Effective Implementation of Plausible Profile (Psqr) Method for Remaining Strength Determination of Complex Corrosion

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Abstract

Accurate remaining strength of corroded pipelines with complex corrosion, such as axially aligned clusters with multiple pitting on pitting metal loss anomalies, has historically been a challenge for operators. Traditional Effective Area Methods (EAM) for assessing the remaining strength of complex corrosion anomalies, such as Modified B31G and RSTRENG can lead to overly conservative results and extensive repair campaigns. In these cases, it is difficult for operators to distinguish between the critical repairs and uncertainties, potentially preventing them from focusing resources into other pipeline mitigation activities. A more detailed evaluation of corrosion geometry through an advanced fitness-for-service method, known as Plausible Profiles (Psqr), can be used to gain a better estimate of the remaining strength of pipeline areas with complex corrosion. However, it is important to understand when this method is applicable and when it will yield the most benefits for pipeline operators. With proper selection criteria, ideal candidate corrosion anomalies can be identified for this method, which will add efficiency to the pipeline remediation process and provide more accurate results. This paper will discuss the criteria for selecting corrosion anomalies for effective implementation of the Psqr method in combination with a rationalized repair strategy. The selection criteria considers aspects associated to anomaly morphology, assessment depth, length/width and potential failure mode. This paper will present how the number of excavations was reduced by more than 70%, with no impact to public safety, based on a case study of a natural gas pipeline. The remaining strength of more than 90 corrosion anomalies was extended, facilitating the optimization of the maintenance planning and expenditure, and supporting the pipeline Integrity Management Plan (IMP).

1. Introduction

According to the 2018 PHMSA Safety Stakeholder Communications Fact Sheet, an estimation of 18% of pipeline failures in the United States (from 1998–2017) were caused by corrosion [1]. Industry methods prescribed by ASME for assessing the remaining life of corrosion anomalies can yield results that are over-conservative. Advanced Fitness-For-Service (FFS) methods can be used to gain a better understanding on the estimation of failure dates of metal loss corrosion anomalies. ROSEN USA has recently used an advanced FFS method called Plausible Profiles (Psqr), developed by TransCanada Pipelines Limited (TC), in collaboration with the Pipeline Research Council International, Inc. (PRCI), for assessing corrosion in pipelines [2,3]. This methodology provided increased accuracy in repair dates to an operator experiencing complex corrosion in one of their pipelines (in comparison to industry methods such as RSTRENG, Modified ASME B31G, Kastner, etc.) [4,5]. The Psqr method presented herein allows for a more accurate integrity assessment, which when combined with a rationalized approach for repairs execution, extended the remaining life of 90+ anomalies by more than 3 years, potentially saving significant maintenance expenditure associated to repairs.

2. The Challenge of Complex Corrosion

In-Line Inspection (ILI) tools are able to detect most types of corrosion anomalies to an adequate accuracy so that maintenance programs can be effective. Therefore, the majority of the corrosion pits and clusters that are commonly found in pipelines are managed effectively as evidenced by the timely discovery of near critical defects in corrosion programs. When existing metal loss anomalies remain

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exposed to the corrosive environment, they may evolve into more intricate and complex morphologies, posing a challenge to both the ILI technology and the assessment method that is used to inspect and determine the integrity of the pipeline. Specifically from the ILI-data point of view, more analysis of the signal data and understanding of the corrosion threat affecting the pipeline is required.

Severe corrosion processes of carbon steel pipelines – such as corrosion under insulation (CUI), mesa type corrosion due to exposure of carbon steel to CO_2 environments, microbiologically influenced corrosion (MIC), and preferential girth weld corrosion – result in complex corrosion anomalies morphologies including elongated and axially aligned metal loss anomalies, pits within pits, and pinholes. These types of morphologies are notoriously challenging to size reliably by most of standard resolution ILI technologies. For example, due to its orientation, an axial slotting anomaly will not lead to a significant response from an Axial Magnetic Flux Leakage ILI tool (MFL-A), and is therefore challenging to detect and reliably size. Figure 1 shows two examples of complex corrosion morphologies.

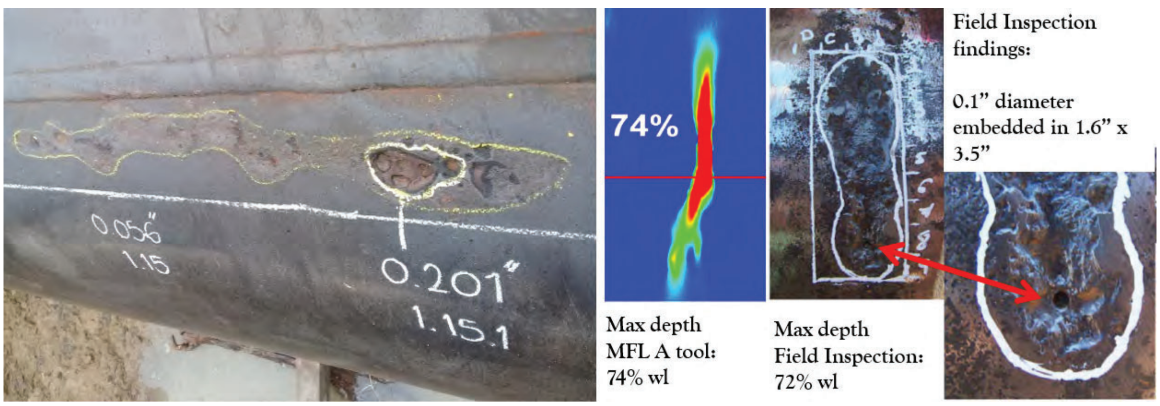

Figure 1. Examples of complex corrosion morphologies. Left – Pits within pits, embedded in an external metal loss area. Right – 0.1" diameter pinhole embedded in a 1.6" × 3.5" metal loss area.

Improved analysis of the ILI data collected, as well as appropriate determination of tolerance ranges and bounds of confidence for integrity assessments, are required to support a comprehensive integrity assessment. The advantages of this approach are considered in terms of focusing the remediation efforts on the truly critical defects, and optimizing future excavation and re-inspection planning.

To determine the remaining strength of complex corrosion, a holistic structural integrity assessment, including FFS analysis, is recommended. Engineering judgement to evaluate functionality and safety based on burst capacity of the pipeline at the corrosion clusters is performed by combining ILI data to identify and size corrosion anomalies, according to clustering interaction rules.

Different studies revealed that the shape of the corrosion anomaly is negligible on the interaction limits, whereas the orientation of the anomaly plays a crucial role on the cluster interaction of multiple corrosion defects which are oriented longitudinally, circumferentially or overlapped. Longitudinal defects typically show larger spacing, which has a greater impact on the pipeline burst pressure calculations. Whereas the impact of circumferentially oriented corrosion anomalies on the failure pressure of corroded pipelines is found to be lower [6]. In this work, the interaction behavior of complex-shaped corrosion anomalies with different morphology and area approaches were considered.

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3. Approaches for Predicting Failure Pressure

3.1 Traditional EAMs

Many models are used in the industry to determine the remaining strength of corroded pipe; each improvement increases the effectiveness and efficiency of the failure pressure predictions. Figure 2 shows three models with different criteria for area approximation. The B31G and modified B31G model uses two parameters (length and depth) to represent the area. RSTRENG refines the area estimation process and has proven to be effective for determining FFS of metal loss anomalies in pipelines. However, RSTRENG may yield overly-conservative results when estimating the profile of the corrosion cluster of anomalies that are circumferentially elongated. A more detailed evaluation of local conditions using the Psqr can potentially improve the relevance of the effective area used in the remaining strength evaluation of such anomalies, resulting in a more favourable calculated failure pressure.

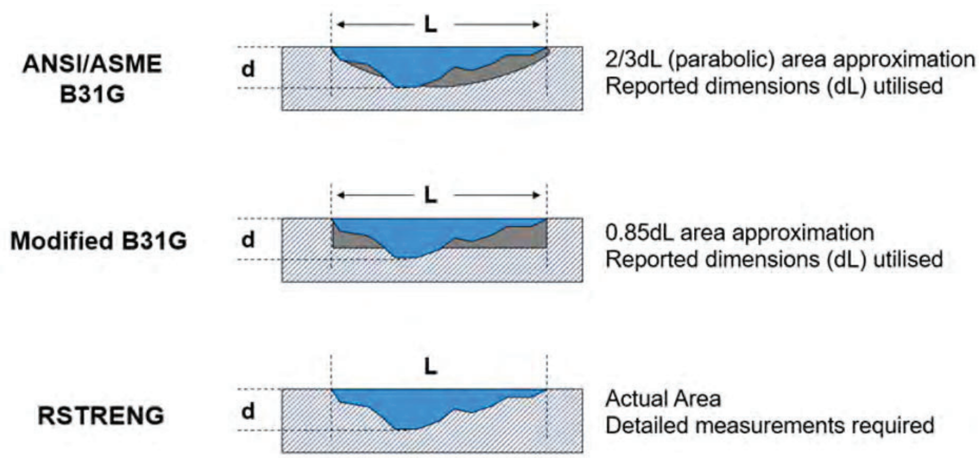

Figure 2. Different effective area methods (EAM) commonly used.

3.2 Plausible Profiles method (Psqr)

Psqr is a method for assessing corrosion in pipelines that aims to overcome a known limitation of RSTRENG when applied to certain shapes of corrosion anomalies which are widely spaced circumferentially [4].

RSTRENG considers a 'worst case' profile by following the deepest-to-deepest path (i.e., 'river bottom profile' or RBP) through the corroded area. This conservative profile only considers longitudinal interaction. It does not therefore account for circumferential spacing – i.e., if the circumferential separation of two adjacent corrosion areas is beyond certain limits, the areas do not need to be combined because they will not interact to lower the overall failure pressure of the corroded section.

The Psqr method retains RSTRENG as its basis but instead of considering a single worst case RBP, it determines multiple plausible failure path profiles. These profiles are generated based on interaction and proximity rules. For each of the plausible profiles, failure pressures are determined according to the burst pressure calculation steps from RSTRENG. The failure pressure results for each plausible profile form a distribution that is then used to determine the estimated Psqr failure

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pressure (defined as the 5th percentile value). The 5th percentile value was determined by TC Energy as a suitable quantity to use based on 30 full scale burst tests. The results showed that the Psqr burst pressure predictions were still conservative but only deviated from actual burst pressure by a coefficient of variation (COV) of 5.8%, whereas RSTRENG deviated by a COV of 8.0% [2].

For corrosion anomalies containing pits that are widely spaced circumferentially, Psqr has proven to be effective reducing unnecessary conservatism associated with deepest-to-deepest assumption of RSTRENG. However, if the deepest pits in the feature are found to be axially aligned (e.g., axial slotting or narrow axial channelling), then the ‘deepest-to-deepest’ river bottom profile will be the most plausible. In this case, the Psqr method will default to using a river bottom profile yielding the same failure pressure as RSTRENG.

In summary, the calculations between RSTRENG and Psqr methods follow the same principle, the only difference between both methods is how the profile of the corroded area is estimated.

As with any methodology, Psqr method does have a few limitations including the following cases:

- Little/no benefit for axially elongated and narrow anomalies, short in axial length, or circumferential width, as it will provide a similar estimated area as the deepest-to-deepest from the river bottom approach.
- If the pipeline is operating at a low stress, or if the anomaly will fail by depth due to an active corrosion mechanism, as the anomalies are more likely to leak rather than rupture (corrosion mitigation would be the threat to address).
- No benefit to individual anomalies not part of a cluster; multiple plausible profiles cannot be modeled.
- Several iterations may need to be run to determine the burst pressure of the anomaly, therefore computing execution time should be considered prior to the assessment.

A summary of both Psqr vs RSTRENG methodologies is presented in Table 1:

Table 1. Plausible Profiles (Psqr) vs RSTRENG.

Criteria	Plausible Profiles (Psqr)	RSTRENG
Effective area estimate	Multiple plausible profiles	Deepest-to-deepest only
Burst pressure	5^{th} percentile	Single profile
Morphology type	Ideal for wider anomalies and Complex Corrosion	Ideal for narrow anomalies
Anomaly Selection (see Section 3.3)	Recommended	Not required

The RSTRENG method is shown in Figure 3a, where the ‘deepest-to-deepest’ path approach is taken in estimation of the anomaly profile. Figure 3b presents three plausible profiles generated for the same cluster, but in reality, this can be multiple profiles depending on the size of the corrosion cluster area.

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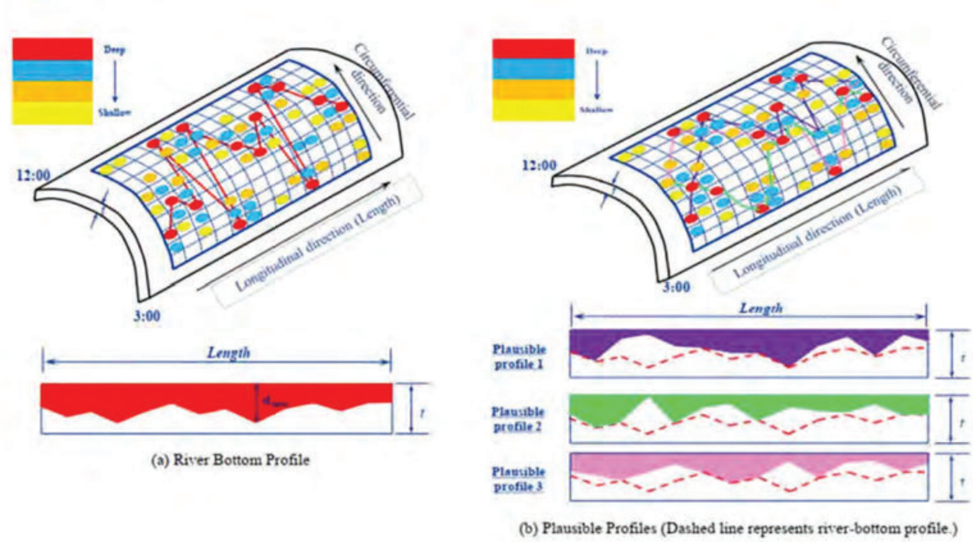

Figure 3. Profile methodology, (a) RSTRENG, and (b) Plausible Profiles (Psqr) [2].

When evaluating complex corrosion clusters, the first step is to build matrices based on the ILI box data assessment depths (reported depth + tool tolerance) of the individual anomalies within a cluster. In Figure 4, an example of the box data from the ILI run is shown (see Figure 4a) and compared against the matrix model used in the Psqr assessment (Figure 4b).

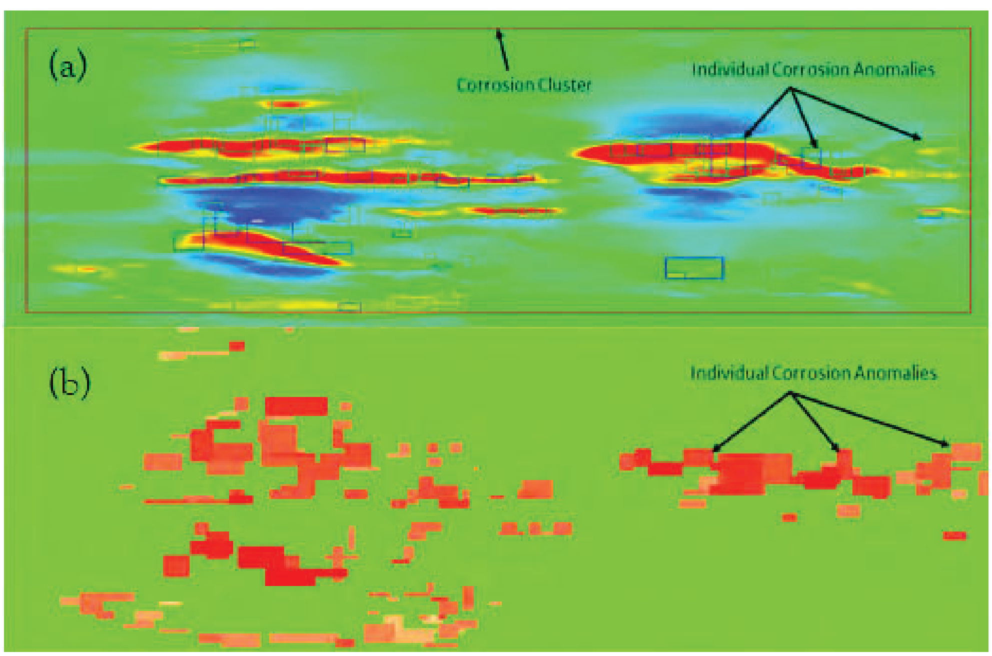

Figure 4. Signal based alignment: (a) ILI signal data aligned with Matrix model (b).

In both the top and bottom images on Figure 4, dark red areas indicate deeper metal loss anomalies, while lighter red or yellow indicate shallower anomalies. Once the matrices are built (Fig. 4b), and assessment parameters are decided upon, the Psqr method is then iteratively carried out for each plausible profile in order to determine burst pressure of the cluster over a specified timeframe.

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3.3 Anomaly selection criteria

Based on the understanding of the capabilities and range of application of the Psqr methodology, a screening criterion can be utilized to select candidate anomalies that have the potential to result in more accurate burst pressures, hence optimizing assessment time and associated costs. Operational requirements and internal risk management policies may be substantially different for each pipeline scenario, and therefore could influence the selection criteria of anomalies for Psqr assessment. From a standard application point of view, among the possible criteria for anomaly selection, length/width, failure mode, and anomaly morphology, are intrinsic attributes to consider when performing an optimal anomaly selection for Psqr assessment.

3.3.1 Anomaly length/width

Anomalies that are narrow in the circumferential direction will likely be qualified as being axially aligned. Axially aligned corrosion will result in little to no benefit in failure pressure increase of the anomaly when compared to RSTRENG. This is because there is not enough circumferential separation amongst the individual anomalies within a cluster to generate numerous plausible profiles, thus a similar result to the 'deepest-to-deepest' path is obtained. Essentially, the RESTRENG 'deepest-to-deepest' path is also the most plausible path.

When considering length and width of candidate anomalies, a value greater than 6 times the wall thickness (6*t*) was selected as the interaction criteria for clustering anomalies (6*t* × 6*t*). Note that a clustering interaction criteria smaller than 6*t* × 6*t* would likely result in most of the anomalies being identified as axially aligned (less profiles are plausible), and therefore Psqr might not add any benefit.

To test if this was a suitable length/width selection threshold, an anomaly screening was performed for a sample of 150 corrosion clusters that had both a length and width of less than 6*t* from a set of test data. Of this sample, all were axially aligned, and all showed equivalent failure pressures to the RSTRENG method.

3.3.2 Failure mode identification (depth/pressure based)

An additional criterion considers that anomalies, depending on the severity and profile of the metal loss area, could fail a depth criteria rather than be limited by failure pressure. Anomalies that have an assessment depth approaching the 80% wall thickness limit criteria following ASME B31G, should not be considered for Psqr analysis.

The time to failure (TTF) for a depth based scenario can be obtained using Eq. 1:

$$\text{TTF (years)} = \frac{(80 - d_t) \times t \times 10}{CGR} \quad (1)$$

where, d_t is the assessment depth of (% t), t is the pipe wall thickness (inch), and CGR is the corrosion growth rate (mils/year).

This assessment criterion constitutes an effective screening method to determine the applicability of Psqr for evaluating anomalies with these characteristics. If the anomaly fails by depth prior to the next ILI, it will not yield a significant repair date extension.

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3.3.3 Anomaly morphology

It was discussed previously that narrow anomalies have a high likelihood of being axially aligned. However, it is possible to have wide and long clusters that have a majority of individual anomalies in an axially oriented pattern, with just a few anomalies that happen to meet interaction criteria causing the width of the cluster to extend. If an anomaly is axially oriented, this approach will identify it in the first stage of the screening process, ruling it out from further assessments.

This is demonstrated visually in Figure 5, in which the width of an axially aligned corrosion cluster is extended due to the position of a couple of individual corrosion anomalies within the cluster.

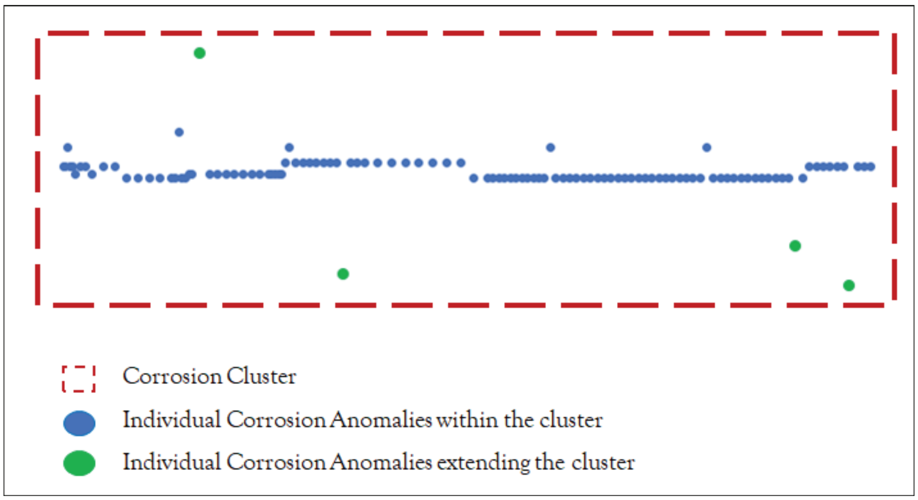

Figure 5. Axially aligned corrosion cluster. Green dots represent anomalies that are causing the cluster to extend circumferentially as a result of the interaction criteria.

4. Rationalization plan approach

One approach to rationalize repairs in pipelines is to implement anomaly grouping in conjunction with the Psqr methodology. The first step in this approach is to identify the anomalies coming due for repair prior to a specified target date. The next step is to group anomalies based on a proximity criteria with the intention of optimizing the repair execution.

Among the criteria considered to define the extent of an excavation, consideration should be given to:

- If a critical anomaly is repaired, what other anomalies will also be incidentally repaired along with the target anomaly? – These other anomalies will no longer be present in the pipeline, hence they are not an integrity concern in future campaigns.
- What would be the extent of the excavations to perform repairs considering anomalies that are in close proximity? – The edge of an excavation could be within a few feet from another anomaly that would require intervention soon.

This allows the operator to be efficient when planning repairs and avoid unnecessary excavations within subsequent years. A schematic of a rationalization plan using a grouping criteria is shown in Figure 6, where a 60 ft grouping criteria was applied.

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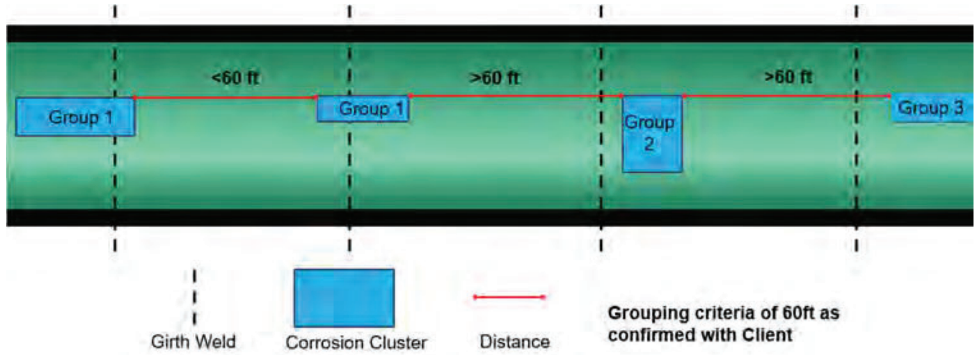

Figure 6. Rationalization plan showing an applied grouping criteria.

It can be seen that if an anomaly falls within the threshold of the grouping criteria, then it will remain within the same group of anomalies, and if the threshold is exceeded then a new group will begin.

The idea is to address the entire group of anomalies in a single effort, with the repair date of the group governed by the repair date of the most critical anomaly. Once the anomaly groups are defined, the Psqr assessment can then be implemented on these critical anomalies in an attempt to extend the remaining life of the entire group.

5. Case study

In this section, a case study is presented showcasing an integrity assessment with a repair rationalization plan, where the Psqr methodology has provided significant benefits for the operator. A natural gas pipeline experiencing complex corrosion was inspected and evaluated using a standard FFS assessment (Original and Modified ASME B31G). The assessment revealed that multiple corrosion anomalies were found due for repair in the near future (before the next planned ILI). In order to get a more accurate screening to forecast repairs, effective implementation of the Psqr method was applied to gain a better understanding of the anomalies being assessed.

5.1 Application of Psqr

The results of the traditional integrity assessments determined that 128 anomalies will need repair before the next ILI planned date. Then, the anomalies were grouped into repair segments using the rationalization methodology outlined earlier in this paper, with a 60 ft grouping criteria applied. Although the grouped repairs are longer in length than repairing individual anomalies, it helped the pipeline operator to perform less excavations and operational disruptions over time.

The goal of this study was to perform a more detailed and accurate assessment on the corrosion anomalies within the repair groups, in an effort to extend the remaining life of the suggested repairs past the date of the next planned ILI.

To support this goal, the selection criteria outlined in previous sections was used to determine which groups of anomalies had the most benefit potential from the effective implementation of the Psqr assessment method. In total, of the initial 128 target anomalies, only 108 were considered for evaluation with Psqr according to the selection criteria previously described.

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5.2 Results

After performing the Psqr assessment, a more accurate depiction of the corrosion behavior and failure date was achieved. Out of the 108 anomalies assessed with Psqr, 98 showed an increase in burst pressure. This demonstrates that 91% of the anomalies chosen based on the screening selection criteria had benefited from the Psqr approach.

Figure 7 depicts the number of required repairs plotted against the year in which an anomaly is due for repair, prior (red bars) and after (green bars) the application of the Psqr assessment. It is clear from the results that the majority of repair dates were extended beyond the next ILI planned date.

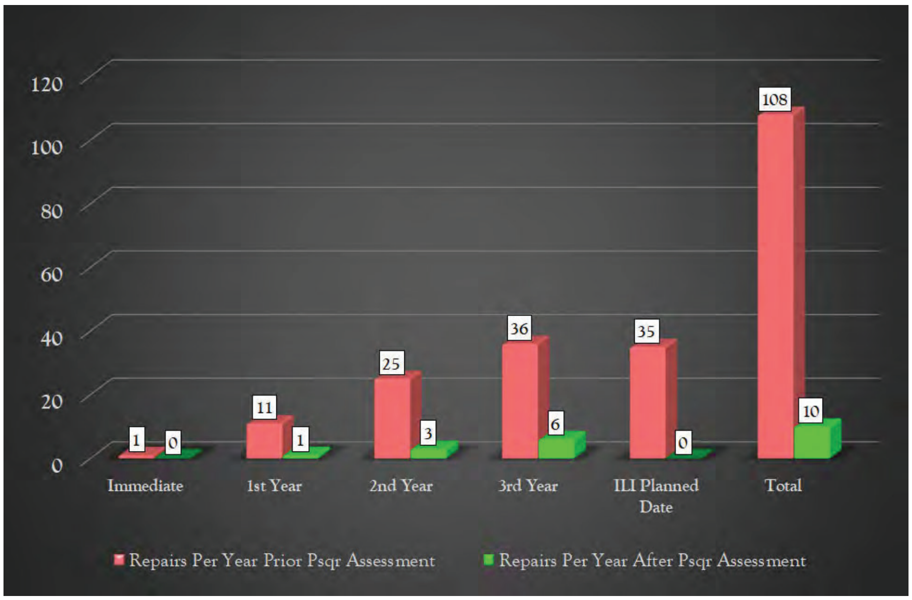

Figure 7. Repair dates prior and after Psqr assessment.

The purpose of the rationalization plan or repair grouping was to reduce the overall amount of excavations, by extending the repair areas and optimize the mitigation efforts. After performing the rationalization plan mentioned in Section 4, the overall number of excavations required was reduced from 108 to 7 locations. This demonstrates that 94% of original excavation repair plan (among the anomalies selected for Psqr), had benefited from the applied rationalization plan.

Figure 8 depicts the number of required excavations plotted against the year in which they will take place, prior (red bars) and after (green bars) the application of the Psqr assessment and rationalization plan. The results showed the importance of a tailored rationalization plan that fits the characteristics of each operator, and how in combination with an advanced FFS, can potentially save significant maintenance expenditure associated to repairs and support the operator's IMP, in this case study more than 90 excavations were avoided.

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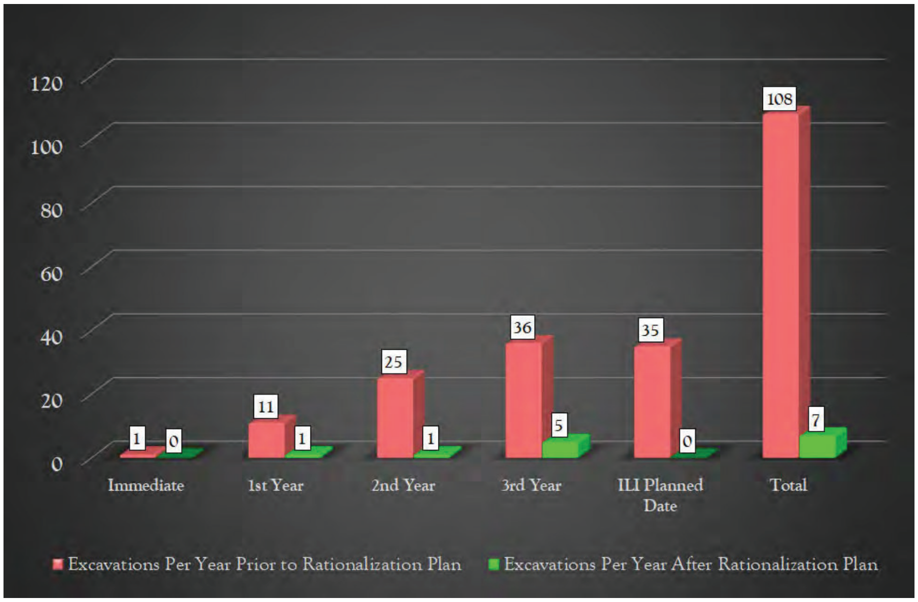

Figure 8. Excavations prior and after the rationalization plan.

6. Conclusions and Recommendations

In many cases, the traditional two parameter models and Effective Area Methods (EAM) for assessing the remaining strength of corroded pipe, such as Modified B31G and RSTRENG, enables operators to optimally select anomalies for remediation. However, when dealing with extensive and/or complex corrosion morphologies, traditional EAM can lead to overly conservative results and extensive repair campaigns. In these cases, it is difficult for operators to distinguish between the critical repairs and uncertainties, potentially preventing them from focusing resources into other pipeline mitigation activities.

Under such scenarios, an appropriate rationalization plan that includes advanced FFS methods, such as the Psqr assessment method, and strategic excavation execution, constitutes a feasible desktop solution to support the operator's integrity management efforts. Furthermore, based on the understanding of the limitations and range of application of the Psqr, a sound anomaly selection criteria helped realizing important gains in terms of execution time and cost.

Following the traditional integrity assessment process would have resulted in significant repairs and maintenance expenditure for the natural gas pipeline presented as the case study in this paper. By extending the repair times of the critical anomalies, the operator avoided unnecessary repairs, and optimized their maintenance campaign efforts for the upcoming years.

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