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Key Performance Indicators (KPIs) for Evaluation of Corrosion Control Status in the Gathering Pipelines of an Oil Production Field of the Amazon Basin in Ecuador

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Abstract

Pipelines are considered the safest and most economical transportation infrastructure for natural resources such as oil and gas. However, pipelines can fail due to different causes including external and internal corrosion. Failures, due to internal and external corrosion, cause considerable loss of resources to the operators of oil and gas pipelines. The National Association of Corrosion Engineers (NACE) published standard practices (NACE SP-0502 Pipeline External Corrosion Direct Assessment Methodology (ECDA) and NACE SP-0116 Multiphase Internal Corrosion Direct Assessment (MP-ICDA)) to support pipeline operators with external and internal corrosion control. In addition, the fifty KPIs methodology was first published in 2013 to get a better understanding the status of internal and external corrosion control for oil and gas infrastructures.

There are many challenges for the corrosion and integrity management of oil production infrastructure in harsh environments such as the Amazon Basin in Ecuador. Petroamazonas EP (PAM) is a public oil and gas producer that operates in several regions of the Amazon Basin in Ecuador. PAM implemented the NACE ECDA and MP-ICDA between the years 2010 and 2015 to assess the risk of external and internal corrosion on some of the gathering pipelines of the Eden Yuturi (EY) field. In 2017, Petroamazonas EP applied the fifty KPIs methodology to complement the ECDA and MP-ICDA and better under the status of internal and external corrosion control of the gathering pipelines of the EY field.

The objective of this paper is to summarize the results of application of the fifty KPIs methodology by PAM.

1. Introduction

This report focuses on the gathering pipeline system of an oil field operated by Ecuador's public petroleum company, Petroamazonas EP (PAM). PAM operates within several regions of the Amazon Basin in Ecuador. These operating regions are called "blocks". The total oil production of PAM was 423,500 Barrels Per Day (BPD) (67,311 m^3/day) as on July of 2017 [1]. The production comes from four main zones: East, West, North, and South. Figure 1 details the percentage of oil production from each one of the zones.

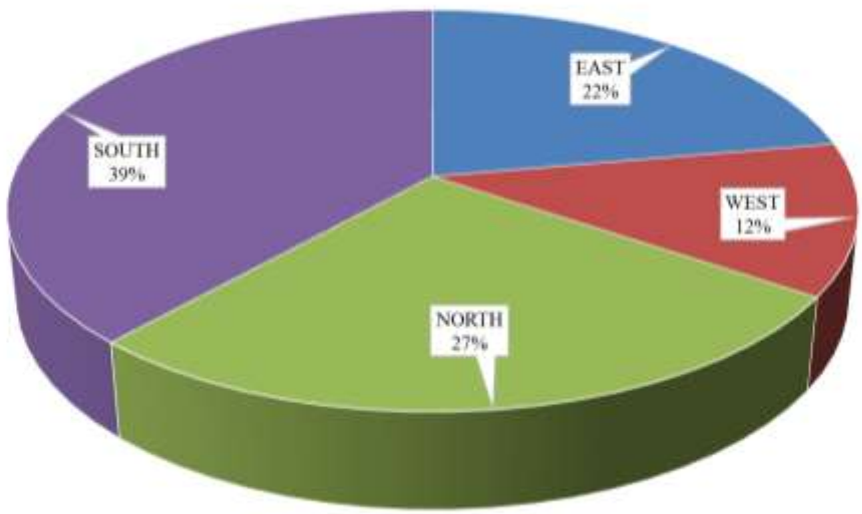

Figure.1 Percentages of Total Oil Production per Zones PAM, July 2017

The gathering pipelines that are the focus of this paper are located in Block 12 of the East zone (Figure 2, Figure 3, and Figure 4). The operating temperature of these pipelines is close to 93ºC (200ºF). The total production from Block 12 is approximately 36,421 BPD (5,790 m^3/day) of oil, 360,154 BPD (57,260 m^3/day) of water and 8 Million Standard Cubic Feet Per Day (MMSCFD) (226,243 m^3/day) of gas [1].

Figure 5 gives a more detailed view of the Eden Yuturi (EY) field, including the production platforms (A, C, D, F, G, H, J, K, and T), the water injection platform (L), and the central Eden Production Facilities (EPF). The EPF were built in 2002 and have undergone several modifications since then. Currently EPF process fluids from:

- Eden Yuturi (EY) field
- Panacocha (PCC) field
- Apaika (APK) field
- ITT field

A PAM's 2010 study [2], shows that internal and external corrosion caused more than 50% of the failures for the gathering pipeline systems of the Blocks 12 and 15 (Figure 6).

- Before 2010, PAM only used hydrostatic test as the integrity validation technique for the gathering pipelines.
- Since 2010, PAM started with the application of the ECDA on several of the gathering pipelines of the Block 12 [3].
- In 2015 PAM completed the implementation of the MP-ICDA on the oldest gathering pipelines from the Block 12 [2].

The gathering pipelines that will be included in the present report are detailed in Table 1.

This report is divided into three sections following the introduction. The next section summarizes the results of the estimation of the fifty KPIs on the gathering pipeline systems of Block 12 [4]. Section three details the results of the application of the fifty KPIs methodology, and section four includes conclusions and recommendations.

Figure 2 EY Production Field in South America (Image from Google Earth).

Figure 3 EY Production Field in Ecuador (Image from Google Earth).

Figure 4 EY Production Field (Image from Google Earth).

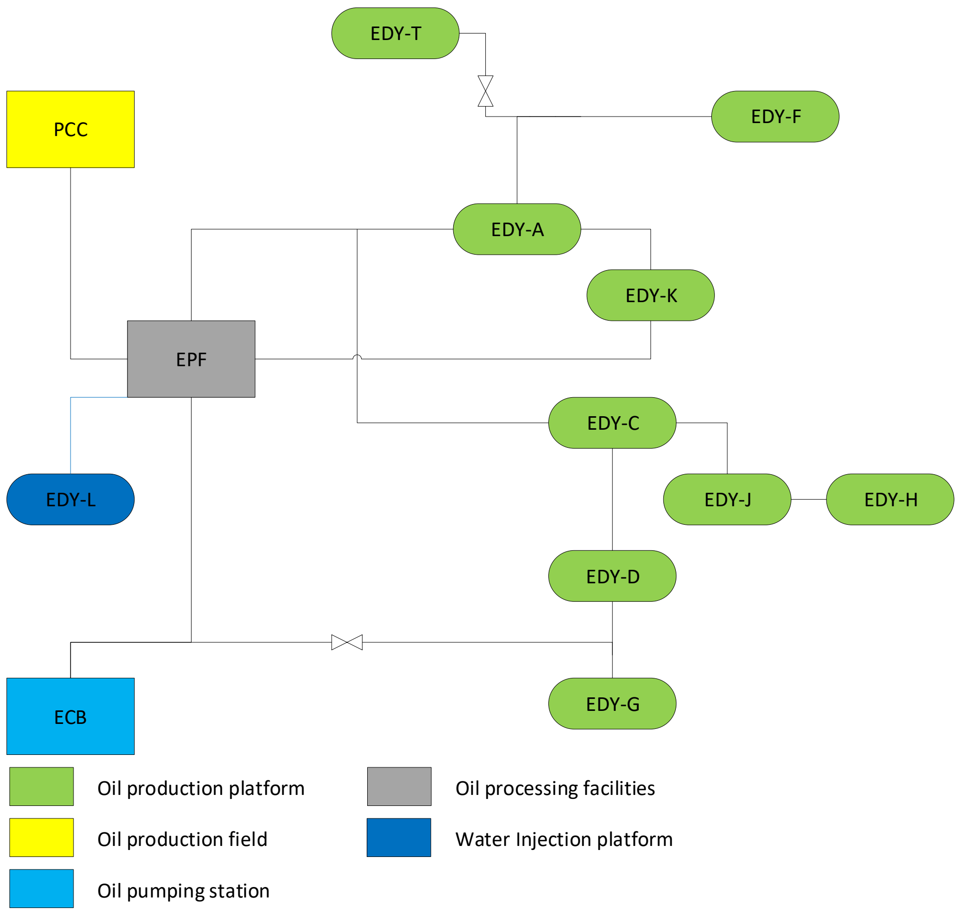

Figure 5 Schematic Diagram of EY Production Field, PAM

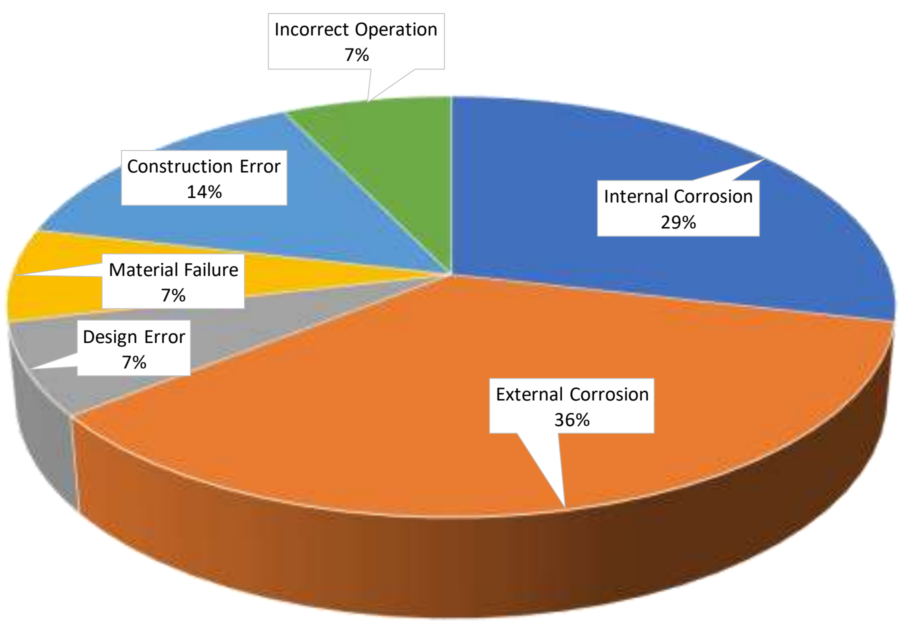

Figure 6 Main Causes of Failures on PAM's Gathering Pipelines

Table 1 EY Gathering Pipelines 2017

Pipeline	Product	Coating		Nominal Diameter		Wall Thickness		Length		Year	Operating Temperature		Operating Pressure	
		Internal	External	(m)	(inches)	(mm)	(inches)	(km)	(miles)	installed	(°F)	(°C)	(psi)	(kPa)
Pad G- Pad D	MP[a]	Amercoat 91	FBE	0.457	18	7.92	0.312	2.84	1.76	2004	185	85	294	2,027
Pad D-Y	MP[a]	Amercoat 91	FBE	0.457	18	7.92	0.312	4.29	2.67	2002	193	89	240	1,655
Pad J-Pad C	MP[a]	Amercoat 91	FBE	0.457	18	7.92	0.312	1.21	0.75	2007	200	93	245	1,689
Pad F-Pad A	MP[a]	Amercoat 91	FBE	0.457	18	7.92	0.312	7.14	4.44	2004	200	93	299	2,062
Pad A-EPF Line 1	MP[a]	Amercoat 91	FBE	0.457	18	7.92	0.312	3.78	2.35	2002	200	93	193	1,331
Pad A-EPF Line 2	MP[a]	TK-505	FBE	0.457	18	7.92	0.312	3.78	2.35	2008	200	93	193	1,331
Pad K-Y	MP[a]	TK-505	FBE	0.305	12	12.70	0.500	0.34	0.21	2009	190	88	200	1,379
Pad H-Pad J	MP[a]		FBE	0.152	6	7.11	0.280	2.86	1.78	2012	191	88	285	1,965
PCC B-PCC C	MP[a]	TK-505	FBE	0.406	16	7.92	0.312	7.60	4.72	2010	190	88	255	1,758
PCC C-EPF	MP[a]	TK-505	FBE	0.406	16	7.92	0.312	24.50	15.22	2010	190	88	770	5,309
DBM-Napo Norte	MP[a]		FBE	0.152	6	7.92	0.312	7.67	4.77	2013	150	66	370	2,551
APK-ECB	MP[a]		FBE	0.457	18	10.31	0.406	24.00	14.91	2013	166	74	462	3,185
ECB-EPF	MP[a]		FBE	0.610	24	12.70	0.500	32.50	20.19	2013	152	67	350	2,413
EPF-EDYL	Water	Plasite 7159	FBE	0.610	24	9.53	0.375	3.24	2.01	2013	170	77	121	834
Pad T-Tee	MP[a]		FBE	0.203	8	8.18	0.322	0.33	0.21	2014	204	96	240	1,655

[a] The gathering pipeline transport a multiphase fluid composed by oil, water and gas

2. Context of Corrosion Control

The results and the rationale for assigning the scores for the KPIs for Corrosion Control Context are shown in Table 2 and the rationale for the KPI scores is described in the following sections.

Table 2 Summary of KPI for Corrosion Control Context

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	DBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
1	0	0	4	4	0	4	3	4	4	4	4	4	4	4	3	0-1: Segment less than 1 km 2-3: Segment greater than 1 km 4-5: Variable segmentation or non
2	3	3	2	3	3	2	2	3	2	2	4	4	4	1	4	0-1: Low or no corrosion risk 2-3: Secondary corrosion risk 4-5: Main corrosion risk
3	3	3	3	3	3	3	3	3	4	4	4	5	5	3	3	0-1: Low consequence of failure 2-3: Medium consequence of failure 4-5: High consequence of failure
4	2	2	1	2	2	1	1	2	2	2	4	5	5	0	3	0-1: Overall corrosion risk low 2-3: Overall corrosion risk medium 4-5: Overall corrosion risk high
5	4	4	4	4	4	3	3	2	2	2	1	1	1	1	0	0-1: Life between 1-5 years 2-3: Life between 5-10 years 4-5: Life more than 10 years

KPI 1: Segmentation of Infrastructure

For the MP-ICDA, PAM created the segmentation of various pipelines. KPI 1 scores were assigned based on this segmentation [2] (Table 1).

KPI 2: Corrosion Risk

Almost all the pipelines transport multiphase fluid (oil, gas, and water), with the exception of the water injection pipeline. It is assumed that the corrosivity of the fluids is similar because production is from the same reservoirs. The higher KPI 2 score was assigned to the gathering pipelines that do not have an internal coating and score was reduced for the pipelines that have internal coating.

KPI 3: Location of Infrastructure

All the pipelines are located in environmentally sensitive areas, as defined by the Code of Federal Regulations (CFR) Title 49, Part 195.6, USA. In addition, the pipelines APK-ECB, 7 ECB-EPF, PCC B-PCC C, PCC C- EPF, and DBM-Napo Norte, are located near national parks and rivers such as the Napo. Therefore, the consequence of failure is medium or high.

KPI 4: Quantification of Risk

This KPI is estimated by the multiplication of KPIs 2 and 3.

KPI 5: Life of Infrastructure

This KPI 5 score was calculated based on information provided in Table 1.

3. Internal corrosion – Model

The results and the rationale for assigning the scores for the KPIs for Internal Corrosion Model are shown in Table 3 and the rationale for the KPI scores is described in the following sections.

KPI 6: Material of Construction

All the gathering pipelines are constructed using pipeline steel API 5L, grades 42, 65, or 70 [5]. Additionally, as shown in Table 1, most of the pipelines are internally coated (lower KPI 6 score) and some are constructed without any coatings (higher KPI 6 score).

KPI 7: Corrosion Allowance

Corrosion allowance is only considered for the pipelines that do not have internal coating. In addition, the gathering pipelines from PCC-C-EPF, APK-ECB, and ECB-EPF have a greater wall thickness on the main river crossings.

KPI 9: Effect of Upset Condition in Upstream Sector on the Current Sector

The gathering pipelines from the EY field (Pads A, C, D, F, G, H, J, K, and T) are not affected by upstream operations. On the other hand, the pipelines from PCC, APK, and ECB are directly affected by upstream operations on pumping equipment, and operating pressure that can accelerate internal corrosion.

Table 3 Summary of KPI for Internal Corrosion Control Model

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	OBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
6 IC	3	3	3	3	3	3	4	4	3	3	3	4	4	3	4	0-1: Material selection based on corrosion 2-3: Material adequate with corrosion control 4-5: Unknown suitability of material
7 IC	4	4	4	4	4	4	3	3	3	3	3	3	3	4	3	0-1: Proper corrosion allowance 2-3: Corrosion allowance with corrosion control 4-5: Improper corrosion allowance
9 IC	1	1	1	1	1	1	1	1	3	3	2	3	3	3	1	0-1: Plan to control of upstream segments implemented 2-3: Plan to control upset upstream not implemented 4-5: No plan to control upset upstream
10 IC	2	2	2	2	2	2	2	2	3	3	2	3	3	2	2	0-1: Plan to control of downstream segments implemented 2-3: Plan to control upset downstream not implemented 4-5: No plan to control upset downstream
11 IC	2	2	2	2	2	2	2	2	3	3	3	3	3	3	2	0-1: Proper knowledge of corrosion mechanisms 2-3: Some knowledge of corrosion mechanisms 4-5: Improper knowledge of corrosion mechanisms
12	1	1	3	3	1	3	3	3	4	4	4	4	4	4	3	0-1: Corrosion rate based on model 2-3: No basis for selection of corrosion rate 4-5: Unknown corrosion rate
14 IC	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	0-1: Corrosion professional involved in all stages 2-3: Corrosion professional involved in some stages 4-5: Corrosion professional not involved
39	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0-1: Corrosion rate reduced after maintenance activities 2-3: Corrosion rate maintained after maintenance activities 4-5: Corrosion rate increased after maintenance activities
40	3	3	3	3	3	3	3	3	3	3	3	2	2	3	3	0-1: Corrosion rate within 10% of expected 2-3: Corrosion rate less than 10% of expected 4-5: Corrosion rate is more than 10% of expected

KPI 10: Effect of Upset Condition in the Current Sector on the Downstream Sector

Upset conditions of all pipelines will affect the EPF separation process.

KPI 11: Mechanisms of corrosion

For all gathering pipelines the main corrosion mechanism is localized corrosion due the high corrosivity of the transported products according to the analysis performed as part of the MP ICDA project [2].

Some pipelines do not have facilities for mechanical cleaning tools. Therefore, the risks of corrosion under deposits and water accumulation are high. Water pipelines are susceptible for Microbiologically Influenced Corrosion (MIC).

KPI 12: Maximum Corrosion Rate (internal surface)

The corrosion rate obtained from the MP ICDA project is used to score KPI 12.

KPI 14: Accessories (internal surface)

Corrosion and integrity engineers were involved in the design and construction stages of the older pipelines and in the establishment of accessories and their locations. However, their involvement is less in the newer pipelines due to costs optimization.

KPI 39: Internal corrosion rate after maintenance activities

The maintenance operations are regulated by the Management of Change (MOC) policies. MOC are implemented to reduce internal corrosion rates after the maintenance activities. However, there are not records or measurements to establish their effectiveness.

KPI 40: Internal corrosion rate reduction after maintenance activities

Most pipelines have facilities for launching and receiving the cleaning tools. For these pipelines, mechanical cleaning is used to reduce internal corrosion. Polyurethane pigs and used for the coated pipelines and mandrel pigs in the un-coated pipelines. However, there is no comparison of the corrosion rates before and after the maintenance activities.

4. Internal corrosion – Mitigation

The results and the rationale for assigning the scores for the KPIs for Internal Corrosion Mitigation are shown in Table 4 and the rationale for the KPI scores is described in the following sections.

Table 4 Summary of KPI for Internal Corrosion Mitigation

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	DBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
16	1	1	1	1	1	1	4	4	1	1	4	4	4	1	4	0-1: No mitigation required based on design 2-3: Mitigation required based on design 4-5: Mitigation required based on current operating conditions
17	2	2	2	2	2	2	4	3	2	2	2	3	3	3	4	0-1: No mitigation required or properly implemented 2-3: Mitigation implemented for current operating conditions 4-5: Mitigation improper for current operating conditions
18	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Mitigated corrosion rate based on baseline 2-3: No basis for selection of mitigated corrosion rate 4-5: Unknown mitigated corrosion rate
19	2	2	2	2	2	2	3	2	2	2	2	2	2	2	4	0-1: 99% Availability of mitigation practices 2-3: 95-99% Availability of mitigation practices 4-5: Less than 95% Availability of mitigation practices

KPI 16: Mitigation to Control Internal Corrosion

Most of the pipelines have internal coatings as a mitigation strategy for internal corrosion. Corrosion rates of some pipelines are reduced by mechanical cleaning and by the addition of corrosion inhibitors.

KPI 17: Mitigation Strategies to Control Internal Corrosion

Most of the pipelines have facilities for mechanical cleaning programs, however these activities are not regularly performed for all the pipelines.

KPI 18: Mitigated Corrosion Rate for Internal Corrosion

The mitigated corrosion rates for internal corrosion has not been established for the EY gathering pipelines.

KPI 19: Effectiveness of Internal Corrosion Mitigation

The effectiveness of internal corrosion mitigation including corrosion inhibitor effectiveness is monitored based on corrosion coupons on the flow pipelines, but there is no direct monitoring for the corrosion rate of the gathering pipelines.

For internally coated pipelines, the corrosion rate from the coupons can't be directly obtained. One of the recommendations of the MP-ICDA project was to test samples of the internal coating to find the estimated life of the system and the corrosion rates after the failure of the coating system [2].

The gathering pipelines from Pad K-Y and Pad T-Tee do not have launchers and receivers for mechanical cleaning.

5. Internal corrosion – Monitoring:

The results and the rationale for assigning the scores for the KPIs for Internal Corrosion Monitoring are shown in Table 5 and the rationale for the KPI scores is described in the following sections.

Table 5 Summary of KPI for Internal Corrosion Monitoring

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	DBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
24	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Two or more complimentary monitoring techniques 2-3: One monitoring technique proven to be effective 4-5: No monitoring or ineffective (not proven) monitoring
25	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Probes in all critical locations an non-critical 2-3: Probes in most of the critical locations 4-5: Probes in some of the critical locations
26	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Corrosion rates from two monitoring within 10% 2-3: Corrosion rates from two monitoring within 11-25% 4-5: Corrosion rates from two monitoring within > 25%
27	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Mitigated corrosion rates from two monitoring within 10% 2-3: Mitigated corrosion rates from two monitoring within 11-25% 4-5: Mitigated corrosion rates from two monitoring within > 25%
32 IC	2	2	4	4	2	4	4	3	3	3	3	3	3	3	3	0-1: Frequency of inspection based on RBI 2-3: Frequency of inspection based on engineering processes 4-5: More than then 10 without inspection
33	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Corrosion rate from monitoring and inspection within 10% 2-3: Corrosion rate from monitoring and inspection within 11-25% 4-5: Corrosion rate from monitoring and inspection within >25%

KPI 24: Internal Corrosion Monitoring Techniques

Coupons are used to monitor internal corrosion rate on some of the gathering pipelines, but the methodology has not proven to be effective.

KPI 25: Number of Internal Corrosion Monitoring Probes

Coupons are installed only at the beginning or end of some of the gathering pipelines. There are not enough monitoring probes for internal corrosion monitoring and further only one type of monitoring technique is used.

KPI 26: Internal Corrosion Rates from Monitoring

Corrosion rates for the gathering pipelines have not been established.

KPI 27: Accuracy of Internal Corrosion Monitoring

There are not enough probes to compare the accuracy of the monitoring techniques.

KPI 32: Frequency of Inspections for Internal Corrosion

The high temperature of operation (above 90°C) restrict the use of ILI tools. Other gathering pipelines have no facilities for the delivery and reception of the ILI tools.

KPI 33: Comparison between Inspection and Monitoring for Internal Corrosion

There is no ILI data and not enough probes for monitoring. Therefore, the comparison can't be made.

6. External corrosion – Mitigation:

The results and the rationale for assigning the scores for the KPIs for External Corrosion Mitigation are shown in Table 6 and the rationale for the KPI scores is described in the following sections.

Table 6 Summary of KPI for External Corrosion Mitigation

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	DBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
20	3	3	3	3	3	3	2	2	3	3	2	1	1	2	2	0-1: Proper mitigation strategies from design stage 2-3: Proper mitigation strategies based on current knowledge 4-5: Mitigation strategies based on outdated knowledge
21	3	3	3	3	3	2	2	2	1	1	1	1	1	2	1	0-1: Corrosion control and baseline from first year 2-3: Corrosion control from first year but baseline not 4-5: Corrosion control implemented but unknown baseline
22	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Mitigated corrosion rate based on baseline 2-3: No basis for selection of mitigated corrosion rate 4-5: Unknown mitigated corrosion rate
23	3	3	3	3	3	3	4	2	2	2	2	2	2	2	2	0-1: 99% Availability of mitigation practices 2-3: 95-99% Availability of mitigation practices 4-5: Less than 95% Availability of mitigation practices

KPI 20: Selection of Mitigation to Control External Corrosion

The coating system for the gathering pipelines is compatible with the cathodic protection system; however, for the oldest pipelines the coating type for the girth welds was not selected adequately.

KPI 21: Implementation of Mitigation to Control External Corrosion

There has been at least one mitigation strategy implemented for all the gathering pipelines. The effectiveness of the mitigation strategies is evaluated using indirect inspection techniques recommended by the ECDA standard practice.

KPI 22: Mitigated External Corrosion Target

Under normal operating conditions, the expected corrosion rate for a steel pipeline with a calibrated cathodic protection system and compatible coating system is 1 milli-inch per year (mpy) or 0.0254 mm/year [6]. However, this target has not yet been established for the gathering pipelines of EY.

KPI 23: Effectiveness of Mitigation for External Corrosion

The cathodic protection systems are operating most of the time, but several external works have accidentally disconnected the systems temporarily reducing the mitigation effectiveness. In addition, the cathodic protection system was installed in the Pad K-Y system after one year of operation.

7. External corrosion – Model:

The results and the rationale for assigning the scores for the KPIs for External Corrosion Model are shown in Table 7 and the rationale for the KPI scores is described in the following sections.

Table 7 Summary of KPI for External Corrosion Model

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	DBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
6 EC	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0-1: Material selection based on corrosion 2-3: Material adequate with corrosion control 4-5: Unknown suitability of material
7 EC	4	4	4	4	4	4	3	3	3	3	3	3	3	4	3	0-1: Proper corrosion allowance 2-3: Corrosion allorwance with corrosion control 4-5: Improper corrosion allowance
9 EC	1	1	1	1	1	1	1	1	3	3	2	3	3	3	1	0-1: Plan to control of upstream segments implemented 2-3: Plan to control upset upstream not implemented 4-5: No plan to control upset upstream
10 EC	3	3	3	3	3	3	2	2	3	3	2	1	1	1	1	0-1: Plan to control of downstream segments implemented 2-3: Plan to control upset downstream not implemented 4-5: No plan to control upset downstream
11 EC	2	2	2	2	2	2	2	2	3	3	3	3	3	3	2	0-1: Proper knowledge of corrosion mechanisms 2-3: Some knowledge of corrosion mechanisms 4-5: Improper knowledge of corrosion mechanisms
13	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Corrosion rate based on model 2-3: No basis for selection of corrosion rate 4-5: Unknown corrosion rate
14 EC	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	0-1: Corrosion professional involved in all stages 2-3: Corrosion professional involved in some stages 4-5: Corrosion professional not involved
41	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0-1: Corrosion rate reduced after maintenance activities 2-3: Corrosion rate maintaned after maintenance activities 4-5: Corrosion rate increased after maintenance activities
42	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0-1: Corrosion rate within 10% of expected 2-3: Corrosion rate less than 10% of expected 4-5: Corrosion rate is more than 10% of expected

KPI 6: Material of Construction

As mentioned on KPI 6 section, all the gathering pipelines from the EY field are constructed from pipeline steel API 5L, grades 42, 65, or 70 [5].

KPI 7: Corrosion Allowance

As explained on KPI 7 section, the corrosion allowance was only considered for the pipelines that do not have internal coating. In addition, the gathering pipelines from PCC-C EPF, APK-ECB, and ECB-EPF have a greater wall thickness on the main river crossings.

KPIs 9 and 10: Upset Condition upstream and downstream

The only parameter that can affect external corrosion is the temperature. The operating temperatures are relatively high (90ºC) and are relatively constant in all segments.

KPI 11: Mechanisms of corrosion

The main corrosion mechanism for all gathering pipelines is localized corrosion that can occur on the external surface when there is a coating failure and the current from the cathodic protection system is not able to reach the metal surface. Additionally, shrinks sleeves were used as the coating system for the girth welds of the older gathering pipelines. Localized corrosion has been identified below disbonded sleeves in some excavations of gathering pipelines with similar operational temperatures as the EPF. Shrink sleeves are identified as a coating system that can create a shielding effect on the cathodic protection current and generate external corrosion mechanisms [3].

KPI 13: Maximum Corrosion Rate (external surface)

According to NACE ECDA standard practice the corrosion rate for an unprotected steel in soil is expected to be 16 mpy (0.4 mm/year). However, this value has not been measured for the EY field conditions.

KPI 14: Accessories (external surface)

Refer to KPI 14.

KPI 41: External corrosion rate after maintenance activities

The maintenance activities for external corrosion included coating repairs in the areas of severe indications according to the indirect inspection surveys performed in accordance to NACE ECDA standard practice. Nevertheless, the corrosion rate has not been measured and the comparison can't be established.

KPI 42: External corrosion rate reduction after maintenance activities

Refer to KPI 41.

8. External corrosion – Monitoring

The results and the rationale for assigning the scores for the KPIs for External Corrosion Monitoring are shown in Table 8 and the rationale for the KPI scores is described in the following sections.

Table 8 Summary of KPI for External Corrosion Monitoring

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	DBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
28	4	4	4	4	4	4	3	3	4	4	3	3	3	3	3	0-1: Two or more complimentary monitoring techniques 2-3: One monitoring technique proven to be effective 4-5: No monitoring or ineffective (not proven) monitoring
29	4	4	4	4	4	4	3	3	4	4	3	3	3	3	3	0-1: Probes in all critical locations an non-critical 2-3: Probes in most of the critical locations 4-5: Probes in some of the critical locations
30	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Corrosion rates from two monitoring within 10% 2-3: Corrosion rates from two monitoring within 11-25% 4-5: Corrosion rates from two monitoring within > 25%
31	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Mitigated corrosion rates from two monitoring within 10% 2-3: Mitigated corrosion rates from two monitoring within 11-25% 4-5: Mitigated corrosion rates from two monitoring within > 25%
32 EC	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0-1: Frequency of inspection based on RBI 2-3: Frequency of inspection based on engineering processes 4-5: More than 10 years without inspection
34	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Corrosion rate from monitoring and inspection within 10% 2-3: Corrosion rate from monitoring and inspection within 11-25% 4-5: Corrosion rate from monitoring and inspection within >25%

KPI 28: External Corrosion Monitoring Techniques

The monitoring techniques for external corrosion concentrate on the cathodic protection polarization criterion. In addition, as already explained the NACE ECDA was used to assess the effectiveness of the coating system for all the gathering pipelines of the EY. However, there is not a good monitoring technique in use for the corrosion below the shielding coatings installed on the oldest pipelines.

KPI 29: Number of External Corrosion Monitoring Probes per unit area

The probes for cathodic protection are located at least every two kilometers for the oldest pipelines, and every kilometer for the newest pipelines. Nevertheless, newer monitoring points have not been installed on the locations detected by the NACE ECDA as critical.

KPI 30: External Corrosion Rates from Monitoring

The corrosion rates are not measured with the monitoring techniques.

KPI 31: Accuracy of External Corrosion Monitoring

There are no probes for external corrosion rate monitoring and the accuracy can’t be established.

KPI 32 Frequency of Inspections for External Corrosion

All gathering pipelines from EY has been inspected using the NACE ECDA methodology. The use of ILI has been restricted by the operating conditions and the presence of internal coatings.

KPI 34 Comparison between Inspection and Monitoring for External Corrosion

No probes were in place to measure external corrosion rates and operating conditions restrict the use of ILI. Severe corrosion was only observed in limited locations during the direct examination.

9. Measurement

The results and the rationale for assigning the scores for the KPIs for Measurements are shown in Table 9 and the rationale for the KPI scores is described in the following sections.

Table 9 Summary of KPI for Measurement

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	DBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
35	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	0-1: All corrosion related data is available and usable 2-3: All corrosion related data is available but not usable 4-5: Not all the corrosion related data is available
36	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Data validated according to documented procedure 2-3: Data not properly validated but used for corrosion rate 4-5: Data not properly validated and used to guide corrosion rate

KPI 35: Measurement

No information is available on how various measurements (such as temperature and pressure).

KPI 36: Validation of the Measured data

The data used for corrosion analysis is not validated using a formal approach.

10. Maintenance

The results and the rationale for assigning the scores for the KPIs for Maintenance are shown in Table 10 and the rationale for the KPI scores is described in the following sections.

KPI 8: Normal Operating Conditions

Normal operating conditions are maintained most of the time for all the gathering pipelines.

KPI 15: Commissioning

All the gathering pipelines were adequately hydrotested but there is not a baseline with ILI.

KPI 37: Procedures for maintenance schedule

The risk level of the sections of the pipelines has been established as part of the implementation of the ECDA and MP-ICDA methodologies. However, maintenance decisions are based on service time or time of last inspection and are not risk based.

KPI 38: Maintenance activities

The maintenance activities are normally planned, but there are some occasions that the tasks are not completed due to reductions in personnel or budget.

Table 10 Summary of KPI for Maintenance

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	DBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
8	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0-1: Operating conditions within range 2-3: 10% Outside proper operating conditions 4-5: Frequent inadequate operating conditions
15	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0-1: Proper commissioning and baseline established 2-3: Proper commissioning but non baseline established 4-5: Improper commissioning
37	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Preventive maintenance based on risk before ALARP 2-3: Preventive maintenance based on higher risk levels 4-5: Corrective maintenance
38	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0-1: All maintenance activities are adequately planned 2-3: Some delays for the implementation of maintenance activities 4-5: Frequent changes to maintenance activities
43	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Corrosion personnel enough and with proper training 2-3: Corrosion personnel is enough and some training 4-5: Insufficient corrosion personnel and training
44	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0-1: All personnel have more than five years of experience 2-3: Only key personnel have more than 5 years of experience 4-5: Unknown experience of corrosion personnel
45	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Automatic collection and storage of corrosion data 2-3: Data measured and manually stored 4-5: Not adequate management of data
46	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Data verified, stored and proactively used 2-3: Data verified and stored but not used proactively 4-5: Not adequate management of data

KPI 43: Workforce Capacity

The number of workers to control internal and external corrosion has been significantly reduced even though the area of responsibility has increased considerably. In addition, the personnel of the maintenance and operation departments have not a clear definition of the responsibilities between external and internal corrosion control.

KPI 44: Workforce Experience and Knowledge

Most of the personnel related with internal and external corrosion control have more than 5 years of experience in similar areas.

KPI 45: Data to Database

There is no clearly established data management process.

KPI 46: Data from Database

Refer to KPI 45.

11. Management

The results and the rationale for assigning the scores for the KPIs for Management are shown in Table 11 and the rationale for the KPI scores is described in the following sections.

KPI 47: Internal Communication Strategy

There is an internal communication strategy for the topics related to corrosion control, however the strategy is not always practiced or documented.

KPI 48: External Communication Strategy

There is a communication department but is not regularly providing information to external parties about topics related to corrosion control.

KPI 49: Corrosion Management Review

There is not a fixed schedule for reviewing all the activities related to corrosion control.

KPI 50: Failure Frequency

In most of the EY gathering pipelines there have not been any failure.

Table 11 Summary of KPI for Management

KPI	Pad G - Pad D	Pad D - Y	Pad J - Pad C	Pad F - Pad A	Pad A - EPF Line 1	Pad A - EPF Line 2	Pad K - Y	Pad H - Pad J	PCC B - PCC C	PCC C - EPF	DBM - Napo Norte	APK-ECB	ECB - EPF	EPF - Pad L	Pad T - Tee	Remarks:
47	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0-1: Proper internal communication 2-3: Some internal communication 4-5: Improper internal communications
48	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0-1: Proper external communication 2-3: Some external communication 4-5: Improper external communications
49	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0-1: Annual revision of KPIs 2-3: Revision of KPIs every 2-5 years 4-5: Not established schedule for KPIs revision
50	1	1	1	1	3	1	1	1	1	1	3	1	1	1	1	0-1: Zero failures between KPIs reviews 2-3: Less than 5 failures between KPIs reviews 4-5: More than 5 failres between KPIs reviews

12. Results of Application of Fifty KPIs to the Gathering Pipelines EY

The results of the application of the fifty KPIs are shown on Figures 7 to 21.

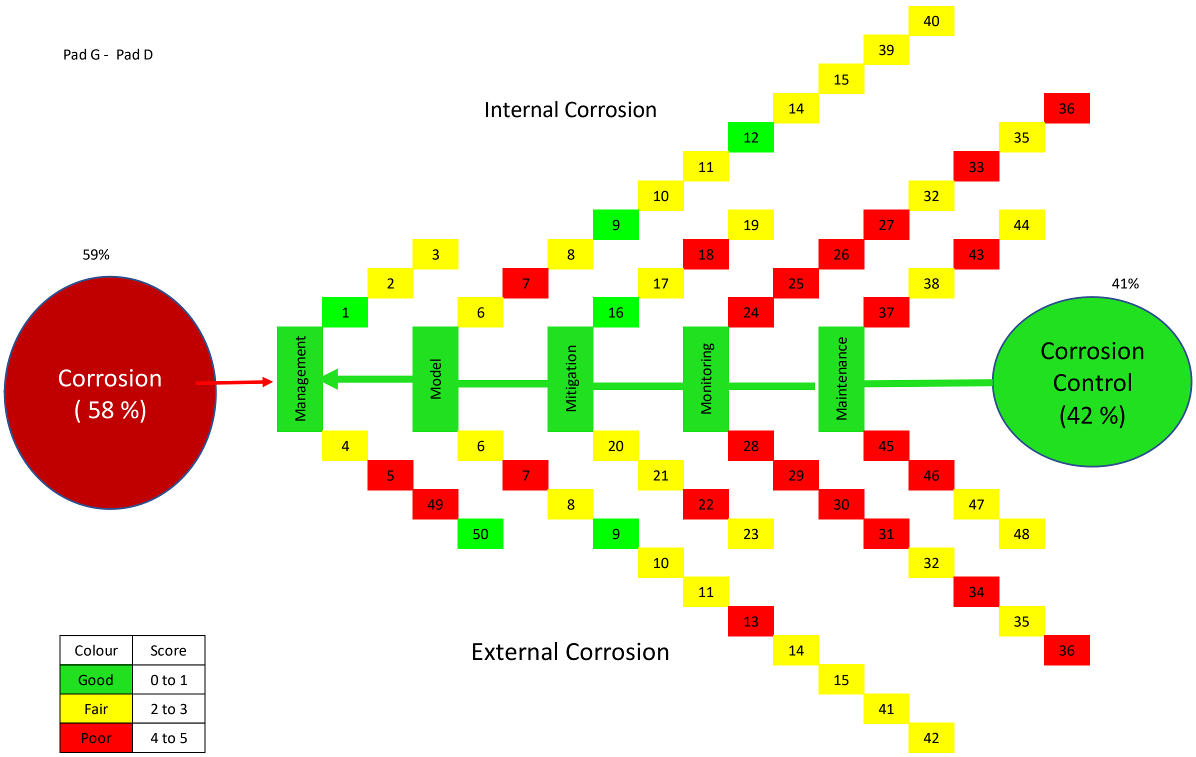

Figure 7 KPI Status Pad G-Pad D Gathering Pipeline, PAM

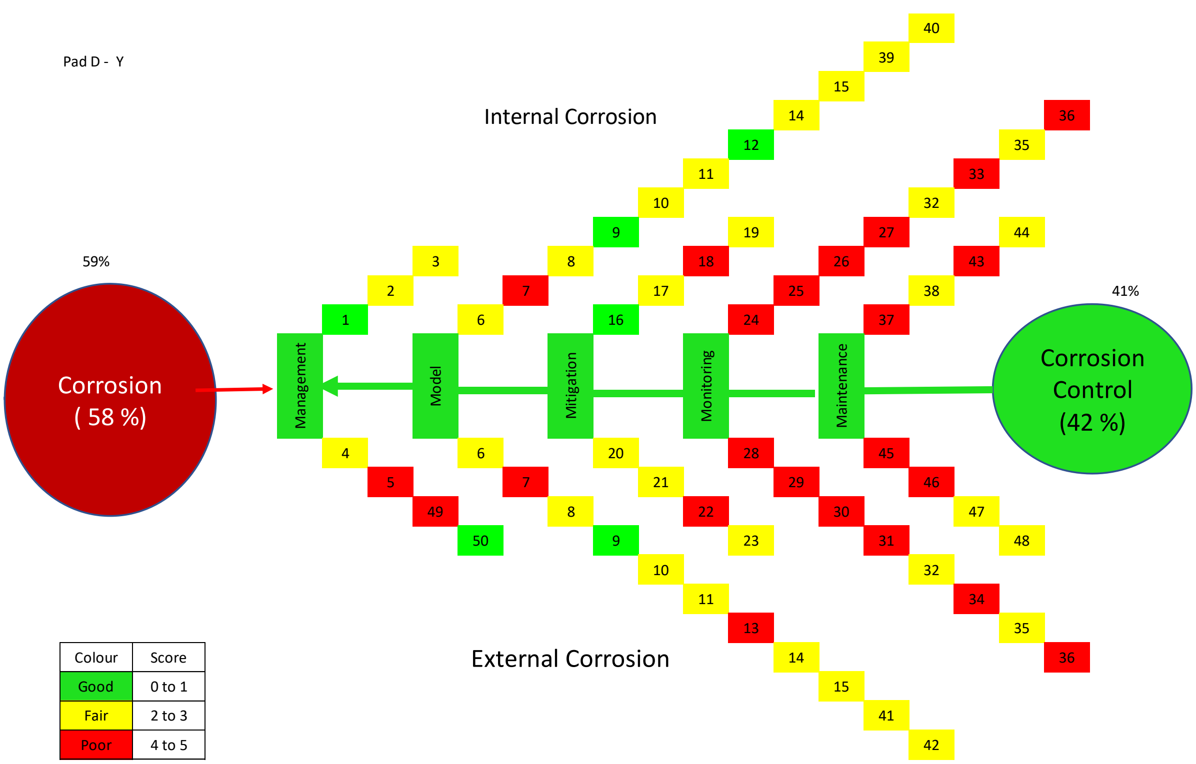

Figure 8 KPI Status Pad D-Y Gathering Pipeline, PAM

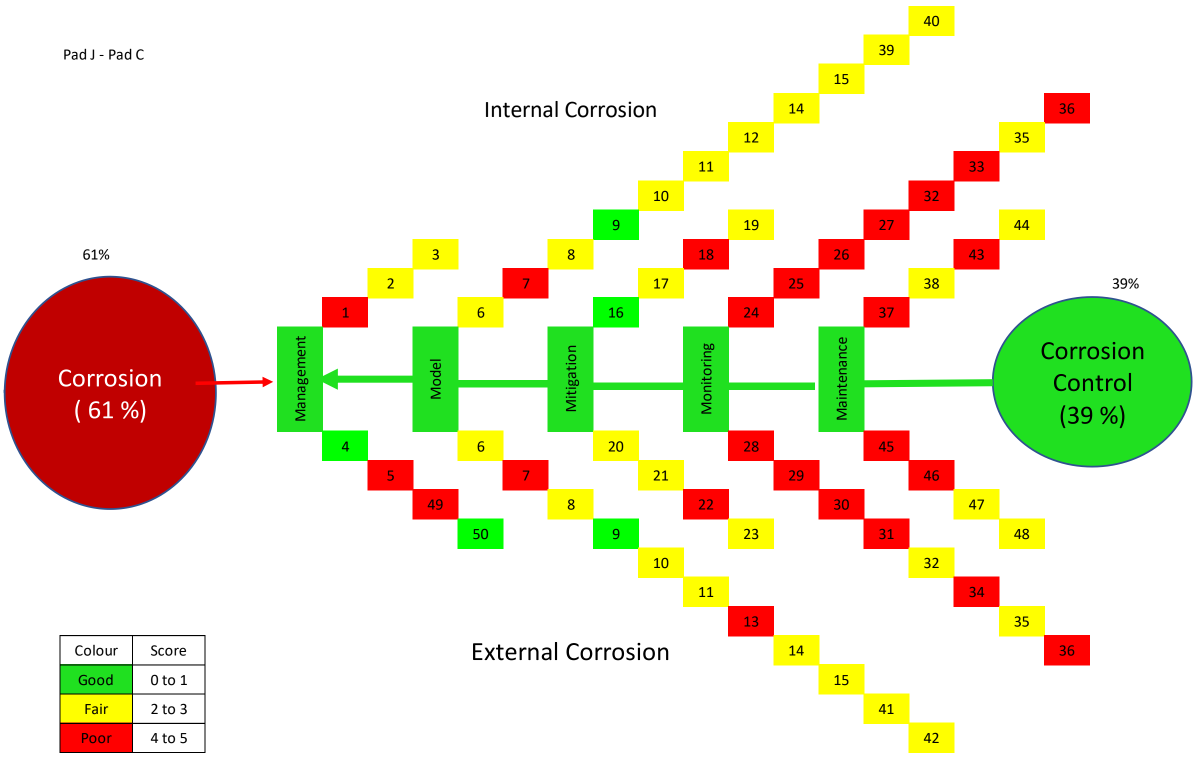

Figure 9 KPI Status Pad J-Pad C Gathering Pipeline, PAM

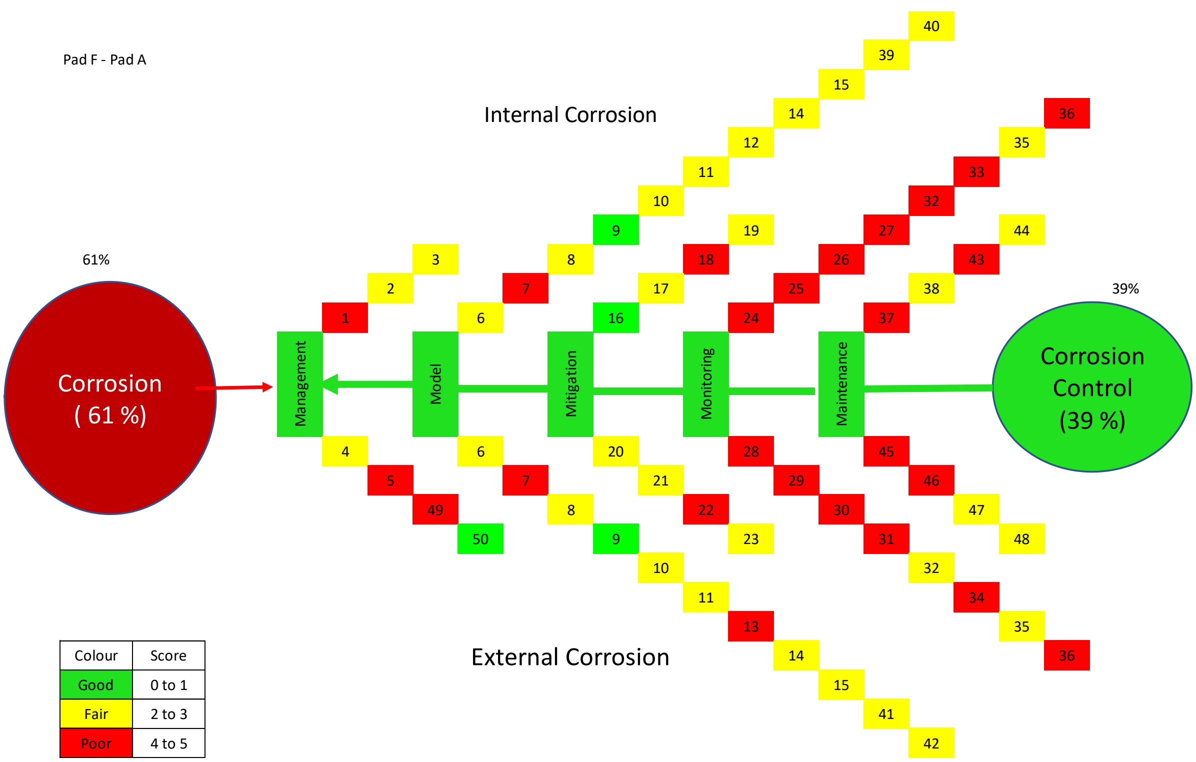

Figure 10 KPI Status Pad F-Pad A Gathering Pipeline, PAM

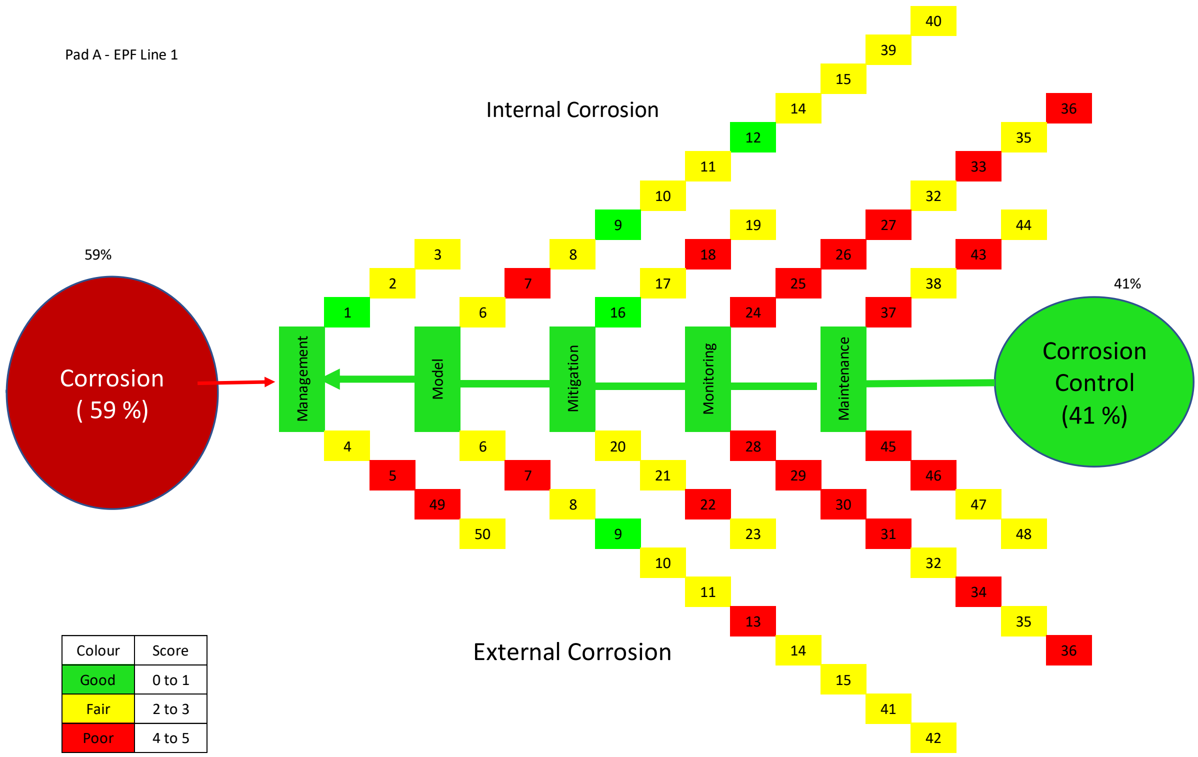

Figure 11 KPI Status Pad A-EPF 1 Gathering Pipeline, PAM

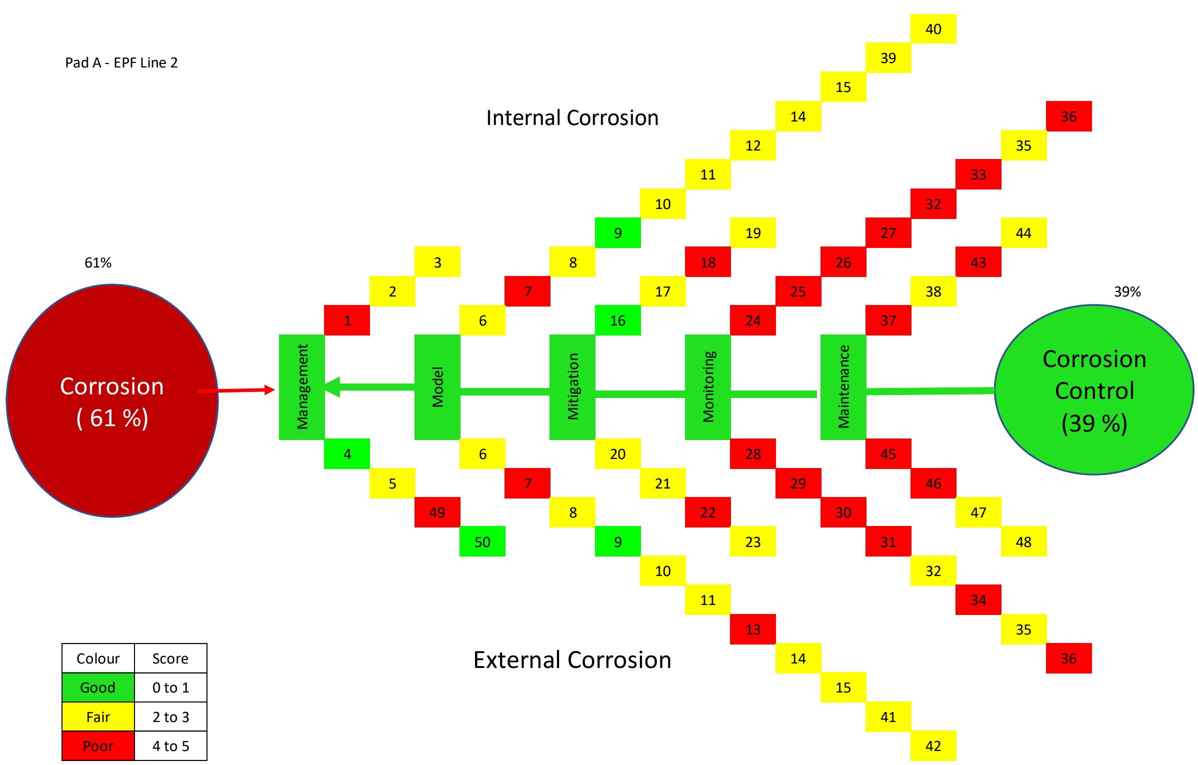

Figure 12 KPI Status Pad A-EPF 2 Gathering Pipeline, PAM

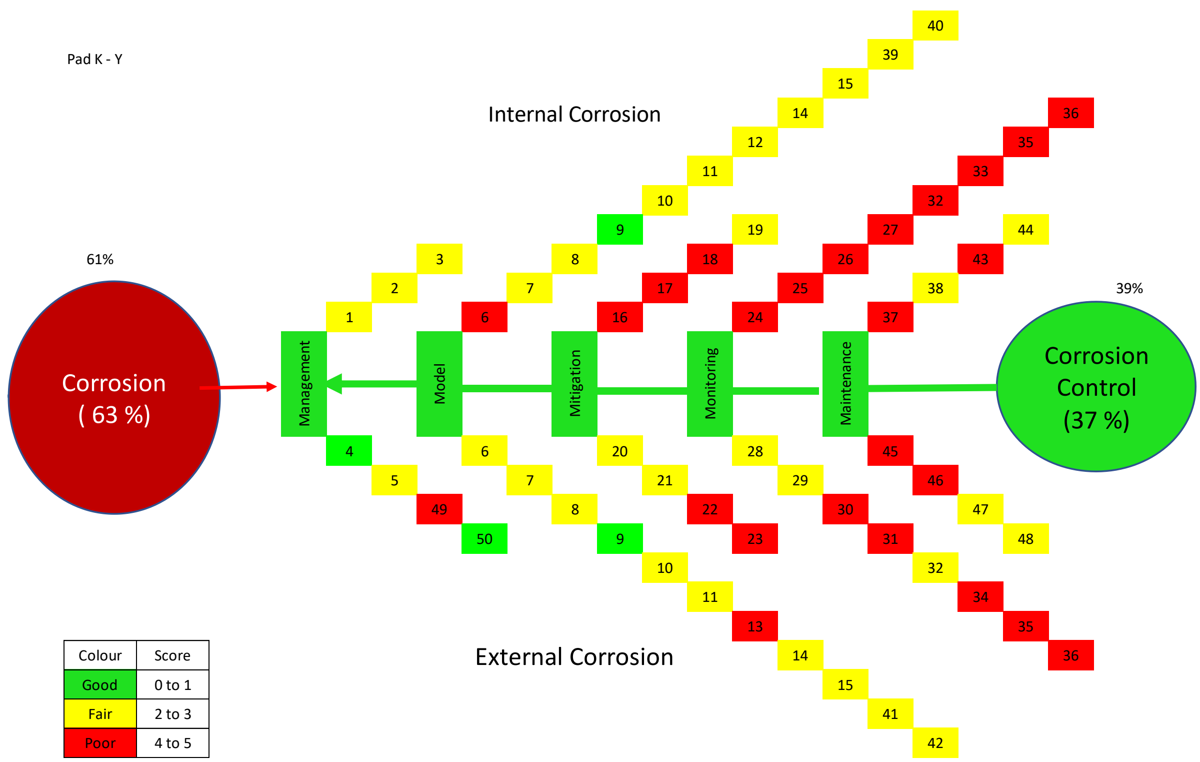

Figure 13 KPI Status Pad K-Y Gathering Pipeline, PAM

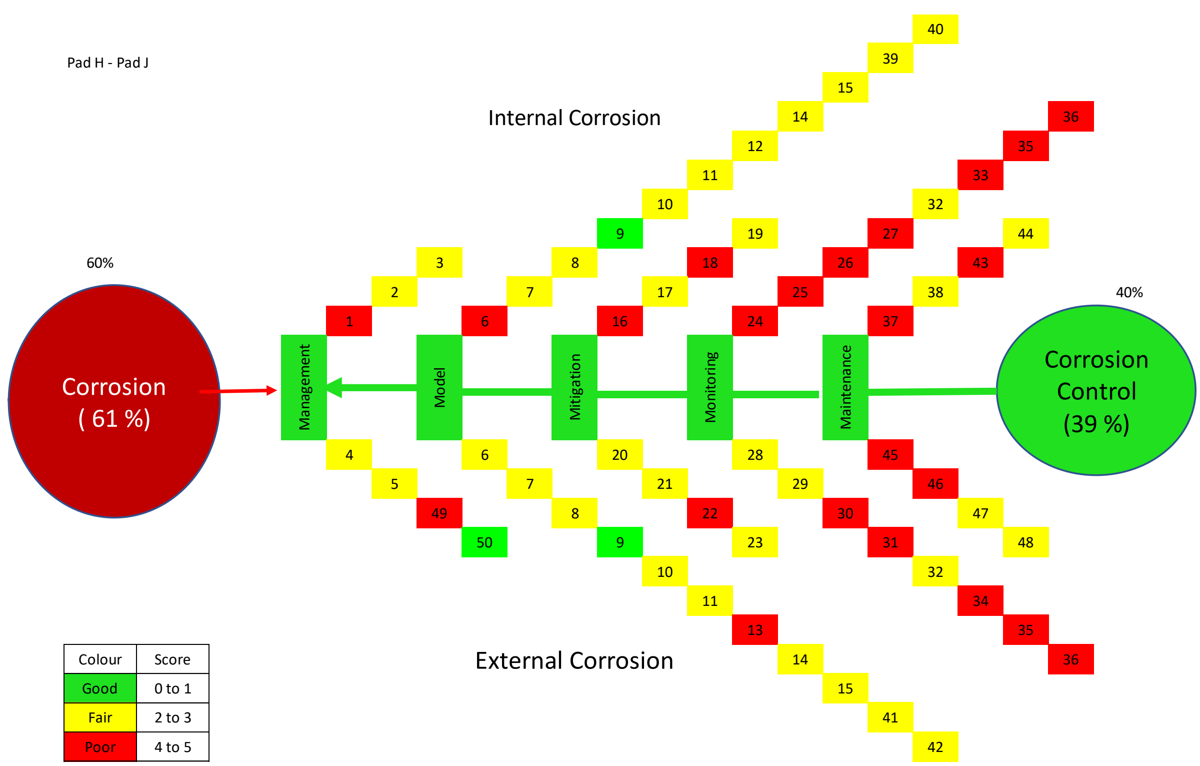

Figure 14 KPI Status Pad H-Pad J Gathering Pipeline, PAM

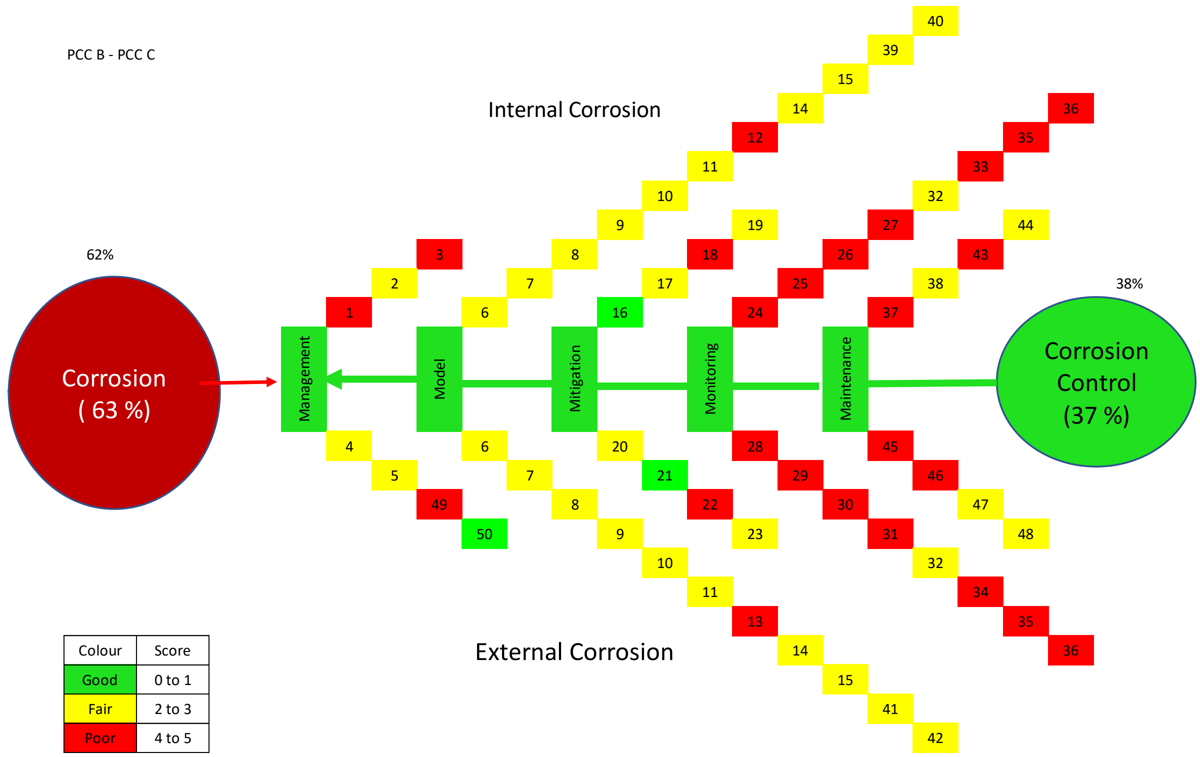

Figure 15 KPI Status PCC B-PCC C Gathering Pipeline, PAM

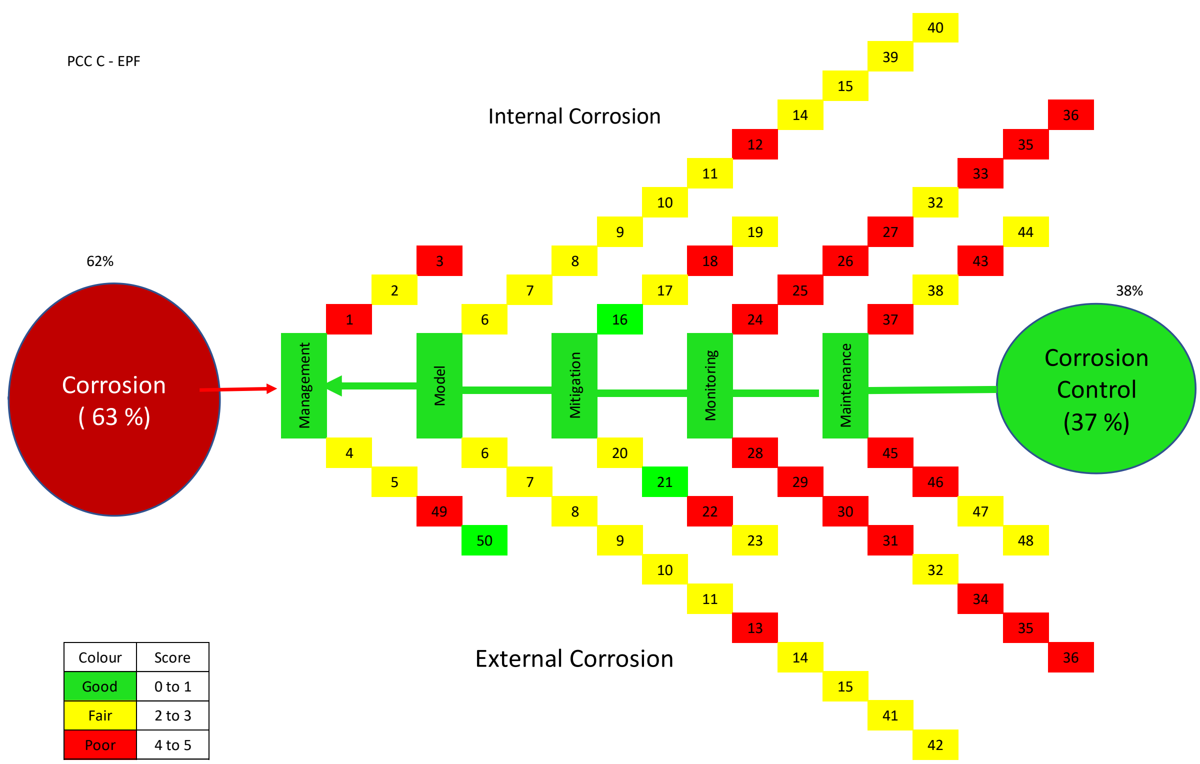

Figure 16 KPI Status PCC C-EPF Gathering Pipeline, PAM

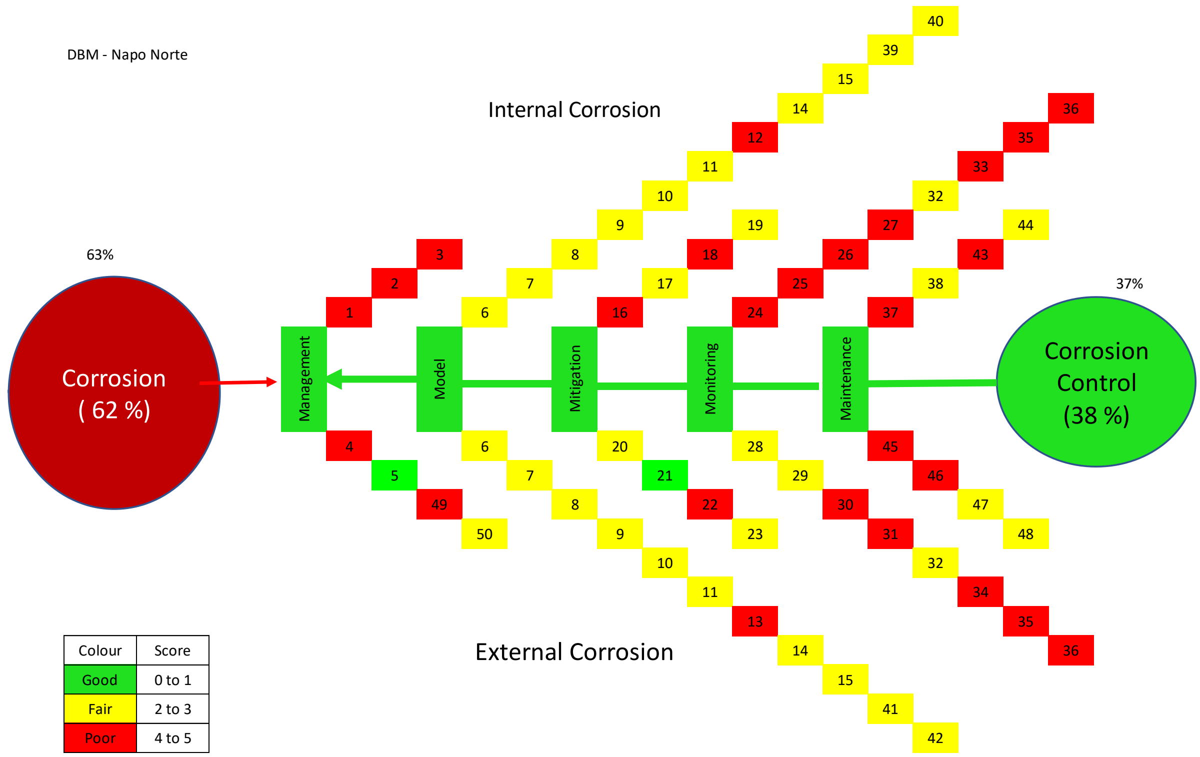

Figure 17 KPI Status DBM-Napo Gathering Pipeline, PAM

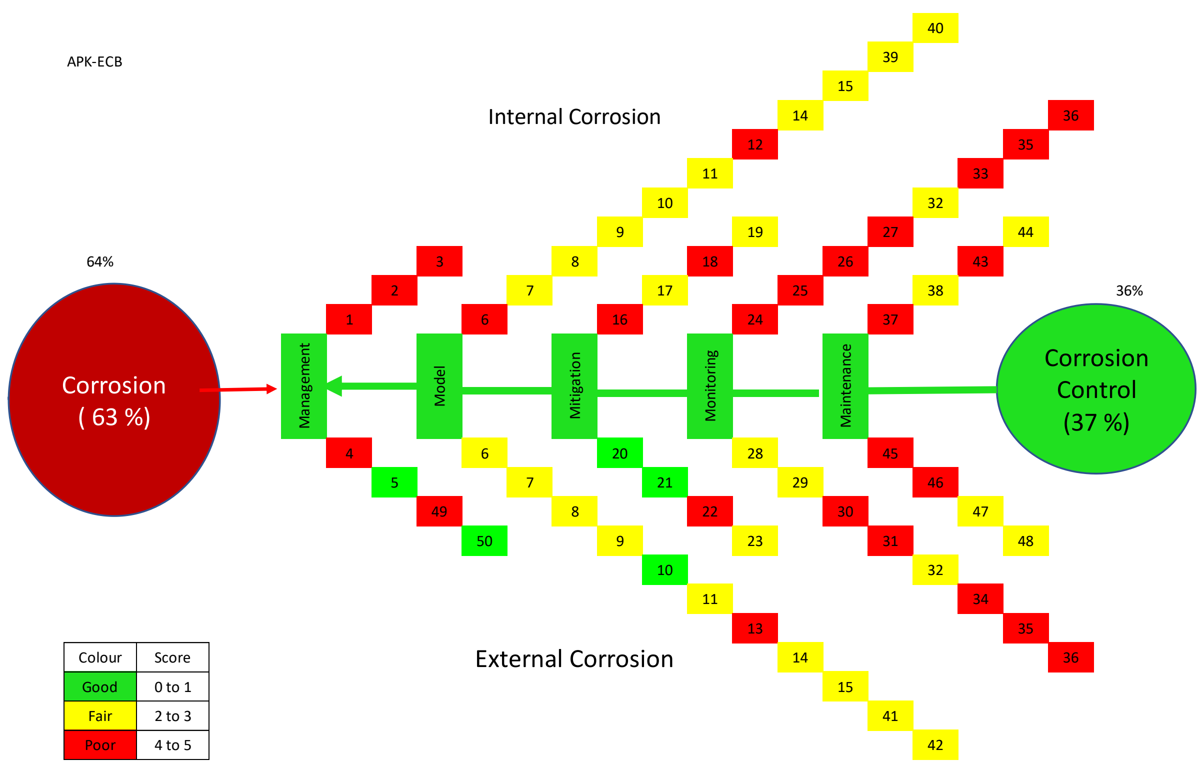

Figure 18 KPI Status APK-ECB Gathering Pipeline, PAM

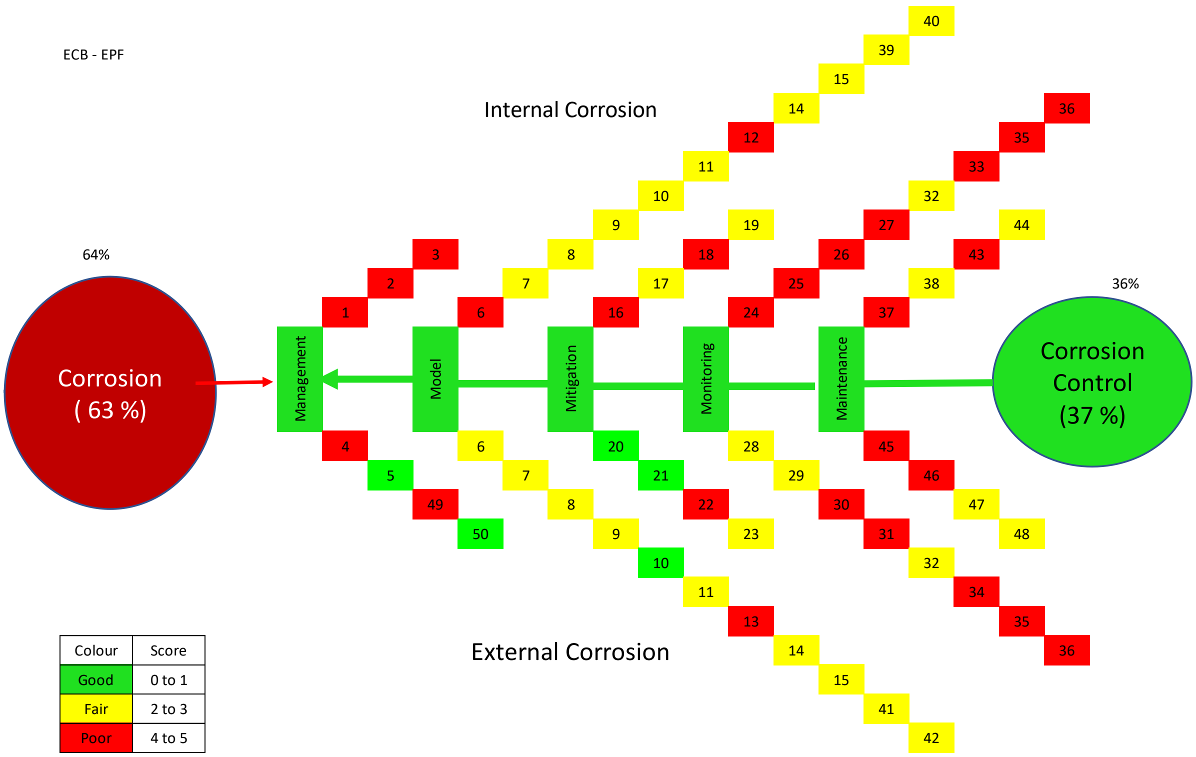

Figure 19 KPI Status ECB-EPF Gathering Pipeline, PAM

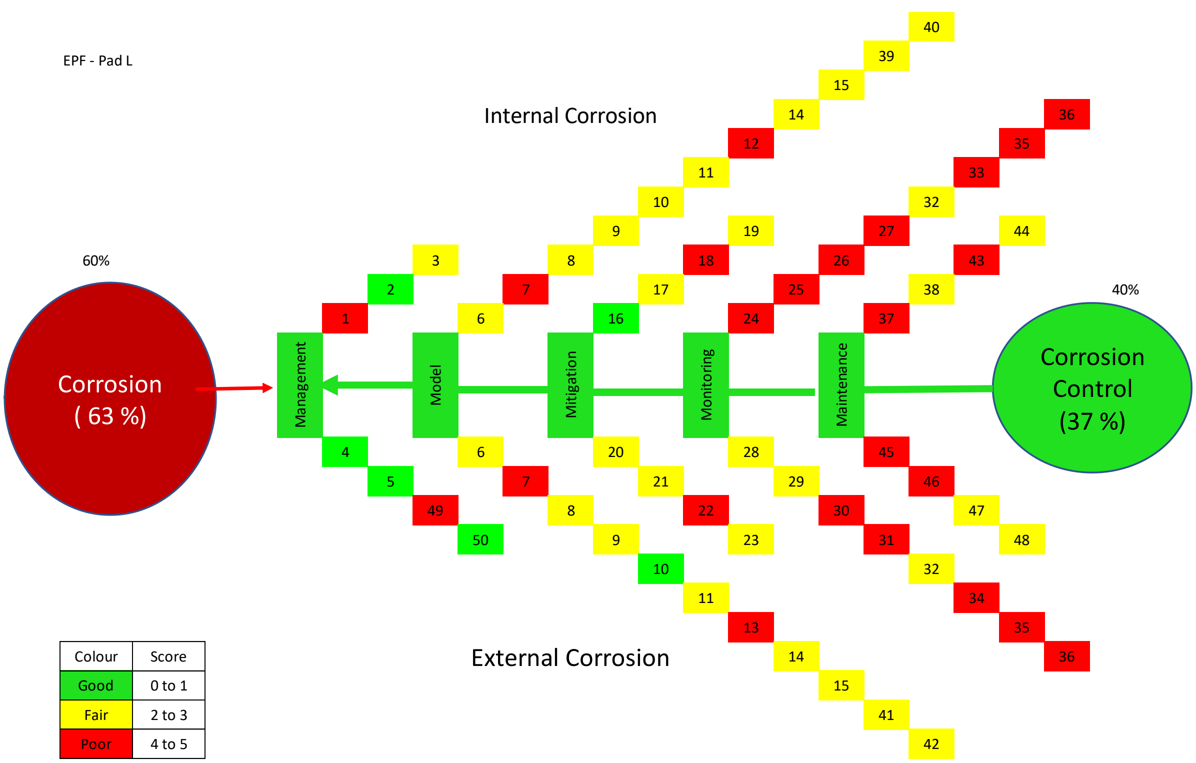

Figure 20 KPI Status EPF-Pad L Gathering Pipeline, PAM

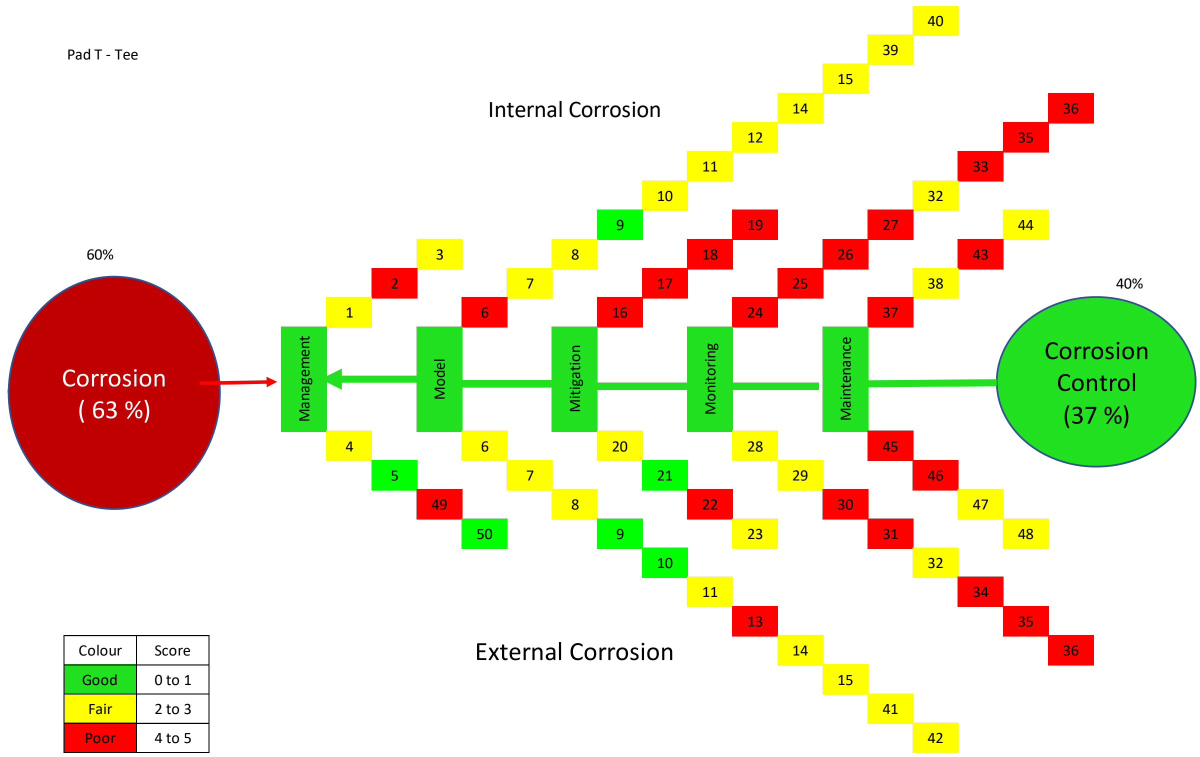

Figure 21 KPI Status Pad T-Tee Gathering Pipeline, PAM

13. Recommendations

The first recommendation of the analysis is to improve internal and external corrosion monitoring for the EY gathering pipelines, by increasing the number of probes, including probes on critical locations, and using complimentary monitoring techniques. This recommendation should be also applied to new pipelines. However, probes are not effective in monitoring localized corrosion.

Another option is to use ILI. However, the majority of the gathering pipelines are internally coated and operate at temperatures that will require cooling fluids for the inspection. Therefore, for such pipelines the use of ILI is difficult and impractical. ILI is a better option to detect localized internal and external corrosion but is not effective for internally coated pipelines. Hence, ILI is not recommended as the primary option.

14. Conclusions

On average the corrosion score, according to the evaluation of 50 KPIs for the gathering pipelines of EY was 61% while the corrosion control score was 39%.

Internal and external corrosion monitoring of the EY gathering pipelines is the weakest corrosion control strategy according to the present analysis.

There is an opportunity for improvement by determining the corrosion rates before and after the maintenance activities of the gathering pipelines.

There is a necessity to schedule regular meetings for the analysis of the corrosion control strategies of the EY gathering pipelines.

The 5-M methodology using the 50 KPI is useful to determine areas for improvement for the corrosion control strategies and to reduce the risk of failure due to degradation mechanisms such as internal and external corrosion.

The 5-M methodology will facilitate a continuous improvement process for the corrosion control of pipelines by Petroamazonas EP.

The 5-M methodology is complementary to the integrity assessment techniques such as ECDA and MP-ICDA.

15. Acknowledgements

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