Proceedings of the 12th International Pipeline Conference
IPC 2018
September 24-30, 2018, Calgary, Alberta, Canada

IPC2018-78216

RISK-BASED INSPECTION OPTIMIZATION FOR VALVE INSPECTIONS

Patrick M. Vibien, M.Sc., P.Eng.
JANA Corporation
Aurora, Ontario, Canada

David A. Joyal, M.A.Sc.
JANA Corporation
Aurora, Ontario, Canada

Ken E. Oliphant, Ph.D., P.Eng.
JANA Corporation
Aurora, Ontario, Canada

William Luff, M.A.Sc.
JANA Corporation
Aurora, Ontario, Canada

ABSTRACT

Many different inspections are conducted on gas transmission and gas distribution pipelines – valve inspections, cathodic protection system inspections, in-line inspection, odorant monitoring, etc. – demanding significant resources and operational expenditures from pipeline operators. Risk-based optimization relating to these kinds of operational activities has been applied in analogous industries. The result has been measurable savings consistently ranging at a level between 20 – 40%. Significantly, this explicitly means that 20 – 40% of many operational activities have been proven not to bring a benefit. In the pipeline industry, however, there has not been a basis to determine which activities bring no value in terms of risk reduction. In this paper, a detailed example is provided for risk-based optimization of valve inspections and the savings are found to be within these expectations. These savings can be taken in either a risk reduction benefit or completely in cost savings. Through development of a valve failure risk model (which independently considers loss of function and loss of containment failures) and an inspection cost model, a set of the optimum risk-cost combinations is developed and can be presented as an optimized inspection curve. Using the curve to establish inspection frequencies is demonstrated, including the impact on operating expenditures. As demonstrated via the presented case studies, the general framework is suitable for optimization of any gas pipeline inspection or maintenance activity.

INTRODUCTION

Inspections play a significant role in gas pipeline integrity management. With the many different inspections that are conducted on gas transmission, distribution and storage systems – valve inspections, cathodic protection (CP) system inspections, in-line inspection, odorant monitoring, etc. – inspection programs also represent significant operational expenditures (OPEX) for pipeline operators. Inspection frequencies are typically set using a prescriptive approach with inspections based on a predefined schedule (e.g., yearly, every five years, etc.). There is often a risk-aware approach to setting the inspection frequencies (e.g., yearly for more critical assets, every five years for less critical). Even with this risk aware approach, there are significant inefficiencies that tend to leave a lot of money and/or risk on the table for a pipeline operator. In the gas industry this tends to be money and not risk that is 'left on the table' as the prescriptive frequencies are typically set conservatively based on 'worst case' assets, which means that many assets are being inspected more frequently than required (experience has shown that 20 – 40% OPEX savings have regularly been achieved). Operators typically sense the inefficiencies and ask the tough questions, such as:

- Why every five years? Why not seven? Or three?
- Why do I inspect new plastic valves at the same frequency as old steel valves?
- What are inspection frequencies based on?

Risk Based Optimization answers these questions (and more) by enabling operators to assess the optimum replacement, maintenance and inspection frequency for a specific asset and assess the true impact of different operating practices on the risk-cost balance.

This paper presents the general framework for implementing a Risk Based Inspection (RBI) optimization approach and presents the results for applying this type of approach to valve inspections for a gas distribution operator. An overview of Risk Based Asset Management is presented followed by a general framework for developing an optimized risk based inspection program for any gas pipeline or maintenance activity. An example application of the methodology to the valve inspection program for a gas distribution operator is summarized. In the specific case presented, the cost of the inspection program was reduced by 40% while maintaining the same level of risk in the system.

NOMENCLATURE

Pipeline risk management, risk based inspection, RBI, optimization, valve inspection

CoF_i	Consequence of failure over interval t_{int} for the ith failure mode
Failure Risk$_i$	Failure risk over interval t_{int} for the ith failure mode directly mitigated by the inspection & repair
i	Failure mode model
Inspection & Repair Cost	Expenditure for inspection and repair of asset
LoF_i	Likelihood of failure over interval t_{int} for the ith failure mode
Mitigation Efficiency	Measure of the efficiency of inspection and repair dollars in reducing *Failure Risk*
t_{int}	Inspection interval, years
Total Risk	Sum of *Failure Risk* and *Inspection & Repair Cost* for an asset

RISK BASED ASSET MANAGEMENT

Overall risk within a pipeline network is effectively determined by the functional requirement of the asset to deliver gas safely. This overall risk is comprised of direct financial risks, health & safety risks, loss of supply control to customers, etc. that might occur with a leak or other functional system failure.

An understanding of the risk of failure of the assets covered by any integrity management plan is among the most important aspects of an effective plan. The probability (or likelihood, or probability distribution of the timing) of failure and the likely consequences of failure are key measures of risk for any asset intensive organization. The combination of these two factors allows for the development of an estimate of the risk in an asset base:

$$\text{Risk} = \text{Likelihood of Failure (LoF)} \cdot \text{Consequences of Failure (CoF)} \quad (1)$$

Risk management (e.g., reduction or mitigation) efforts can be directed at reducing the *Likelihood of* Failure (*LoF*), the *Consequence of Failure* (*CoF*), or both. For gas transmission, distribution and storage system operators, both of these strategies are key to effective operations: there is a major focus on reducing the *LoF* (i.e., avoiding leaks, ruptures or loss of service) through effective design and timely replacement at the end of life of an asset and by regular inspection to ensure low *LoF*; there is also significant effort put into minimizing potential *CoF*, including leak surveying, the acquisition of rights of way, pipeline rerouting to avoid higher-consequence (i.e., more populated) areas, advanced control systems and valves to minimize release of product, evacuation/contingency planning, etc.

Risk-based asset management requires conscious and informed decisions regarding asset risk based on a clear assessment of that risk within the asset base. Critical to this is ensuring that the risk assessments upon which risk decisions are made are reflective of the true system risk. There is growing discussion in the pipeline industry around moving toward quantitative (probabilistic) risk modeling approaches that measure risk in absolute terms, and moving away from other approaches based on subjective risk assessments such as the subject matter expert (SME) approach, index models or relative assessment models. The most advanced probabilistic risk models for assets (or asset systems) effectively simulate the physical progression of failure modes in the asset, and the potential outcomes of failure, to generate a distribution of the level of risk.

There have been numerous recent developments in the area of risk-based asset management, such as the development and introduction of the ISO 55000 series [1], the PAS 55 [2] asset management system standards and the API RP 1173 [3] pipeline safety management system standard, and the broad movement towards quantitative (QRA) or probabilistic (PRA) risk assessment methodologies. The improved ability of these PRA approaches that enable optimized asset management, compared to alternative approaches, has led to a drive towards PRAs where quantitative models are developed to create an accurate, probabilistic picture of asset risk. These probabilistic models are rapidly replacing outdated approaches such as risk indices and prescriptive maintenance and inspection practices.

In the RBI approach, asset inspection plans are developed based on prioritizing the inspection of the assets in the system where inspection will offer the greatest risk mitigation benefit. For example, deploying inspection resources to inspect a potential leak in an area with no potential for confinement and accumulation of leaking gas is less beneficial from a risk mitigation perspective than inspecting an area under pavement adjacent to a structure where a leak may migrate and accumulate to dangerous levels. In the RBI approach, this risk prioritization may be accomplished down to an individual asset or component basis. This allows for the deployment of inspection resources on the basis of risk benefit, permitting the most cost-effective risk mitigation for the activity level.

As discussed previously, the increased ability of PRA approaches, compared to alternative approaches, has led to a drive towards PRAs where quantitative models are applied to create an accurate, probabilistic picture of asset risk. Given the overwhelming benefits, these probabilistic models are rapidly replacing outdated approaches such as risk indices and prescriptive maintenance and inspection practices.

RBI OPTIMIZATION APPROACH

Many pipeline inspections are a failure finding activity intended to identify hidden or unrevealed failures before they can become major incidents (e.g., leaks, valve seizure). The aim is to maximize the availability of the asset or minimize the failure time at a reasonable operational cost. In the RBI approach, asset inspection plans are developed based on prioritizing the inspection of the assets in the system where inspection will offer the greatest risk mitigation benefit. This risk prioritization may be accomplished down to an individual asset or component basis. This allows for the deployment of inspection resources on the basis of risk benefit, permitting the most cost-effective risk mitigation.

The *Failure Risk* is the risk of failure of the component, within the inspection interval, for the failure modes that are directly and effectively mitigated by the inspections and associated repairs. For example, a gas leak survey is an inspection method that might detect valve leaks but not a seized valve so including the leak risk, but not the valve functional failure risk, in the *Failure Risk* would be appropriate for a leak survey inspection. A valve inspection that included both leak evaluation and valve functional evaluation would include both the leak risk and valve functional failure risk.

The approach taken to optimization inspection plans is to balance the *Failure Risk* (e.g., risk of failure associated with the inspection interval) with the *Inspection & Repair Cost* to minimize the *Total Risk*. The *Total Risk* being the sum of *Failure Risk* and *Inspection & Repair Cost*. The inspection frequency affects the *Failure Risk* with decreasing inspection frequency typically increasing failure risk as there is more time for random- or age-related failures to occur. Conversely, increasing inspection frequency reduces the *Failure Risk*. *Inspection & Repair Cost* is amortized over the inspection interval so the longer the inspection interval the lower the average yearly *Inspection & Repair Cost*. Combined, with *Failure Risk* increasing with increasing time between inspections and average *Inspection & Repair Cost* decreasing with increasing time between inspections, there is typically a minimum *Total Risk* at a certain inspection frequency.

The generalized equation for the minimized annual *Total Risk* for inspection interval t_{int} is:

$$\min(Annual\ Total\ Risk\ (t_{int})) = \min\left(\frac{Inspection\ \&\ Repair\ Cost + \sum Failure\ Risks(t_{int})}{t_{int}}\right) \qquad (2)$$

Where no other constraint is imposed, this frequency is where the incremental *Failure Risk* is equal to the incremental annual *Inspection & Repair* costs and represents the optimized interval. The implication is that an incremental dollar spent on inspection reduces *Failure Risk* by a dollar.

Figure 1 shows a typical *Total Risk* curve for an individual asset. In the example, a minimum is seen at the 5-year inspection interval. In this case, beyond the two-year inspection interval, the *Total Risk* is relatively insensitive to the inspection frequency and the optimum inspection frequency will be very sensitive to *Inspection & Repair Costs*. In some cases where *Failure Risk* is growing very slowly, the curve will be downward sloping with no minimum (not shown), in which case the inspections may provide limited risk benefit.

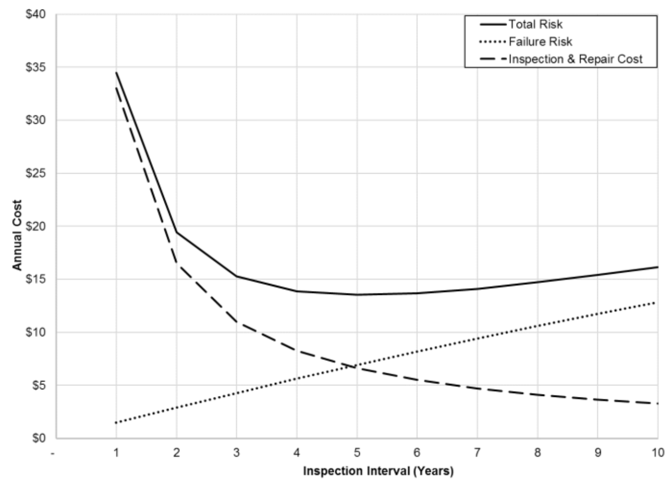

FIGURE 1: TYPICAL ANNUAL *TOTAL RISK* PROFILE FOR AN INDIVIDUAL ASSET

The aim of the PRA-based RBI is to develop the accurate *Total Risk* for each individual asset permitting the development of an optimized plan. To achieve this objective, accurate estimates of the *Inspection & Repair Cost* and *Failure Risk* are required. The following sections detail the development of these estimates.

INSPECTION & REPAIR COST ESTIMATES

Obtaining a realistic and comprehensive estimate of the costs associated with the inspection and repair of an asset is important. In the optimization process, this *Inspection & Repair Cost* is weighed against the *Failure Risk* to identify the optimum inspection interval for the asset. A higher *Inspection & Repair Cost* will, on its own, drive to longer inspection intervals and a lower *Inspection & Repair Cost* will, on its own, drive to shorter inspection intervals.

In estimating *Inspection & Repair Costs*, variable costs with an attribution of overhead should be included. This might include wages, travel, truck, equipment, consumables, and a portion of administration. *Inspection & Repair Cost* for a given asset will reflect the particulars of that asset such as equipment size, location, type, etc. For instance, with a valve, a rural above ground valve has different challenges and inspection costs compared to an urban below ground valve that should be reflected in the asset *Inspection & Repair Costs*.

FAILURE RISK ESTIMATE

Inspections are a failure finding activity intended to identify certain failures and mitigate the consequences of those failures before they can become major incidents and translate into a more significant risk cost. Inspections typically do not address all possible failure modes but are rather targeted to specific failure modes of the asset. For a pipe, the failure modes could be loss of containment (e.g., leak) or evidence of coating deterioration; for more complex assets with multiple functions, failure modes could include loss of calibration (e.g., meters), seizing (e.g., valves), setpoint loss (e.g., relief valves, odorization), etc. The *Failure Risk* of each failure mode addressed by the inspection and repair must be estimated and then combined to create an accurate estimate of *Failure Risk* that can be offset by the inspection and repair.

As shown in Equation (3), the *Failure Risk* for an inspection interval is estimated by summing the *Failure Risk* over the inspection interval for each of the relevant failure modes. In turn, estimates of the *LoF* over the inspection interval and the *CoF* for each failure mode are required.

$$Failure\ Risk(t_{int}) = \sum_{i}^{n} Failure\ Risk_i\ (t_{int}) = \sum_{i}^{n} (LoF_i\ (t_{int})\ \cdot CoF_i) \qquad (3)$$

To most effectively compare the risk of different failure modes and to be able to compare *Failure Risk* to *Inspection & Repair Cost* for the optimization process, the *Failure Risk* and *Inspection & Repair Cost* need to have comparable units.

The overall process of developing the *Failure Risk* includes the following steps:

1. Identify the specific failure modes that the inspections are designed to find and the intended consequences avoided
2. Construct the quantitative risk model for each failure mode
3. Develop the *LoF* mathematical model for each failure mode and "Tune" each *LoF* model to asset and failure data to identify those asset factors that are pertinent to predicting the failure and parameterize the model (i.e., fit the model parameters)
4. Develop the *CoF* mathematical model for each failure mode and parameterize the model

The *LoF* and *CoF* models are specific to each type of asset, its functions and the scope of inspections. The general approaches to the steps for estimating *Failure Risk* are discussed below.

Failure Model Development

The first step is to identify the failure modes addressed by inspection and repairs to be included in the model. There are many established tools for characterizing the failure modes and consequences of an asset[1]. These tools, with SME input, can be used to identify and narrow the failure modes that are addressed by inspections and repairs.

Risk Model Development

A schematic for each failure mode should be constructed clearly describing the failure mode, consequences of failure and role of the inspection and repair. Judicious choices may be made to exclude inconsequential risks, particularly based on low consequence failures. Low probability but high consequence failures should be included [4].

LoF Model Development and Parameterization

A quantitative model expressing the *LoF* for each failure mode should be developed. This model should consider available asset data describing characteristics, e.g., asset manufacturer and model, age, installation, etc. that are relevant.

The model output should provide a time based statistical probability of a failure during a given time interval for each asset. This is achieved by "tuning" the model to existing inspection and failure history data to provide the appropriate model parameters.

CoF Model

A mathematical model expressing the *CoF* for each failure mode should be developed. Again, this model should consider available data describing asset characteristics. For pipeline applications, these may include pressure, size, location, environment, population density, etc. that are relevant.

OPTIMIZATION

Using the *Failure Risk* model, it is possible to develop an optimized inspection curve representing the *Failure Risk* vs *Inspection & Repair Cost* as shown in Figure 2. The curve represents the optimal allocation of valve inspection and repair spending to achieve a given level of failure risk. Any point above the curve (it is not possible to go below the curve as this would be better than optimum) represents an inefficiency that can be optimized to:

- Reduce spending for the same level of risk,
- Reduce risk for the same level of spending, or
- A combination of both.

This is illustrated in Figure 2 by a typical prescriptive inspection and repair program. The point represented by the prescriptive inspection program lies above the curve indicating inefficiency. The horizontal distance to the optimized inspection curve suggests and quantifies the potential to reduce *Inspection & Repair Costs* without increasing *Failure Risk*. Alternatively, the vertical distance to the optimized inspection curve suggests and quantifies the additional *Failure Risk* reduction potential

[1] Failure Modes and Effects Analysis (FMEA), Cause & Effect, Tree Analysis, Fault Tree Analysis, HAZOP Analysis, Event Tree Analysis, etc.

that could be achieved with the same *Inspection & Repair Costs* if deployed more optimally.

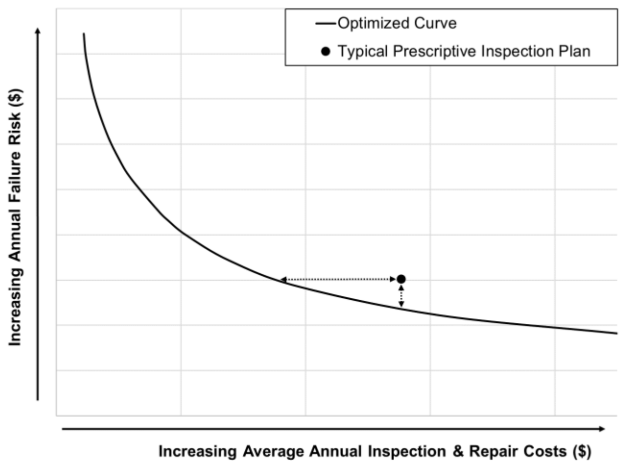

FIGURE 2: TYPICAL PRESCRIPTIVE INSPECTION PLAN VS. OPTIMIZED INSPECTION CURVE SHOWING INSPECTION RESULTS

Inefficiencies in the inspection program can be reduced by either one or a combination of these strategies to a point on the curve but no further. However, from the asymptotic slope of the curve as *Inspection & Repair Costs* increase, it is evident that additional inspection spending becomes less efficient in reducing *Failure Risk.* This efficiency can be termed *Mitigation Efficiency* and is a measure of the efficiency of inspection and repair dollars in reducing *Failure Risk* and can be calculated as per Equation (4).

$$Mitigation\ Efficiency = \frac{\Delta(\$\ Failure\ Risk\ Reduction)}{\Delta(\$\ Spent\ on\ Inspection\ \&\ Repair)} \quad (4)$$

Figure 3 shows a typical curve for *Mitigation Efficiency* added to Figure 2. The *Mitigation Efficiency* is seen to decrease to well below 1.0 as the curve plateaus. The optimum inspection program occurs where the *Mitigation Efficiency* equals 1.0, that is where an incremental $1 spent in *Inspection & Repair Costs* will reduce *Failure Risk* by an equivalent amount (i.e., $1). This point is indicated in Figure 3 by the solid square and represents the true optimized inspection program when no other constraints are present.

In some cases, constraints on the inspection interval may exist, such as regulatory requirements or other practical requirements (e.g., seasonal access, equipment availability). The constraints can be included in the model. The constraints will typically result in a shift in the optimum curve and a reduction in the potential efficiencies.

As illustrated in Figure 3 (dotted arrow), adjusting the inspection program from the typical prescriptive to optimized program shows an increase in *Failure Risk* with significant reduction in *Inspection & Repair Costs*. This is typical for prescriptive inspection programs which tend to over prescribe inspections over an optimal approach. Without increasing risk, though, the work has identified the potential for 20 – 40% reductions in *Inspection & Repair Costs* through the RBI process.

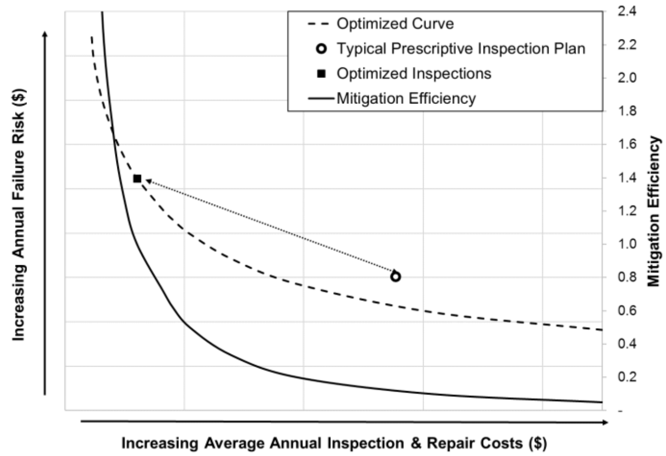

FIGURE 3: MITIGATION EFFICIENCY AND OPTIMUM INSPECTIONS

CASE STUDY – GAS DISTRIBUTION VALVES

A case study is presented based on the application of this probabilistic risk based inspection optimization process. The study was conducted for a gas distribution company with close to 10,000 distribution valves. The valves were of different size, type and generation and were installed above and below ground from high density urban to rural environments. The company was following essentially a prescriptive inspection policy resulting in yearly inspection for approximately 90% of valves and every 5 years for the remaining 10% of valves. The inspection program specifically addressed being able to access and operate the valve as well as verifying for gas leaks to atmosphere. The company had a significant annual budget for these inspections and as part of an overall strategic drive towards risk based optimization identified the valve inspection program as an opportunity for applying risk based optimization.

The company provided *Inspection Cost* data and the process described above for estimating *Failure Risk* was followed.

- Two failure modes addressed by the inspection program were identified:
    - Leak to atmosphere, i.e., *Leak*
    - Valve malfunction so it could not be actuated, i.e., *Actuation Failure*
- Failure models were developed for each failure mode with the following consequences
    - *Leak*: potential for ignition or explosion and related consequences

- *Actuation Failure*: potential for increased consequences during an incident due to a delay in isolating gas flow
- For each failure model:
    - the *LoF* model was developed, tuned and parameterized based on data shared by the company including asset data and historical inspection data
    - the *CoF* model was developed and parameterized based on a combination of company data, industry data and SME input

Only *Leaks* and *Actuation Failures* where considered in the model as the company's current inspections only addressed these failure modes. In this example, it was unnecessary, and conservative, to include repair costs in the model as the company's repair costs, triggered by the inspections, were nominal. Repairs could be performed in conjunction with the inspection (e.g., valve greasing, stem tightening, clearing access to the valve) and rarely required replacement or additional visits. This assumption was conservative as it reduced the *Inspection & Repair Costs* leading to more frequent inspections.

The *LoF* models considered a number of asset parameters such as valve type, size, above/below ground, etc. and were tuned with 8+ years of inspection data. The *CoF* considered some of the same asset factors and additional factors such as population density, frequency of emergency valve use, and the health and safety risks associated with valve leaks and with not being able to actuate a valve in an emergency. In combination, these models provided a far more nuanced risk profile for each valve within the overall body of valves than previously used by the company.

Figure 4 shows the percentage of valves on each inspection interval based on the company's prescriptive approach to assigning inspection intervals. The company imposed an inspection frequency constraint of no more frequent than annual and no less than every 10 years. The RBI optimization process recommended an inspection interval for each valve with the resulting distribution shown in Figure 5. Originally 90% of valves were on a 1-year inspection interval but the risk based optimization suggests this is justified for less than 10% of valves. For 40% of valves, the optimum has moved to 3 years. For 20% of valves, the recommend inspection interval was 10 years, largely a result of the company's imposed constraint. The remainder of the valves are distributed over other intervals.

The optimum inspection intervals clearly represent a significant reduction in total annual inspection program cost over the prescriptive program. The impact of the change on risk was examined using the optimized inspection curve as developed through the RBI process and showed that:

- The prescriptive program was operating at about 10% *Mitigation Efficiency*
- The program *Inspection Cost* could be reduced by about 40% without increasing *Failure Risk*

The fully optimized program (where \$1 of inspection costs reduces \$1 of risk) could reduce *Inspection Costs* by 70% while increasing *Failure Risk* by 84% (this alternative is a theoretical point) that suggested overall system risk could be potentially reduced more cost effectively by spending in different areas, where \$1 spent reduces risk by more than \$1.

Based on this information, the company is now able to make appropriately informed risk based decisions on changes to the valve inspection program and, when applied more broadly to other risk mitigation activities, ensure resources are most efficiently applied.

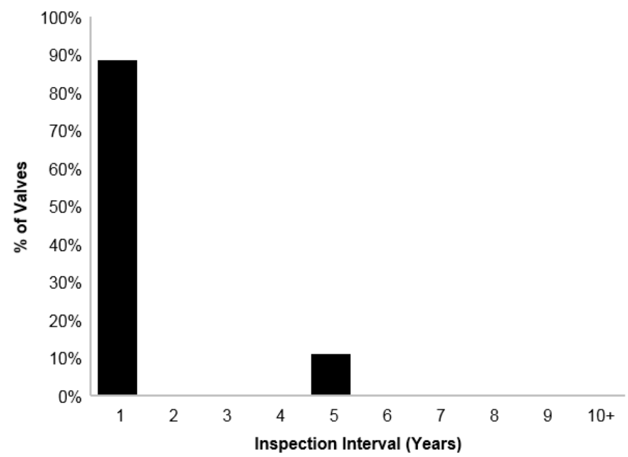

FIGURE 4: PERCENTAGE OF VALVES ON INSPECTION INTERVALS BASED ON COMPANY'S PRESCRIPTIVE INSPECTION INTERVALS

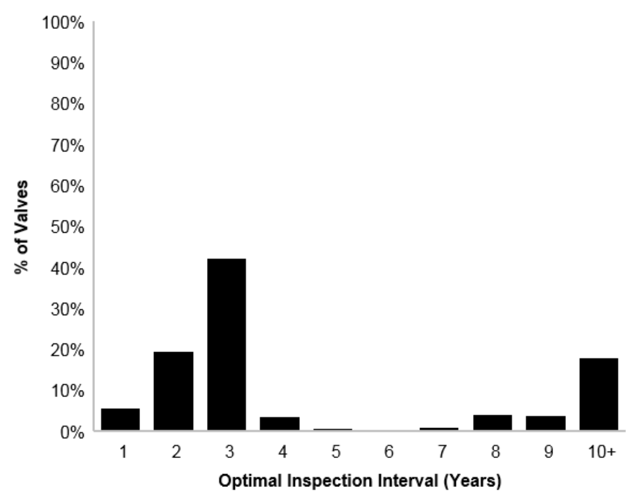

FIGURE 5: PERCENTAGE OF VALVES ON OPTIMIZED INSPECTION INTERVALS BASED ON RBI PROCESS

CONCLUSION

The process and benefits of a quantitative and probabilistic risk based inspection (RBI) approach to inspection planning were demonstrated. A risk-informed business decision making process based on the optimized inspection curve was presented. A case study was presented which showed the program *Inspection Cost* could be reduced by about 40% without increasing *Failure Risk*.

The same approach has been applied to other inspection programs, such as leak survey and odorant management, yielding a range 20 – 40% value savings over existing prescriptive inspection programs.

REFERENCES

[1] ISO, 2014, "Asset management – Overview, principles and terminology," ISO 55001:2014.
ISO, 2014, "Asset management – Management systems – Requirements," ISO 55002:2014.
ISO, 2014, "Asset management – Management systems – Guidelines for the application of ISO 55001," ISO 55003:2014.

[2] BSI, 2008, "Asset Management", BSI PAS 55:2008.

[3] ANSI/API, 2015, "Pipeline Safety Management Systems", ANSI/API Recommended Practice 1173.

[4] Bryce, Wayne and Oliphant, Ken. "Managing Low Probability – High Consequence Pipeline Risk." JANA, Aurora, ON.