic increasing function. This is also logic as the higher failure probability infers more CIs to be executed.

Results of the SA on parameter m are shown in Figure 5.5, with following discussion points.

- Values of OTW follow an exponential function function with decreasing trend and be converged to a minimum year. This is logic as the smaller value of m is, the less failure probability, and therefore the OTW will be deferred longer;
- Values of impact follow a monotonic increasing function. This is also logic as the higher failure probability infers more CIs to be executed.

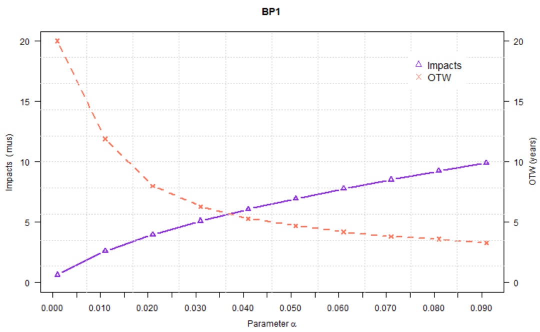
Results of the SA on the ratio CI/PI are shown in Figure 5.6, with following discussion points.

- Values of OTW follow an exponential function function with decreasing trend and be converged to a minimum year. This is logic as if the value of CI is not much different from PI, there is no need to perform PI often, the operators can just execute a CI when pumps fail. However, if the ratio is high, it means it will be very costly to let the system fails, hence it is advisable to shorten the time window to execute PIs to prevent possible failures from happening;
- Values of impact follow a monotonic increasing function. This is also logic as the higher ratio of CI/PI, the more impacts will be incurred with CI and therefore the annual cost will increase.

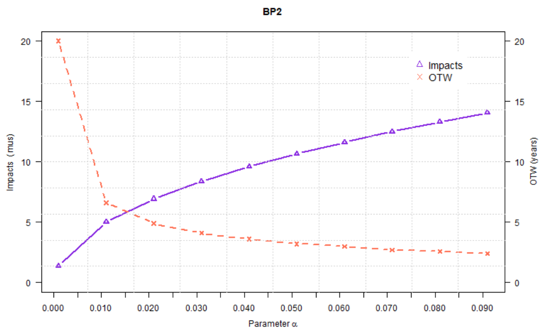
5.4 Return on Investment

It is important to note that in asset management context, the Return on Investment (ROI) is understood different from the ROI used for CAPEX projects. In CAPEX project, ROI is a ratio between the Net Present Value (NPV) of benefits (e.g. positive sum of cash flow) incurred over a pre-defined life cycle of a project (e.g. 20 or 30 years), at which there is a salvage value of the facility.

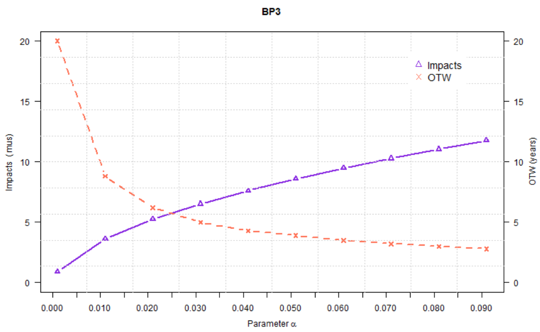
In asset management context, the ROI encompasses the ROI used in CAPEX project. This can be obviously seen in the impact curves shown in Figure 5.3. If the owner follows the optimal time window defined to execute a PI on any individual pump, the return on investment compared to other strategy that follow different time window is the difference of the impacts.



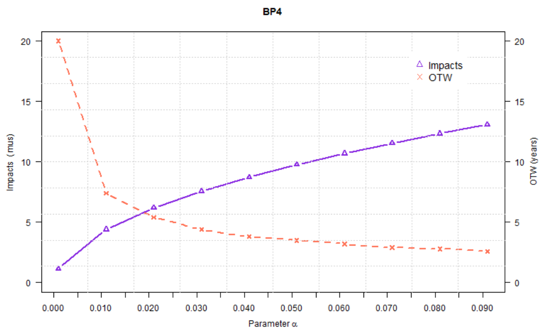
a - BP#1



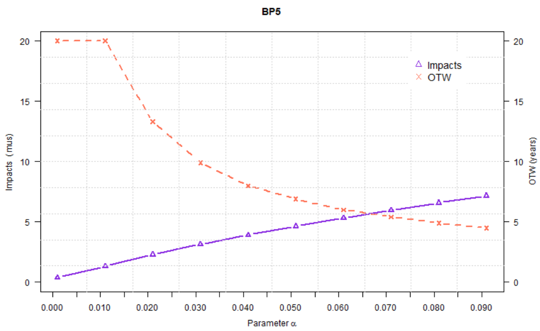
b - BP#2



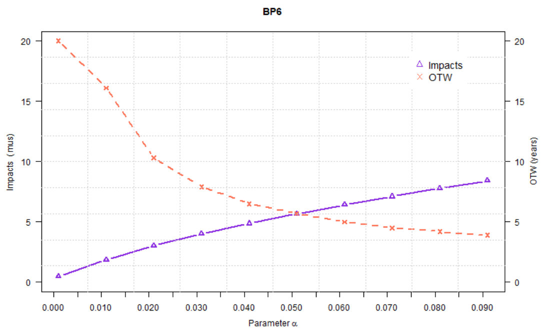
c - BP#3



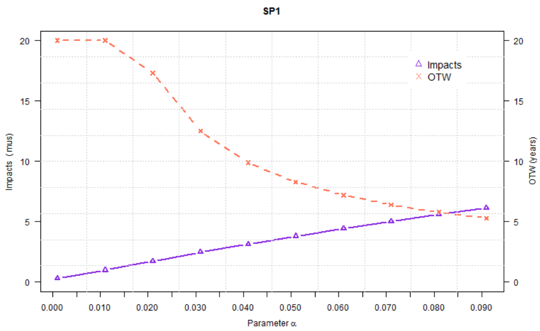
d - BP#4



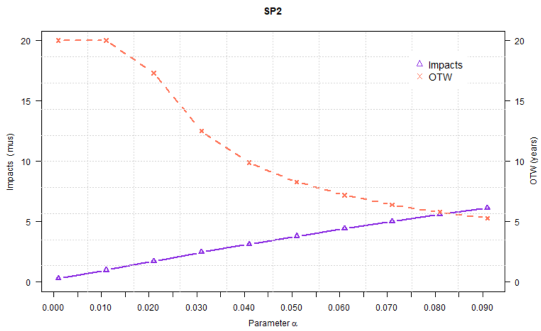
e - BP#5



f - BP#6

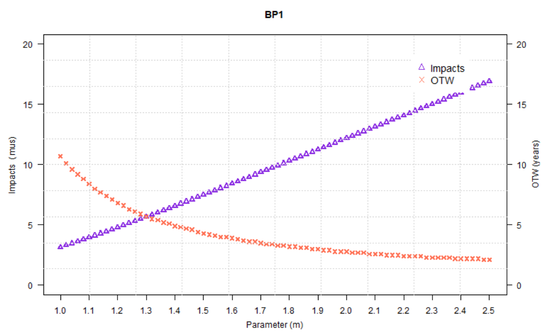


g - SP#1

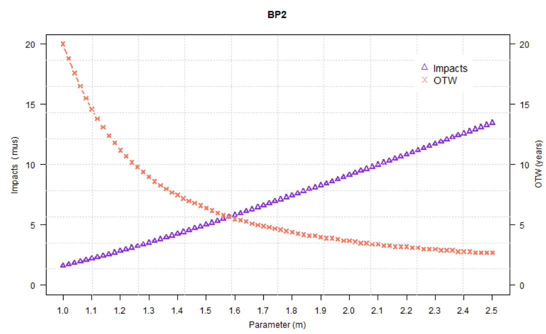


h - SP#2

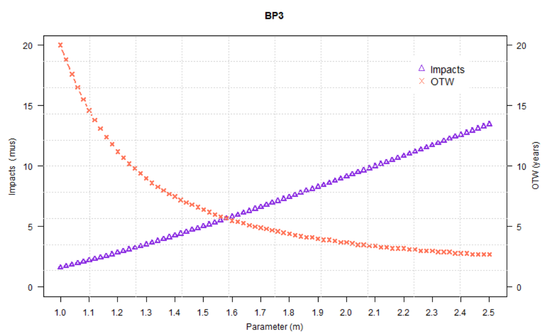
Figure 5.4: Sensitivity Analysis (α)



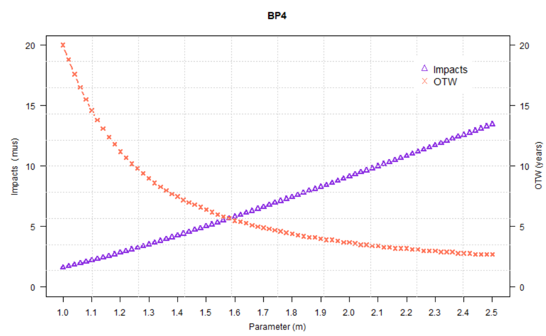
a - BP#1



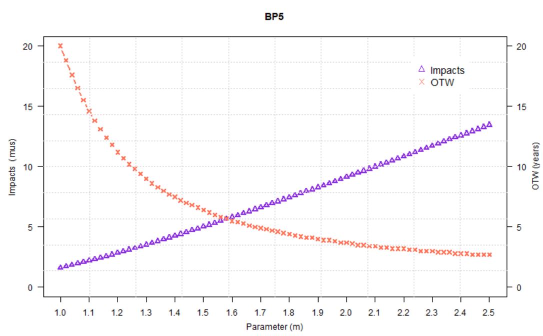
b - BP#2



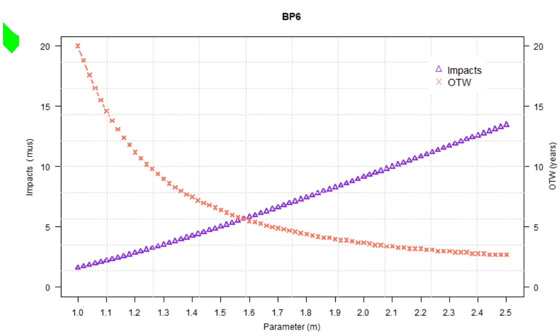
c - BP#3



d - BP#4



e - BP#5



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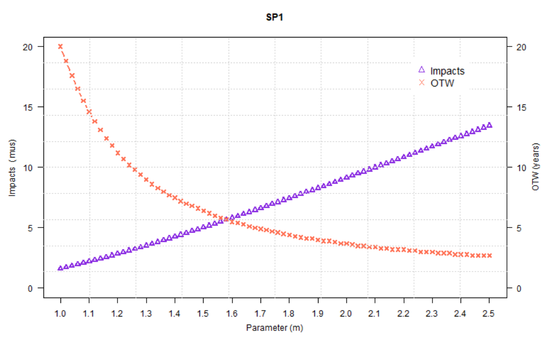
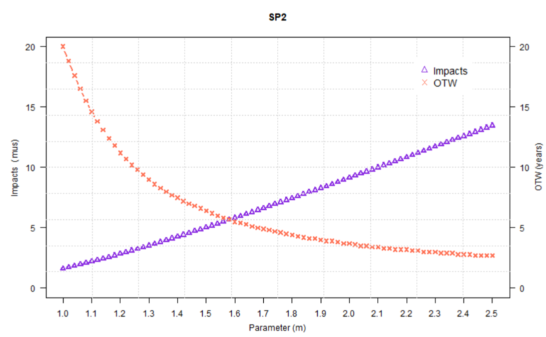
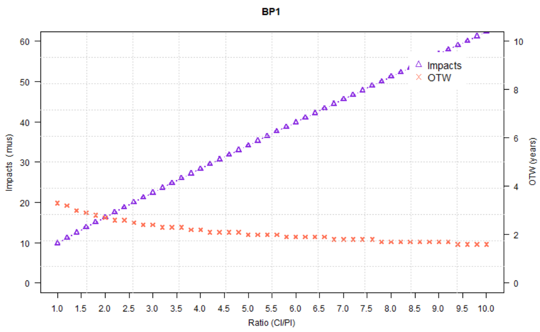


g - SP#1

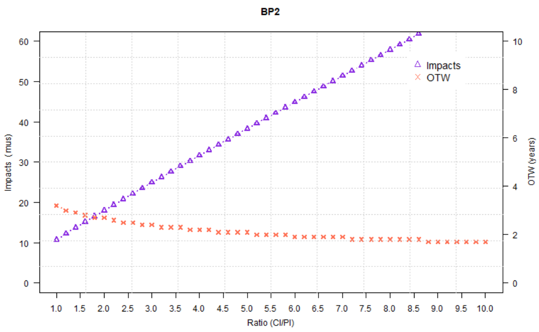


h - SP#2

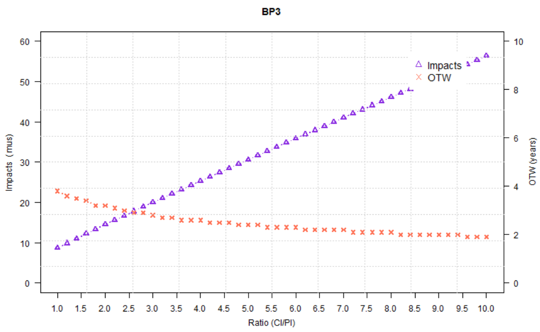
Figure 5.5: Sensitivity Analysis (m)



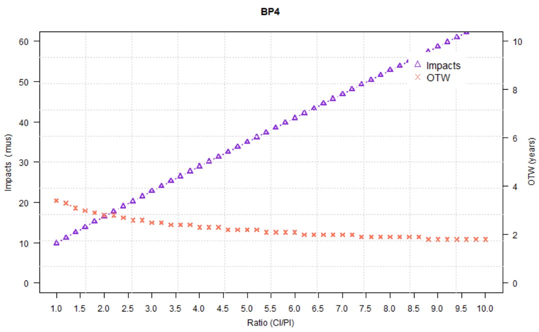
a - BP#1



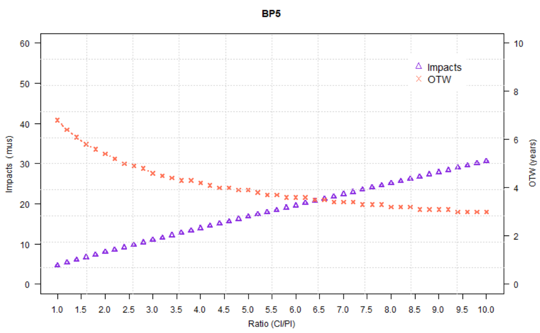
b - BP#2



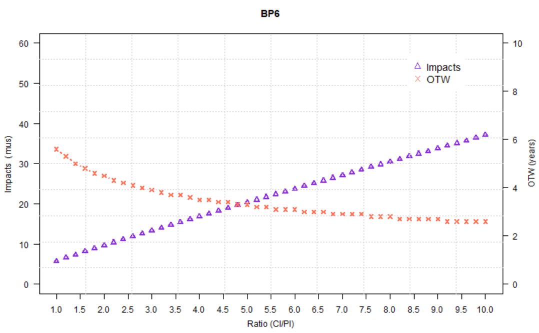
c - BP#3



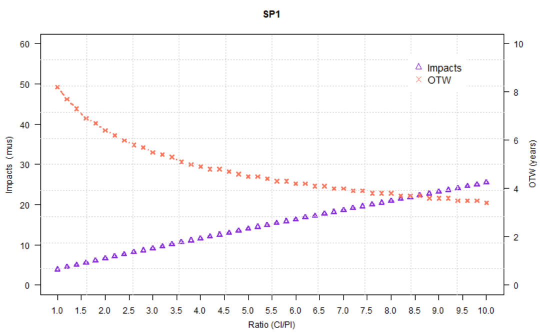
d - BP#4



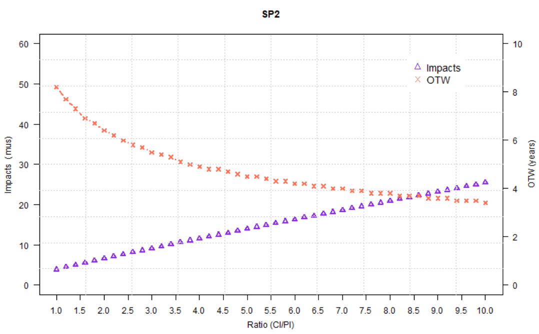
e - BP#5



f - BP#6



g - SP#1



h - SP#2

Figure 5.6: Sensitivity Analysis (CI/PI)

Chapter 6

Conclusions and Recommendations

Conclusions and recommendations have already presented in Chapter 4 for individual assets under investigation. This section is hence only to provide a high level conclusions and recommendations.

6.1 Conclusions

- Pumps have been operated in non-optimal control approach that might lead to higher failure probability of total system failure in a long run;
- Daily data on operation and power consumption is poorly recorded in non-relational table structure that is of little use for data analysis, especially when considering the huge amount of data recorded over time. This data shall be considered a very important part of management as it shall be used for energy audit and investigation on reliability of pumps and the system;
- No real time measurement of production and power consumption per pump. This leads to the impossibility of calculating the reliability of pump over time;
- No systematic inspection/testing strategy;
- Piping supports suffer significant deterioration and wear out;
- Existing FDAS system is not working;
- No lighting and grounding protection system in place.

6.2 Recommendations

- Establishment of control philosophy to optimally operate pumps in a manner to protect pumps from being failed;
- Establishment of a good asset management practice (see recommendation in the Appendix);
- Establishment of a benchmark value for monitoring energy efficiency;
- Hiring an asset management expert/specialist to help the IAM to design a good platform to record data concerning daily production and power consumption via web-based system (This does not need to involve a consulting company. Hiring a specialist to work with the IAM will eventually save cost for Maynilad in a long run);
- Establishment of a optimal inspection/testing regime for all assets. This testing regime shall be developed using the concept of optimality based on a solid mathematical modeling approach and best practices learnt from the industry (e.g. case based reasoning methodology);

- Redesign the FDAS system, lighting and grounding system. This shall be an immediate action to be executed prior to next raining season.

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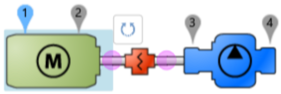
Appendix A

Vibration Data

Expertise Report

Filter: Equipment name (+) \ Tree order (+)

Location	PAGCOR\	Fixed speed
Designation		
Equipment	BOOSTER PUMP #1	
Designation		
Abbreviation	BP#1	
Serial No		
Model		
Periodicity (d)	*Normal* 60 *Alarm* 15	



Previous Advice	*Condition*	*Rotation Speed*

Date 15/11/2018 10:55:42	**FAIR**	*Speed*	19.8 Hz / 1190 rpm
	Health is not acceptable for a long time service.	*Author*	u1
Condition DfCnd		*System - Serial*	FALCON - 11407
		Sensor	
		Connector	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Misalignment and Pump cavitations

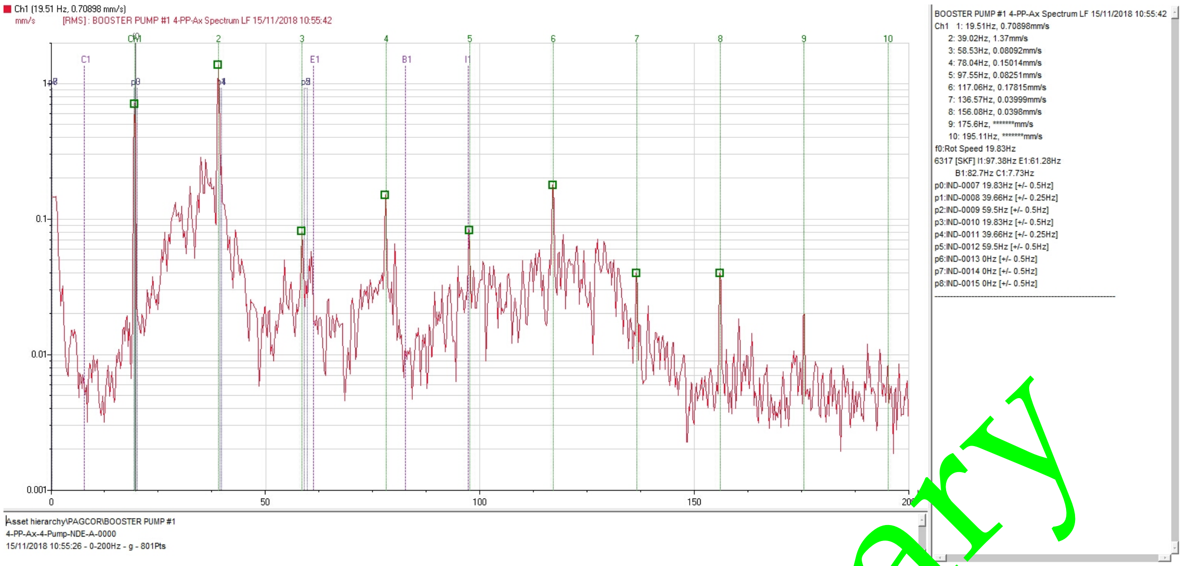
Good overall state for component 'Electric motor'.
Fair state for the component 'Pump'.
Highest vibrations measured at Pump OB Bearing Vertical with Overall velocity of 3.44mm/s and dominant peak of 2x Motor RPM caused by Misalignment, Pump Cavitations and Pump IB Bearing Noise/ Lubrications

Recommendations

Realign Motor and Pump Shaft

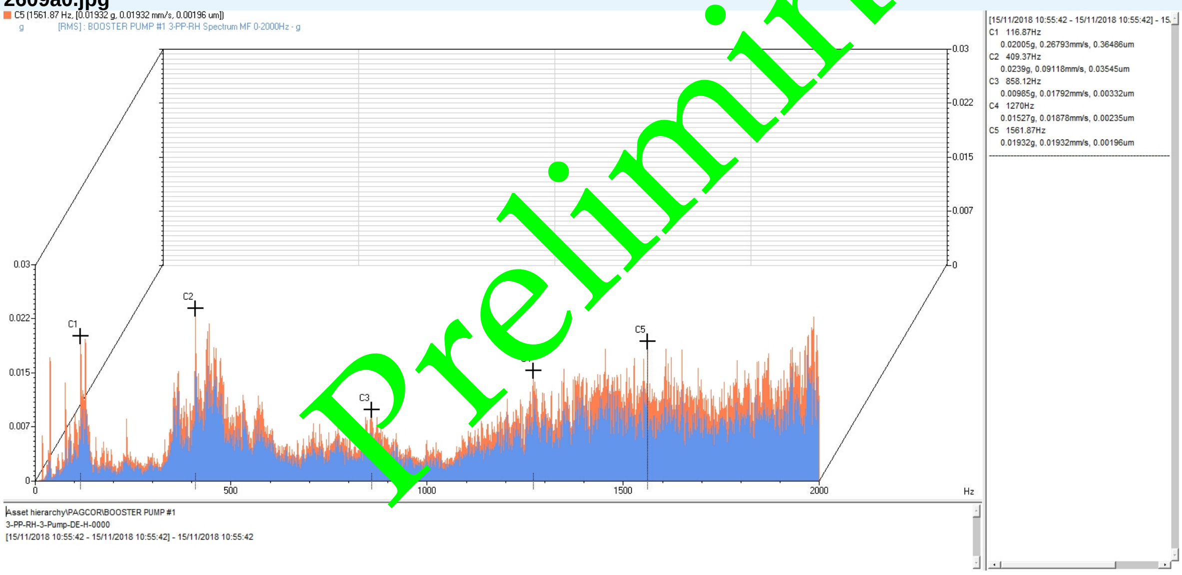
Realign Motor and Pump shaft or coupling using Precision Laser Alignment tool.
Cavitation to be watched: process control and action might be needed. Follow the dynamic behavior of the pump to prevent impeller damage.
Regrease Pump Bearings with fresh grease.

180c58.jpg



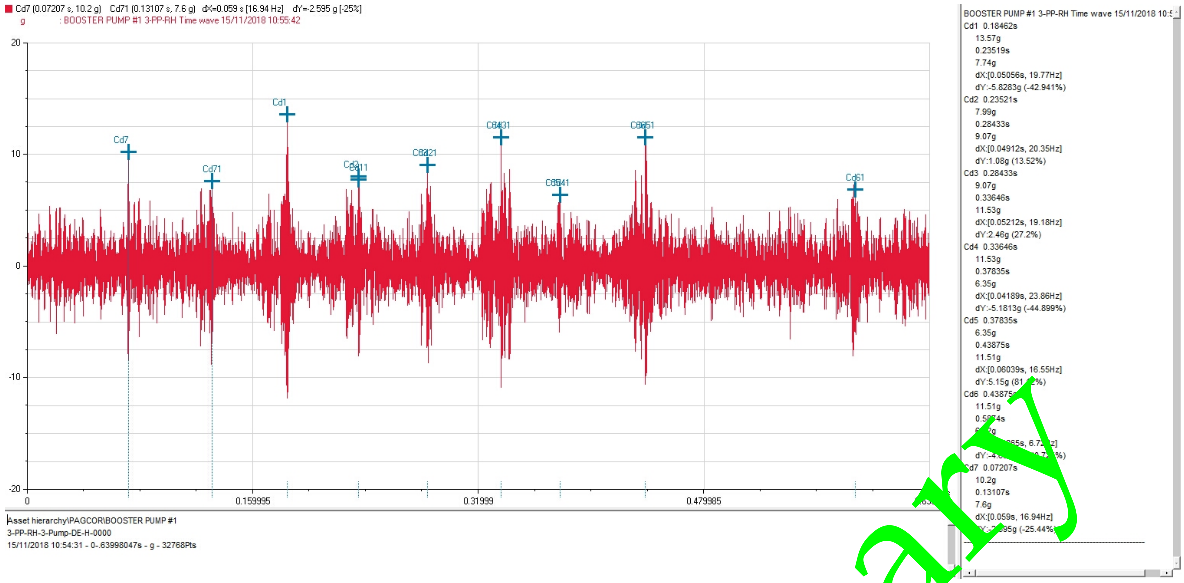
2x Peak is an indication of slight misalignment

2609a0.jpg

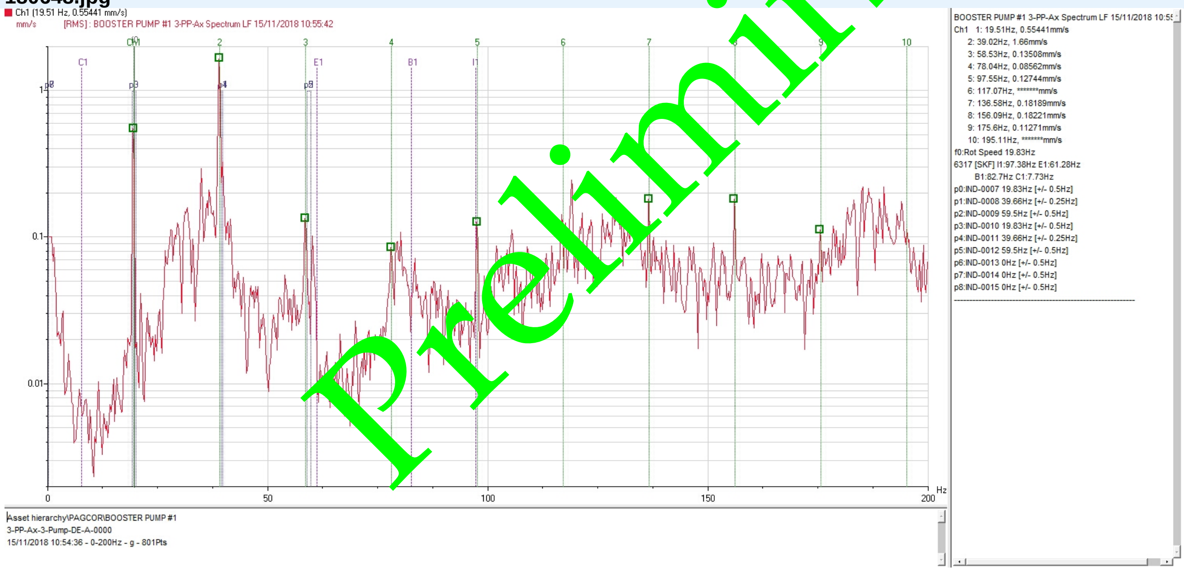


Elevated base or humps are an indications of Noise from Pump Cavitations and Bearing Noise

a0cb2.jpg

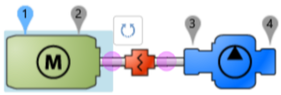


180648.jpg



2x Peak is an indication of slight misalignment

Location Designation	**PAGCOR**	Fixed speed
Equipment Designation	**BOOSTER PUMP #2**	
Abbreviation	**BP#2**	
Serial No		
Model		
Periodicity (d)	*Normal* **60** *Alarm* **15**	



Previous Advice	***Condition***	***Rotation Speed***

Date **15/11/2018 10:52:36**	**FAIR** *Health is not acceptable for a long time service.*	*Speed*	**19.5 Hz / 1171 rpm**
Condition **DfCnd**		*Author*	**u1**
		System Serial	**FALCON - 11407**
		Sensor	
		Connector	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Pump Bearings Fault - Lubrication

Good overall state for component 'Electric motor'.

Fair state for component 'Pump'.

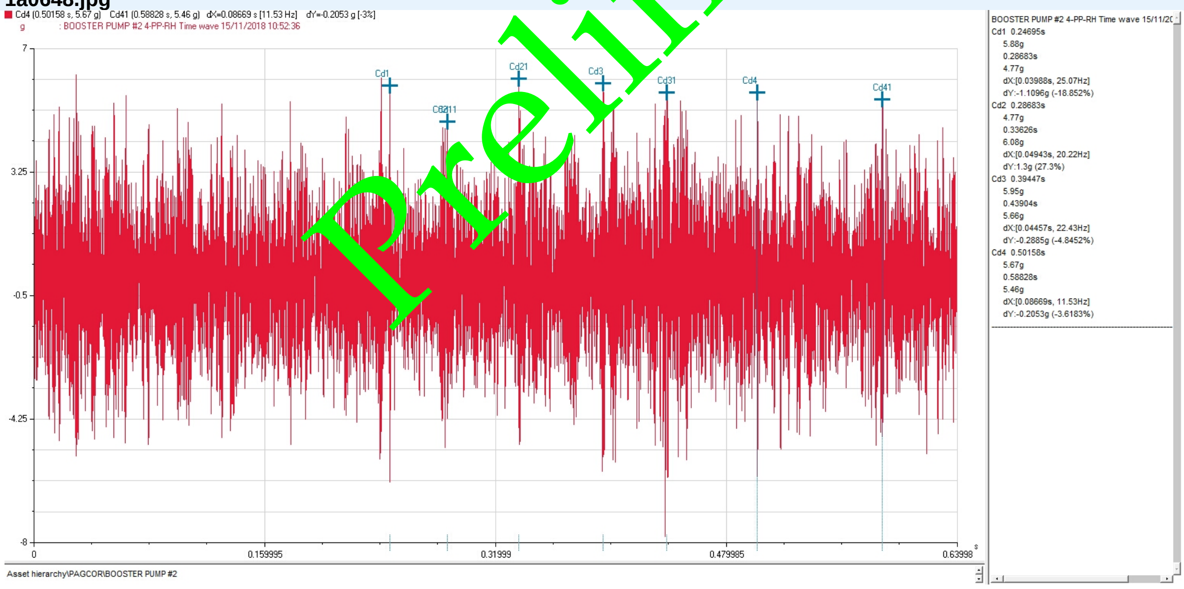
Highest vibrations measured at Pump OB Bearing Axial with Overall velocity of 2.79mm/s caused by Pump Bearings Early stage Fault - Outer Race.

Recommendations

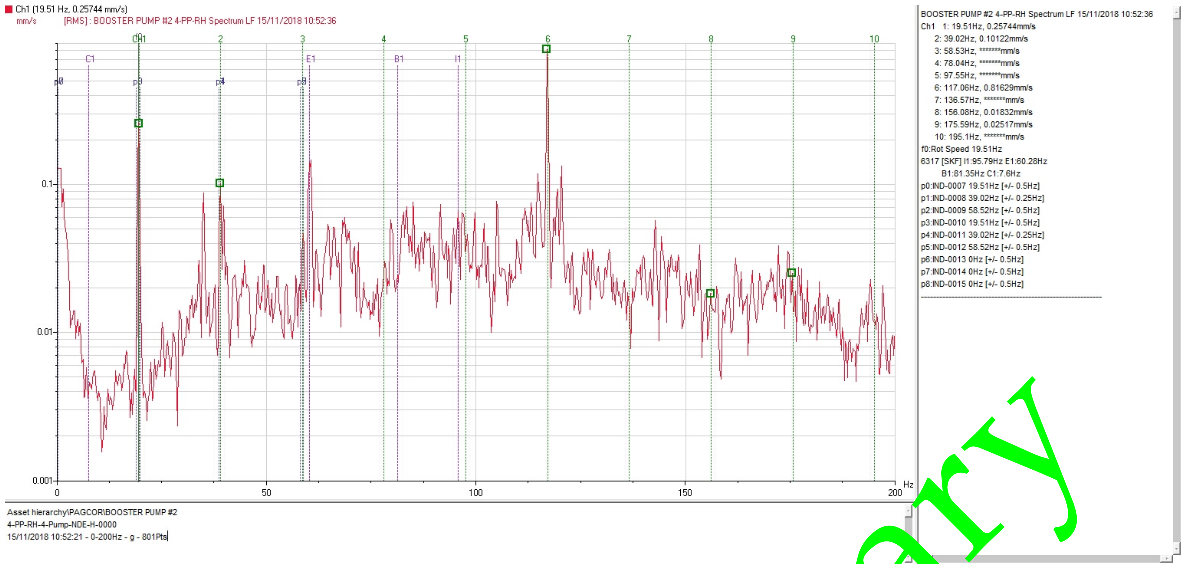
Purge Pump Bearings with fresh greases

Purge Pump Bearings with fresh greases

1a0648.jpg

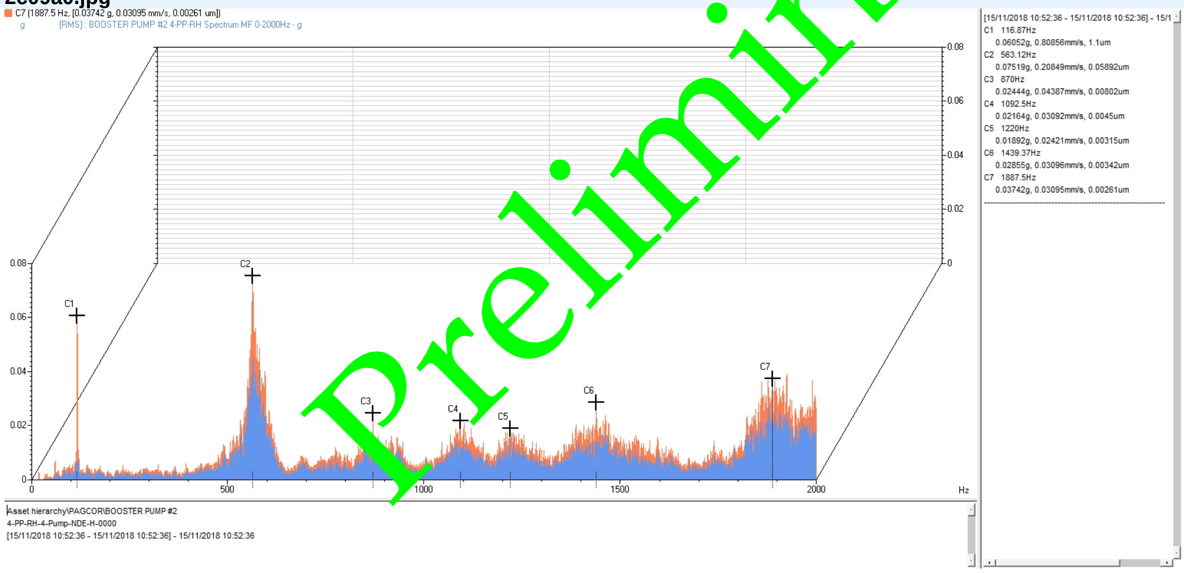


29098a.jpg



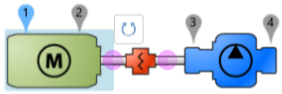
1x BPFO peak - Bearing Outer Race Fault

2c09a0.jpg



Noise generated at High frequencies due to lubrications problem

Location	PAGCOR\	Fixed speed
Designation		
Equipment	BOOSTER PUMP #3	
Designation		
Abbreviation	BP#3	
Serial No		
Model		
Periodicity (d)	*Normal* 60 *Alarm* 15	



Previous Advice	***Condition***	***Rotation Speed***

Date 15/11/2018 10:49:19	FAIR	Speed	19.8 Hz / 1190 rpm
Condition DfCnd	***Health is not acceptable for a long time service.***	Author	u1
		System Serial	FALCON - 11407
		Sensor	
		Connector	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Misalignment and Pump Cavitations

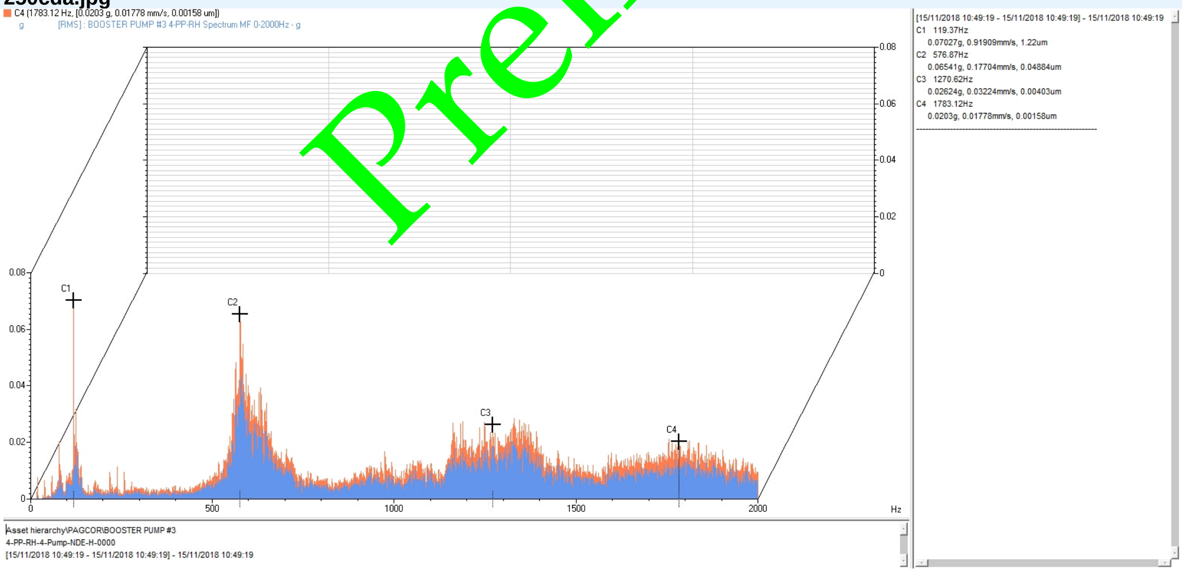
Good overall state for component 'Electric motor'.
Fair state for the component 'Pump'.
Highest vibrations measured at Pump OB Bearing Vertical with Overall velocity of 5.55mm/s and dominant peak of 1x Blade Pass Frequency (119.25Hz) caused by Misalignment and Pump Cavitations

Recommendations

Realign Motor & Pump Shaft, Monitor Cavi

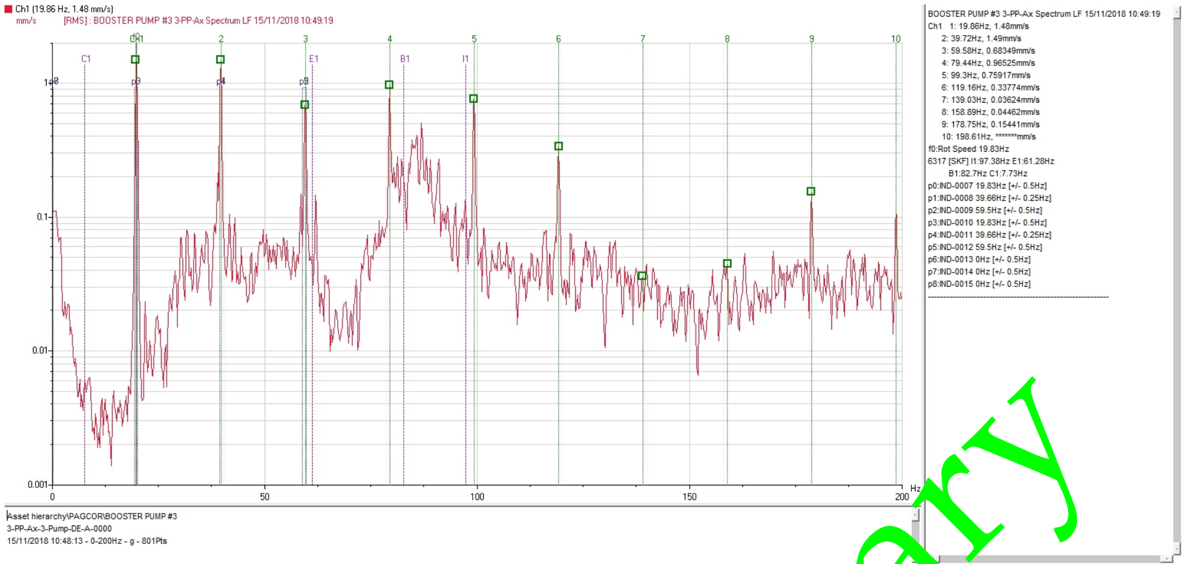
Realign Motor and Pump shaft or coupling using Precision Laser Alignment tool.
Cavitation to be watched: process control and action might be needed. Follow the dynamic behavior of the pump to prevent impeller damage.

250cda.jpg



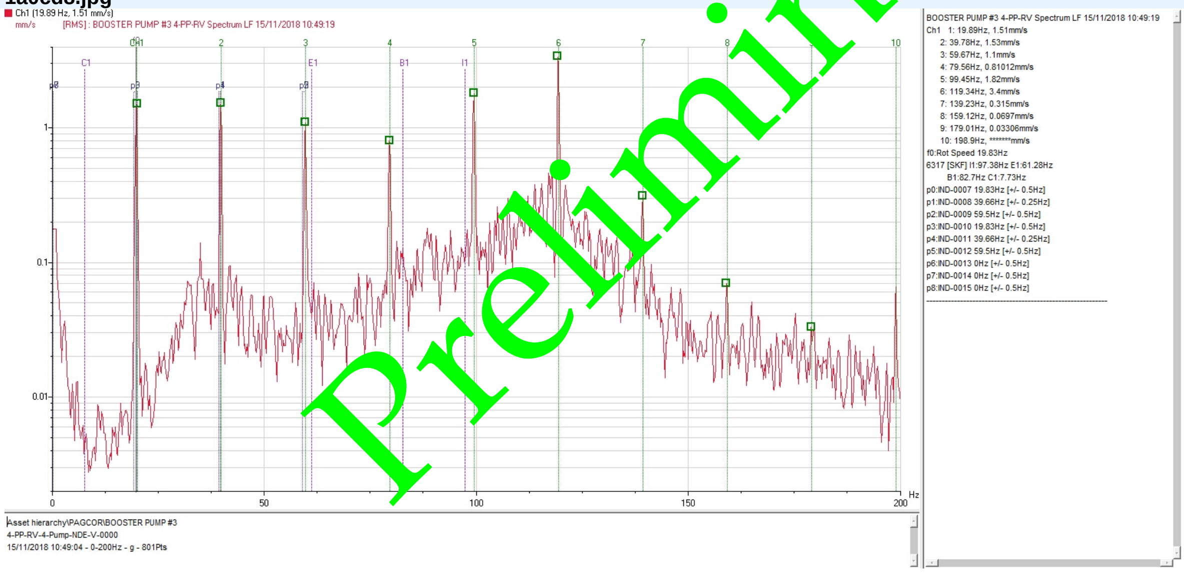
1x Blade Passing Frequency peak and elevated base or humps are an indications of pump cavitations Fault

2709f6.jpg



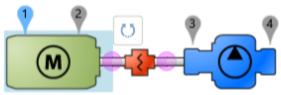
1x, 2x peak are an indications of slight Misalignment. Magnitude is minimal, but s[illegible]eed [illegible]arify actual alignment conditions.

1a0cd8.jpg



Dominant peak at Blade Passing Freq due to cavitations

Location	PAGCOR\	Fixed speed	
Designation			
Equipment	BOOSTER PUMP #4		
Designation			
Abbreviation	BP#4		
Serial No			
Model			
Periodicity (d)	Normal 60 Alarm 15		



Previous Advice	Condition	Rotation Speed

Date	GOOD	Speed	19.83 Hz / 1190 rpm
15/11/2018 10:46:08	*Health is good for a long time service without restriction.*	Author	u1
Condition		System Serial	FALCON - 11407
DfCnd		Sensor	
		Connection	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Vibrations are within acceptable levels

Good overall state for component 'Electric motor'.

Good overall state for component 'Pump'.

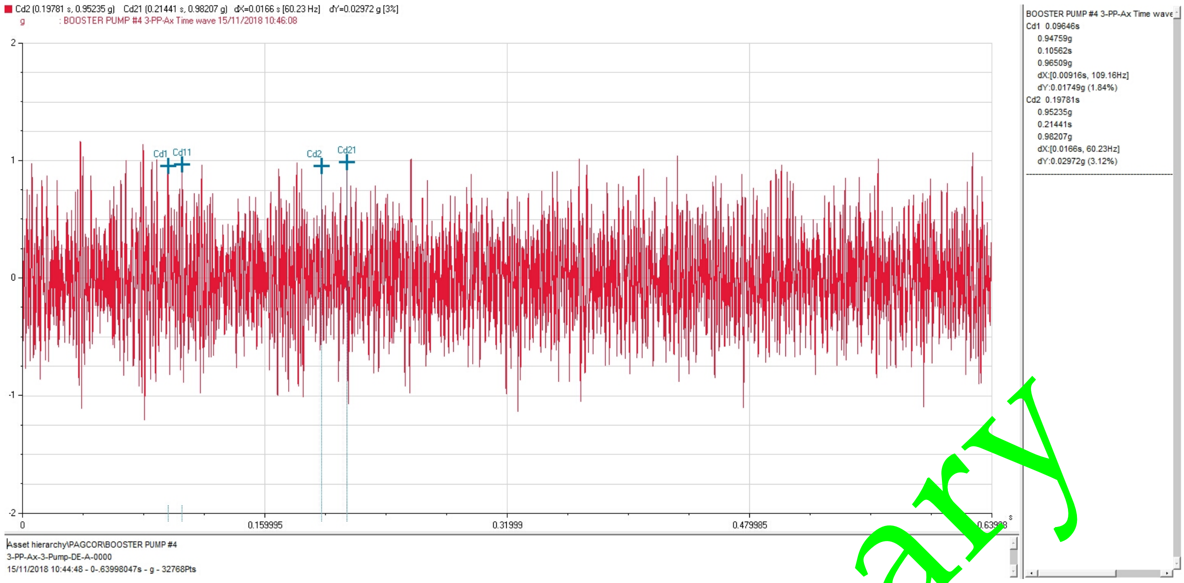
Recommendations

Continue monitor vibrations periodically

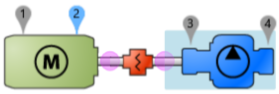
Continue monitor vibrations periodically

3009f6.jpg

340bfe.jpg


Cd2 (0.19781 s, 0.95235 g) Cd21 (0.21441 s, 0.98207 g) dX=0.0166 s [60.23 Hz] dY=0.02972 g [3%]
g : BOOSTER PUMP #4 3-PP-Ax Time wave 15/11/2018 10:46:08
Cd1 Cd11
Cd2 Cd21
0
0.159995
0.31999
0.479985
s
BOOSTER PUMP #4 3-PP-Ax Time wave
Cd1 0.09646s
0.94759g
0.10562s
0.96509g
dX:[0.00916s, 109.16Hz]
dY:0.01749g (1.84%)
Cd2 0.19781s
0.95235g
0.21441s
0.98207g
dX:[0.0166s, 60.23Hz]
dY:0.02972g (3.12%)
Asset hierarchy\PAGCOR\BOOSTER PUMP #4
3-PP-Ax-3-Pump-DE-A-0000
15/11/2018 10:44:48 - 0-.63998047s - g - 32768Pts

Location	PAGCOR\	Fixed speed
Designation		
Equipment	BOOSTER PUMP #5	
Designation		
Abbreviation	BP#5	
Serial No		
Model		
Periodicity (d)	Normal 60 Alarm 15	



Previous Advice	Condition	Rotation Speed

Date 15/11/2018 10:40:18	FAIR	Speed 19.83 Hz / 1185 rpm
Condition DfCnd	*Health is not acceptable for a long time service.*	Author u1 System Serial FALCON - 11407 Sensor Connection

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Pump Cavitations & Bearing Noise at Pump

Good overall state for component 'Electric motor'.

Fair State for the component 'Pump'.

Highest vibrations measured at Pump OB Bearing Axial with Overall velocity of 3.84mm/s caused by Pump Cavitations and Bearing Noise at Pump IB Bearing.

Recommendations

Monitor the evolution

Cavitation to be watched: process control and action might be needed. Follow the dynamic behavior of the pump to prevent impeller damage.

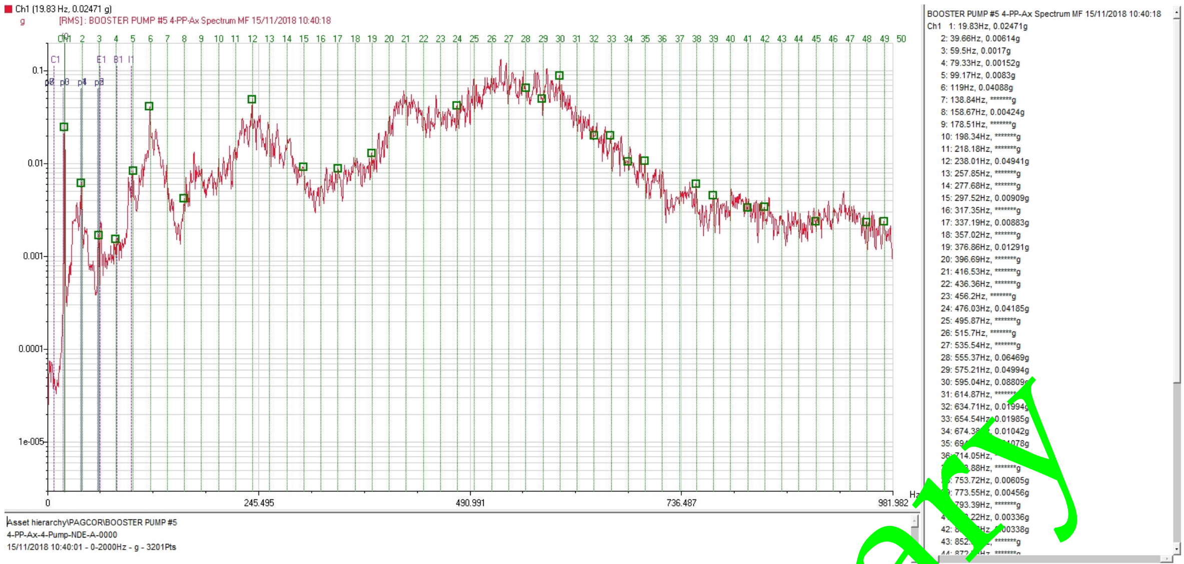
☐Location "3-Pump-DE" slight

☐Location "4-Pump-NDE" to be watched

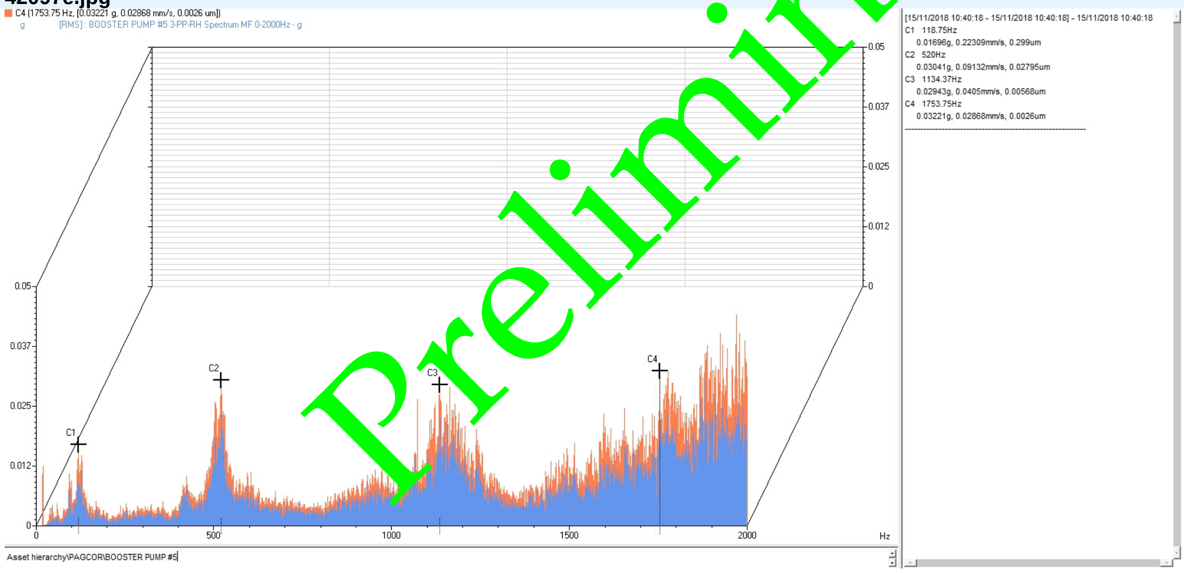
Regrease Pump IB Bearing with fresh greases

360bfe.jpg

3d09a0.jpg

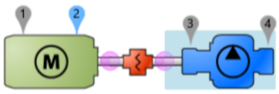


42097e.jpg



Elevated base or humps at High frequencies are an indications of combination Noise from Pump Cavitations and Lubrication issues

Location	**PAGCOR**	
Designation		
Equipment	**BOOSTER PUMP #6**	**Fixed speed**
Designation	**BP 6**	
Abbreviation	**BP#6**	
Serial No	**AD139026-1**	
Model	**KSB 40M HEAD**	
Periodicity (d)	*Normal* **60** *Alarm* **15**	



TECO

Previous Advice	*Condition*	*Rotation Speed*

Date **15/11/2018 10:36:28**	**FAIR** *Health is not acceptable for a long time service.*	*Speed*	**19.8 Hz / 1185 rpm**
Condition **DfCnd**		*Author*	**u1**
		System Serial	**FALCON - 11407**
		Sensor	
		Connector	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Pump Cavitations & Pump OB Brg Noise

Good overall state for component 'Electric motor'.

Fair State for the component 'Pump'.

Highest vibrations measured at Pump OB Bearing Vertical with Overall velocity of 3.17mm/s caused by Pump Cavitations & Pump OB Bearing Noise

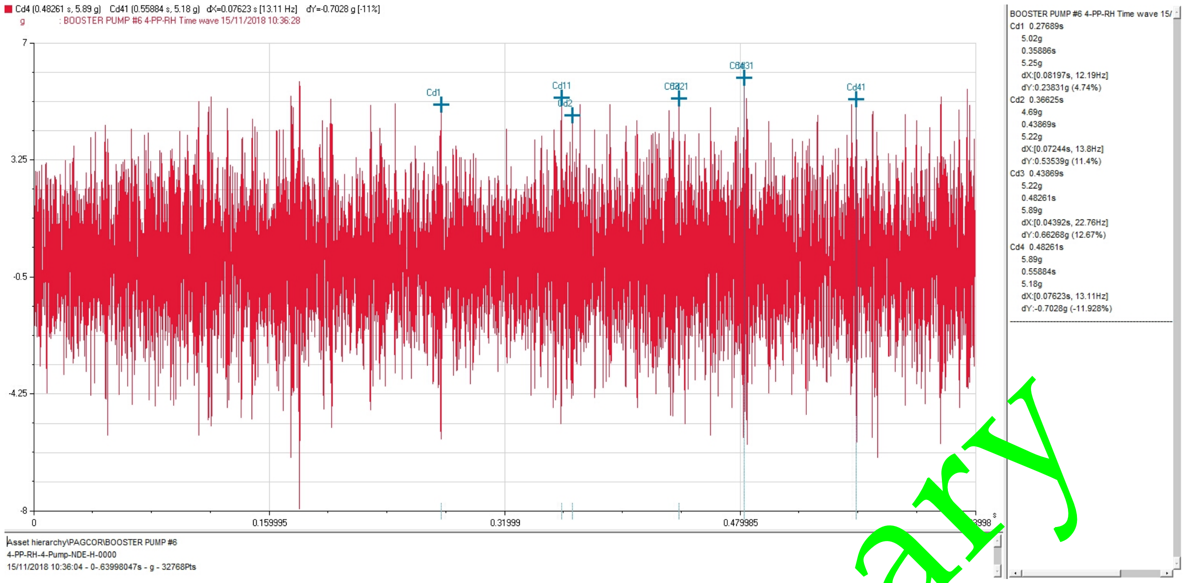
Recommendations

Monitor Slight cavitations

Monitor Slight cavitations, Regrease Pump OB Bearing with fresh greases

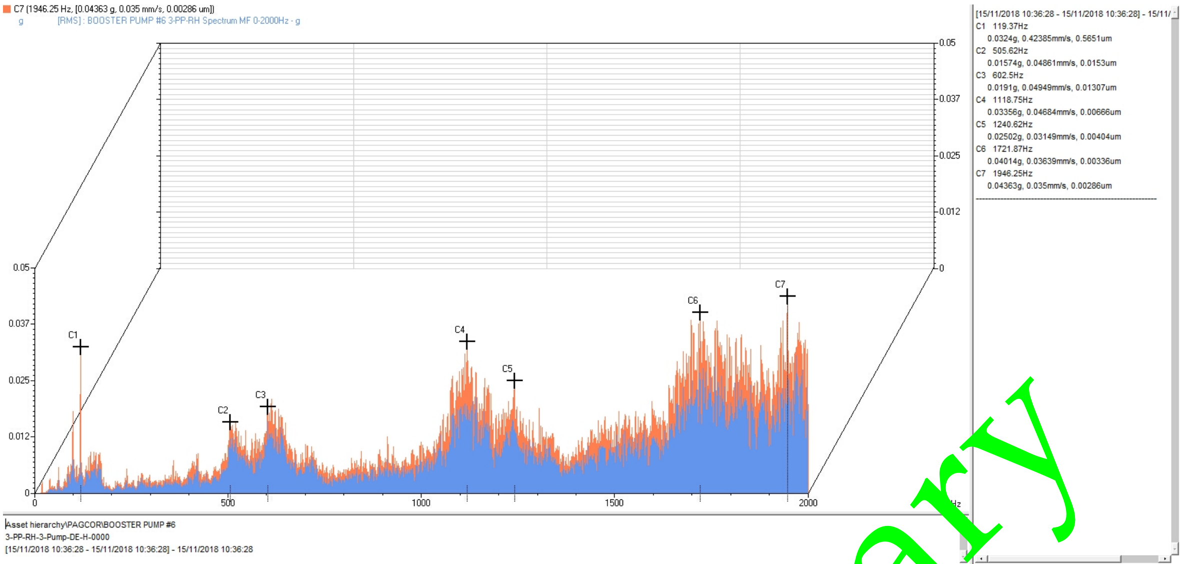
1809d8.jpg

200648.jpg



350b18.jpg

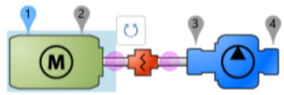
45097e.jpg



Elevated base or humps at High frequencies are an indications of combination Noise from Pump Cavitations and Lubrication issues at Pump OB Bearing

4609a0.jpg

Location	PAGCOR\	Fixed speed
Designation		
Equipment	STORAGE PUMP #1	
Designation		
Abbreviation	SP#1	
Serial No		
Model		
Periodicity (d)	Normal 60 Alarm 15	



Previous Advice	Condition	Rotation Speed

Date	FAIR	Speed 17.5 Hz / 1051 rpm
15/11/2018 11:02:24	*Health is not acceptable for a long time service.*	Author u1
Condition		System Serial FALCON - 11407
DfCnd		Sensor
		Connector

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Misalignment and Pump Cavitations

Good overall state for component 'Electric motor'.

Fair State for the component 'Pump'.

Highest vibrations measured at Pump OB Bearing Axial with Overall velocity of 4.47mm/s and dominant peak of 2x Motor RPM caused by Misalignment and Pump Cavitations

Recommendations

Realign Motor and Pump Shaft

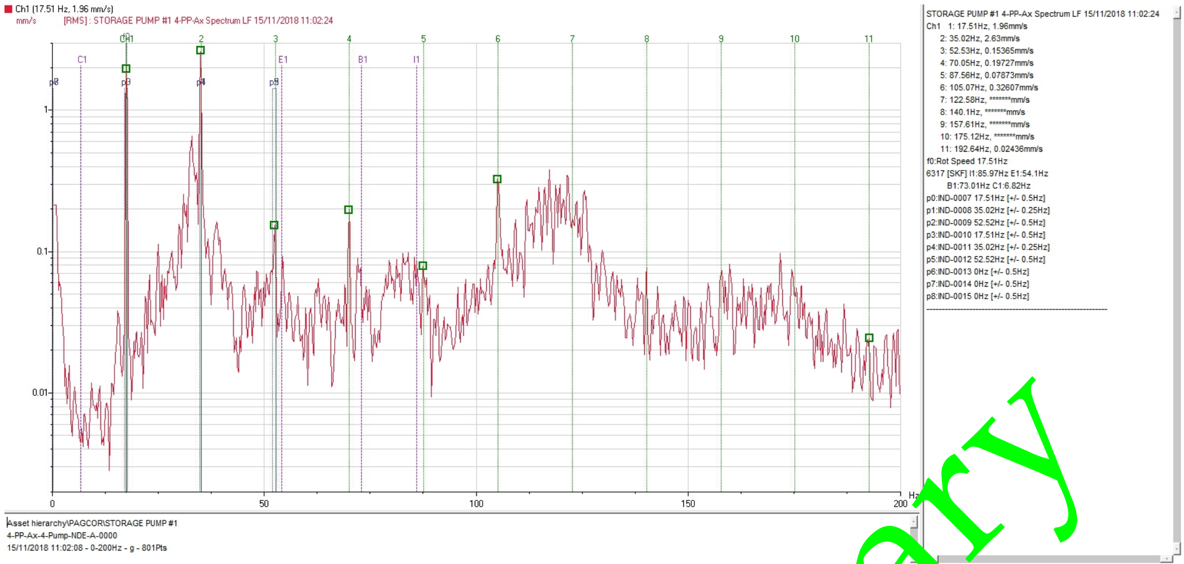
Realign Motor and Pump shaft or coupling using Precision Laser Alignment tool.

Cavitation to be watched: process control and action might be needed. Follow the dynamic behavior of the pump to prevent impeller damage.

120cd8.jpg

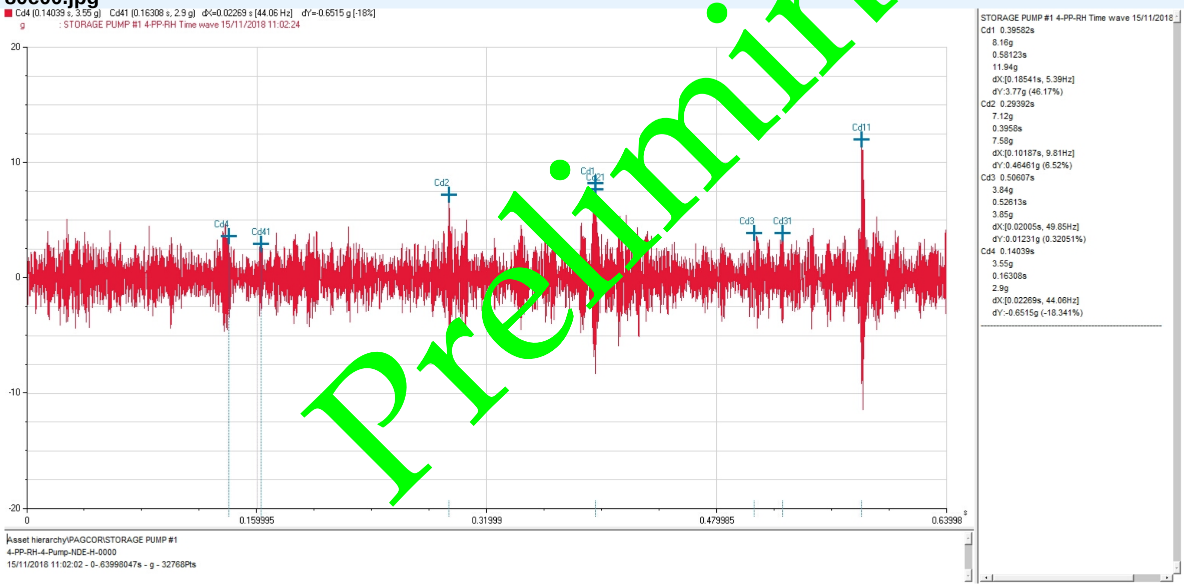
Elevated base or humps are an indications of Noise from Pump Cavitations

20cce.jpg

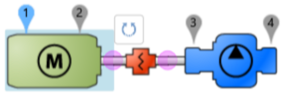


1x and 2x Peak at FFT - are an indications of Misalignment

80c00.jpg



Location	PAGCOR\	Fixed speed
Designation		
Equipment	STORAGE PUMP #2	
Designation		
Abbreviation	SP#2	
Serial No		
Model		
Periodicity (d)	Normal 60 Alarm 15	



Previous Advice	*Condition*	*Rotation Speed*

Date 15/11/2018 10:59:20	FAIR	*Speed*	17.5 Hz / 1051 rpm
Condition DfCnd	***Health is not acceptable for a long time service.***	*Author*	u1
		System Serial	FALCON - 11407
		Sensor	
		Connection	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Pump Cavitations

Good overall state for component 'Electric motor'.

Fair State for the component 'Pump'.

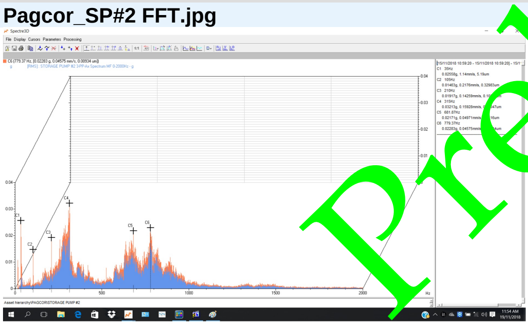
Highest vibrations measured at Pump OB Bearing Axial with Overall velocity of 2.87mm/s caused by Pump Cavitations

Recommendations

Monitor the evolution

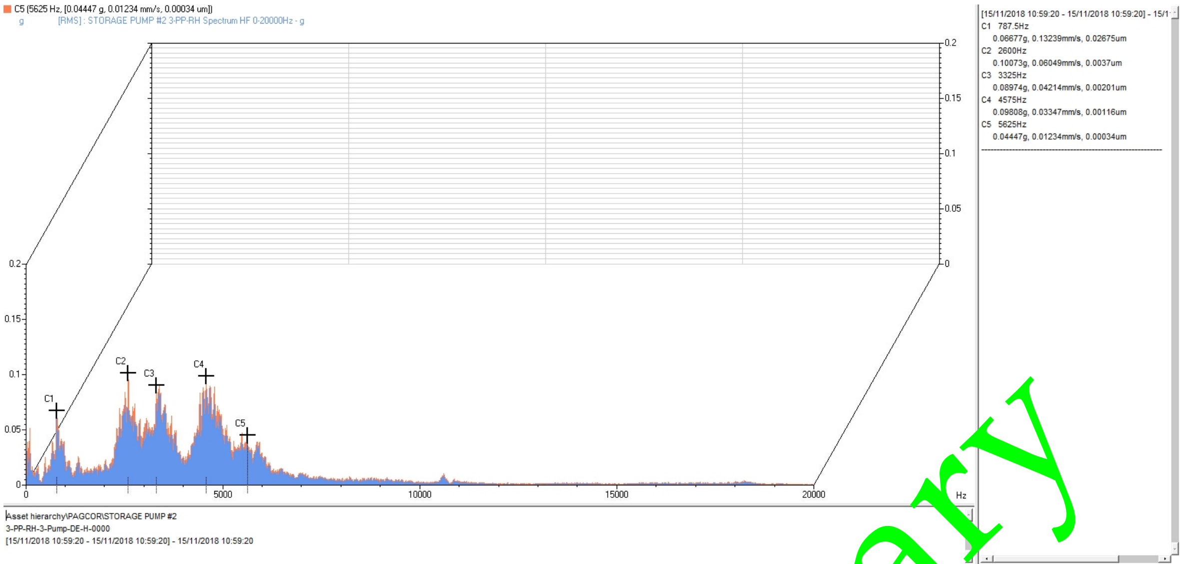
Cavitation to be watched: process control and action might be needed. Follow the dynamic behavior of the pump to prevent impeller damage.

Pagcor_SP#2 FFT.jpg



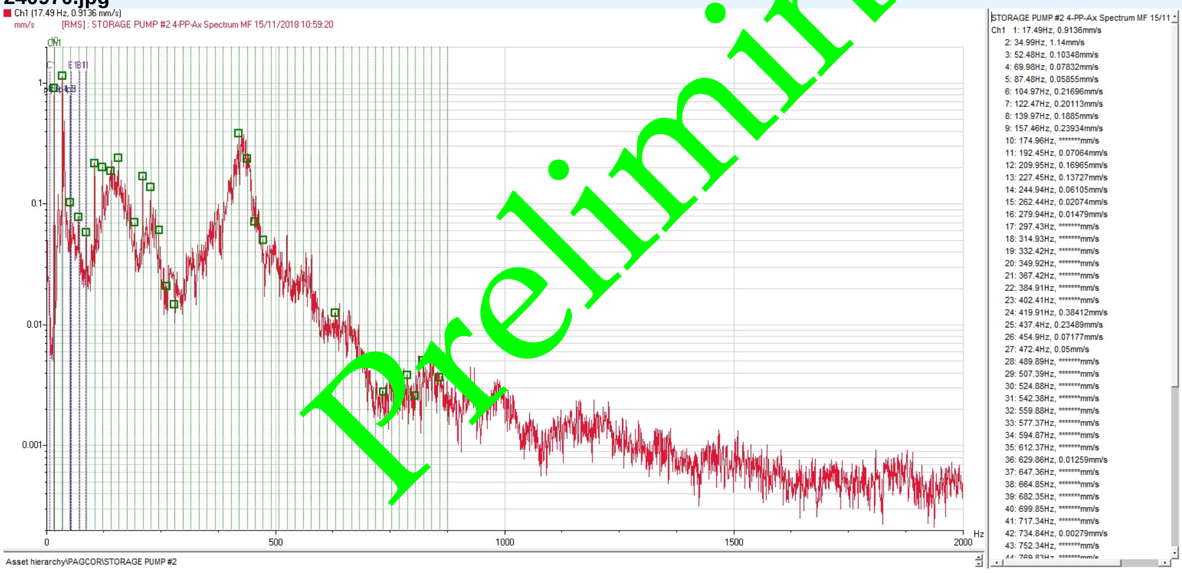
Elevated base or humps are an indications of Noise from Pump Cavitations

160c58.jpg

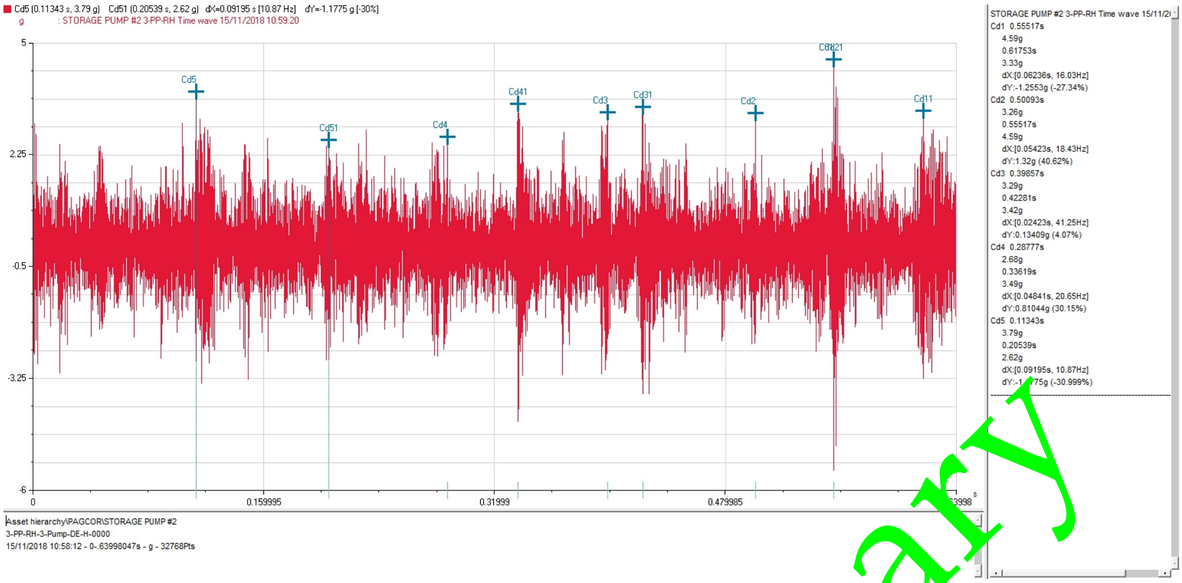


Elevated base or humps are an indications of Noise from Pump Cavitations

240970.jpg

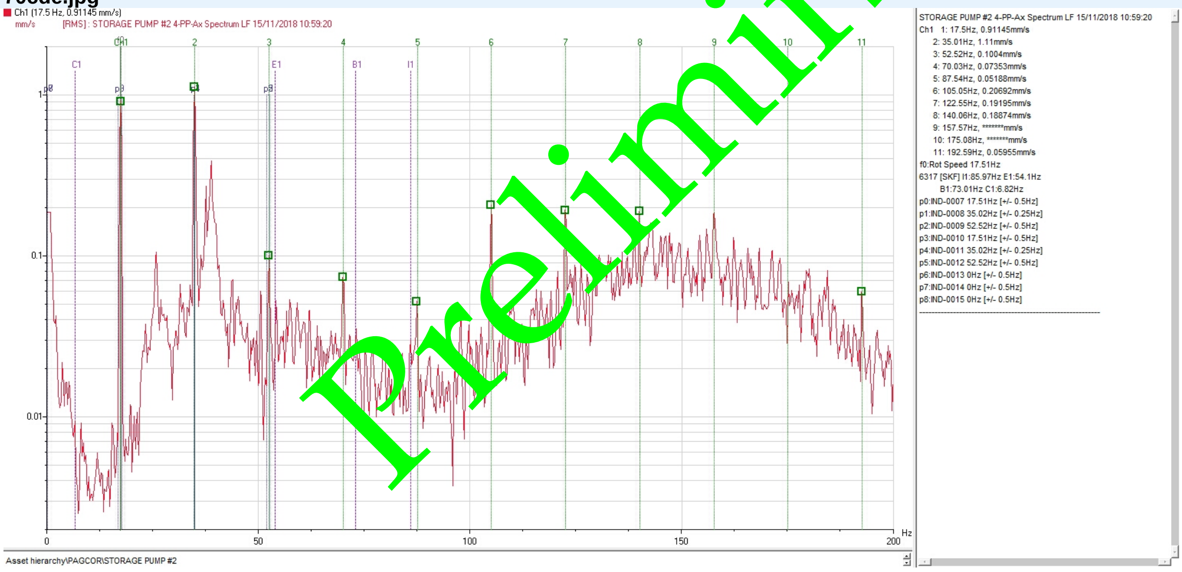


60cda.jpg

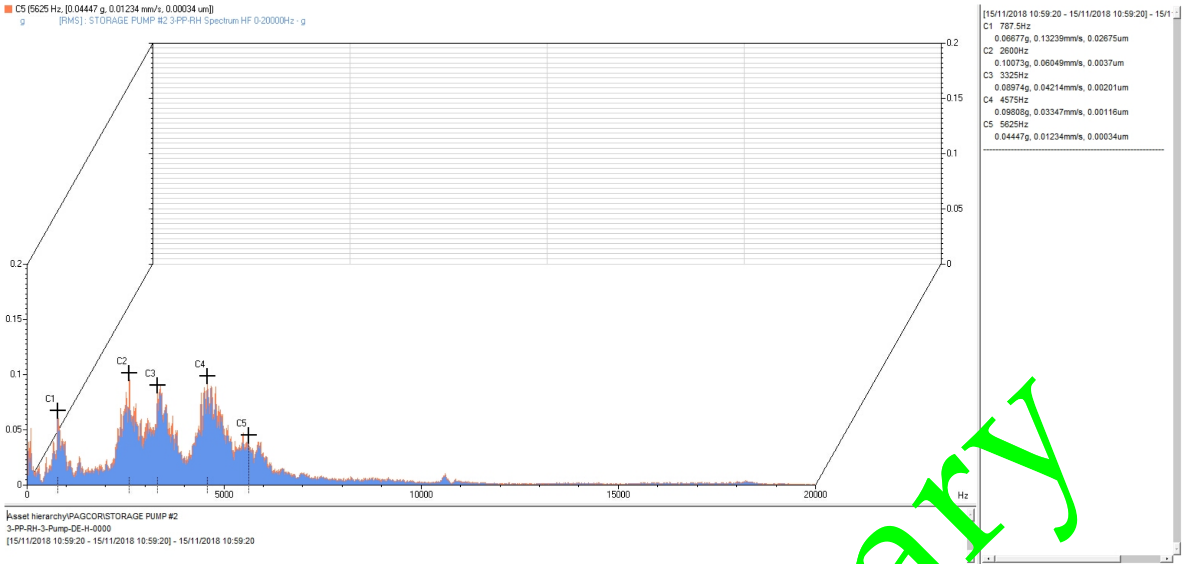


Non Periodic Pulsation due to cavitations

70cde.jpg

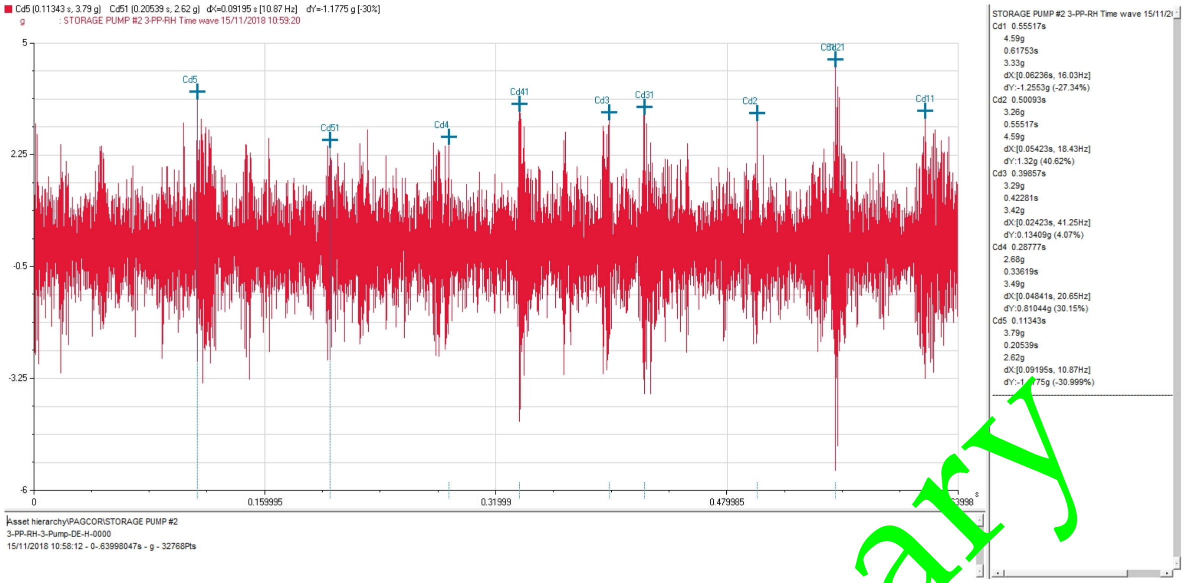


160c58.jpg



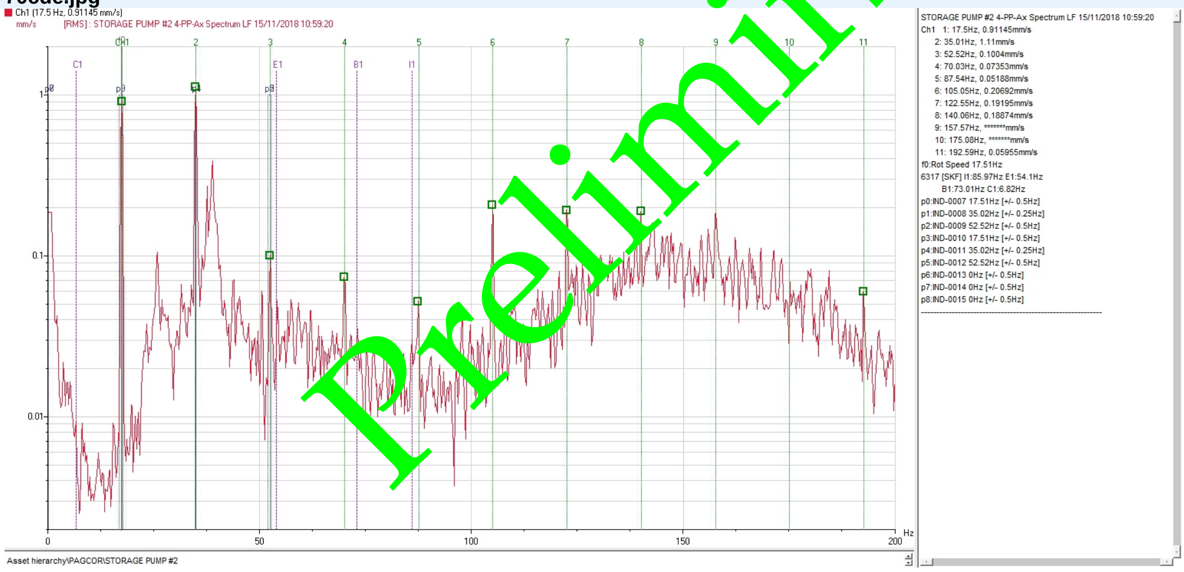
240970.jpg

60cda.jpg



Cd5 (0.11343 s, 3.79 g) Cd51 (0.20539 s, 2.62 g) dX=0.09195 s [10.87 Hz] dY=-1.1775 g [-30%]
g : STORAGE PUMP #2 3-PP-RH Time wave 15/11/2018 10:59:20
STORAGE PUMP #2 3-PP-RH Time wave 15/11/20
Cd1 0.55517s
4.59g
0.61753s
3.33g
dX:[0.06236s, 16.03Hz]
dY:-1.2553g (-27.34%)
Cd2 0.50093s
3.26g
0.55517s
4.59g
dX:[0.05423s, 18.43Hz]
dY:1.32g (40.62%)
Cd3 0.39857s
3.29g
0.42281s
3.42g
dX:[0.02423s, 41.25Hz]
dY:0.13409g (4.07%)
Cd4 0.28777s
2.68g
0.33619s
3.49g
dX:[0.04841s, 20.65Hz]
dY:0.81044g (30.15%)
Cd5 0.11343s
3.79g
0.20539s
2.62g
dX:[0.09195s, 10.87Hz]
Asset hierarchy\PAGCOR\STORAGE PUMP #2
3-PP-RH-3-Pump-DE-H-0000
15/11/2018 10:58:12 - 0-.63998047s - g - 32768Pts

70cde.jpg



Ch1 (17.5 Hz, 0.91145 mm/s)
mm/s [RMS] : STORAGE PUMP #2 4-PP-Ax Spectrum LF 15/11/2018 10:59:20
STORAGE PUMP #2 4-PP-Ax Spectrum LF 15/11/2018 10:59:20
Ch1 1: 17.5Hz, 0.91145mm/s
2: 35.01Hz, 1.11mm/s
3: 52.52Hz, 0.1004mm/s
4: 70.03Hz, 0.07353mm/s
5: 87.54Hz, 0.05188mm/s
6: 105.05Hz, 0.20692mm/s
7: 122.55Hz, 0.19195mm/s
8: 140.06Hz, 0.18874mm/s
9: 157.57Hz, *******mm/s
10: 175.08Hz, *******mm/s
11: 192.59Hz, 0.05955mm/s
f0:Rot Speed 17.51Hz
6317 [SKF] I1:85.97Hz E1:54.1Hz
B1:73.01Hz C1:6.82Hz
p0:IND-0007 17.51Hz [+/- 0.5Hz]
p1:IND-0008 35.02Hz [+/- 0.25Hz]
p2:IND-0009 52.52Hz [+/- 0.5Hz]
p3:IND-0010 17.51Hz [+/- 0.5Hz]
p4:IND-0011 35.02Hz [+/- 0.25Hz]
p5:IND-0012 52.52Hz [+/- 0.5Hz]
p6:IND-0013 0Hz [+/- 0.5Hz]
p7:IND-0014 0Hz [+/- 0.5Hz]
p8:IND-0015 0Hz [+/- 0.5Hz]
Asset hierarchy\PAGCOR\STORAGE PUMP #2

Appendix B

Recommended Maintenance Program

Asset Code	Name	Asset Description	Component	Failure Mode	Criticality	Failure Pattern	Task	Frequency	Done by	Comments
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head.	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Test/measure motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-PAGPS-0022	Storage Pump 1	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head.	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.

Asset Code	Name	Asset Description	Component	Failure Mode	Criticality	Failure Pattern	Task	Frequency	Done by	Comments
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-PAGPS-0033	Storage Pump 2	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head.	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-PAGPS-0052	Booster Pump 1	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-PAGPS-0062	Booster Pump 2	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-PAGPS-0063	Booster Pump 2	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head.	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-PAGPS-0064	Booster Pump 2	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-PAGPS-0065	Booster Pump 2	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-PAGPS-0066	Booster Pump 2	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-PAGPS-0067	Booster Pump 2	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0068	Booster Pump 2	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.

Asset Code	Name	Asset Description	Component	Failure Mode	Criticality	Failure Pattern	Task	Frequency	Done by	Comments
WSO-PAGPS-0069	Booster Pump 2	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-PAGPS-0070	Booster Pump 2	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-PAGPS-0071	Booster Pump 2	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0072	Booster Pump 2	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-PAGPS-0073	Booster Pump 2	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-PAGPS-0074	Booster Pump 2	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-PAGPS-0075	Booster Pump 2	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-PAGPS-0076	Booster Pump 2	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head.	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-PAGPS-0072	Booster Pump 3	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head.	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.

Asset Code	Name	Asset Description	Component	Failure Mode	Criticality	Failure Pattern	Task	Frequency	Done by	Comments
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-PAGPS-0082	Booster Pump 4	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head.	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.

Asset Code	Name	Asset Description	Component	Failure Mode	Criticality	Failure Pattern	Task	Frequency	Done by	Comments
WSO-PAGPS-0092	Booster Pump 5	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-PAGPS-0102	Booster Pump 6 - SPARE (dedicated)	Horizontal pump between bearings	Bearings	bearing failure caused by false brinelling	High	Age-related	Rotate pump shaft 2-1/4 times	Every shift	Operator	Ensure that pump is isolated from power source
WSO-PAGPS-0102	Booster Pump 6 - SPARE (dedicated)	Horizontal pump between bearings	Bearings	Bearing failure caused by contaminated oil	High	Random	Inspect oil for water contamination Regrease as necessary	Weekly	Maintenance contractor	
WSO-PAGPS-0102	Booster Pump 6 - SPARE (dedicated)	Horizontal pump between bearings	Starter; Auto start system	Fail to start	High	Random	Start pump and run for at least 2 hours. Check all functionalities.	Monthly	Operator	Do this during visit by maintenance contractor.

The list represents an initial recommended maintenance program for the mechanical (including motors and instruments) assets in Pagcor Pumping Facilities. The methodology used in its development is RCM (Reliability-Centered Maintenance). It is not intended to be the final list and should be treated as a "living" program. This simply means that it should always be reviewed and continuously improved over time. However, in doing this, the organization responsible for its sustainability should be aware of the methodologies and concepts used in RCM.

CRITICALITY MATRIX (Generic)

CONSEQUENCES	PROBABILITY		
			High (product not delivered)
			Medium (reduced delivery of product)
			Low (low of minimum operational interruption)
	Low <20%/yr	High >80%/yr	

Criticality:

Appendix C

Conceptual Design

C.1 Mechanical

Refer to the set A3 drawings and electronic files

C.2 WEM

Refer to the set A3 drawings and electronic files

C.3 FDAS

Refer to the set A3 drawings and electronic files

C.4 Bill of Quantity

Bill of Quantity

No.	Description	Items	CAT	CS	IT	Unit Cost	Quan.	Unit	Total	Remarks
1	Instrumentation	Pressure gauge	M	2	7	2,500.00	7	pcs	17,500.00	for replacement of defective PG
2	Instrumentation	Pressure gauge	M	2	6	2,500.00	16	pcs	40,000.00	to be tapped near intake/discharge of pump
3	Pump and motor	Bearing grease	M	2	1	3,000.00	1	lot	3,000.00	
4	Interior lighting	Manual light switch	F	2	5	1,000.00	1	pcs	1,000.00	
5	Outside lighting	80 Watts LED street light	F	2	6	1,500.00	5	pcs	7,500.00	
6	Sound protection	Earmuffs	M	3	9	500.00	5	pcs	2,500.00	for visitors
7	Pump house ventillation	Louver panels (1.2 x 1.5 m)	M	3	5	2,500.00	64	pcs	160,000.00	
8	Internal Data	Valve/Fitting performance curve	M	-	10	-	1	lot	-	from manufacturer
9	Controls	VFD control package	M	3	5	75,000.00	4	pcs	300,000.00	
10	Instrumentation	Portable UFM	M	4	7	100,000.00	1	pcs	100,000.00	
11	Instrumentation	Calibration of UFM	M	-	7	50,000.00	1	pcs	50,000.00	
12	Instrumentation	Calibration of Pressure gauges	M	-	7	1,000.00	7	pcs	7,000.00	Separate calibration fees
13	Motor	Grounding cable	X	4	6	1,000.00	8	pcs	8,000.00	
14	Structural support	Support saddle	S	4	4	12,000.00	30	pcs	360,000.00	
15	Asset reconditioning	Paint	S	-	1	4,500.00	1	lot	4,500.00	Hempathane, primer and top coat included
16	Pipe design	Suction strainer	M	3	6	5,000.00	8	pcs	40,000.00	
17	Internal Data	Asset tags	P	3	4	1,000.00	1	lot	1,000.00	
18	Housekeeping	Plastic catching basin	M	3	1	100.00	8	pcs	800.00	
19	Instrumentation	Vibration monitoring probes	M	4	2	25,000.00	16	pcs	400,000.00	
20	Pipe design	Air vent	P	3	6	20,000.00	8	pcs	160,000.00	
21	Pump and motor	Alignment bolt and washer	M	3	2	300.00	32	pcs	9,600.00	
22	Pipe design	Flow conditioner	P	3	6	10,000.00	6	pcs	60,000.00	
23	Pipe design	Long radius elbow with guide vanes	P	3	5	15,000.00	6	pcs	90,000.00	
24	Pipe design	Flange type long radius elbow	P	3	4	15,000.00	6	pcs	90,000.00	
25	Pipe design	Pipe (700mm)	P	3	5	30,000.00	1	lot	30,000.00	
26	Pipe design	Pipe (600mm)	P	3	5	30,000.00	1	lot	30,000.00	
27	Pipe design	Rubber expansion joint	P	-	6	6,000.00	16	pcs	96,000.00	
28	Machine foundation	Pile footing	S	3	4	30,000.00	32	pcs	960,000.00	
29	Pipe outdoor protection	Angle bar	S	-	6	500.00	25	pcs	12,500.00	
30	Pipe outdoor protection	GI sheet	S	-	6	2,000.00	12	pcs	24,000.00	
31	Pipe outdoor protection	Welding rod	S	-	6	1,200.00	1	lot	1,200.00	
32	Machine foundation	Foundation Block RCC (3x1.5x1.25)	S	3	5	25,000.00	6	pcs	150,000.00	
33	Machine foundation	Foundation Block RCC (3x1.5x1)	S	3	5	20,000.00	2	pcs	40,000.00	
34	Service reliability	Booster Pump	M	3	6	500,000.00	1	pcs	500,000.00	
35	Service reliability	Storage Pump	M	3	6	400,000.00	1	pcs	400,000.00	
36	Service reliability	BP motor	X	3	6	500,000.00	1	pcs	500,000.00	Necessary for another pump
37	Service reliability	SP motor	X	3	6	400,000.00	1	pcs	400,000.00	Necessary for another pump
38	Instrumentation	Vibration analysis	M	-	7	25,000.00	1	lot	25,000.00	Monthly Monitoring
39	Asset reconditioning	Pump and motor realignment	M	-	1	2,500.00	1	lot	2,500.00	Per realignment
40	Service reliability	Check valve	M	-	6	120,000.00	2	pcs	240,000.00	Necessary for additional pump
41	Service reliability	Butterfly valve	M	-	6	45,000.00	4	pcs	180,000.00	Necessary for additional pump
42	Service reliability	VFD control package	M	-	6	75,000.00	2	pcs	150,000.00	Necessary for additional pump
43	Service reliability	Air valve (for additional pumps)	P	-	6	10,000.00	4	pcs	40,000.00	Necessary for additional pump
44	Service reliability	Foundation Block RCC (3x1.5x1.25)	S	-	6	25,000.00	1	pcs	25,000.00	Necessary for additional pump
45	Service reliability	Foundation Block RCC (3x1.5x1)	S	-	6	20,000.00	1	pcs	20,000.00	Necessary for additional pump
46	Service reliability	Pipe (700mm)	P	-	6	10,000.00	1	lot	10,000.00	Necessary for additional pump
47	Service reliability	Pipe (600mm)	P	-	6	10,000.00	1	lot		Necessary for additional pump
48	Service reliability	Pipe (500mm)	P	-	6	10,000.00	1	lot		Necessary for additional pump
49	Service reliability	Support saddle	S	-	6	12,000.00	2	pcs	24,000.00	Necessary for additional pump
50	Smoke Detectors		F	5	4	2,160.00	18	units	38,880.00	
51	Heat Detectors		F	5	4	1,620.00	4	units	6,480.00	
52	Manual Pull Station		F	5	4	1,890.00	4	units	7,560.00	
53	Horn Strobe Annunciator		F	5	4	2,700.00	4	units	10,800.00	
54	Twisted Pair wire 2.5mm2		F	5	4	108.00	275	lm	29,700.00	
55	20mmØ IMC pipe		F	5	4	540.00	60	lengths	32,400.00	
56	Locknut and Bushing		F	5	4	1,350.00	1	lot	1,350.00	
57	15mmØ FMC Conduit		F	5	4	1,890.00	20	lm	37,800.00	
58	FMC Connectors		F	5	4	1,890.00	1	lot	1,890.00	
59	Junction Box		F	5	4	2,160.00	1	lot	2,160.00	
60	Hangers and Supports		F	5	4	810.00	1	lot	810.00	
61	Testing and Commissioning		F	5	4	1,890.00	1	lot	1,890.00	