Enhanced Pipeline Risk Assessment

Part 1—Probability of Failure Assessments
Revision 2.1

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This document presents new material that is to be incorporated into the book: *Pipeline Risk Management Manual, 4th Edition*, by W. Kent Muhlbauer, published by Gulf Publishing Co. This material should be viewed as a book excerpt. As a standalone document, it lacks some of the definitions and discussions that can be found in other chapters of that book. Philosophies of risk, data management, segmentation, dealing with uncertainty, and specifics of all variables impacting pipeline risk are among the topics into which this new material fits. The intricacies of dispersion modeling, receptor vulnerabilities, product characteristics, and other aspects of consequence modeling are also not fully developed in this excerpt. The reader is referred to the 3rd edition text (and 4th edition, when available) for details and clarifications of concepts that are not fully developed in this document.

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Revision History

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1. **Introduction**

Scoring or ranking type pipeline risk assessments have served the pipeline industry well for many years. However, risk assessments are being routinely used today in ways that were not common even a few years ago. The new roles of risk assessments have prompted some changes to the way risk algorithms are being designed. The changes lead to more robust risk results that better reflect reality and, fortunately, are readily obtained from data used in previous assessments.

2. **Background**

Scoring systems as a means of analysis have been around for a long time. When knowledge is incomplete and a decision structure is needed to simultaneously consider many factors, scoring systems often appear. Boxing matches, figure skating, beauty contests, financial indices, credit evaluations, and even personality and relationship “tests” are but a few examples.

Many risk assessments are based on such scoring systems. They were often a simple summation of numbers assigned to conditions and activities that are expected to influence risks. Whenever more risk-increasing conditions are present with fewer risk-reducing activities, risk is relatively higher. As risky conditions decrease or are offset by more risk-reduction measures, risk is relatively lower.

The form of these algorithms is normally some variation on:

\[ \text{CondA} + \text{CondB} + \ldots \text{CondN} = \text{Relative Probability of Failure (or relative Consequence of Failure)} \]

Or sometimes:

\[ (\text{CondA} \times \text{WeightA}) + (\text{CondB} \times \text{WeightB}) + \ldots (\text{CondN} \times \text{WeightN}) = \text{Probability of Failure} \]

Where

- \text{CondX} represents some condition or factor believed to be related to risk, evaluated for a particular piece of pipeline.
- \text{WeightX} represents the relative importance or weight placed on the corresponding condition or factor—more important variables have a greater impact on the perceived risk and are assigned a greater weight.

In the pipeline industry, relative risk scoring or ranking systems have been around for decades. Early published works from the late 1980’s and early 1990’s in scoring type risk assessments include:

- Dr. John Kiefner’s work for AGA (via Battelle),
- Dr. Mike Kirkwood from British Gas,
- W. Kent Muhlbauer’s first edition of *The Pipeline Risk Management Manual*, and
- Mike Gloven’s work at Bass Trigon.
Such scoring systems for specific pipeline operators can be traced back even further, notably in the 1980’s with gas distribution companies faced with repair-replace decisions involving problematic cast iron pipe.

Variations on this type of scoring algorithm have now been in common use by pipeline operators for many years. The choices of categorization into failure mechanisms, scale direction (higher points = higher risk or vice versa) variables, and the math used to combine variables are some of the differences among these type models.

This approach is often chosen for its intuitive nature, ease of application, and ability to incorporate a wide-variety of data types. These methodologies have served the industry well in the past. Prior to 2000, such models were used primarily by operators seeking more formal methods for resource allocation—how to best spend limited funds on pipeline maintenance, repair, and replacement. Risk assessment was not generally mandated and model results were seldom used for purposes beyond this resource allocation. There are of course some notable exceptions where some pipeline operators incorporated very rigorous risk assessments into their business practices, notably in Europe where such risk assessments were an offshoot of applications in other industries or already mandated by regulators.

The role of risk assessment in the U.S. expanded significantly in the early 2000’s when the Pipeline and Hazardous Materials Safety Administration (PHMSA) began mandating risk ranking of all jurisdictional gas and liquid pipelines that could affect a High Consequence Area (HCA). Identified HCA segments were then scheduled for integrity assessment and application of preventative and mitigative measures depending on the integrity threats present.

3. “Limitations” in Previous Approaches

The simple scoring assessment is still a useful screening and prioritization tools. However, these earlier risk-ranking models were generally not intended for use in applications where outside parties were requesting more rigorous risk assessments. For example, risk assessment has now been used in setting design factors, addressing land use issues, etc, while previously, the assessment was typically used for internal decision support only.

Given their intended use, the earlier models did not really suffer from “limitations” since they met their design intent. They only now appear as limitations as the new uses are factored in. Those still using older scoring approaches recognize the limitations brought about by the original modeling compromises made. Some of the more significant compromises arising from the use of the simple scoring type assessments include:

- Without an anchor to absolute risk estimates, the assessment results are useful only in a rather small analysis space. Without a population of scores to compare, the results offer little useful information regarding risk-related costs or appropriate responses to certain risk levels. Results expressed in relative numbers are useful for prioritizing and ranking but are limited in their ability to forecast real failure rates or costs of failure.
- Difficult to directly link to integrity re-assessment timing. Without additional analyses, the scores do not suggest appropriate timing of ILI, pressure testing, direct assessment, or other integrity verification efforts.
• Potential for masking of effects when simple expressions cannot simultaneously show influences of large single contributors and accumulation of lesser contributors. For instance, an unacceptably large threat—very high chance of failure from a certain failure mechanism—could be hidden in the overall failure potential if the contributions from other failure mechanisms are very low. This is because, in some calculations, failure likelihood will only approach highest levels when all failure modes are coincident in one location. A very high threat from only one or two mechanisms would only appear at levels up to their pre-set cap (weighting). In actuality, only one failure mode will often dominate the real probability of failure. Similarly, the benefit of a very effective mitigation measure is lost when the maximum benefit from that measure is artificially capped.¹

• Some older models are unclear as to whether they are assessing, for instance, the likelihood of corrosion occurring or the likelihood of pipeline failure from corrosion—a subtle but important distinction since damage does not always result in failure.

• Some previous approaches have limited modeling of interaction of variables (now required in some IMP regulations). Older risk models often did not adequately represent the contribution of a variable in the context of all other variables. Simple summations cannot properly integrate the interactions of some variables.

• Some models forced results to parallel previous leak history—maintaining a certain percentage or weighting for corrosion leaks, third party leaks, etc—even when such history might not be relevant for the pipeline being assessed.²

• Balancing or re-weighting was often required as models attempt to capture risk in terms that represent 100% of the threat or mitigation or other aspect. The appearance of new information or new mitigation techniques required re-balancing which in turn made comparison to previous risk assessments problematic.

• Some models can only use attribute values that are bracketed into a series of ranges. This creates a step change relationship between the data and risk scores. This approximation for the real relationship is sometimes problematic.

• Some models allowed only addition, where other mathematical operations (multiply, divide, raise to a power, etc) would better parallel other engineering models and therefore better represent reality.

• Simpler math does not allow orders of magnitude scales and such scales better represent real world risks. Incident frequencies and related probabilities can commonly range, for example, from nearly annually to less than 1 in ten million chance per year.

Notes:

1. In general, the use of pre-set weightings or averaging of conditions can obscure higher probabilities of one or more failure mechanisms. The user of such models is usually cautioned to either examine enough lower level results (prior to averaging or application of weighting) to ensure this does not happen, or to migrate to an algorithm that will prevent the masking.

2. The assumption of a predictable distribution of future leaks predicated on past leak history is somewhat realistic, especially when a database with enough events is used and conditions and activities are constant. However, one can easily envision scenarios where, in some segments, a single failure mode should dominate the risk score and
result in a very high probability of failure rather than only some percentage of the total. Even if the assumed distribution is valid in the aggregate, there may be many locations along a pipeline where the pre-set distribution is not representative of the particular mechanisms at work there.

Users of the older scoring type risk assessments should recognize these potential difficulties in such methodologies. These “limitations” were always recognized by serious practitioners and workarounds could be implemented when more definitive applications were needed. However, when the limitations are coupled with the need to get more out of the risk assessments, the case for change becomes compelling.

4. Improvement Opportunity

4.1 Why Change Now?

While the previous generation of algorithms served the industry well, the technical compromises made can be troublesome or unacceptable in today's environment of increasing regulatory and public oversight. Risk assessments commonly become the centerpiece of any legal, regulatory, or public proceedings. This prompts the use of assessment techniques that more accurately model reality and also produce risk estimates that are anchored in absolute terms: “consequences per mile year,” for example. Fortunately, a new approach to algorithm design can do this while making use of all previously collected data and not increasing the costs of risk assessment. The advantages of the new algorithms are that they can overcome many of the previously noted limitations:

- More intuitive;
- Better models reality;
- Eliminates masking of significant effects;
- Makes more complete and more appropriate use of all available and relevant data;
- Enhances existing algorithms to better comply with U.S. IMP regulations;
- Distinguishes between unmitigated exposure to a threat, mitigation effectiveness, and system resistance—this leads directly to better risk management decisions;
- Eliminates need for unrealistic and expensive re-weighting of variables for new technologies or other changes; and
- Flexibility to present results in either absolute (probabilistic) terms or relative terms, depending on the user's needs.

4.2 Change Without Pain

A migration from an older style risk assessment to the new approach is quite straightforward. An objective of the new approach is to retain the advantages of earlier approaches such as their simplicity and intuitively transparent nature, and still avoid overly-analytic techniques that often accompany more absolute quantifications of risk. In all risk analyses, the designer of the assessment model must strike a balance between complexity and utility—using enough
information to capture all meaningful nuances (and satisfy data requirements of all regulatory oversight) but not information that adds little value to the analysis.

The new model described here uses the same data as previous approaches, but uses it in different ways. Weightings are not needed, but as with older models, valuations sometimes must still need to arise from engineering judgment and expert experience when “hard data” is not available. The new valuations are, however, more verifiable and defensible since they are grounded in absolute terms rather than relative. Some time and energy will still need to be invested into setting up the new assessment model with legitimate values for the systems being assessed. This investment is no greater than that needed to set up and maintain the older models.

In recent risk model upgrades, the time needed to convert older scoring type risk assessment algorithms into the new approach has averaged less than 40 hours. The new approach makes use of previously-collected data to help with continuity and to keep costs of conversion low. The primary algorithm modifications consist of simple and straightforward changes to categorization of variables and the math used to combine them for calculating risk scores. The new algorithms are easily set up and executed in spreadsheets, desktop databases—SQL handles all routines very readily, or GIS environments. No special software is needed.

5. Characteristics of the New Algorithms

5.1 Risk Triad

The suggested basis for this model is to examine each failure mechanism (threat) in three parts for:

- Exposure (unmitigated),
- Mitigation effects, and
- Resistance to failure.

These three elements make up the Risk Triad, for evaluating probability of failure (PoF). They are generally defined as follows:

- Exposure = likelihood of force or failure mechanism reaching the pipe when no mitigation applied,
- Mitigation = actions that keep the force or failure mechanism off the pipe, and
- Resistance = the system’s ability to resist a force or failure mechanism applied to the pipe.

The evaluation of these three elements for each pipeline segment results in a PoF for that specific segment.

An intermediate level, termed “Probability of Damage”—damage without immediate failure—also emerges from this approach. Using the first two terms without the third—exposure and mitigation, but not resistance—yields the probability of damage.

\[
\text{Probability of Damage (PoD)} = f(\text{exposure, mitigation})
\]
Probability of Failure (PoF) = f(PoD, resistance)

This avoids a point of confusion sometimes seen in previous assessments. Some older models are unclear as to whether they are assessing the likelihood of damage occurring or the likelihood of failure—a subtle but important distinction since damage does not always result in failure. Calculation of both PoD and PoF values creates an opportunity to gain better understanding of their respective risk contributions.

This three part assessment also helps with model validation and most importantly, with risk management. Fully understanding the exposure level, independent of the mitigation and system’s ability to resist the failure mechanism, puts the whole risk picture into clearer perspective. Then, the role of mitigation and system vulnerability are both known independently and also in regards to how they interact with the exposure. Armed with these three aspects of risk, the manager is better able to direct resources more appropriately.

### 5.2 Model Features

Other characteristics of this model distinguish it from previous risk assessment approaches and include the following.

1. **Measurement Scales**
   Mathematical scales that simulate the logarithmic nature of risk levels are employed to fully capture the orders-of-magnitude differences between “high” risk and “low” risk. The new scales better capture reality and are more verifiable—to some extent, at least. Some exposures are measured on a scale spanning several of orders of magnitude—“this section of pipeline could be hit by excavation equipment 10 times a year, if not mitigated (annual hit rate = 10)” and “that section of pipeline would realistically not be hit in 1000 years (0.001 annual hit rate).”

   The new approach also means measuring individual mitigation measures on the basis of how much exposure they can independently mitigate. For example, most would agree that “depth of cover,” when done as well as can be envisioned, can independently remove almost all threat of third party damage. As a risk model variable, it is theoretically perhaps a variable that can mitigate 95-99% of the third party damage exposure. If buried deep enough, there is very little chance of third party damage, regardless of any other mitigative actions taken. “Public Education” on the other hand, is recognized as an important mitigation measure but most would agree that, independently, it cannot be as effective as depth of cover in preventing third party damages.

   Improved valuation scales also means a more direct assessment of how many failures can be avoided when the pipeline is more resistant or invulnerable to certain damages.

2. **Variable Interactions**
   This model uses combinatorial math that captures both the influences of strong, single factors as well as the cumulative effects of lesser factors. For instance, 3 mitigation measures that are being done each with an effectiveness of 20% should yield a combined mitigation effect of about 49%. This would be equivalent to a combination of 3 measures rated as 40%, 10%, and 5% respectively, as is shown later. In other cases, all aspects of a particular mitigation must simultaneously be in effect before any mitigation benefit is
achieved. An example is high patrol frequency with low effectiveness or a powerful ILI but with inadequate confirmatory investigations.

These examples illustrate the need for OR and AND “gates” as ways to more effectively combine variables. Their use eliminates the need for “importance-weightings” seen in many older models.

The new approach also provides for improved modeling of interactions: for instance, if some of the available pipe strength is used to resist a threat such as external force, less strength is available to resist certain other threats.

3. Meaningful Units
The new model supports direct production of absolute risk estimates. The model can be calibrated to express risk results in consistent, absolute terms: some consequence per some length of pipe in some time period such as “fatalities per mile year.” Of course, this does not mean that such absolute terms must be used. They can easily be converted into relative risk values when those simpler (and perhaps less emotional) units are preferable. The important thing is that absolute values are readily obtainable when needed.

6. Mathematics

6.1 Orders of Magnitude

As noted, logarithmic scales are used to better characterize the range of failure probabilities. This is a departure from how most older scoring models approach risk quantification. It is a necessary aspect to properly mirror real-world effects and express risk estimates in absolute terms.

Since logarithms are not a normal way of thinking for most, a more intuitive substitute is to speak in terms of orders of magnitude. An order of magnitude is synonymous with a factor of 10 or “10 times” or “10X.” Two orders of magnitude means 100X, and so forth, so an order of magnitude is really the power to which ten is raised. This terminology serves the same purpose as logarithms for the needs of this model. So, a range of values from 10E2 to 10E-6 (10² to 10⁻⁶) represents 8 orders of magnitude (also shown by: \( \log(10E2) – \log(10E-6) = 2-( -6) = 8 \)). This PoF model measures most mitigation effectiveness and resistance to failure in terms of simple percentages. The simple percentages apply to the range of possibilities: the orders of magnitude. So, using an orders of magnitude range of 8, mitigation that is 40% effective is reducing an exposure by 40% of 8 orders of magnitude which has the effect of reducing PoF by 3.2 orders of magnitude. For example, if the initial PoF was 0.1—the event was happening once every 10 years on average—it would be reduced to 0.1 / 10^{40% x 8} = 0.1 / 10^{3.2} = 6.3E-5. The mitigation has reduced the event frequency by over 1000 times—only one in a thousand of the events that would otherwise have occurred will occur under the influence of the mitigation.

Numbers for mitigated PoF will get very, very small whenever the starting point (unmitigated PoF) is small: 1000 times better than a “1 in a million” starting point is very small; 1000 times better than a “1 in a 100” starting point is not so small. See also mitigation.
It might take some out of their comfort zone to begin working with numbers like this. If so, relative scales are easily created to be surrogates for the complex numbers. However, having access to the complex—and more correct—values at any time will add greatly to the risk model’s ability to support a wide range of applications.

Creating a correct range of orders of magnitude for a model is part of the tuning or calibration process.

### 6.2 Effective Zero

For some calculations, a lower limit or “effective zero” is needed to make the mathematical relationships perform properly. An effective zero is also a concept grounded in reality. Intelligent minds are never absolutely certain of anything. There is always some very slim possibility of almost anything. So, the effective zero can be seen as assigning a value to what we mean when we say “never.” For instance, to most, a chance of an event of around 1 in a trillion or perhaps $1 \times 10^{-12}$ is the equivalent of saying “never.” This then would be the “effective zero” value to use in the risk assessment equations. There are some subtleties involved in selecting this value, as will become apparent when some risk values are generated. The value is also subject to change when a risk model is calibrated to produce results in absolute terms such as failures per mile-year.

### 6.3 AND Gates, OR Gates

The probabilistic math used to combine variables to capture both the effects of single, large contributors as well as the accumulation of lesser contributors is termed “OR” & “AND” “gates.” Their use in pipeline risk assessment modeling represents a dramatic improvement over most older methods. This type of math better reflects reality since it uses probability theory of accumulating impacts to

- Avoid masking some influences;
- Captures single, large impacts as well as accumulation of lesser effects;
- Shows diminishing returns;
- Avoids the need to have pre-set, pre-balanced list of variables;
- Provides an easy way to add new variables; and
- Avoids the need for re-balancing when new info arrives.

**OR Gates**

OR gates imply independent events that can be added. The OR function calculates the probability that any of the input events will occur. If there are $i$ input events each assigned with a probability of occurrence, $P_i$, then the probability that any of the $i$ events occurring is:

$$P = 1 - [(1-P_1) \times (1-P_2) \times (1-P_3) \times ... \times (1-P_i)]$$
**OR Gate Example:**

To estimate the probability of failure based on the individual probabilities of failure for stress corrosion cracking (SCC), external corrosion (EC) and internal corrosion (IC), the following formula can be used.

\[ P_{\text{failure}} = \text{OR}[P_{\text{SCC}}, P_{\text{EC}}, P_{\text{IC}}] = P_{\text{SCC}} \text{ OR } P_{\text{EC}} \text{ OR } P_{\text{IC}} \]
\[ = \text{OR}[1.05E-06, 7.99E-05, 3.08E-08] \]
\[ = \text{OR}[1-(1-1.05E-06)(1-7.99E-05)(1-3.08E-08)] \]
\[ = 8.10E-05 \]

The OR gate is also used for calculating the overall mitigation effectiveness from several independent mitigation measures. This function captures the idea that probability (or mitigation effectiveness) rises due to the effect of either a single factor with a high influence or the accumulation of factors with lesser influences (or any combination).

\[ \text{Mitigation} \% = M_1 \text{ OR } M_2 \text{ OR } M_3 \ldots \]
\[ = 1 - [(1-M_1) * (1-M_2) * (1-M_3)*
\]
\[ = 1 - [(1-0.40) * (1-0.10) * (1-0.05)] \]
\[ = 49\% \]

or examining this from a different perspective,

\[ \text{Mitigation} \% = 1 - \text{[remaining threat]} \]
\[ \text{Where remaining threat} = [(\text{remnant from } M_1) \text{ AND } (\text{remnant from } M_2) \text{ AND } (\text{remnant from } M_3)] \ldots \]

**AND Gates**

AND gates imply “dependent” measures that should be combined by multiplication. Any sub-variable can alone have a dramatic influence. This is captured by multiplying all sub-variables together. For instance, when all events in a series will happen and there is dependence among the events, then the result is the product of all probabilities. In measuring mitigation, when all things have to happen in concert in order to gage the mitigation benefit, this means a multiplication—therefore, an AND gate instead of OR gate. This implies a dependent relationship rather than the independent relationship that is implied by the OR gate.

**AND Gate Example:**

Here, the modeler is assessing a variable called “CP Effectiveness” (cathodic protection effectiveness) where confidence in all sub-variables is necessary in order to be confident of the CP Effectiveness—[good pipe-to-soil readings] AND [readings close to segment of interest] AND [readings are recent] AND [proper consideration of IR was done] AND [low chance of interference] AND [low chance of shielding] . . . etc. If any sub-variable is not satisfactory, then overall confidence in CP effectiveness is dramatically reduced. This is captured by multiplying the sub-variables.

When the modeler wishes the contribution from each variable to be slight, the range for each contributor is kept fairly tight. Note that four things done pretty well, say 80% effective each, result in a combined effectiveness of only ~30% (0.8 x 0.8 x 0.8 x 0.8) using straight multiplication.
7. **Probability of Failure**

The most compelling definition of probability is “degree of belief” regarding the likelihood of an event occurring in a specified future period. Probability is most often expressed as a decimal ≤ 1.0 or a percentage ≤ 100%. Historical data, usually in the form of summary statistics, often partially establishes our degree of belief about future events. Such data is not, however, the only source of our probability estimates.

Probability is often expressed as a forecast of future events. In this application, the expression has the same units as a measured event frequency, ie events per time period. When event frequencies are very small, they are, for practical purposes, interchangeable with probabilities: 0.01 failures per year is essentially the same as a 1% probability of one or more failures per year. When event frequencies are larger, a mathematical relationship is used to convert them into probabilities, ensuring that probabilities are always between 0 and 100%.

The pipeline risk assessment model described here is designed to incorporate all conceivable failure mechanisms. It is then calibrated using appropriate historical incident rates, tempered by knowledge of changing conditions. This results in estimates of failure probabilities that match the judgments and intuition of those most knowledgeable about the pipelines, in addition to recent failure experience.

7.1 **Failure Mechanisms**

This model recognizes that the two general types of failure mechanisms—time dependent and time independent—require slightly different calculation routines. Time dependent mechanisms of corrosion and fatigue can be initially measured in terms of how much damage they are causing over time. Mils per year (mpy) is a common measure of corrosion metal loss and can also be used to measure crack growth rates if some simplifying assumptions are used. The initial “damage rate” measurement will then be used to calculate a time-to-failure (TTF) and then a probability of failure (PoF), perhaps in failures/mile/year. TTF and PoF can be estimated using common engineering and statistical relationships, either very complex (fracture mechanics, finite element analyses, etc) or with simple approximations (% of Barlow-required thickness, etc).

For time-independent failure mechanisms such as third party damage, weather, human error, and earth movement events, the process is a bit simpler. Constant failure rate or random failure rate events are assessed with a simple “frequency of occurrence” analysis. The estimated frequency of occurrence of each time-independent failure mechanism can be directly related to a failure probability—PoF—and then combined with the PoF’s from the time-dependent mechanisms. As previously noted, the frequency values and probability values are numerically the same at the low levels that should be seen in most pipelines.

Time-independent failure modes are assumed to either cause immediate failure or create a defect that leads to a time-dependent failure mechanism.

As an example of failure mechanism categorization, ASME B31.8 Appendix S nomenclature identifies time-dependent threats as External Corrosion (EC), Internal Corrosion (IC), Stress Corrosion Cracking (SCC), and fatigue. Time independent threats are Third Party damage (TP), Incorrect Operations (IO), weather and other outside forces such as earth movement.
events (WOF) and Equipment failures (EQ, classified as “random”). Also noted are potential manufacturing (MFG) and construction (CON) issues as contributors to failure potential. In this modeling approach, all possible weaknesses are best captured as variables impacting the resistance— the ability of a pipeline segment to resist failure when exposed to a threat—rather than as threat categories since they are not themselves failure mechanisms.

The model described here supports any logical categorization of threats or failure mechanisms. The following table summarizes one categorization scheme.

### Table 7.1-1 Failure Mechanism Categories

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<th>Failure Mechanism</th>
<th>Mechanism Type</th>
<th>Probability Model Structure</th>
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| Third Party, geohazards, human error, sabotage, theft | Time-independent | \( (\text{failure rate}) = \frac{\text{[unmitigated event frequency]}}{10^{\text{[threat reduction]}}} \)  
Where \( \text{[threat reduction]} = f(\text{mitigation effectiveness, resistance}) \) |
| Ext corrosion, Int corrosion, Fatigue, SCC | Time-dependent | \( (\text{failure rate in year one}) = 1 / (5 \times \text{TTF}^2) \) or \( 1 - \exp(-1 / \text{TTF}) \) or other user-defined relationship, where \( \text{TTF} = \frac{1}{[(\text{available pipe wall}) - (\text{wall loss rate}) \times (1 - \text{mitigation effectiveness})]} \) |
| Equipment failure | Time-independent | \( (\text{unit failure rate}) \times (\text{number of units}) \) |

Equipment failure can often be included as part of the other mechanisms, where valves, flanges, separators, etc are treated as the same as pieces of pipe but with different strengths and abilities to resist failure. Large rotating equipment (pumps, compressors) and other pieces will often warrant independent assessment.

Under the assumption that most forecasted failure rates will be very small, this document will often substitute “probability of failure” (PoF) for “failure rate.” So, the two basic equations used are modified from the table above and become:

\[
\text{PoF}_{\text{time-indep}} = \frac{\text{[unmitigated event frequency]}}{10^{\text{[threat reduction]}}} \\
\text{where} \\
\text{[threat reduction]} = f(\text{mitigation, resistance})
\]

\[
\text{PoF}_{\text{time-dep}} = f(\text{TTF}) \\
\text{where} \\
\text{TTF} = \text{“time to failure”} = \frac{(\text{available pipe wall})}{[(\text{wall loss rate}) \times (1 - \text{mitigation})]}
\]

And then:

\[
\text{PoF} = f(\text{PoF}_{\text{time-indep}}, \text{PoF}_{\text{time-dep}})
\]

Terms and concepts underlying these equations are discussed in the following sections.

### 7.2 Exposure

“Exposure” is the name given to this model’s measure of the level of threat to which the pipeline segment is exposed, if absolutely no mitigation measures were present. It can be thought of as a measure of how active a failure mechanism is in the pipeline’s environment.
Each failure mechanism contributes some threat exposure to each pipeline segment. Exposure is measured differently for the two different categories of failure mechanisms:

- **MPY for degradation or time-dependent mechanisms include:**
  - External corrosion,
  - Internal corrosion,
  - Fatigue, and
  - SCC.

- **Events per length-time (mile-year, for instance) for time independent / random mechanism include:**
  - Third party,
  - Incorrect operations,
  - Weather,
  - Land movements (geohazards),
  - Equipment failures, and
  - Theft/sabotage.

### 7.2.1 MPY

For time-dependent threats, the unmitigated exposure, measured in mpy, is often easy to conceptualize, as is discussed in a later section. The mpy values for all of these threats lead to an estimate of Time to Failure (TTF). TTF is defined as the time period before failure would occur, under the assumed wall loss and available strength assumptions. TTF is an intermediate calculation leading to a probability estimate.

\[
TTF = \text{available pipe wall} / \left[ \frac{\text{wall loss rate}}{1 - \text{mitigation effectiveness}} \right].
\]

The relationship between probability of failure and TTF is established by the model designer (see discussion in later section).

Integrity verifications (pressure test or ILI) can “re-set” the clock at the measured wall thickness, overriding any assumed wall losses. Mpy is then applied to the new measured wall thickness to determine again when failure theoretically would occur (under very conservative assumptions).

### 7.2.2 Events per Length-Time

For time-independent threats, exposure should also be quantified independently of any mitigation. Since historical data and typical pipeline experience does not include mitigation-free scenarios, this type of analysis may seem unusual. However, quantifying threats in this manner provides a better understanding of the exposure and helps in tuning the model to actual experience.

The concept of measuring a threat as if there was absolutely no mitigation applied normally requires a bit of “imagineering.” For example, in the case of third party damage, one must envision the pipeline in a completely unmarked ROW (actually indistinguishable as a ROW), with no one-call system in place, no public education whatsoever, and buried with only a few millimeters of cover—just barely out of sight. Then, a “hit rate” is estimated—how often would such a pipe be struck by agricultural equipment, homeowner activity, new
construction, etc.? This exercise is actually very illuminating in that it forces one to recognize the inherent threat exposure without the often taken-for-granted role of mitigation.

A range of possibilities can be useful in setting boundaries for assigning exposure levels to specific situations. A process for estimating a range of exposure levels is

- Envisioning the worst case scenario for a completely unprotected, specific length of pipe and extrapolating (or interpolating) that scenario as if it applied uniformly over a mile of pipe and
- Envisioning the best case scenario and extrapolating (or interpolating) that scenario as if it applied uniformly over a mile of pipe.

**Examples for Third Party Damage Potential**

- Example worst case scenario: 2500 ft of pipe with 1" cover, no signs, no information available to excavators, located in an active farming and construction zone with potential for line strikes every week. Assessor assigns a value of 50 hits per year for 2500’ = 100 hits/mi-yr

- Example best case scenario: 10 miles of pipe in controlled, uninhabited desert, no utilities, area with limited access. Assessor assigns 0 hits on 10 miles in 100 years = 0.001 hits/mi-yr

In order to help anchor all estimates, a guidance chart can be used:

**Table 7.2.2-1. Exposure Levels**

<table>
<thead>
<tr>
<th>Failures/yr</th>
<th>Years to Fail</th>
<th>Approximate Rule Thumb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000,000</td>
<td>0.000001</td>
<td>Continuous failures</td>
</tr>
<tr>
<td>100,000</td>
<td>0.0001</td>
<td>fails ~10 times per hour</td>
</tr>
<tr>
<td>10,000</td>
<td>0.001</td>
<td>fails ~1 times per hour</td>
</tr>
<tr>
<td>1,000</td>
<td>0.01</td>
<td>fails ~3 times per day</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>fails ~2 times per week</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>fails ~1 times per month</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>fails ~1 times per year</td>
</tr>
<tr>
<td>0.1</td>
<td>100</td>
<td>fails ~1 per 10 years</td>
</tr>
<tr>
<td>0.01</td>
<td>1000</td>
<td>fails ~1 per 100 years</td>
</tr>
<tr>
<td>0.001</td>
<td>1,000</td>
<td>fails ~1 per 1000 years</td>
</tr>
<tr>
<td>0.0001</td>
<td>10,000</td>
<td>fails ~1 per 10,000 years</td>
</tr>
<tr>
<td>0.00001</td>
<td>100,000</td>
<td>fails ~1 per 100,000 years</td>
</tr>
<tr>
<td>0.000001</td>
<td>1,000,000</td>
<td>One in a million chance of failure</td>
</tr>
<tr>
<td>0.0000000001</td>
<td>1,000,000,000</td>
<td>Effectively, it never fails</td>
</tr>
</tbody>
</table>

It is sometimes difficult to imagine the lower ends of the exposure scale. Values implying frequencies like once every 100,000 years or 10,000,000 years are not normally mentioned in the pipeline industry. The reality, however, is that these are real and valid numbers for many stretches of pipeline. A 0.1 mile stretch of pipeline with one exposure (hit or near miss) in 80 years implies a frequency of 0.00125 (once every thousand years). If there were no exposures in 80 years—and many lines do exist for decades with no exposures—then one
could reasonably assign a frequency of 1/100,000 or higher. When there is little or no historical data, a comparable situation and/or judgment can be used.

With practice, several distinct advantages of the approach become apparent:

- Estimates can often be validated over time through comparison to actual failure rates on similar pipelines.
- Estimate values from several causes are directly additive. For example, many external force threats such as falling objects, landslide, subsidence, etc, each with their own frequency of occurrence can be added together for an overall exposure level.
- Estimates are in a form that consider segment-length effects and supports PoF estimates in absolute terms (failures per mile-year) when such units are desired.
- Avoids need to standardize qualitative measures such as “high,” “medium,” and “low.” Experience has shown us that such standardizations often still leave much room for interpretation and also tend to erode over time and when different assessors become involved.
- Can directly incorporate pertinent company and industry historical data.
- When historical data is not available, this approach forces subject matter experts (SME) to provide more considered values. It is more difficult to present a number such as 1 hit every 2 years, compared to a qualitative labels such as “high.”

Many geohazards are already commonly expressed in units that are directly linked to event frequency. Recurrence intervals for earthquakes, floods, and other events can be used to establish exposure.

7.3 Mitigation

Threat reduction occurs either through reducing the exposure to the threat—mitigation—or reducing the failure likelihood in the face of threats or resistance.

In most cases in this model, a percentage is assigned to a mitigation measure that reflects its possible impact on risk reduction. For example, a value of 90% indicates that that measure would independently reduce the failure potential by 90%. A mitigation range for each measure is set by the best-case amount of mitigation the variable can independently contribute. So, the “best” possible level of mitigation is an estimate of how effective the measure would be if it was done as well as can be envisioned. A very robust mitigation can theoretically reduce the threat level to a very low level—sometimes independently eliminating most of threat.

In order to capture the belief that mitigation effects can be dominated by either strong independent measures or by accumulation of lesser measures, OR gate math is used, as previously discussed.
Two methods of applying mitigation benefit are used in this model:

- For time-dependent mechanisms: exposure \( x \times (1 - \text{mit}) \) where mit = simple %
- For time-independent mechanisms: exposure \( / \text{(mit)} \) where mit = simple % applied to an order of magnitude range

As noted in the discussion of “orders of magnitude” (Section 6.1), the mitigation effectiveness is modeled as reducing exposure in proportion to its % through the full exposure scale. So, for time independent mechanisms, mitigation that is 50% effective on a scale spanning 6 orders of magnitude means that exposure is effectively reduced 1,000 times (3 orders of magnitude). As was pointed out, this means that very small exposures turn into very, very small threats under the influence of strong mitigation. This fails to capture the notion of diminishing returns—the doctrine that mitigation effectiveness is diminished as more and more is applied and the exposure is effectively reduced to close to zero. The diminishing returns analogy is not embraced here because most exposures are measured in incident rates (over time or distance or both). A rate or count of incidents seems less sensitive to the idea of disproportionate effectiveness. If 90% mitigation eliminates 9 out of the next 10 possible incidents, then it is not relevant if those next 10 potential incidents occur in one year or one thousand years.

An underlying premise in assigning values, is that mitigation and vulnerability can work together to eliminate most of the threat.

### 7.4 Resistance

Resistance, as the second component of threat reduction—along with mitigation—allows ready distinction between the damage potential and the failure potential. Resistance is simply the ability to resist failure in the presence of the failure mechanism. For time-dependent mechanisms, it is a measure of available strength, including:

- Wall thickness,
- Wall thickness “used up” for known loadings,
- Possible weaknesses in the wall, and
- Material strength including toughness.

For time-independent mechanisms, resistance includes the above factors plus considerations for external loadings:

- Buckling resistance,
- Puncture resistance,
- Diameter to wall thickness (D/t) ratio, and
- Geometry.

This is where the model considers most construction and manufacture issues involving longitudinal seams, girth welds, appurtenances, and metallurgy, as discussed in a later section.
7.5 Time Dependent Failure Mechanisms (TTF Calculations)

As previously noted, the underlying form of this calculation is as follows:

\[ \text{PoF}_\text{time-dep} = f(\text{TTF}) \]
where
\[ \text{TTF} = \frac{\text{“time to failure”}}{[(\text{wall loss rate}) \times (1 - \text{mitigation effectiveness})]} \]

TTF is the time until the pipe leaks, given the estimated pipe wall thickness and the rate of wall loss from the failure mechanisms. This calculation involves many considerations and several steps as discussed below.

7.5.1 Effective Pipe Wall

An evaluation of pipe strength is critical to risk assessment and plays a large role in evaluating failure probability from all mechanisms, but especially the time-dependent mechanisms of corrosion and fatigue.

Pipe wall thickness as a measure of pipe strength and ability to resist failure incorporates pipe specifications, current operating conditions, recent inspection or assessment results, unknown pipe properties such as toughness and seam condition, as well as known or suspected stress concentrators and special external loading scenarios. This model captures these in a variable called “effective pipe wall.”

Aspects of structural reliability analysis (SRA) are implicit in this approach since probability of defects is being overlaid with stresses or loads. A very robust SRA will use probability distributions to fully characterize the loads and resistances-to-loads, while this simplified approach uses point estimates. Simplifications employed here allow more direct calculations instead of Monte Carlo type routines often used in the more robust SRA calculations.

Measured pipe wall thickness could be used directly to calculate remaining strength (available wall) if we have confidence that

- The measurement captures all defects that currently exist.
- There are no imperfections/weaknesses in the steel.
- There are no unintended stresses that are “using up” some strength.

Realistically, all measurements have limitations and many pipelines will have some age-of-manufacture issues as well as other issues that make us question the true available pipe strength, regardless of what a wall thickness measurement suggests. Issues include low freq ERW seam, inclusions, laminations, low toughness, girth weld processes, weakenings from other threat exposures, etc. Effective pipe wall captures such uncertainty about true pipe strength by reducing the estimated pipe wall thickness in proportion to uncertainty about possible wall weaknesses.
7.5.2 Estimates of Effective Pipe Wall

This is a more complex aspect of the risk evaluation—necessarily because the use of available and anticipated information must be done in several iterative steps. It is a fairly comprehensive analysis, incorporating the following:

- Pipe specification;
- Last measured wall thickness;
- Age of last measured wall thickness;
- Wall thickness “measured” (implied) by last pressure test;
- Age of last pressure test;
- Estimated metal loss mpy since last measurement;
- Estimated cracking mpy since last measurement;
- Maximum depth of a defect surviving at last pressure test;
- Maximum depth of a defect surviving at normal operating pressure (NOP) or last known pressure peak;
- Detection capabilities of last ILI, including data analyses and confirmatory digs; and
- Penalties for possible manufacturing/construction weaknesses (see following section for details).

In simultaneously considering all of these, the model is able to much more accurately respond to queries regarding the “value” of performing new pressure tests or new ILI. The value is readily apparent as are suggested re-assessment intervals. All data and all assumptions about exposure and mitigation are easily viewed and changed to facilitate model tuning and/or what-ifs.

The analysis begins with what is known about the pipe wall. In general, an owner will always know:

1. That the pipe is not failing at its current pressure and stress condition (NOP).
2. The wall thickness that was last measured (visual, UT, ILI, implied by pressure test, etc or default to nominal design).

The beginning point of the analysis is these two factors. In addition, the owner (in the US) is now also normally required by regulation to estimate the potential for damages to the pipe since the last inspection. That estimated damage rate is used to calculate an effective wall thickness at any time after the last measurement was taken. An integrity verification inspection or test will adjust the estimated effective wall thickness.

7.5.3 Steps to Effective Wall Estimate

The steps required in the model’s time-dependent failure mechanism analysis are as follows:

1. NOP-based wall: Produce an estimated wall thickness, based on leak-free operation at current NOP. This may include an estimate of the deepest non-leaking defect that could be present at this pressure.
2. **Pressure test based wall**: Calculate an estimated wall thickness based on the most recent pressure test. This might be the original post-construction test. It can also be a recent higher-than-normal pressure to which the segment has been exposed.

3. **ILI based wall**: Calculate an estimated wall thickness based on the most recent inspection. This is normally ILI, but can also be bell hole exams where reliable and comprehensive wall thickness measurements were taken. The accuracy of the inspection for all types of possible defects should be a part of this estimate.

4. **Exposure**: Produce an estimate of steel metal-loss / crack-growth in the absence of any mitigation. This includes at least external corrosion, internal corrosion, and cracking and should reflect, for instance in the case of external corrosion, the corrosion rate of the pipe if it was buried uncoated and unprotected in the segment’s environment.

5. **Mitigation**: Evaluate the effectiveness of current mitigation measures. This effectiveness will be used to directly offset (reduce) the steel deterioration rate that would otherwise occur.

6. **Estimated pipe wall**: Calculate an estimated pipe wall. This is the larger of the pipe wall thickness estimates based respectively on:
   - NOP (and largest surviving defect),
   - Last pressure test minus possible metal-loss / crack-growth since, and
   - Last inspection minus possible metal-loss / crack-growth since.

   Additional estimates might be warranted when metal-loss and cracking scenarios are evaluated separately.

7. **Effective pipe wall**: Assign a penalty to reduce pipe strength whenever there is the possibility of manufacture or construction issues that would reduce the pipe’s strength. This is an adjustment factor used to move from an estimated pipe wall to an effective pipe wall.

8. **Resistance**: Calculate the available pipe wall by comparing the effective pipe wall with the wall thickness needed to contain NOP.

9. **TTF**: Calculate the TTF by dividing the metal-loss / crack-growth rate into the available wall. This value can directly support an IMP, as is discussed below.

10. **PoF**: convert the TTF into a PoF for the current year. This value is combined with the time-independent failure assessments for an overall PoF for each pipeline segment.

It is recognized that this modeling approach makes several simplifying assumptions that do not fully account for the complex relationships between anomaly sizes, types, and configurations with leak potential, rupture potential, and fracture mechanics theories. In addition, metal loss and cracking phenomena have been shown to progress in non-linear fashion—sometimes alternating between rapid progression and complete stability. A constant deterioration rate is used only as a modeling convenience in the absence of more robust predictive capabilities. It should be noted that remaining strength calculations and TTF estimates should not be taken as precise values but rather as relative measures that characterize overall system behavior but may be significantly inaccurate for isolated scenarios.
Nonetheless, after accounting for uncertainty and application of appropriate safety factors, the TTF values directly support integrity management in a way that previous approaches could not. A re-assessment interval is readily apparent from these calculations. Integrity assessment schedules can be directly linked to calculations that fully integrate all pertinent data.

More details of these overall steps follow:

**NOP-Based Wall**

For a burst-model, the wall thickness implied by leak-free operation at NOP can be calculated by simply using Barlow relationship with NOP to infer a minimum wall thickness. Since defects can be present and not be causing failure, a value for “max depth of defect surviving NOP” can also be assumed. This value is somewhat arbitrary since the depth of defect that can survive at any pressure is a function also of the defect’s overall geometry. The assumed wall thickness based solely on operating leak-free at NOP can be calculated as follows:

\[
pipe\_\text{wall\_barlow\_NOP} = \frac{[\text{NOP}]\times[\text{Diameter}]}{2\times[\text{SMYS}]\times1000} - \text{(max depth defect surviving NOP)}
\]

This simple analysis accounts for defects that are present but are small enough that they do not impact effective pipe strength by using the variable “max depth of defect surviving NOP.” The analysis could be made more robust by incorporating a table or chart of defect types and sizes that could be present even though the pipe has integrity at NOP. An appropriate value can be selected knowing for instance that a pressure test at 100% SMYS on 16”, 0.312, X52 pipe could leave anomalies that range from 90% deep 0.6” long to 20% deep, 12” long. All combinations of geometries having deeper and/or longer dimensions would fail. Curves showing failure envelopes can be developed for any pipe.

**Pressure-Test Based Wall Thickness Estimate**

To conclude that there is greater wall thickness than implied by NOP, additional information must support that premise. The above analysis can be repeated using the test pressure instead of the NOP. Then, using an estimated deterioration rate (discussed below) from the time of test until today, another pipe wall estimate is produced. This can be compared to the estimate from the NOP. If this conservatively estimated deterioration since the test suggests a larger wall thickness than implied by the Barlow-NOP calculation, then this value can be used instead of the minimum wall needed for NOP per Barlow.

**ILI-Based Wall Thickness Estimate**

The calculation next uses the last actual measurement taken, including the uncertainty surrounding the measurement and the age of the measurement. This measured pipe wall value will override the other wall thickness estimates (from NOP and since the last pressure test), if the measured value shows with confidence that even more pipe wall is available. The capability of the measurement tool and the validation process is important. Better knowledge, obtained by either greater detection capability of all possible defects and/or a more aggressive validation program, reduces uncertainty in the measurement. As with the estimate based on pressure test, this estimate should include possible degradation of pipe wall since the measurement.
If an integrity assessment, including accuracy considerations, indicates “no anomaly,” there could nonetheless be an anomaly present that is below the detection capability of the assessment. However, it is not normally appropriate to simply assume that such below-detection anomalies exist everywhere. Such ultra-conservatism will be counterproductive to risk management. It is more appropriate to use knowledge of possible failure mechanisms, applied conservatively, to estimate possible defects.

The modeler can use an assessment of integrity inspection capability (IIC) to adjust all measured or inferred wall thicknesses. The adjustment should be based on the largest surviving defect after the most recent inspection. It can also somewhat consider the severity of the defect—how much might it contribute to likelihood of failure. For instance, a detected lamination is normally not a significant threat to integrity unless it is very severe or also has the potential for blistering or crack initiation, both of which are very rare.

A complication in evaluating IIC is that several defect types must be considered. IIC is not consistent among inspection tools and defect types, so some generalizations are needed. Examples of defect types include metal loss (internal or external corrosion), axial cracks, circumferential cracks, narrow axial corrosion, long seam imperfections, SCC, dents, buckles, laminations, inclusions. Inspection or assessment techniques often focus on one or two of these with limited detection capabilities for the others. Since most ILI assessments provide unequal information on cracking versus metal loss, a two-part calculation is required in the TTF assessment. This is illustrated in Example 1 below.

A matrix can be set up capturing the beliefs about IIC. For example, see Table 7.5.3-1, below.
Table 7.5.3-1. IIC Benefit Matrix

<table>
<thead>
<tr>
<th>Inspection Type</th>
<th>Validation (Pig-Digs) Protocol</th>
<th>Defect Type</th>
<th>Max Surviving Defect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>External Corrosion</td>
<td>Internal Corrosion</td>
<td>Axial Crack</td>
</tr>
<tr>
<td>MFL high resolution</td>
<td>Aggressive 5, 5, 100, 10, 20</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Routine 10, 10, 100, 50, 50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Min 15, 15, 100, 50, 50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>MFL std resolution</td>
<td>Aggressive 10, 10, 100, 50, 50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Routine 15, 15, 100, 50, 50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Min 20, 20, 100, 50, 50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>5, 5, 100, 20, 20</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>TFI</td>
<td>20, 20, 10, 10, 50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>EMAT</td>
<td>50, 50, 10, 10, 50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Ultrasound shear wave crack tool</td>
<td>100, 100, 100, 100, 100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Caliper, sizing, gauging, inertial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Press test</td>
<td>5, 5, 5, 5, 2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

This matrix is a simplification and is based on one analyst’s interpretation of information available at the time of this writing. It should be modified when the user has better information available.

Values shown represent defect sizes (depths normally), expressed as percentage of wall thickness, that might remain after the assessment. A value of 100 means that the assessment technique has no detection capabilities for that defect type. The last 2 columns aggregate the various defects into two categories and assign an IIC to each category based on the capabilities for the specific defects. As an example of the use of this matrix, consider a pipeline that has been evaluated with a High Res MFL tool with a routine validation protocol. The corresponding maximum surviving defects for this assessment are 10% of wall for metal loss and 100% of wall for axial cracks. So, no information regarding crack presence is obtained.
**Exposure**

Estimating an un-mitigated exposure level for time-dependent threats is more straightforward than for time-independent mechanisms. In the case of corrosion, the pipe metal’s reaction to its environment establishes a rate for metal loss by corrosion. For cracking, the relationship is more complex, involving the environment, stress levels, and metallurgy, but still readily visualized.

Each segment of pipeline would have varying degrees of exposure to each of the time-dependent mechanisms:

- External corrosion,
- Internal corrosion,
- Fatigue cracking,
- SCC, and
- Possibly, slow-acting geohazards.

Exposure to corrosion and fatigue type phenomena are expressed as metal degradation rates, mils-per-year (mpy) of pipe wall loss (1 mil = 1/1000th of an inch). Although metal loss is actually a loss of mass and is perhaps best characterized by a loss of volume, using a one-dimensional measure—depth of metal loss—conservatively assumes “narrow and deep” corrosion versus “broad and shallow.” It is, after all, the loss of effective wall thickness that is of primary importance in judging impending loss of integrity for time-dependent failure mechanisms. MPY is also the metric commonly used by corrosion control experts to characterize metal loss. In some cases, considerations of volume or weight loss instead of thickness loss might be warranted—note the difference in depth associated with a 1 lb/year metal loss when a pitting mechanisms is involved versus a generalized surface corrosion.

To fully estimate cracking potential, concepts of fracture mechanics must be applied, including possible presence of defects, type of defects, stress levels including stress concentrators, metallurgy, etc. As one important variable—sometimes as the only measure of exposure—fatigue cycles are usually measured, both in terms of their magnitude and frequency. The two general types of fatigue loadings commonly seen are large magnitude low frequency cycles as is typically seen in internal pressure fluctuations and smaller magnitude but more frequent cycles typically seen in traffic or temperature loading scenarios.

All scenarios involving all combinations of frequency and magnitude should be identified. Most will be directly additive. In other cases, OR gate math applied to all simultaneous causes ensures that any scenario can independently drive fatigue and also show the cumulative effect of several lesser exposures.

SCC can be considered a special form of degradation involving both cracking and corrosion. Since aggressive corrosion can actually slow SCC crack-growth rates, the interplay of cracking and corrosion phenomena can be difficult to model. Recent literature has identified factors that seem to be present in most instances of SCC. These factors can be used to estimate an exposure level, expressed in units of mpy, and this exposure can be added to internal corrosion, external corrosion, and fatigue crack-growth, for an overall exposure level.
Other forms of environmental cracking, blistering, or other damages, should also be considered in the exposure estimates for time-dependent mechanisms.

As a modeling convenience, mpy and mils lost assumes uniform damage rate. This is normally not the case. Allowances for more aggressive, shorter duration damage rates might be warranted.

Theoretically, the mpy rate applies to every square centimeter of a pipe segment—the degradation could be occurring everywhere simultaneously. This is because the model sees no difference among any of the square centimeters of pipe wall within the segment—all characteristics are constant, as was set by the dynamic segmentation process.

There are now available, several published sources suggesting possible defaults or estimates for corrosion rates and even crack growth rates.

**Mitigation**

Mitigation includes anything that reduces the potential for or aggressiveness of the failure mechanism. The best possible value for each mitigation variable is determined based on that variable’s perceived ability to independently mitigate the threat. A distinction is made between mitigation and resistance as was earlier noted.

Common mitigation measures for external corrosion include coating and application of cathodic protection (CP). These two are usually employed in parallel. Since each can independently prevent or reduce corrosion, an OR gate is appropriate in assessing the combined effect. Some practitioners rate these measures as equally effective, in theory at least. Using the assumption of independent effects with the associated OR gate math, the combined measures of CP and coating done to 80% and 85% level of effectiveness respectively, would reduce external corrosion by 1-(1-0.8)(1-0.85) = 97%. So, an unmitigated corrosion rate of 16 mpy, would be reduced to about 0.5 mpy after mitigation in this scenario.

When a coating is assessed as, say 80% effective in reducing corrosion, this actually means that 80% of the coated pipe is fully protected and 20% has essentially no protection from coating. This is analogous to a weather forecast where a 40% chance of rain does not mean that the rain is somehow 40% of what it would otherwise be. It actually implies that 40% of the viewing area will probably see some rain while 60% will see none. Nonetheless, as a modeling convenience, the mitigation effectiveness as it is used here is numerically reducing the rate of the exposure rather than predicting certain lengths of pipe wall will corrode and others will not.

CP effectiveness is measured by a variety of factors including various pipe-to-soil voltage and other over-line surveys, survey protocols (on, off, de-polarized, etc) interpretation of survey results, rectifier inspections, interference potential, and others. The interactions of CP variables can suggest OR gate math in some cases and AND gate math in others.

Typical internal corrosion mitigation measures include:

- Internal coatings,
- Monitoring via coupon or other probe,
• Inhibitor injection,
• Regular cleaning,
• Sweeping of liquid accumulations, and
• Product treatments.

These are generally independent measures and can be related using OR gate math. A critical inclination angle calculation can be used to supplement and support exposure and mitigation estimates for internal corrosion.

Mitigation against fatigue is achieved through reduction of cycles—directly reducing the exposure level. Use of pipe casings or other load transfer techniques would reduce the transmission of the exposure to the pipe and could be considered mitigation measures. Otherwise, choice of metallurgy, wall thickness, and stress level reduce crack growth potential from a resistance standpoint (although there is some gray area for classifying certain factors as resistance vs. mitigation).

**Estimated Pipe Wall**

The estimated pipe wall reflects the best estimate of how much metal is present and available to resist failure. Either cracking or metal loss may dominate the calculation, depending upon the estimated aggressiveness of each and the date/type of assessments performed. For many risk assessments, the two phenomena are best tracked independently.

Remaining wall thickness, or maximum surviving defect sizing, can be estimated using some simple relationships like the Barlow equation specified in US pipeline regulations. This has limitations since it does not accurately capture the effects of defect size (depth versus length and width are important) or type (cracking phenomena are not captured by the Barlow relationship). When increased accuracy is required, metal loss sizing routines such as RSTRENG and ASME B31.8G or fracture mechanics relationships can be substituted. It is recommended that the more robust calculations be used when data is available since the Barlow will produce overly conservative results. For example, in a 72% design factor pipeline, with a 12.5% wall thickness manufacturing tolerance, loss of only 15% wall would predict failure. Ignoring the manufacturing tolerance is often suggested in order to reduce the over-conservatism when Barlow is used (and this is consistent since ASME recommendations are to use nominal wall value in Barlow calculations).

**Effective Pipe Wall**

An estimated pipe wall thickness has now been created. The effective pipe wall calculation begins with this value and adjusts or penalizes it for anything that implies a reduced strength in that metal. A potential weakness is modeled as being equivalent to reduced wall thickness.

Possible manufacturing/construction weaknesses are identified for each pipeline segment. Typical age-of-manufacture/construction issues include

• Increased longitudinal seam susceptibilities (low freq ERW, for instance);
• Hard spots;
• Laminations;
• Low toughness;
- Girth weld weaknesses;
- Miter joints;
- Wrinkle bends;
- Stress concentrators;
- Sub-standard appurtenances; and
- Any other possible weaknesses.

The amount of weakness actually produced by these factors is often very situation-specific. Generalizations are used to avoid the sophisticated finite element analyses that would be required to fully model all of the possibilities. Some generalizations are available from industry standards and even regulations. Note the seam factor used in U.S. regulations for pipeline design—this is an example of an adjustment value.

The effective pipe wall estimate can now be used for available wall calculation (time-dependent mechanisms) and in external force resistance models (third party pipe wall puncture resistance and landslide buckling resistance, for example). However, nominal pipe wall is often used in certain external force variables such as D/t and “geometry” factor since their influences are very coarse. Using effective pipe wall everywhere can also lead to troublesome to circular calculations, so some simplifications are often needed.

The following examples illustrate some derivations of the effective pipe wall estimates.

**Example 1**

A non-leaking pipeline segment has a nominal wall thickness of 0.320” after accounting for the manufacturing tolerance of 12.5%. The Barlow calculation using NOP shows that a minimum of 0.210” is required to contain normal operating pressure. (Considering also the max defect depth that could survive at this pressure, assuming a long corrosion defect, would bring the minimum wall thickness down substantially.) The conservatively estimated deterioration rate in this segment is 10 mpy from a combination of 8 mpy metal loss and 2 mpy cracking. Since it has been 15 years since an evaluation has been done, the calculated pipe wall is 0.320 – 15*10/1000 = 0.170”. The minimum wall implied by NOP is higher, so the current estimate of pipe wall thickness is 0.210”. Noting the difference in estimates, the mpy deterioration rate is assumed to be too conservative and should be adjusted downward.

A high resolution MFL ILI tool with routine confirmation excavations (follow-up) is used to assess integrity. This technique is assumed to have no capabilities to detect longitudinal crack-like indications and +/-10% accuracy of metal loss anomalies, so [integ_insp_capability1] = 10 and [integ_insp_capability2] = 100 where 100 means that a defect up to 100% of pipe wall could exist undetected by the inspection. The assessment indicates a minimum wall in this segment of 0.300”. So, ILI-estimated wall thickness for metal loss is 0.300 x 90% = 0.270”. For cracking, the available wall could actually be 0.00” since the integrity assessment is assumed to have no detection capabilities. The pipe wall estimate based on possible metal loss is 0.270”, derived from ILI measurement and accuracy. Since we have confirmed that the conservatively estimated deterioration rate has not occurred, we can now adjust the estimated wall with cracking to be (wall after metal loss) – (mils potentially lost by cracking) = 0.270 – (2 mpy x 15 years) = 0.240”. Since there is not a measured value to override this estimate, then it shall become the value for pipe wall estimated based on possible cracking.
These values along with the corresponding damage rates are used to set re-assessment intervals for cracking and metal loss mechanisms respectively.

For an overall pipe wall estimate, we can now use the smaller or 0.240”. This is then adjusted for possible metal weaknesses to get effective pipe wall.

Without the ILI, the pipe wall would have been assumed to be 0.210”. So, the ILI improved the risk picture by removing uncertainty by providing a better estimate. This was done by a direct metal loss measurement and an inferred adjustment to possible cracking. The ILI information also prompts a revision of the deterioration rate, further reducing the conservatism brought on by uncertainty.

**Example 2**
Same scenario as above except that a 1.25 x MOP pressure test is the chosen integrity assessment technique. This technique is modeled to have a capability to find all defect types to the extent that they fail at the test pressure. The Barlow calculation using the test pressure indicates a minimum effective wall thickness of 0.263” (Note that a 1.5 x MOP test would have led to a 0.315” wall.) So, 0.263” is the value for pipe wall thickness estimate to be used in obtaining effective pipe wall.

This example assumes that a more robust inspection is achieved via pressure test, so risk is reduced more than in the previous example where a defect-specific ILI was used. That assumption will not always be valid.

**Example 3**
This example shows where the analysis might at first seem counterintuitive until all aspects are simultaneously considered. Consider the following two segments from a very old, large diameter gathering pipeline:

<table>
<thead>
<tr>
<th>Segment Number</th>
<th>OD (in)</th>
<th>Wall (in)</th>
<th>Grade</th>
<th>SMYS for Max Press Calc (psi)</th>
<th>SMYS for Min Wall Remain (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>30.625</td>
<td>0.320</td>
<td>?</td>
<td>24000 (default)</td>
<td>52000</td>
</tr>
<tr>
<td>106</td>
<td>30</td>
<td>0.374</td>
<td>X52</td>
<td>52000</td>
<td>52000</td>
</tr>
</tbody>
</table>

Note that the SYMS assumed for maximum operating pressures is 24,000 psig (per US regulations) but the assumed SYMS for minimum wall estimates is 52,000 psig, the documented value of nearby segments. Using this latter value results in smaller remaining wall thicknesses and should be used to maintain conservativeness in the assessment.

From inspection, some might say that segment 106, with a heavier wall would have a lower PoF, if all other factors are equivalent. After all, 106 would have a much higher maximum pressure based on the available SMYS information. However, given that nothing beyond “leak free at NOP” can be conservatively assumed, the apparently heavier wall of 106 is not germane to the current analysis. Conservatively estimated corrosion rates over many years, without offsetting integrity verifications, have essentially made the two segments’ wall thicknesses roughly equivalent. They are not exactly equivalent, because the slightly larger diameter of 100 causes the assumed wall thickness of 100 to be slightly larger than 106’s.
Table 7.5.3-3. Data for Example 3

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
<td>0.103</td>
<td>502</td>
<td>0.077</td>
<td>0.0530</td>
<td>6.8%</td>
</tr>
<tr>
<td>106</td>
<td>0</td>
<td>0.101</td>
<td>1297</td>
<td>0.075</td>
<td>0.0545</td>
<td>7.3%</td>
</tr>
</tbody>
</table>

In this type of analysis, higher grade (stronger) steels tend to have a higher (worse) PoF compared to lower strength steels. This is true because the mpy deterioration applies equally to all strengths of steel. So, heavier wall steel has the longest TTF, regardless of strength. If two wall thicknesses are equal, the one with the lower strength will have a longer TTF because it begins with a thicker wall under the “leak free at NOP” initial premise—i.e., it takes more wall thickness of a lower strength steel to contain the operating pressure.

When pipe grade is unknown, the often-recommended default of 24,000 psig is not conservative when calculating remaining wall thickness. Since the mpy deteriorates high strength steel as readily as low strength, using a higher SMYS default results in lower remaining wall and quicker TTF—a more conservative assessment overall.

**Resistance (Available Pipe Wall)**

The difference between the available pipe wall thickness and the thickness required for anticipated loads (internal pressure, external loads) is the thickness of metal that can be lost before failure occurs. This estimated “extra” wall thickness represents a safety margin—failure potential is reduced as this increases since the TTF will be increased. This “available wall” can be also used in subsequent estimates of resistance to other failure mechanisms such as external forces. Similarly, the available wall estimate can be reduced on the basis of other results from the risk assessment. For instance, when external forces are “using up” more pipe strength, this reduces strength available to withstand other failure mechanisms.

Again, some significant simplifying assumptions underlie this value and should be carefully considered by the modeler.

**TTF**

This represents the time period before failure would occur, under the assumed wall loss and available strength assumptions. TTF = (available pipe wall) / [(wall loss rate) x (1-mitigation effectiveness)]. For these time-dependent mechanisms, TTF is an intermediate calculation leading to a PoF estimate.

A new integrity inspection can “reset the clock” for this calculation as can any new information that would lead to a revised wall thickness estimate.

**From TTF to PoF**

The PoF is calculated as the chance of one or more failures in a given time period. The degradation rate is assumed to be occurring everywhere simultaneously. Therefore, the number of degradation points in a segment does not theoretically impact the estimate. In reality, there is an uncertainty associated with each degradation estimate and larger segments will have more possible degradation points and increased chance of outliers—locations...
having larger than estimated degradation rates. The calculated probability assumes that at least one point in the segment is experiencing the estimated degradation rate and no point is experiencing a more aggressive degradation rate.

The relationship between TTF and year one PoF is an opportunity to include segment length as a consideration, at the modeler’s discretion. A relationship that shows increasing PoF as segment length increases is defensible since the longer length logically means more uncertainty about consistency of variables and more opportunities for deviation from estimated degradation rates.

The PoF calculation estimates the time to failure, measured in time units since the last integrity verification, by using the estimated metal loss rate and the theoretical pipe wall thickness and strength. It is initially tempting to use the reciprocal of this days-to-failure number as a leak rate—failures per time period. For instance, 1800 days to failure implies a failure rate of once every \((1800/365) = 4.9\) years or \(1/(1800/365) = 0.202\) leaks per year. However, a logical examination of the estimate shows that it is not really predicting a uniform leak rate. The estimate is actually predicting a failure rate of \(~0\) for 4 years and then a nearly 100% chance of failure in the fifth year.

Some type of exponential relationship can be used to show the relationship between PoF in year one and TTF. The relationship:  
\[
\text{PoF} = 1 - \text{EXP}(1/\text{TTF})
\]

where PoF = (probability of failure, per mile, in year one) produces a smooth curve that never exceeds PoF = 1.0 (100%), but produces a fairly uniform probability until TTF is below about 10 (i.e., a 20 yr TTF produces \(~5\%\) PoF). This does not really reflect the belief that PoF’s are very low in the first years and reach high levels only in the very last years of the TTF period. The use of a factor in the denominator will shift the curve so that PoF values are more representative of this belief. A Poisson relationship or Weibull function can also better show this, as can a relationship of the form PoF = 1 / (fctr x TTF^2) with a logic trap to prevent PoF from exceeding 100%. The relationship that best reflects real world PoF for a particular assessment is difficult if not impossible to determine. Therefore, the recommendation is to choose a relationship that seems to best represent the peculiarities of the particular assessment, chiefly the uncertainty surrounding key variables and confidence of results. The relationship can then be modified as the model is tuned or calibrated towards what is believed to be a representative failure distribution.

### 7.7 Time Independent Failure Mechanisms

As previously noted, the underlying form of this calculation is as follows:

\[
\text{PoF} = \frac{\text{[unmitigated event frequency]}}{10^{\text{[threat reduction]}}}
\]

Where

\[
\text{[threat reduction]} = f(\text{mitigation effectiveness, resistance})
\]

Threats modelled as mostly random in nature, third party, theft, sabotage, incorrect operations, geohazards, etc, are sensitive to segment length since the threat is assumed to be uniformly distributed across the entire segment. This results in a leak rate per length per time period (such as PoF / mile / year) which is then multiplied by the segment length to get a failure probability for the segment. A direct multiplication or summation of failure probabilities is acceptable when numerical values are very small.
One of the keys to the new approach in risk assessment is to capture the orders of magnitude spans between risk levels. Older scoring systems did not normally provide for this.

The best possible value for each mitigation variable is determined based on that variable’s perceived ability to independently mitigate the threat. The mitigation is applied to the possible span—orders of magnitude—of exposure.

Discussion and notes regarding some assessments for specific failure mechanisms follow. The patterns shown in these examples can be applied to any other time-independent failure mechanism. Mitigation measures are often already defined from previous risk assessments and their assessed effectiveness can be used in this model.

7.7.1 Third Party

Third party damage is modeled as a time-independent failure mechanism. It is assumed that any third party damage that does not result in an immediate failure, initiates a time-dependent mechanism such as corrosion or fatigue.

Exposure
Exposure is the estimated events/per mile-year from excavation activity and certain other external forces. Unless considered elsewhere in the model, impacts should include:

- Excavation—farm equipment, construction equipment, dredging, boring. piles.
- Traffic—vehicles, rail, marine, air.
- Falling objects—trees, utility poles, buildings, meteors, etc (anything that could fall onto the ROW).

External impacts—landslides, rock falls, etc—are normally considered in the Geohazard assessment (see Section 7.3.3).

Mitigation
Mitigation = \( f(\text{cover}, \text{patrol}, \text{one-call}, \text{damage prevention program}, \text{ROW condition}, \text{signs/markers}, \text{etc.}) \). Some comments on measuring effectiveness of some specific mitigation measures follow:

- One-call effectiveness is generally an AND gate between sub-variables such as system type, notification requirement, and response. The AND gate is applicable since all sub-variables together represent the effectiveness of the mitigation.
- The mitigation of patrol is normally an AND gate between patrol type and frequency. Patrol type implies an effectiveness and includes combinations of different types—ground-air, for example.
- External protection is typically an OR gate between cover, warning mesh/tape, exterior protection since each measure can act independently to reduce the PoF.
- Casing is a mitigation if it is thought of as something added to a pipeline system. If it is considered part of the pipeline system, then it is a resistance. Either categorization can be used since either will have the same impact on PoF.
Maximum effectiveness of each mitigation measure should represent the modeler’s belief about how much the failure potential is reduced by that measure independent of any other measure. For example, casing pipe or extreme depth of cover should probably warrant 95-99% reduction in exposure levels.

**Resistance**

Resistance = \( f(\text{pipe wall thickness, pipe geometry, pipe strength, stress level, manufacturing and construction issues}) \). The pipe wall thickness and material toughness can be used to assess puncture resistance. The geometry, diameter and wall thickness, can measure resistance to buckling and bending. Since internal pressure induces longitudinal stress in the pipe, a higher internal pressure can indicate reduced resistance to external forces.

### 7.7.2 Incorrect Operations

The time-independent failure mechanism of human error is measured as “incorrect operations.” Specifically, the potential for failure directly precipitated by a ‘real time’ human error, is measured here. Examples of such failures include improper operation of valves causing overpressure or disabling of control or safety devices. Such failures usually require that a sequence of unlikely events, including failure of highly reliable safety devices, all occur.

As a modeling convenience and due to the normally consistent aspects of human error reduction across all failure mechanisms, the role of possible human error in all other failure mechanisms is often also assessed in one location in the risk analysis. This includes the potential for error in design and maintenance activities related to safety systems, corrosion control, third party damage prevention, and others. Results of this analysis are used to adjust mitigation effectiveness estimates. When human error potential is higher, mitigation effectiveness is conservatively assumed to be lower. For example, when procedures or training are found to be inadequate, then effectiveness of corrosion control methods might be more suspect; when instrument calibration and maintenance records are missing, effectiveness of safety devices is questionable.

**Exposure**

For exposure estimates, abnormal, unintended, inappropriate actions that could lead to pipeline failure are “events.” Frequency of “events” is exposure. Measures employed to avoid an incident is mitigation. Ability of the system to resist a failure when exposed to an incident is resistance. So, stress level is resistance as well as exposure and is appropriately included in both aspects of the analysis. The unmitigated exposure level for this mechanism should be based on a completely untrained workforce, with no procedures in place, no records of design or maintenance, no SCADA benefits, etc. As with some other exposure estimates, such an unmitigated scenario may required some imagination on the part of the assessors.

Exposure level should include an assessment of all pressure sources that can overpressure the pipeline segment of interest. Sources of potential overpressure typically include source pressure, thermal overpressure, and surges. All of these are modeled as real time human error exposures. Safety devices are ignored at this point in the analysis. Each source is assigned an event frequency, based on how often the overpressure event is theoretically possible.

When the threat is continuous, a pre-set value can be assigned. An example is a pipeline that is downstream of a pressure reducing regulator that prevents the high upstream pressure from
affecting the downstream pipeline (remember, no benefit from the safety device is credited yet). When this high pressure source can overpressure the segment, the exposure is continuous. Surge potential can also be considered in this part of the model.

Mitigation
Mitigation measures typically thought to reduce failure potential include:

- Safety systems,
- Training,
- Procedures,
- Proactive surveying,
- Maintenance practices,
- Materials handling,
- Quality assurance,
- Hazard Identification, and
- Others.

Some of the less obvious mitigation measures are briefly discussed below.

✓ [Surveys] is a mitigation variable that shows how much proactive information collection, digestion, and reaction to new information is being done. It overlaps aspects of surveys employed in other threat mechanisms (CIS, aerial patrol, depth cover, etc) but additional “credit” given here as evidence of overall corporate philosophy of proactively addressing possible exposures.

✓ [Maintenance practices] indicates a sensitivity to keeping things in high working order. It should be an AND gated variable combined with variables such as one measuring effectiveness of safety devices, since the latter requires the former in order to realize its full capability.

✓ [Materials] captures the company’s processes to ensure correct materials are used. This includes material selection and control as replacements/additions to the system are made.

✓ [QA] applies to quality control checks in design, construction, operations, and maintenance. The ability of such measures to reduce exposure can be assessed.

✓ [HazID] captures programs that identify and prompt appropriate actions to avoid human errors.

Resistance
The segment’s resistance to human error caused failures can be modeled as a function of:

- System safety factor,
- Stress level (% SMYS),
- Time-to-overpressure,
- Etc.
7.7.3 Geohazards

The potential for damages or failure from geologic or hydraulic forces, although a relatively rare threat for most pipelines, can be the main risk driver for certain segments and a challenge for risk assessment.

Exposure
One way to measure this exposure threats is to sum the contributions from each of three geohazard categories:

\[
\text{Exposure} = \text{[geotech]} + \text{[hydrotech]} + \text{[seismic]}
\]

Where:

\[
\begin{align*}
\text{Geotech} &= \text{[landslide probability]} \times \text{[landslide severity]} \\
\text{Hydrotech} &= \text{[erosion]} + \text{[subsidence]} + \text{[buoyancy]} + \text{[flood-bank erosion]} + \text{[flood-undercut]} + \text{[debris loadings]} \\
\text{Seismic} &= \text{[fault]} + \text{[liquefaction]} \\
\quad \text{Fault} &= \text{expected failure rate due to fault actions} \\
\quad \text{Liquefaction} &= \text{[peak ground acceleration (PGA)]} \times \text{[soil suscept]}
\end{align*}
\]

This general failure mechanism category includes mechanisms of two specific types: those that produce constant forces and those that produce random events. The constant forces can be modeled as continuously “using up” available pipe strength, thereby reducing resistance to other failure mechanisms. Of high priority would be the identification of coincident application of such geohazards with pipe weaknesses or higher exposures to other failure mechanisms. The forces generating random events are usually better modeled as non-continuous.

The process for assigning PoF values to these phenomena should include the use of historical incident rates and published recurrence interval data whenever available.

Mitigation
Mitigation measures are often phenomena-specific if not situation-specific and might require special handling in the assessment. Mitigation measures typically thought to reduce failure potential include:

- Strain gauges,
- Barriers,
- Soil removal,
- Erosion control structures,
- Drain control, and
- Etc.

Resistance
Resistance can be assessed in a fashion similar to third party (refer to Section 7.7). Resistance measures typically thought to reduce failure potential include:
• Supports,
• Anchors, and
• Pipe designs.

7.8 Final PoF

All failure probabilities and risk valuations should be normalized spatially and temporally. Units such as failures/mile-year are convenient for all mechanisms except equipment and certain materials/construction issues. In those cases, a segmentation strategy or assumptions regarding anomalies per unit length can be used to normalize.

The relationship between leak frequency and failure probability is often assumed to be exponential. The exponential relationship fits many observed rare-event phenomena and is frequently used in statistical analysis.

The probability of no events can be calculated from:

\[ P(X)_{EVENT} = \left( \frac{(f \times t)^X}{X!} \right) \times \exp(-f \times t) \]

Where:
- \( P(X)_{EVENT} \) = probability of exactly \( X \) events
- \( f \) = the average spill frequency for a segment of interest, events/year
- \( t \) = the time period for which the probability is sought, years
- \( X \) = the number of events for which the probability is sought, in the pipeline segment of interest.

The probability for one or more events is evaluated as follows:

\[ P(\text{probability of one or more})_{EVENT} = 1 - P(X)_{EVENT} \]

where \( X = 0 \).

At very small event frequencies, the probability values are equal to the event rates. So, the two can be used interchangeably until the event rates become higher.

In the risk assessment, a probability of failure is calculated for each pipeline segment for each threat. Under the assumption that each failure mechanism is basically independent, these probabilities are combined through an OR gate equation to give an overall failure probability for the segment. The segment probabilities are combined to give an overall PoF.

\[
\text{PoF} = f(\text{PoF}_{\text{time-indep}}, \text{PoF}_{\text{time-dep}})
\]

PoF values associated with each failure mechanism are combined using the widely accepted premise in probability theory that the “chance of one or more failures by any cause” is equal to 1 minus “the chance of surviving cause A” times “the chance of surviving cause B” times,
etc. So, for a model that has categorized threats into third party, TTF, theft/sabotage, incorrect operations, and geohazard, the relationship would be:

$$\text{PoF}_{\text{overall}} = 1 - [(1 - \text{PoF}_{\text{thdpty}}) \times (1 - \text{PoF}_{\text{TTF}}) \times (1 - \text{PoF}_{\text{theftsab}}) \times (1 - \text{PoF}_{\text{incops}}) \times (1 - \text{PoF}_{\text{geohazard}})]$$

Where \( P_X \) = Failure Probability associated with failure mechanism \( X \) (Prob of one or more failures/ (mile*yr) or other appropriate units)

A simple summation of failure probabilities is acceptable when numerical values are very small.

While the assumption of independence is made for purposes of probabilistic math, dependences can also be modeled. For example, the effective pipe wall calculated in the TTF routines can be used in the resistance calculations for external forces. Similarly, the effects of external loadings can influence the “available wall” calculations in the TTF routines.

**Combining Segments**

Threats modeled as mostly random in nature including third party, theft, sabotage, incorrect operations, geohazards, etc, are sensitive to segment length since the PoF is based on an exposure per unit length. So, longer length segments have more exposure and hence, more PoF. A simple multiplication of segment length by its PoF per unit length yields the segment’s total PoF.

The PoF calculation from TTF is theoretically not segment-length-sensitive, for reasons previous noted. However, to further account for uncertainty in TTF estimates, including a segment length consideration might be justified.

**PoF Example**

This example illustrates the normalizing of segment PoF values and their combination into an overall PoF for a pipeline.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>PoF</th>
<th>Total (per year)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment</td>
<td>Length (ft)</td>
<td>Time-Independent (per mile-year)</td>
<td>Time-Dependent (per year; year 1)</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>2000</td>
<td>0.0004</td>
<td>5.60E-06</td>
<td>1.57E-04</td>
</tr>
<tr>
<td>A2</td>
<td>20</td>
<td>0.01</td>
<td>6.00E-07</td>
<td>3.85E-05</td>
</tr>
<tr>
<td>A3</td>
<td>600</td>
<td>0.0003</td>
<td>2.50E-07</td>
<td>3.43E-05</td>
</tr>
<tr>
<td>total</td>
<td>2620</td>
<td></td>
<td>2.30E-04</td>
<td>per year</td>
</tr>
</tbody>
</table>

In this example, three segments of varying lengths have been assessed. Each has a PoF for time-dependent failure mechanisms and a PoF for time-independent failure mechanisms. The former is in units of probability per mile-year (or failures per mile-year) and the latter in units of probability per year. The time-independent value is normalized by multiplying by the segment length in miles. The total column shows the combined PoF for each segment, using...
an OR gate to combine the time independent and time dependent probabilities. This shows that the 20 ft segment A2 is more problematic than the 600 ft segment A3, even though the latter is 30 times longer. For a final PoF value representing all three segments, the segment-specific PoF’s are combined using an OR gate. This results in a PoF of 2.3E-4 for the 2620 ft pipeline which equates to a value of 4.63E-4 failure rate per year. This can be compared to a benchmark value from, say, US pipeline OPS failure statistics, representing average, median, worst-case, or any other comparative value. In the example, the overall PoF suggests a 0.023% annual PoF for this 2620 ft which is approximately equal to the benchmark rate.

This example also illustrates the importance of incorporating length into the analysis at some point. Note that segment A2 is several orders of magnitude more likely to fail than the others, but since it is a short length, its contribution does not overshadow the other segments whose lower-PoF-but-for-longer-lengths values are equally important. In this example, the time-dependent PoF dominates the overall PoF.

8. Calibration and Validation

For some applications of pipeline risk assessment, especially in the early stages, relative risk values are the only values that will be required. Relative values can often adequately support prioritization and ranking protocols. The need for calibration—tuning model output so that it mirrors actual event frequencies—might be unnecessary in initial stages. In that case, only validation—ensuring consistent and believable output from the model—is required.

Prior to the need for PoF results expressed in absolute terms—failures per mile-year, for instance—the PoF values can be stripped of their time period implication and be used as relative numbers. A 2.3% PoF does not mean a 2.3% annual probability of failure until the risk assessment has been calibrated—it only means a 2.3% chance of failure over some time period. This might be one year or one hundred years. Until the calibration is done, the 2.3% value can be used as a relative measure of PoF.

Experience has shown, however, that risk management permeates so many aspects of the organization that a good risk model’s role will eventually be expanded. As its output becomes more familiar, new users and new applications arise. Ultimately most assessments will be asked to anchor their output in absolute if not monetary terms. When this happens, the need for both validation and calibration arises.

Incident history is one of the important pieces of evidence to consider when calibrating risk assessment results. This includes all incidences of measured metal loss, crack like indications, damages found, anomalies detected, plus actual failures. In most cases, knowledge of all previous repairs will be relevant.

An incident impacts our degree of belief about future failure potential in proportion to its relevance as a predictor. Some will directly impact exposure estimates. Even if it has little or no direct relevance as a predictor, the related investigation would certainly yield information useful in effective pipe wall calculations.
A mechanism must exist to remove the “penalty” when there is no longer any relevance. An example would be where an ineffective coating is the root cause of a corrosion incident and that coating is subsequently replaced. Another example is a high incidence of third party damages or near-misses associated with some land use that has since changed.

All PoF estimates can be calibrated by using relevant historical failure rates when available. This generally involves the following steps:

- Perform detailed analysis of historical leak data.
- Evaluate data in the context of similar pipelines (similar environments and O&M practices) in other companies.
- Determine relevance of each incident to all segments of pipeline.
- Use relevant data to calibrate or tune the algorithms so that absolute risk levels—expressed in annualized costs, for example—can be produced.

Failures outside of the segment of interest might or might not be relevant so some historical data should be adjusted on the basis of engineering judgment and experience.

If model results are not consistent with a chosen benchmark, any of several things might be happening:

- Benchmark is not representative of the assessed segments,
- Exposure estimates are too high or too low,
- Mitigation effectiveness is judged too high or too low, and
- Resistance to failure is judged too high or too low.

The distinction between PoF and probability of damage (but not failure) can be useful in diagnosing where the model is not reflecting reality. Mitigation measures have several aspects that can be tuned. The orders of magnitude range established for measuring mitigation is critical to the result, as is the maximum benefit from each mitigation, and the currently judged effectiveness of each. A trial and error procedure might be required to balance all these aspects so the model produces credible results for all inputs.

Similar to the use of a benchmark for model validation, a carefully structured interview with SME’s can also identify model weaknesses (and also often be a learning experience for SME’s). If an SME reaches a risk conclusion that is different from the risk assessment results, a drill down into both the model and the SME’s basis of belief should be done. Any disconnect between the two represents either a model error or an inappropriate conclusion by the SME. Either can be readily corrected. The objective should be to make the risk assessment model house the collective knowledge of the organization—anything that anyone knows about a pipeline’s condition or environment, or any new knowledge of how risk variables actually behave and interact, can and should be captured into the analysis protocol.

Users should be vigilant against becoming too confident in using any risk model output. Especially when such output is expressed in numbers that appear to be very precise, it is easy to fall into an “illusion of knowledge.” Regardless of the extent of the modeling rigor employed, assumptions and simplifications are still needed in any analysis. The uncertainty
surrounding a risk assessment cannot be eliminated and a model without some simplifications is not justifiable in such a high uncertainty environment. The very nature of extremely rare events makes planning difficult. For example, an event might be very precisely measured to have a recurrence interval of 88 years. This is very useful information when the event is compared to many other events with say, intervals of 2 years and 250 years. However, the once-every-88 year event could occur next year, in year 24, in year 67, or even twice in any year.

Even though the more robust algorithms discussed here use almost all pertinent information, they are still normally set up to receive and produce point estimates only. In reality, many variables will vary over time as well as along a pipeline. To better model reality, the changes in many parameters like pressure, soil resistivity, wall thicknesses, etc should be captured by creating a distribution of the variations over time or space. Such distributions can also at least partially quantify the uncertainty surrounding all measurements. The range of possibilities for all pertinent variables must be understood and accounted for in producing the risk estimates.