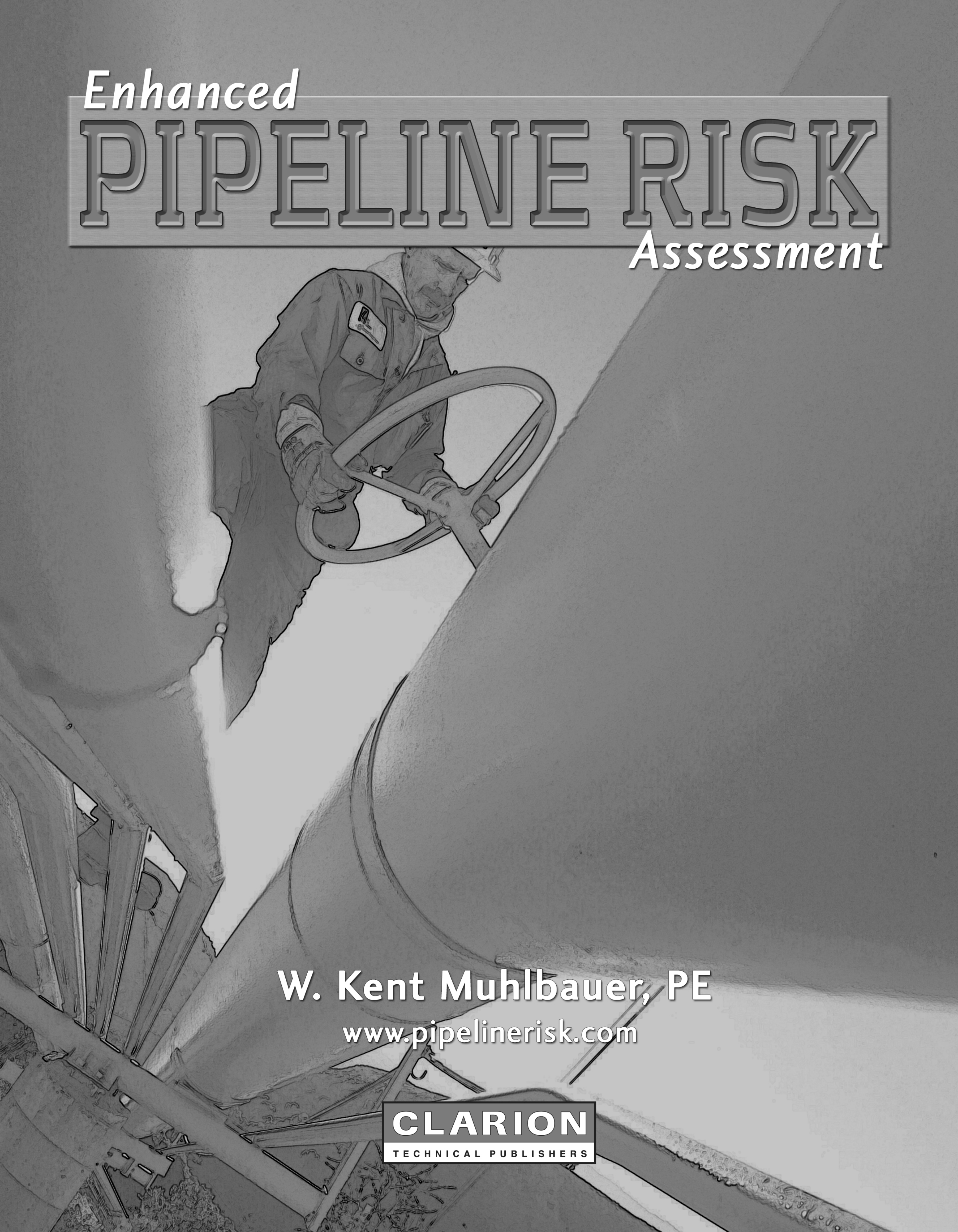

Enhanced PIPELINE RISK Assessment

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Enhanced Pipeline Risk Assessment

Part 1—Probability of Failure Assessments

Part 2— Assessments of Pipeline Failure Consequences

Enhanced Pipeline Risk Assessment

Part 1—Probability of Failure Assessments
Rev 3

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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, uncertainty, and other variables impacting pipeline risk are among the topics into which this new material fits. The reader is encouraged to refer to the 3rd edition text for details and clarifications of concepts that are not fully developed in this document.

This material represents ideas and possible approaches to problem solving that may or may not be appropriate in certain situations and applications. The user of this material is strongly urged to exercise careful judgment in the use of all information presented here. Author provides no guarantee, expressed or implied, with regard to the general or specific application of this information. The user accepts all liability in any and all applications of any material taken from this document.

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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:

> CondA +CondB +… CondN = Relative Probability of Failure (or relative Consequence of Failure)

Or sometimes:

> (CondA x WeightA) + (CondB x WeightB) + … (CondN x WeightN) = Probability of Failure
>
> Where
>
> CondX represents some condition or factor believed to be related to risk, evaluated for a particular piece of pipeline.
>
> 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,
- 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 DOT, OPS—now, 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. Serious practitioners always recognized these "limitations" and worked around them 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 ;
- Greatly enhances ability to demonstrate compliance 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 man-hours. The new approach makes use of existing 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 PoF Algorithms

5.1 Risk Triad

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

- Exposure
- Mitigation effects
- 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.

Probability of Damage (PoD) = *f* (exposure, mitigation)

Probability of Failure (PoF) = *f* (PoD, resistance)

This avoids a point of confusion sometimes seen in previous assessments. Some risk assessment 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 roles 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 PoF Assessment Steps

The overall steps for assessment of PoF under the new algorithms are as follows:

1. Exposure: Estimate exposure from each threat
    a. Degradation rate from time-dependent failure mechanisms
    b. Event rate from time-independent failure mechanisms
2. Mitigation: Estimate combined effect of all mitigations
    a. Identify all mitigation measures
    b. Rate effectiveness of each
3. Resistance:
    a. Produce best estimate of current pipe strength by finding the "governing" information from:
        i. Pipe wall implied by last pressure test
        ii. Pipe wall implied by last inspection (including ILI, bell hole exam, etc)
        iii. Pipe wall implied by assumption of leak-free at current NOP
        iv. Possible pipe wall weaknesses
    b. Estimate pipe's resistance to failure from each threat
4. PoF: Calculate PoF from each threat
    a. Risk Triad: combine Exposure, Mitigation, Resistance
    b. TTF and then PoF for time-dependent failure mechanisms
    c. PoF for time-independent failure mechanisms
    d. Combine all PoF's

5.3 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. So, if three aspects are each rated as 80% and each are essential to the performance of the mitigation, then the mitigation is actually only about 51%. See section 5.5 for a discussion of the math involved.

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.

5.4 Orders of Magnitude

As noted, logarithmic or "orders of magnitude" 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 (10^2 to 10^{-6}) represents 8 orders of magnitude, which is 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 a 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 $0.1 / 10^{(40\% \times 8)} = 0.1 / 10^{3.2} = 6.3E-5$. 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.

5.5 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 1×10^{-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.

5.6 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.

<u>OR Gates</u>
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:

$$P = 1 - [(1-P_1) * (1-P_2) * (1-P_3) * \ldots * (1-P_i)]$$

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.

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

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).

$$\begin{aligned} \text{Mitigation \%} &= M_1 \text{ OR } M_2 \text{ OR } M_3 \ldots.. \\ &= 1 - [(1-M_1) * (1-M_2) * (1-M_3) * \ldots * (1-M_i)] \\ &= 1 - [(1-0.40) * (1-0.10) * (1-0.05)] \\ &= 49\% \end{aligned}$$

or examining this from a different perspective,

Mitigation % = 1 – [remaining threat]
Where
[remaining threat] = [(remnant from M_1) AND (remnant from M_2) AND (remnant from M_3)] …

<u>AND Gates</u>
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 ~40% (0.8 x 0.8 x 0.8 x 0.8) using straight multiplication.

6. Probability of Failure

The most compelling definition of probability is "degree of belief." When we speak of the probability of a pipeline failure, we are expressing our 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, i.e. 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.

6.1 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. 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, rupture estimates, etc) or with simple approximations (% of Barlow-required pipe wall 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 is noted elsewhere in this document, 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. While the ASME reference categorizes these last as 'random' failure mechanisms, they are really potential weaknesses, not failure mechanisms. In the modeling approach recommended here, 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 6.1-1 Failure Mechanism Categories

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

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

$$PoF_{\text{time-indep}} = [\text{unmitigated event frequency}] / 10^{[\text{threat reduction}]}$$

where

[threat reduction] = *f* (mitigation, resistance)

$$PoF_{\text{time-dep}} = f(\text{TTF})$$

where

TTF = "time to failure"

= (available pipe wall) / [(wall loss rate) x (1 – mitigation)]

And then:

$$PoF = f(PoF_{\text{time-indep}}, PoF_{\text{time-dep}})$$

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

6.2 From TTF to PoF

The PoF is normally calculated as the chance of one or more failures in a given time period. In the case of time-dependent failure mechanisms, TTF estimates are produced. 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 TTF estimate is expressed in time units and is calculated by using the estimated pipe wall degradation rate and the theoretical pipe wall thickness and strength, as was shown above. In order to combine the TTF with PoF from all other failure mechanisms, it is necessary to express the time-dependent failure potential as PoF. This requires a conversion of TTF to PoF. It is initially tempting to use the reciprocal of this days-to-failure number as a leak rate—failures per time period. For instance, 5 years to failure implies a failure rate of once every five years or 0.20 failures per year. However, a logical examination of the TTF estimate shows that it is not really predicting a uniform failure 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. Nonetheless, use of a uniform failure rate is conservative and helps overcome potential difficulties in expressing degradation rate in probabilistic terms. This is discussed later.

An exponential relationship can be used to show the relationship between PoF in year one and TTF. A recommended relationship to use at least in the early stages of the risk assessment is:

PoF = 1-EXP(-1/ TTF)
where
PoF = probability of failure per mile (or km) in year one

This relationship produces a smooth curve that never exceeds PoF = 1.0 (100%), but produces a fairly uniform probability estimate, inversely proportional to TTF, until TTF is below about 5 years (i.e., a 20 yr TTF produces ~5% PoF). As noted, 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.

The relationship between TTF and PoF includes segment length as a consideration. PoF logically increases as segment length increases since a longer length logically means more opportunity for active failure mechanisms, more uncertainty about variables, and more opportunities for deviation from estimated degradation rates.

6.3 Role of Inspection and Testing

Inspection and testing plays a significant role in pipeline failure potential. An operator will often have several pieces of information, differing in age and accuracy, for a single pipeline location. For example, he will often know the date and pressure level of the last pressure test, results and accuracy of the latest ILI, and perhaps also non-destructive evaluation (NDE) measurements taken from bell hole examinations over the years. The challenge is to integrate all of these and extract the most information from the data.

The model makes a distinction between inspection results that produce measurements of damage and those that produce measurements of damage rate. The former shows where a previously active damage rate has resulted in damage such as metal loss or cracks. The latter provides an estimate of currently active damage rates—a metal loss rate or crack growth rate. Both measurements are derived from inspections of various types, but they are used differently in the model. The use of this information in the model should mirror the deliberations of a SME. In other words, the model is designed to arrive at the same conclusions that would emerge from an SME studying the same information.

Damages are quantified as either metal loss—depth and/or volume of metal loss from internal and external corrosion—or cracking—depth and shape characteristics of cracks. Damages are obtained from any or all of the following sources:

- Measurements from ILI;
- Measurements from NDE (including simple visual investigations); and/or
- Other (such as inferential results drawn from corrosion coupons, probes, analyses of pigging effluents, and other sources).

Actual measurements of damage should override damage estimates that were derived from indirect data. In the absence of actual measurements, estimates of damage are produced by taking the most recent measurement and then applying the estimated damage rate for the period since the measurement was taken.

Damage *rates* for internal corrosion, external corrosion, and cracking are used to estimate the remaining service life and PoF of a pipeline segment. As with damage estimates, each of these damage mechanisms can have rate estimates based on any or all of the following:

- Calculations based on ILI measurements
- Calculations based on NDE measurements
- Inferential information from pressure testing
- Other (such as from corrosion coupons, probes, analyses of pigging effluents, and other sources)

This damage rate is applied to the segment from the time of the last damage measurement until the time of the risk assessment. It is also used to forecast future conditions.

Each measurement—for either damage or damage rate—carries its own accuracy, age, and confidence level. Accuracy involves the potential error band of the tool itself, but also potential for operator-, procedural-, and other inaccuracies. Confidence level should be based not only on the accuracy and age of the measurement but also the location relevance. In some instances, but not all, a nearby measurement may provide some information for the pipeline segment being evaluated. All of these aspects must be considered when making conclusions about current conditions. For instance, a highly accurate NDE taken 3 years ago might yield as much information about current conditions as a less accurate ILI performed one year ago. By conservatively considering all the aspects that make up a SME's confidence in a measurement, the measurements are made to be equivalent. Once made equivalent, the model can legitimately use the smallest damage rate.

A new integrity inspection can "reset the clock" by overriding older and/or less accurate data. This is the value of inspection or testing: obtaining new information that leads to a better estimate of current pipe integrity. As an added 'bonus' in this approach to integrating various inspection techniques, a cost-benefit to various inspections can be easily created. This allows comparisons of highly-accurate, but potentially more expensive, inspection options with lower-accuracy but inexpensive options. In the case of indirect measurements such as certain ILI techniques, the follow-up protocols must also be considered in assessing the accuracy of the inspection.

See Section 9 for examples of direct integration of inspection and testing data into a risk assessment.

7. 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:

Pipe Wall Degradation Rate for time-dependent mechanisms

- External corrosion,
- Internal corrosion,
- Fatigue, and
- SCC.

Events per length-time (mile-year, for instance) for time independent / random mechanism

- third party
- incorrect operations
- weather
- land movements (geohazards)
- equipment failures
- theft/sabotage

7.1 Exposure as MPY (Pipe Wall Degradation Rate)

For time-dependent threats, each segment of pipeline can have varying degrees of exposure to each of the time-dependent mechanisms such as:

- External corrosion,
- Internal corrosion,
- Fatigue cracking, and/or
- SCC.

These exposures can potentially cause a damage rate—a rate of pipe wall loss or crack growth through the pipe wall. The exposure from each threat, whether producing a corrosion or cracking damage rate, is measured in mils per year where 1 mil = $1/1000^{th}$ of an inch. Note that an important distinction is being made between *damage* and *damage rate*. This discussion centers on damage rate. Damage—the amount of pipe wall lost due to previously active damage rates—is the focus of the discussion on "effective pipe wall."

In the case of corrosion, the pipe metal's reaction to its environment establishes a rate for metal loss by corrosion. 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 the metric commonly used by corrosion control experts and can refer to pitting—a more aggressive and localized damage—or general corrosion 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.

MPY can also be used to measure crack growth rates if some simplifying assumptions are used. Crack propagation is a very complex mechanism. To fully estimate cracking potential, concepts of fracture mechanics must be applied, including possible presence of defects, characteristics 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 a consistent rate of damage. This is normally not the case in reality. Both corrosion and cracking are known to exhibit a relatively wide range of rates even when all conditions appear to be unchanging. Allowances for more aggressive, shorter duration damage rates might be warranted for certain modeling applications.

Unless additional details are incorporated into the model, the potential mpy rate applies to every square centimeter of a pipe segment—the degradation could be occurring everywhere simultaneously. 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.

7.1.1 Probability of MPY

Exposure can be thought of as the *probability* of a certain damage rate. The unmitigated exposure—from soil as an electrolyte, in the case of buried pipeline—is assumed to be fairly uniform at a given location. It is considered to be the baseline damage rate. Whether or not the baseline damage rate is actually causing pipe damage depends on mitigation effectiveness. Where there is no mitigation, the exposure is 100% of the base rate. Where mitigation reduces the likelihood of the damage rate occurring, the damage rate is modeled to be less. The premise is that a 10% chance of 100 mpy damage rate is equivalent to a 10 mpy damage rate. The usefulness of this simplification and possible ramifications to the assumption are discussed here. The user should satisfy himself that a probability-weighted mpy is a valid modeling approach for his needs.

The rationalization that a probability of a baseline damage rate can be modeled as a constant damage rate equivalent to the probability multiplied by the baseline damage rate, can be examined through an example. Suppose that there is an estimate of a 10% chance of a 50 mpy annual damage rate. Further, suppose that a loss of 50 mils results in failure. Is this essentially the same as a 5 mpy damage rate?

In the original expression, 10% chance of 50 mpy, there is a 10% chance of a failure after 1 year which implies failure every 10 years or 0.1 failures per year. In the second expression, assuming a constant 5 mpy damage rate, a failure-causing loss of 50 mils requires 50 mils/5 mpy = 10 years suggesting failure after 10 years or 0.10 failures per year. Both calculations appear to produce the same TTF and failure frequency using such simplifying calculations.

In reality though, conceptual complications arise . In the case of a constant 5 mpy, there would be an extremely low probability of failure in the first years since damages would not have accumulated to the point where failure could occur. As a matter of fact, failure is forecast only in year 10. However, in the case of 10% chance of 50 mpy, there is a real chance of failure in early years. If the 50 mpy does occur in year one or year two, then failure would occur in those years.

The complications are avoided and the simplifying rationalization can be used if a conservative translation between the TTF and failure rate (or PoF) is used. When the PoF is modeled as being essentially inversely proportional to TTF, then the probability-adjusted, constant mpy will always produce a PoF that is equivalent to the probability-of-the-baseline-mpy PoF. Leak rate = 1/TTF captures this relationship. Leak rate is essentially equivalent to PoF so long as leak rate values are small. However, when TTF is less than one, the leak rate is greater than one and no longer represents PoF. The exponential relationship previously suggested, PoF = 1-EXP(-1/ TTF), is consistent with a commonly assumed relationships between leak rate and PoF (see discussion later in this document), avoids the complication with small TTF values, and allows PoF to derive directly from TTF.

7.2 Exposure as 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.

7.2.1 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

Expressing beliefs in numbers requires a change in mindset for some. It is common to hear that something will "never" happen or that steps must be taken to ensure a certain event is "practically impossible." Do such terms suggest "once every 100 years"? Once every million years? Or even lower frequencies? Assigning numbers to these qualitative terms removes the emotionalism and makes the term real. In order to help anchor all exposure estimates, a guidance chart can be used:

Table 7.2.1-1. Exposure Levels

Failures/yr	Years to Fail	Approximate Rule Thumb
1,000,000	0.000001	Continuous failures
100,000	0.00001	fails ~10 times per hour
10,000	0.0001	fails ~1 times per hour
1,000	0.001	fails ~3 times per day
100	0.01	fails ~2 times per week
10	0.1	fails ~1 times per month
1	1	fails ~1 times per year

0.1	10	fails ~1 per 10 years
0.01	100	fails ~1 per 100 years
0.001	1,000	fails ~1 per 1000 years
0.0001	10,000	fails ~1 per 10,000 years
0.00001	100,000	fails ~1 per 100,000 years
0.000001	1,000,000	One in a million chance of failure
0.0000000001	1,000,000,000	Effectively, it never fails

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.

8. Mitigation

Threat reduction occurs either through reducing the exposure to the threat—mitigation—or reducing the failure likelihood in the face of threats—resistance. An underlying premise in assigning values, is that mitigation and resistance can work together to offset much of the threat exposure, thereby reducing the PoF. In this section, mitigation is discussed.

In this model, a percentage is assigned to a mitigation measure that reflects its possible effectiveness in 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 as degradation rate) x (1-mitigation)
- For time-independent mechanisms: (exposure as event frequency) / $10^{[\text{mitigation}]}$

As noted in the discussion of "orders of magnitude," 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.

8.1 Mitigation of Time-Dependent Failure Mechanisms

For time-dependent mechanisms such as corrosion and fatigue, mitigation is a direct reduction in exposure. Recall that exposure for these mechanisms is measured as a degradation rate in units of mpy. Since the previously-estimated exposure is a constant or baseline threat, it is the mitigation estimate that introduces the probabilistic component required for PoF estimates. For instance, baseline exposure might be estimated to be 12 mpy, but the effects of mitigation lead to a conclusion that there is only a 20% chance of that 12 mpy damage actually occurring on the pipeline segment. This is equivalent to a 2.4 mpy damage rate, as was shown in the discussion of exposure.

8.1.1 External Corrosion

Common mitigation measures for external corrosion include coating and application of cathodic protection (CP). These two are usually employed in parallel and provide redundant protection. 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.

8.1.1.1 Coating Effectiveness

Coating is designed primarily to provide a barrier to the electrolyte. Therefore, discounting its role in supporting CP, coating effectiveness is appropriately assessed in terms of its barrier effectiveness or defect rate.

In the absence of good coating defect rate information for a particular pipeline, the rate can be inferred by using some general corrosion failure rates. For instance, based roughly on US DOT failure statistics, assume that the overall failure rate of a subject pipeline is 0.001 failures per mile-year. Next, assume that 30% of these failures are due to corrosion. Finally, assume that for each corrosion failure, there are 100 coating failures that are protected by CP (so, only one out of every 100 coating defects leads to a failure). Using several representative pipe diameters, this leads to coating failure rates on the order of 1 per million square feet. With several key assumptions, this suggests that an "average" coating has a failure rate on the order of 10E-6 per square foot per year. Perhaps poor coatings are several orders of magnitude worse and superior coatings are several orders of magnitude better. A scale from these very rough assumptions can be generated and is illustrated below

Table 8.1.1.1-1 Sample Linkage of Coating Descriptors to Coating Defect Rates

Coating Evaluation	Assumed % Effectiveness of Coating	Defect Rate Implied by % Effectiveness	Score	Estimated Defect Rate from Calculation (per sq ft per year)
excellent	0.9999999	1E-07	0.9	5.01E-07
good	0.99999	1E-05	0.8	2.51E-06
fair	0.99	0.01	0.5	0.000316
poor	0.9	0.1	0.2	0.039811
absent	0	1	-1	1

By observation, a score is assigned to each qualitative descriptor to be used in a simplifying formula. This links the descriptor—perhaps carried over from a previous risk assessment—to a defect rate implied by that descriptor. The values in the last columns are then calculated using the initial coating score and the simple formula:

$$PoD = 10^{([\text{coating score}]x(-7))}$$

Where

PoD = probability of defect per square foot per year.

[coating score] = assigned value of coating effectiveness based on current condition description, scaled from -1 to 1.0 with 1.0 being a nearly perfect coating (defect rate of one every 10^7 or 10,000,000 square feet).

This is obviously a very coarse assessment and should be replaced by better knowledge of the specific pipeline being evaluated.

To better visualize the implications of this simple relationship, yields the following 'defect rate estimates' for a sample pipe diameter of 12". For various lengths of the 12" pipe, the probability of a defect is estimated. This can then be used to help validate and tune the coating assessment protocols since records and/or SME's can often relate actual experiences with a particular coating to such defect rates.

Table 8.1.1.1-2 Visualizing Coating Defect Rates

Coating Score	**Defect Rate per sq ft per year**	**Probability of Defect in Segment, per year for varying lengths of 12" pipe, (L = ft of length)**				
		L = 1	L = 10	L = 100	L = 1000	L = 5280
excellent	5.0E-07	0.00%	0.00%	0.02%	0.16%	0.83%
good	2.5E-06	0.00%	0.02%	0.18%	1.75%	8.91%
fair	3.2E-04	2.46%	22.1%	91.8%	99%	100%
poor	4.0E-02	11.8%	71.4%	100%	100%	100%
absent	1.0E+07	100%	100%	100%	100%	100%

In the above table, a mile of "good" coating has about a 9% chance of having at least one defect. A 'fair' coating under this system is almost certain to have at least one defect every 1000 ft. These results might seem reasonable for a specific pipeline's coating. They show that the probability of a coating defect is proportional to both the quality of coating and the length of the segment (length as a surrogate for surface area of the segment). If the results are not consistent with expert judgment—perhaps ratings for "fair" are too severe, for instance—then the modeler can simply modify the equation that relates coating score to defect rate.

Of course, this model is using many assumptions that might not be reasonable for many pipelines. In addition to the highly arguable initial assumptions, many complications of reality are ignored, including:

- Coatings fail in many different ways;
- The meaning of coating "failure" (shielding vs increased conductance vs. holiday etc); and
- The failure rates of pipelines (DOT data includes all ages, types, conditions, environments, etc, of coatings).

Nonetheless, these assignments of PoD capture the perceived relationship between coating quality and surface area in estimating probability of coating damage or defect. Note that in this application, the probability of a defect diminishes rapidly with diminishing segment length. As segments are combined to show PoF along longer stretches of the pipeline, the small PoD's must be preserved (and not rounded to 0.0). The modeler should be cautious that, through length-reduction and rounding, the probabilities are not lost.

8.1.1.2 CP Effectiveness

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. This is fully discussed elsewhere in the text.

For purposes of this model, CP effectiveness is expressed as a reliability rate in protecting steel beneath coating defects. The factors used to judge CP effectiveness therefore should produce an estimate of how many coating defects have been compensated by CP or, phrased another way, "How many of the coating defect areas will experience the mpy exposure rate because the CP has failed to protect the pipe?" The specifics of estimating the CP effectiveness rate are discussed elsewhere.

8.1.1.3 Combining Coating and CP

The following example illustrates the process of estimating external corrosion mitigation effectiveness. With an assumed coating defect rate of 0.005 (5 defects per 1,000 square feet of coating), and 17, 623 ft^2 of coated pipe surface area, the expectation is for a coating defect count of 88 per linear mile of pipeline. If CP effectiveness is judged to fully address 999 out of every 1000 coating defects, then the frequency of corroding defects is 0.09 per mile or one episode of corrosion every 1/0.09 = 11.3 miles or 9% chance of one or more corroding locations. Under the premise that, mathematically, a 9% chance of a corrosion rate occurring anywhere is the same as corrosion occurring everywhere at 9% of that rate, then the mitigation effectiveness is 1 – 0.9 = 91% and the mitigated external corrosion rate is modeled to be 91% less than the unmitigated corrosion rate.

The key variables and calculations results from the above example are shown in the table below.

Table 8.1.1.3-1 Example of Results of Coating-CP Mitigation Effectiveness

Attribute	Effectiveness
Coating defect rate per 1,000 ft^2	0.005
Total ft2 of pipe surface area	17623
Resultant number of defects per mile of pipeline	88.1
Number of CP failures per coating defect	0.001
Resultant number of unprotected coating defects per mile	0.0881
Final mitigation effectiveness against external corrosion	91.2%

*UNITS?

Recall that the degradation rates in this model are actually probabilistic estimates of damage rates—the baseline damage rate and the probability of that damage rate being experienced by the pipe. As an example of the relationship between coating PoD and CP effectiveness, consider the analysis shown in Table 8.1.1.3-2.

Table 8.1.1.3-24 CP Compensating for Coating Defects

Coating Condition	Coating Defect Type	Prob of Defect Type per sq ft	Is CP fully eff?	Prob of CP protecting pipe	Scenario Prob	Resultant MPY
excellent	none	99.9%	Y	0.9	89.9%	0
			N	0.1	10.0%	0
	hole	0.1%	Y	0.9	0.072%	0
			N	0.1	0.008%	16
	shielding	0.0%	Y	0.9	0.018%	0
			N	0.1	0.002%	16
Final probability of 16 mpy damage rate per sq ft					0.010%	16
Final probability of 0 mpy damage rate per sq ft					99.99%	0

The column "Scenario Prob" shows the estimated probability of the corrosion rate shown in the "MPY" column. Adding up all events that result in 16 mpy shows that there is a 0.010% of 16 mpy. There is also a 99.99% chance of 0 mpy corrosion. This simple analysis shows that the "excellent" coating, coupled with 90% effective CP, results in a 0.01% chance of 16 mpy damage rate per square foot of pipe. So, every 1,000 square feet of pipe has a mitigated exposure of 1,000 ft^2 x (0.01% / ft^2) x 16 mpy = 1.6 mpy. This value is then used for TTF estimates, leading to estimates of PoF for external corrosion.

8.1.2 Other Time-Dependent Mitigations

See discussions in text.

8.2 Mitigation of Time-Independent Failure Mechanisms

For time-independent mechanisms such as third party damage, incorrect operations, and geohazards, mitigation is modeled as a reduction in exposure. Recall that for these mechanisms, exposure is measured in events per length of pipe, per time period and will usually span several orders of magnitude. Therefore, mitigation will also span orders of magnitude. For instance, a very effective mitigation might reduce event frequency from 10 times per year to once every 100 years.

Discussion of mitigation for specific time-independent failure mechanisms is shown in a subsequent section of this document.

9. 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.

Inspection and testing provide essential input into estimations of a pipeline's ability to resist failure. Section 6.3 discusses how integrity assessment data of varying ages and accuracies can be integrated. This section continues that discussion and suggests an overall methodology to assessing resistance.

9.1 Current Pipe Strength

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.

Current 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 factors 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 and avoid the need for iterative analyses (such as Monte Carlo type simulations) sometimes seen 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.

9.2 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. The challenge lies in determining what information tells us the most about the pipe condition today. A coarse measurement of wall thickness, taken recently, can be more valuable than a very precise measurement taken long ago. Every piece of direct or indirect data might yield the most useful knowledge. Therefore, all of the following should be incorporated:

- Pipe specification;
- Last measured wall thickness;
- Detection capabilities of last wall measurements, including data analyses and confirmatory digs in the case of ILI;
- Age of last measured wall thickness;
- Wall thickness "measured" (implied) by last pressure test;
- Maximum depth of a defect surviving at 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 normal operating pressure (NOP) or last known pressure peak; and
- strength-reduction ""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 usually know at least:

1. That the pipe has integrity 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.

9.3 Procedure to Estimate Resistance

The steps required in the model's time-dependent failure mechanism analysis may initially appear to be daunting. However, they are actually very intuitive and leave a trail of very useful information:

1. <u>NOP-based wall</u>: Produce an estimated wall thickness, based on leak-free operation at current NOP (if that assumption is defensible). This may include an estimate of the deepest non-leaking defect that could be present at this pressure.
2. <u>Pressure test based wall</u>: Calculate a pipe wall thickness inferred by 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. <u>Inspection based wall</u>: 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. It will sometimes be prudent to model different defect types since detection sensitivities vary (see Table 7.5.3-1).
4. <u>Exposure</u>: 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. <u>Mitigation</u>: 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. <u>Estimated pipe wall</u>: 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.

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 used to estimate resistance to failure follow.

9.3.1 NOP-Based Wall

This is the entry point into the effective pipe wall estimate. The wall thickness implied by leak-free operation at normal operating pressure (NOP) can be calculated by simply using a hoop stress calculation 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. Since countless defect geometries are possible, assumptions are required.

With assumptions, the implied wall thickness based solely on operating leak-free at NOP, pipe_wall_NOP, can be calculated as follows:

pipe_wall_NOP = ([NOP]*[Diameter]/(2*[SMYS]*1000) - (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.

Of course, the estimate of pipe_wall_NOP pre-supposes that the portion of pipe being evaluated is indeed not leaking and is exposed to the assumed NOP.

9.3.2 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.

9.3.3 Inspection-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 just below the detection capability of the assessment. 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 9.3-1, below.

Table 9.3.3. IIC Benefit Matrix

Inspection Type	Validation (Pig-Digs) Protocol	Defect Type, max surviving defect size as % of wall thickness							Max Surviving Defect	
		External Corrosion	Internal Corrosion	Axial Crack	Circum Crack	Dent/ Gouge	Ovality/ Buckling	Laminations	Metal Loss	Crack
MFL high resolution	Aggressive	5	5	100	10	20	50	50	5	100
	Routine	10	10	100	50	50	50	50	10	100
	Min	15	15	100	100	50	50	50	15	100
MFL std resolution	Aggressive	10	10	100	50	50	50	50	10	100
	Routine	15	15	100	100	50	50	50	15	100
	Min	20	20	100	100	50	50	50	20	100
Ultrasound		5	5	100	100	20	20	5	5	100
TFI		20	20	5	10	50	50	50	20	5
EMAT		50	50	10	10	50	50	10	50	10
Ultrasound shear wave crack tool		50	50	10	10	50	50	10	50	10
Caliper, sizing, gauging, inertial		100	100	100	100	5	5	100	100	100
Pressure test		5	5	5	5	2	2	2	5	5

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.

9.3.4 Estimated Pipe Wall

The estimated pipe wall reflects the best estimate of how much metal is present and available to resist failure. This model assumes that a defect just below detection threshold exists, with "just below detection threshold" estimated using a hoop stress calculation assuming a relatively long length. 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).

9.3.5 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 15 year old, non-leaking pipeline segment has a nominal wall thickness of 0.320" after accounting for the manufacturing tolerance of 12.5%. The Barlow hoop stress 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. A calculation can be done to estimate today's wall thickness based degradation since original installation. Since it has been 15 years since construction, the calculated pipe wall is 0.320" – (15 years) x (10 mpy) x (1 inch / 1000 mils) = 0.170". The minimum wall implied by NOP is higher, so the current estimate of pipe wall thickness is 0.210".

A high resolution MFL ILI tool with routine confirmation excavations (follow-up) is subsequently 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,. The assessment measures 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. 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 (sensitive to presence of cracks) 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 should use the crack-adjusted value of 0.240". This is then adjusted for possible metal weaknesses to get effective pipe wall which can be used to estimate the ability of the pipe to withstand other threats such as external forces.

Without the ILI, the pipe wall would have been assumed to be 0.210". So, the ILI improved the risk picture by removing some uncertainty. This was done by a direct metal loss measurement and an adjustment for possible cracking. The ILI information also may prompt 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.

In both of these examples, extreme cases of defects left behind after integrity assessment are possible. The user might wish to include additional conservatism by allowing for the possibilities of such defects. Note that both examples concluded much less pipe wall than nominal wall thickness. This will often be sufficient conservatism.

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 9.3.5-1. Data for Example 3

Segment Number	OD (in)	Nominal Wall (in)	Grade	SMYS for Max Press Calc (psi)	SMYS for Min Wall Remain (psi)
100	30.625	0.320	?	24000 (default)	52000
106	30	0.374	X52	52000	52000

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 a 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 nominal 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 9.3.5-2. Data for Example 3

Segment Number	Press Test Min Wall (psig)	Max Op Press Min Wall (in)	Max Calc P (psig)	Min Wall for NOP (in)	Max Defect Depth Surviving at NOP (in)	PoF
100	0	0.103	502	0.077	0.0530	6.8%
106	0	0.101	1297	0.075	0.0545	7.3%

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.

9.3.6 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 (using "leak" criteria; "rupture" criteria might predict failure with less wall loss, depending on defect size assumptions). 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.

10. Time Independent Failure Mechanisms

A general discussion of PoF assessment for some time-independent failure mechanisms is offered here. As previously noted, the underlying form of this calculation is as follows:

PoF = [unmitigated event frequency] / $10^{[\text{threat reduction}]}$
Where
[threat reduction] = *f*(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 failure 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 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.

10.1 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.

<u>Exposure</u>
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, and 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.

10.1.1 Mitigation

Mitigation = f(cover, patrol, one-call, damage prevention program, ROW condition, signs/markers, 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.

10.1.2 Resistance

Resistance = f(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.

10.2 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.

10.2.1 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 require 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.

10.2.2 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.

10.2.3 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.

10.3 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.

10.3.1 Exposure

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

Exposure = [geotech] + [hydrotech] + [seismic]

> Where:
>
> Geotech = [landslide probability] * [landslide severity]
>
> Hydrotech = [erosion]+[subsidence]+[buoyancy]+[flood-bank erosion]+[flood-undercut]+[debris loadings]
>
> Seismic = [fault] + [liquefaction]
>
> > Fault = expected failure rate due to fault actions
> >
> > Liquefaction = [peak ground acceleration (PGA)] * [soil suscept]

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.

10.3.2 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.

10.3.3 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.

11. 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 = [(f *t)^X / X !] * exp (- f * 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(probability of one or more)EVENT = 1 – Probability of no spills
= 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.

$$PoF = f(PoF_{\text{time-indep}}, PoF_{\text{time-dep}})$$

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 <u>any</u> 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:

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

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.

12. Calibration and Validation

Users should be vigilant against becoming too confident in using any risk model output without initial and periodic 'reality checks'. Especially when risk output is expressed in numbers that appear to be very precise, it is easy to fall into what has been termed 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 multiple times in any year. Decision-making should recognize this at all times.

12.1 Calibration vs. 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% <u>annual</u> 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 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.

A risk assessment model producing estimates of absolute risks—events or costs per pipeline length and per time period—is calibrated or "tuned" to produce results that are consistent with beliefs about the real failure probabilities. Such beliefs are normally based on historical experience, tempered by knowledge of changing factors. The process of calibrating risk assessment results begins with establishing plausible future leak rates based on relevant historical experience. These rates become 'targets' for risk assessment outputs, with the belief that large populations of pipeline segments, over long periods of time, would have their overall failure estimates approach these targets. The risk assessment model is then adjusted so that its outputs do indeed approximate the target values.

12.2 Use of Incident History

Incident history is one of the important pieces of evidence to consider when both validating and 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 incident's "penalty" in the risk assessment 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.

12.3 SME Validation

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. A good objective of risk assessment 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.

12.4 Diagnosing Disconnects Between Results and Reality

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.

Point Estimates

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.

Enhanced Pipeline Risk Assessment

Part 2— Assessments of Pipeline Failure Consequences
Revision 2

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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.

This material represents ideas and possible approaches to problem-solving that may or may not be appropriate in certain situations and applications. The user of this material is strongly urged to exercise careful judgment in the use of all information presented here. Author provides no guarantee, expressed or implied, with regard to the general or specific application of this information. The user accepts all liability in any and all applications of any material taken from this document.

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1. Introduction

Understanding and quantifying potential consequences from a pipeline failure[1] is a challenging undertaking. Estimates of potential consequences must address the questions:

- What can be harmed by a pipeline failure?
- How badly is it likely to be harmed?

The variables that will fully answer these questions include specifics of and interactions among receptors, product, spill size, and dispersion. Even though receptor dose-response analyses and other aspects of epidemiology and toxicology are generally not warranted for pipeline products, the problem remains quite complex.

Since there are an infinite number of combinations of receptors interacting with an infinite number of spill scenarios, the range of possibilities is literally infinite. So, all consequence estimations will include some simplifications and assumptions in order to make the solution process manageable. Lower level models tend to model only worst-case scenarios, disregarding the normally very low probability of such scenarios actually occurring. Higher-level models will characterize the range of possibilities, perhaps even producing a distribution to represent all possible scenarios.

To quantify consequence, a choice of some measurable level of harm or damage is first required. Fatalities or dollar values are common measures. Alternatively, one could choose an effect such as thermal radiation level or overpressure level, which in turn implies a certain possible range of damages. This is discussed in the "Threshold" section below (page 11).

As with PoF (probability of failure), the designer of the CoF (consequences of failure) 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 ignoring less significant information. By identifying more critical variables and taking advantage of some modeling conveniences, the following structure is offered as one possible assessment approach that is both manageable and robust enough to be a serious decision-support tool.

The enhancements recommended here improve upon consequence assessments typically associated with scoring or indexing risk assessments. The main enhancements are:

1 Characterize the range of consequence scenarios, including their respective probabilities of occurrence, rather than basing the assessment on a point estimate like "worst case."

2 Use of hazard zones and their associated probabilities of occurrence as a key ingredient in the assessment.

3 Characterize receptors and their potential damage rates within hazard zones.

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[1] For purposes here, "failure" is defined as the unintended loss of pipeline contents.

2. Scope

Especially in the case of a more detailed assessment, an infinite number of consequence scenario permutations are possible. Since it is impractical to model all possible permutations of consequence scenarios, some narrowing of focus and modeling “short cuts” are needed. Even a higher-level screening can become enormously complex even when only considering a few variables. The intent of narrowing the focus is to produce a manageable number of scenarios that fairly represent the range of possibilities.

Before scenarios are generated, an overall scope of the consequence assessment must be established. Defining this scope includes:

1 Specifying the consequences of interest—what kinds of receptors and what kinds of potential damages are to be measured.

2 Specifying the range of products and pipeline size-pressures to model.

3 Specifying the units of measure—relative consequences or specific damage states or expressions of “expected loss” in monetary units per time period.

4 Specifying the rigor of the analysis—very detailed with numerous permutations vs high level screening.

Consider two examples illustrating the range of possible scope complexities.

<u>Scoping Example 1</u>
As an example of a rather narrow scope, the modeler of a natural gas transmission pipeline system might determine his extent of pipeline consequence assessment to be as follows:

- Consequences of interest: potential thermally-related damages (fire and fire effects) to humans, including injuries and fatalities. Property damages will be considered to be proportional to injury potential.
- Systems to be included: dry, sweet, natural gas only, diameters ranging from 6” to 36” and pressures up to 1480 psig.
- Units are to be relative only—risk values are meaningful only in the context of other risk values obtained by the same measuring process. An “absolute” measure of risk is not needed.
- Analyses should be sufficient for regulatory compliance and segment ranking only—no monetizing of consequences is needed.

This scope should lead the modeler to a relatively narrow range of consequence potential, perhaps focusing solely on worst-case scenarios. Meeting this scope could entail the establishment of only one hazard zone—for example, the US regulatory potential impact radius (PIR) based on pressure and diameter—with some minimal characterization of receptors within that hazard zone.

Scoping Example 2
As an example of the other end of the range of scoping possibilities, consider the following consequence assessment specification.

- Consequences of interest: all potential damages from thermal effects, overpressure potential, and contamination (toxic) effects to
  - The public, including human injuries and fatalities;
  - Property;
  - Environment; and
  - Damages associated with loss of supply including business interruption costs.

- Systems to be included: transmission lines carrying dry, sweet, natural gas, sour gas (H_2S), ethane, butane, propane, gasoline, and crude oils; distribution and gathering lines carrying low pressure natural gas, diameters ranging from 2" to 40" and pressures from 15 psig up to 1480 psig.

- Units are to have the potential for expressing results in absolute terms of dollars per mile year, where all potential consequences are valued in dollars.

- Analyses should be robust enough that produced values can be relied upon for financial decision-making. This will encompass and exceed requirements for regulatory compliance.

This scope should lead the modeler to develop multiple appropriate scenarios with fairly detailed considerations of receptor proximities and characteristics.

The following discussions focus on this latter example—a more robust scope of assessment—since it requires a more challenging model development. The first example can be considered a subset of the second, making this discussion pertinent to that type model also.

2.1 Simplified Relative Consequences

In some cases, a measure of relative consequences is the only metric needed. For those, there is normally not a need to calibrate or tune the relative consequence results to actual consequences measured in dollars or other "cost" units.

To create a simple, relative consequence model, the key aspects of consequences can be combined in a simple multiplication. The main components of the assessment can be:

LIF = PH x R x S x D
where
LIF = Leak Impact Factor, comprised of
Product hazard (PH),
Receptors (R),
Spill volume (S), and
Spread range or dispersion (D).

This equation shows that if any one of the four components is zero, then the consequence, and the risk, is zero. Therefore, if the product is absolutely non-hazardous (including pressurization effects), there is no risk. If the spill volume or dispersion is zero, either from "no leak" or from some type of secondary containment, then there is no risk. Similarly, if there are no receptors (human or environmental or property value) to be endangered from a leak, then there is no risk. As each component increases, the consequence and overall risk increases.

This relative model is discussed in greater detail elsewhere.

Another simplified consequence relationship is proposed by Reference 3 as an extension to the now familiar potential impact radius (PIR) calculation used in U.S. DOT regulations for natural gas. With consequences measured solely by human injury/fatality potential, the number of people potentially affected by a release of a flammable gas is shown to be a function of:

- The area impacted (A),
- The probability of ignition, and
- The population density (Pop).

The area impacted is shown to be proportional to pressure (P) and diameter (D) of the pipe (the PIR calculation), $A \sim PD^2$. The ignition probability is assumed to be loosely proportional to diameter. So the final relationship can be simplified to something like:

$$\text{Consequence} = \text{Fctr} \times \text{Pop} \times PD^3$$

Where:

Fctr = a calibration factor, set by experience or desire for results within a certain numerical range
Pop = measure of relative population density, unitless
P = relative pressure, unitless
D= relative diameter, unitless

As with the previous equation, this produces a relative measure of CoF for potential direct harm to humans.

These and other simple relationships can be a useful screening tool or even the basis of all CoF considerations. Increasingly, however, practitioners of pipeline risk assessment recognize the need for more complete and discriminating ways to model risks.

2.2 Probability (of Consequence) Distributions

A limitation in simpler approaches to consequence assessments is that the worst case scenario, no matter how improbable, is often the entire basis of the estimate. In reality, the vast majority of possible failure and consequence scenarios do not nearly approach the magnitude of the worst case. The full range of possibilities is best viewed as a frequency or probability distribution. Unfortunately, distributions are cumbersome to work with. Use of distribution graphs and FN curves (failure count or frequency (F) versus consequence, where consequences are often the possible number of fatalities (N)) show the range of possibilities and are powerful graphical tools. Such representations are more readily assimilated into decision-making when the curves are converted into point estimates that also capture the range of potential scenarios.

The suggestion here is to identify and combine the range of possible consequence scenarios, and their respective probabilities of occurrence, into an “expected loss” value, discussed in the next section. While the concept of expected loss is not a new concept in risk, especially in financial matters, it is perhaps unfamiliar to many who are beginning the practice of formal pipeline risk assessment.

One benefit of this approach is that, by simulating real probability distributions, most (if not all) possible scenarios will be bounded by the analysis. The analysis therefore captures the high-consequence-extremely-improbable scenarios; the low-consequence-higher-probability scenarios, and all variations between. It does this without overstating the influence of either end of the range of possibilities. The use of probabilities ensures that the influences of certain scenarios are not over- or under-impacting the results.

3. Measuring Risk as Expected Loss

In a more robust risk assessment—beyond relative results—potential consequence estimates are combined with the PoF estimates (see Part 1 of this paper series) to arrive at final risk estimates. This combination of probability and consequence is intended to fairly represent the risk. Risk can therefore be viewed as the amount of potential loss that has been created by the presence of the pipeline. Risk expressed in this fashion is called "expected loss" (EL). It encompasses the classical definition of risk: probability x consequences, but expresses risk as a probability of various potential consequences over time. Costs are a convenient common denominator for all types of losses, but monetizing losses is not without problems (see later discussion on receptors).

The phrase "expected loss" carries some emotionalism. It implies that a loss—including injuries, property damages, and perhaps even fatalities—is being forecast. This often leads to the question: "why not avoid this loss?" Most can understand that there is no escaping the fact that risks are present. Society embraces risk and even specifies tolerable risk levels through its regulatory policy-making and spending habits. EL is just a measure of that risk. Nonetheless, such terms should be used very carefully, if at all, in risk communications to less-technical audiences. This is more fully discussed elsewhere.

<u>CoF as a Part of EL Estimates</u>

As previously noted, the better CoF assessments will embody all possible consequences (losses) with their respective likelihoods. Theoretically, each possible consequence scenario cost is multiplied by a probability of occurrence to arrive at a probability-adjusted consequence cost (dollars) for each possible consequence scenario. For practical reasons, a subset of all possible scenarios is used to approximate the distribution of all possible scenarios. Characterizing the possible scenarios requires estimates, all along each pipeline, of the following:

1 Probabilities of various spill sizes,

2 Estimates of hazard zone distances associated with each spill size,

3 Characterization of receptors at various distances from the release, and

4 Costs or relative units representing the value associated with damages to the various receptors that may occur.

While this list is short, producing reasonable estimates for each item can be very challenging. When estimates from these aspects are combined, the results will represent probability and value (or "cost" measured in units such as dollars) of consequences.

Each point on a pipeline produces its own unique potential consequences and hence its own expected loss possibilities. Each point on each pipeline has a distribution of possible failure and consequence scenarios. Under this proposed methodology, this distribution of possible scenarios is expressed as a single point estimate—the expected loss at that point. The monetized CoF values represent point estimates of all possible consequence scenarios. These will be multiplied by point estimates of PoF at that location to obtain a risk value. Risk is therefore expressed as a cost over some time period—dollars per year, for instance, for a particular location. The time aspect arises from the probability of failure and probability of various consequence scenarios.

The individual expected values for all scenarios at all points along the pipeline can be combined to produce an expected loss for the entire pipeline. Multiple pipelines can have their EL's combined for a measure of the risk of an entire operation. The ability to aggregate risks in this way is a very powerful decision-support feature. EL values directly suggest levels of appropriate risk management actions, as will be discussed later.

Annualizing all potential consequences is another modeling convenience. The annualizing can however, obscure the fact that very large consequence scenarios are embedded in the expected loss. A $100,000 loss event that occurs once every 10 years is mathematically equivalent (with some simplifying assumptions) to an expected loss of $10,000 per year. In this representation, a uniform loss rate—the same dollar loss each period—is really not the expectation. However, the total expected losses over time are fairly represented by the average annual expectation. This presents some financial planning challenges when one considers that while the expected loss on an annualized basis might be acceptable to an organization, that cost might actually occur in a tremendous one-year event and then no costs for decades—no doubt a much less acceptable situation. Similarly, from a risk-tolerance perspective, a 10-year $100,000 event is usually quite different from an annual $10,000 event. While the mathematical equivalence is convenient, other considerations challenge the notion of equivalency and will need to be more fully explored in the more robust assessments.

In summary, the EL, as it is proposed here, will represent an average rate of loss from the combination of all loss scenarios at a specific location along a pipeline. An $11K/year EL may represents a $100K loss every ten years and an annual $1K loss ($100K / 10 yrs + $1K/yr = $11K/yr). It is therefore a point estimate representing a potentially wide range of potential consequences.

4. Hazard Zones

The CoF estimate needed for the EL calculation is best based upon potential hazard zones that might arise from a pipeline failure. A hazard zone is a geographical area in which certain spill/leak effects are expected. The effects can be expressed as a level of damage to a receptor—number of fatalities or injuries; fatality/injury rate; dollar damages to property; remediation costs to sensitive environment, etc—or as an effect—overpressure level; thermal radiation; direct flame impingement, etc. These are two types of effects are closely linked, as is discussed in a following section on thresholds.

The probability of a given hazard zone occurring is a function of the probability of the associated scenario occurring. The scenario probability is dependent upon the probabilities of failure, leak size, product dispersion, and ignition. The potential consequences from each scenario are dependent upon the receptors exposed. The probabilistic combination of all possible scenarios results in the risk—expressed as EL—as has been discussed in a previous section.

4.1 Receptors

As the term is used here, a "receptor" is anything that can be harmed by a pipeline release. Receptors include people, animals, vegetation, buildings, property, and even corporate reputation. Some possible receptor damages include: human fatality; human injury; property damage; environmental damage; and service interruption costs.

Setting receptor valuations is a challenging aspect of risk modeling. Estimating potential damages in real terms, however, mandates these valuations. Using a common measure such as dollars forces some difficult judgments to be made among various receptor damages. For example, not only must a value be assigned to human life, but also to environmental damage, damage to or extinction of a threatened and endangered species, irreparable contamination of a recreational or drinking water source, and any other potential consequence. Little guidance is offered here for some of these valuations since they involve many socio-political and even moral/ethical considerations that vary greatly among decision-makers and even over time from the same decision-maker. Note that the ability to express risk in monetary terms is a great advantage in many applications, justifying the effort required to produce receptor valuations.

Receptor sensitivities are another aspect that can be included in the model. Receptor damage is dependent upon the duration and intensity of the event, as well as receptors' vulnerability to the effects. Longer duration, higher intensity events cause the most damage; low intensity, short duration cause the least, and many possibilities exist between the extremes.

Valuations and sensitivities require certain information, even if captured as only simplifying assumptions. For each receptor, such as population, environment, drinking water, waterways, basic information needed for valuations includes:

- Receptor characterization (type of people, type of buildings, etc),

- Receptor density (units per area),
- Receptor vulnerabilities (susceptibility to harm, mobility, etc), and
- Shielding and distance of receptors.

Receptor impacts can be either acute or chronic, as is more fully described elsewhere. Included with chronic impacts—consequences that tend to worsen over time—is secondary effects. This includes fires ignited and/or spreading by autoignition from heat flux; explosions such as boiling-liquid-expanding-vapor-explosions (BLEVE); soot and ash fallout; pollution; etc.

4.2 Product Hazards

The types of damages potentially produced by a pipeline failure are obviously highly dependent upon the types of product that is released. Products transported in pipelines therefore play a large role in estimates of hazard zone distances.

Most products have at least some degree of both acute and chronic consequence potential, even though in many cases, one will dominate and the other is only a remote possibility. For instance, natural gas presents an almost entirely acute consequence potential since an unignited release will normally dissipate quickly and no significant toxic effects are associated. However, scenarios involving leaked gas accumulation (basements, sewers, etc) have a chronic aspect since in these scenarios the situation can become more consequential over time.

Acute hazards associated with the release of hydrocarbon gases and liquids typically transported by pipeline include several flammability scenarios, explosion potential, and the more minor hazard of spilled material displacing air and asphyxiating creatures in the oxygen-free space. Contact toxicity is another acute hazard with some products. Chronic hazards include scenarios of contamination and toxicity, generally from liquid spills.

4.3 Thermal and Overpressure Effects

Thermal events are normally of prime interest for hydrocarbon pipelines. The probability and intensity of a thermal event is a function of ignition potential and burning characteristics. Product characteristics such as heat of combustion and boiling point are good surrogates for a product's probability of ignition and intensity of heat production, as is discussed elsewhere. The likelihood of an ignition source is a function of the nearby environment including density of flame sources (perhaps modeled as a function of land use), likelihood of spark generation (perhaps a function of soil type and pressure-diameter relationship), and the type of product.

Once ignition has occurred, any of several flammability scenarios might result. Scenarios of concern include:

- Flame Jets—where an ignited stream of material leaving a pressurized vessel creates a long flame jet with associated radiant heat hazards and the possibility of a direct impingement of flame on other nearby equipment.
- Vapor Cloud Fire—where a cloud encounters an ignition source and causes the entire cloud to combust as air and fuel are drawn together in a flash fire situation.
- Liquid Pool Fires—where a liquid pool of flammable material forms—often some distance from the leak site—ignites, and creates direct flame and radiant heat damages.
- Fireballs—this is normally associated with BLEVE episodes where a vessel, engulfed in flames, violently explodes creating a large fireball with the generation of intense radiant heat. A fireball may also occurs as a rapid deflagration of a flammable vapor cloud. While a BLEVE is not thought to be a potential for subsurface pipeline facilities, a fireball from the ignition of a vapor cloud produces similar heat impacts.
- Vapor Cloud Explosion—potentially occurs as a vapor cloud combusts in such a rapid manner that a blast wave is generated. The transition from normal burning in a cloud to a rapid, explosive event is not fully understood. Deflagration—rapid flame front movement—is the more common event. A confined vapor cloud explosion is more common than unconfined, but note that even in an atmospheric release, trees, buildings, terrain, etc can create partial confinement conditions. Any explosive event can have associated missiles and high velocity debris whose damage potentials have been dramatically demonstrated, but are very difficult to accurately model.

4.4 Thresholds

As used here, a threshold is a decision point, a point of interest, a point above which some certain impact is expected. A hazard zone is defined by an associated threshold. Speaking of a hazard zone without knowing what threshold is expected at that distance is not meaningful.

A distinction is made between threshold intensities and threshold damage states. The intensity of an exposure—heat flux level in the case of thermal events, overpressure level in the case of explosions, concentration in the case of toxicity—can be used as a threshold. Similarly, the resulting damage state from intensity of exposure can be viewed as a threshold So, a threshold can either directly define the hazard zone—distance to a certain intensity—or it can imply a damage state on which the hazard zone is based—"distance at which a 1% mortality rate is expected". While there are many threshold intensities that might be of interest, there are far more damage states. Damage state definitions such as "90% chance of at least one fatality" or "50% chance of more than $100K in property damage" or ">1000 cubic yards of contaminated soil" are but a sample of the countless definitions upon which a threshold could be based.

The distinction between the types of thresholds can become blurred as a modeler will often associate a heat-, overpressure-, or toxicity-based intensity threshold with a level of damage to a receptor, and then use the threshold definitions interchangeably. For instance, a heat intensity of X units will theoretically result in an estimated 1% mortality of exposed, unshielded populations. When chosen as a threshold, the X units of heat intensity may be referred to as the "1% mortality" threshold. However, preserving the "X units of heat intensity" definition is important since the alternate definition implies that receptors are always present. Putting aside the original exposure intensity of interest may result in modeling confusion when probabilities of threshold intensities are modeled independently of varying receptor characteristics.

As suggested above, most hazard zone estimates and receptor characterizations are closely intertwined. The former usually embed some assumptions about potential receptors as well as a choice of a damage level for the receptor of interest. The level of damage chosen—1% fatality rate, for instance—sets the effect of interest—thermal radiation level, for instance—which in turn determines the distance to the edge of the hazard zone. All are based on numerous assumptions. Atmospheric conditions, orientation of flame, mobility of populations, shielding, are but a few of the required assumptions for the mortality criteria exampled.

A hazard zone that is to be expressed as a distance from a point on a pipeline is most easily based solely on some threshold intensity effect, independent of possible receptors. It could alternatively be based upon some potential damage level. However, this would make the distance dependent upon nearby receptors rather than upon the pipeline alone. Granted, the thresholds are themselves often based upon some possible damage state, but keeping that basis indirect allows the threshold to be a function solely of pipeline properties. This makes modeling easier—a hazard zone based on pipeline characteristics can first be estimated and then receptors within that hazard zone can be quantified. This is further discussed later.

As an example of the creation and use of a threshold, consider the equation for natural gas PIR based on reference 1. This has been adopted by US regulations and is a mandatory consideration for determining HCA's for jurisdictional US natural gas transmission pipelines. Since countless scenarios are possible and various types of damage can occur, some choices were made in determining the PIR hazard zone distance. In reference 1, the implicit assumptions used to estimate the PIR include the following:

- Full, guillotine rupture, leak is fed by both open ends of pipe;
- No vapor cloud explosion potential;
- Trench fire (horizontal jet fire) is dominant effect;
- Rapid ignition of escaping gas;
- Effective release rate as a multiple of the peak initial release rate; and
- Heat intensity of 5000 BTU/(hr-ft^2).

The chosen heat intensity level corresponds to a level below which wooden structures would probably not burn and sheltered persons are not injured. Unsheltered persons would be exposed to a 1% chance of fatality as they seek shelter or distance themselves from the heat.

According to this reference, a level of 5,000 BTU/(hr-ft^2) "…establishes the sustained heat intensity level above which the effects on people and property are consistent with the definition of a high consequence area. Note that in the context of this study, an HCA is defined as the area within which the extent of property damage and the chance of serious or fatal injury would be expected to be significant in the event of a rupture failure." These assumptions and choices have been deemed appropriate for US gas pipelines by US legislators and regulators.

This illustrates the choice of a threshold intensities—5,000 BTU/(ft^2-hr)—which implies a damage state based threshold—most significantly, a 1% chance of fatality. The threshold intensity is mostly relevant in terms of its expected damage potential. The damage potential assumes the presence of receptors. The 1% fatality rate in the above example occurs IF the assumed population is present and exposed as assumed.

More detailed assessments may use multiple thresholds for each type of impact. For instance, thermal effect thresholds corresponding to third degree burns, first degree burns, and autoignition of wood could be used. Overpressure (blast) levels corresponding to "window breakage only," "heavy structural damage to wood frame buildings," "ear drum rupture," and "serious internal injuries" could be used. In the case of toxicity, multiple exposure-effect dosage levels might be of interest, perhaps varying according to types of accumulation—inhalation, ingestion, skin absorption.

4.5 Migration From Leak Site

Note that a hazard zone may originate some distance from the point of pipeline failure. In the case of delayed or no ignition, the product may have migrated some distance prior to ignition. This moves the origination point for the thermal effects. The cloud centroid or liquid pool center then becomes the point from which the hazard zone extends. Centroid is used to refer to the center from which thermal or overpressure effects are emerging.

The thermal effect can also move back towards the leak site as the "trail" of combustible spilled product is consumed. This creates a hazard zone along the "trail." Scenarios can also be envisioned where the leak site experiences little or no damage while areas farther from the pipeline are damaged. Examples include a liquid spill where a ditch or sewer catches and moves the spilled product away from the leak; or an HVL "puff" release where the cloud, fully decoupled from any other vapors escaping from the pipeline, drifts some distance before finding an ignition source. These scenarios are difficult to model and rare enough that they can generally be ignored since they would be included anyway in conservative scenarios involving an ignited trail of product. Including the migration possibility without the decoupling-from-the-source possibility produces larger (more conservative) hazard zones.

Making a distinction between the path and the event centroid may be useful. In the absence of some type of dispersion modeling, the path is often set to zero distance, making the centroid coincident with the spill site (on top of the pipe). This is a convenient way to model, but will miss-characterize damage potential when, for instance, scenarios like those described above occur.

In the case of liquid spills, the migration-distance estimate must always consider topography, making these scenarios more location-specific and difficult to model. Where the topography is relatively consistent, some "rules" can be developed to facilitate assessment. The rules establish appropriate migration estimates for the majority of the pipeline length and are adjusted only when certain major changes are encountered. For example, a hazard zone can be based on a predominant topography—say, "prairie" or "level pasture"—and, where the pipeline crosses a ditch or stream of certain characteristics, a different set of assumptions creates a different migration distance.

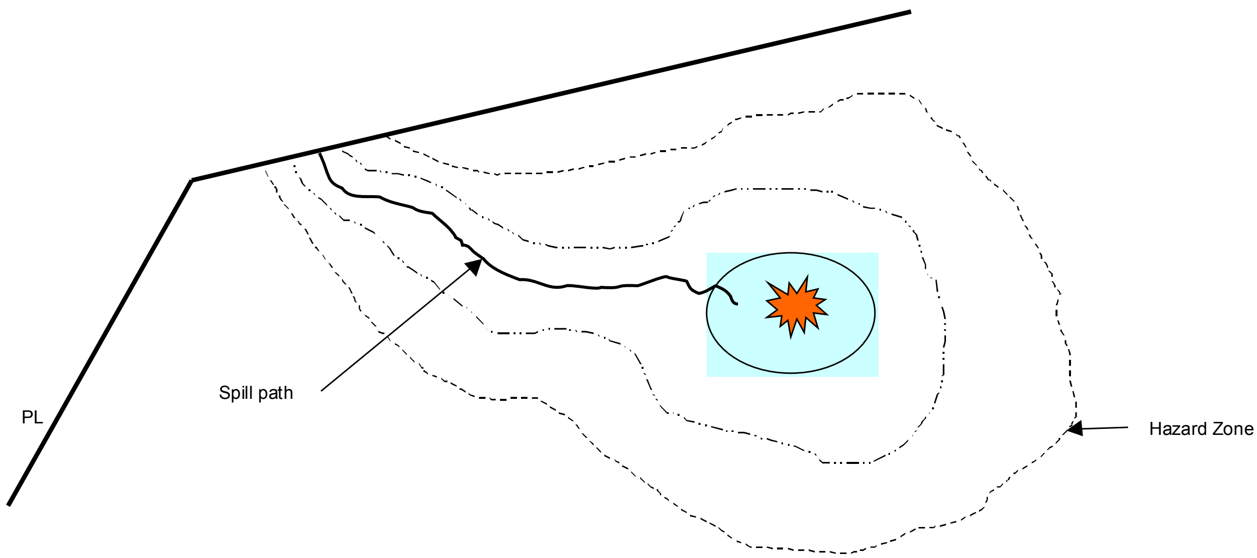

Figure 4.5-1. Migration of Centroid from Spill Site

In the case of HVL's and gas releases, the hazard zone should also consider meteorology. This is generally stable over long stretches of pipeline, but conceivably can cause modeling complications under scenarios where weather patterns change over short distances. Examples include canyons, coastal regions, and perhaps even shielded (from wind) versus unshielded locations where "confinement" increases the explosion potential of a vapor cloud.

For general consequence assessment, the recommendation is to simply add the migration distances to the hazard zone distances. While this inflates the hazard zone distances for many scenarios, it also captures the scenarios where the hazard zone is actually enlarged by the migration path of material that can combust or contaminate. Of course, the assessment can always be supplemented with site-specific analyses that better characterize the full range of possibilities, even the most rare scenario.

4.6 Estimating Hazard Zones

As already discussed, countless hazard distances can be created from the possible failure scenarios of most hydrocarbon pipelines. The objective is to model a manageable number of scenarios and, most importantly, have the chosen scenarios represent the full range of possibilities.

Hazard zones based on threshold intensities such as heat, overpressure, and toxicity/contamination are a function of two general sets of release conditions:

- Pipeline / product characteristics
- Dispersion potential, including:
    - Topography effects if liquid release or
    - Meteorology effects if gaseous release.

Product characteristics are grouped with pipeline characteristics since the operating conditions—pressure, temperature, flow rate—will influence how the product behaves when released.

As previously noted, thresholds based on a receptor effect or damage state, such as fatality, injury, property damage, environmental harm, require the above parameters plus another:

- Receptor proximities and characteristics

One modeling objective is to establish hazard zone distances in a way that the same distance can apply to large stretches of pipeline. This allows for efficient and consistent characterization of receptors within hazard zones. The range of scenarios used to evaluate hazard zones is narrower when the receptor characterizations are separated from the threshold definitions. For instance, initially avoiding the complexity of approximating population density, shielding, mobility, and potential exposure times reduces the number of permutations required to estimate a hazard zone. Hazard zone estimation can therefore efficiently begin using only the factors that establish threshold intensity distances. These are primarily the pipeline and product characteristics and dispersion potential. Then, receptor characterizations can be later added to the analysis.

In this suggested approach, the "probability of a damage state" is sought, so some liberties with measurement units are taken. Probabilities of occurrence are combined with possible distances to thresholds and expressed as distance. Probabilities can be viewed as implying either the chance of a hazard zone occurring or the probability of a certain damage state, given the manifestation of the hazard zone. In other words, the probability of the hazard distance and the probability of various damage states can both be captured in the probability number assigned to the distance. Mathematically, the two are treated as identical. So, a hazard zone distance of 1,000 ft with a 1% probability embodies the belief that there is only a 1% chance of a threshold damage level extending this far, or, if this distance is reached, damages will only be 1% of what they would be immediately adjacent to the centroid. Given the high levels of uncertainty and variability in possibilities, such liberties and simultaneous representations or alternative interpretations are not unreasonable.

Expressing the threshold as a proportion of the theoretical maximum hazard distance might be more intuitive to some. The underlying assumption is that a certain percentage of the maximum hazard zone produces a certain threshold. For instance, the first 10% of the maximum hazard zone may be assumed to produce a high probability of fatalities and complete property destruction; while the zone between 10% and 80% of maximum hazard distance produces no fatalities—injuries only, and 50% property destruction; and finally, at distances beyond 80% of the maximum possible impact distance, damages are assumed to be minimal. These are examples for illustration only.

The use of hazard zones is of course a modeling convenience. However, they should represent reasonable assumptions and capture the logical premise that damage severity will decrease as distance from the event increases. When establishing threshold zones, the modeler should keep in mind that actual intensities of thermal events are in fact usually proportional to the *square* of the distance. Therefore, potential damages will normally drop very dramatically with increasing distance. See transmissivity / emissivity discussions. Contamination potential can often be assumed to decrease with increasing distance since dilution, absorption, evaporation, etc. have more opportunity to reduce contaminant levels after the spill has moved some distance. The rate of drop in damage potential with increasing distance might be receptor- or threshold-dependent.

4.7 Using a Fixed Hazard Zone Distance

Based on sound analyses, hazard zones for groups of similar pipelines—same product, diameter, pressure range, etc—could be set at some consistent nominal distance. The selected hazard zone should represent the distances at which damages *could* occur, but are thought to exceed the actual distances that the vast majority of pipeline release scenarios would impact.

A conservative hazard zone distance adopted for an HVL pipeline release, for example, should be based upon a compilation of calculation results generally up to the distance at which a full pipeline rupture, at maximum operating pressure with subsequent ignition, could expose receptors to significant thermal damages, plus the additional distance at which blast (overpressure) damages could occur in the event of a subsequent vapor cloud explosion. It is often useful to make fixed hazard zone distances very conservative. This makes them more defensible in some situations and perhaps even comforting to skeptical audiences. Sources of conservatism in a fixed maximum hazard zone distance for HVL pipelines might include:

- Overestimation of probable pipe hole size,
- Overestimation of probable pipeline pressure at release,
- Stable atmospheric weather conditions at time of release,
- Ground level release event,
- Maximum cloud size occurs immediately prior to ignition,
- Extremely rare, unconfined vapor cloud explosion scenario with overpressure threshold set at low level (corresponding to only minimal damages),
- Overpressure effects distance added to ignition distance (assume explosion epicenter is at farthest point from release), and/or
- Final distance used is longer than distance that models predict.

These conservative parameters ensure that actual damage areas are well within the maximum possible hazard zones. Additional parameters that could be adjusted in terms of conservatism include mass of cloud involved in explosion event; overpressure damage thresholds; effects of mixing on LFL distance; weather parameters that might promote more cohesive cloud conditions and/or cloud drift; release scenarios that do not rapidly depressurize the pipeline; possibility for sympathetic failures of adjacent pipelines or plant facilities; ground level versus atmospheric events; potential for high velocity jet release of vapor and liquid in downwind direction.

While conservatism offers some benefits, it obviously also carries drawbacks. Combining layers of conservative assumptions introduces a bias towards overstating actual risks. In the case of hazard zone estimation, such bias can produce alarming distances that have extremely low probabilities.

5. CoF Reduction Measures

Consequence reduction measures are opportunities to reduce the potential losses from an event in progress. Reduction can be through limiting the range of released product and/or limiting the impact to receptors. There are more opportunities to reduce consequences of chronic events since they tend to worsen with the passage of time and intervention opportunities exist. Most acute events offer little or no consequence reduction opportunities since the largest hazard zones tend to occur immediately after release and then independently improve over time.

If a reduction measure can reduce the size of the hazard zone, then fewer receptors are exposed and consequences are lower. The hazard zone can theoretically be reduced through changes such as pressure reduction, secondary containment, and/or changes to the product stream. Such measures are generally impractical, however, for most pipelines. Leak detection and emergency response can also play a role in hazard zone size, especially in chronic events involving unignited liquid releases. If a small release is detected before a contamination plume can become larger or migrates to additional sensitive receptors, the hazard zone is reduced. However, leak detection/emergency response usually cannot significantly change the size of an acute thermal hazard zone. Additional consequence-reduction opportunities, less common for cross-country pipelines but possible within facilities such as tank farms and pump stations, include fire suppression systems, secondary containment, and more advanced leak detection opportunities.

Depending on the detail of the consequence assessment, receptor sensitivities may or may not be considered. If receptor sensitivities are included in the initial hazard zone estimation, then receptor protection can also be included as a consequence reduction factor. Shielding and reduction in exposure time (perhaps through rapid evacuation) are examples of protection opportunities for human receptors. An analysis that considers population mobility can also consider when early warning and/or shielding enhances the escape opportunities for that population.

If the hazard zone is created directly from a threshold intensity—thermal radiation or overpressure level, for example—then receptor protection can be evaluated separately. A factor to account for the benefits of shielding is included in the example below.

Consequence reduction measures are valued in the same way as mitigation measures in PoF (see Part 1 of this paper series). Two questions are asked and answered in performing the valuation—”how effective can the measure be if it is done as well as can be imagined?” and then, “how well is it being done in the situation being assessed?” A direct reduction in possible damage state and/or hazard zone size is the easiest way to quantify the value of these mitigation measures.

6. Estimating Consequences

As has been described in the previous sections, the key aspects of the consequence assessment proposed here are:

1. Scope of assessment,
2. Thresholds,
3. Hazard zones,
4. Receptor characterizations,
5. Consequence reduction measures, and
6. Expected Loss calculations.

These ingredients are developed sequentially in the assessment process, with the expected loss values being the consequence measures that are combined with PoF estimates to obtain final risk estimates. The recommended steps to estimate consequences and risks along a pipeline are:

1. Establish scope of assessment
2. Establish thresholds/damage states of interest
3. Estimate all possible hazard (threshold) distances and associated probabilities at all points along each pipeline.
4. Divide the possible hazard distances into a manageable number of zones.
5. Associate damage states with each distance zone.
6. Characterize receptors within each zone.
7. Combine all aspects into expected loss estimates.

6.1 Steps 1-3

Estimate hazard distances (threshold distances) for representative pairings of leak size and ignition scenarios. For example, using hole size as a surrogate for leak size, holes sizes of "rupture," "leak," and "pinhole" could be paired with ignition scenarios of "immediate," "delayed," and "no ignition," resulting in nine pairings or permutations, as is shown in a following example. Hole sizes could also be linked directly to failure mechanism, material toughness, and other pertinent factors.

6.3 Step 4

Compile all possible threshold distances and categorize them into zones. For example, suppose that threshold effect distance estimations produced distances ranging from 0 ft to 560 ft. An inconsequential scenario—perhaps a pinhole leak, immediately detected, and fully contained—produces no hazard zone and the most extensive scenarios produce a threshold distance of up to 560 ft. The modeler might want to create three zones such as:

Table 6.3-1. Hazard Zones

Zone	Distance (radii)
1	0-80 ft
2	81-250 ft
3	251-560 ft

The number of zones is up to the modeler. All events within a zone are treated as the same, so this implies no differences in potential damages at the closest and farthest point of the zone. Wider zones require more "averaging" of possibly widely-differing potentialities within the zone. More categories will result in more resolution but also more efforts in subsequent steps.

Each zone represents a collection of numerous potential damage thresholds. In actuality, there are no sharp demarcations between possible zones, so zone boundaries are a modeling convenience. For instance, 20% of the possible scenarios might produce hazard zones from 0 to 200 ft and 10% of the scenarios could produce distances of from 50 ft to 400 ft. These overlapping distances do not necessarily suggest break points for zones so any choice of break point is a compromise. A cumulative probability chart and/or graphical presentation of the various thresholds associated with various scenarios will help the modeler to establish zones and associated probabilities. See Figure 6.3-1.

In the above example, the modeler chose to use three zones. He also chose to make zones not equivalent in size—basing his groupings a non-linear reduction in impact intensity with increasing distance. Non-uniform zone sizes might also better represent the relative frequency of events. Perhaps scenarios leading to threshold distances beyond 250 ft are so rare, that a larger zone captures an equivalent number of scenarios as the smaller zones. Each zone will have a probability derived from the probabilities of all the individual scenarios that can produce a threshold distance that falls in the zone.

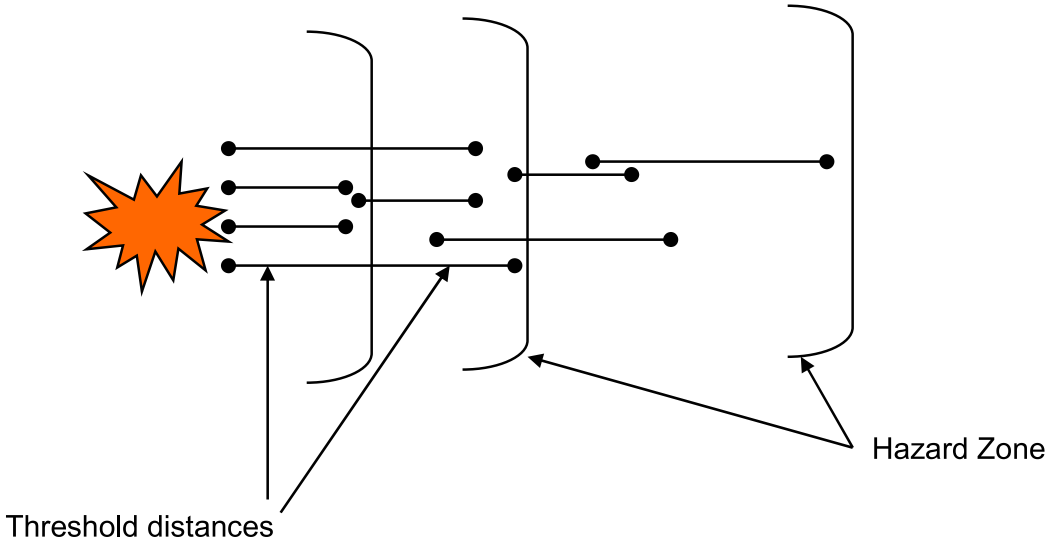

Figure 6.3-1. Visualizing Ranges of Thresholds and Setting Zones

As is illustrated in Figure 6.3-1, there are some scenarios in the farthest zone that produce no impacts in the closest zone. For instance, a scenario where leaked product migrates completely out of the closer zones (via sewer or puff cloud drifting, for example) before finding an ignition point. At the ignition point, the thermal effects are far from the release point and the receptors closer to the pipeline.

In many cases, a circular hazard area is a fair representation. However, given certain topographies and/or meteorological phenomena, ellipses or other shapes might be more representative of true hazard areas.

This creation of hazard zones is a modeling convenience. It is easier to make the necessary receptor characterizations within a few zones rather than for each possible threshold distance. The trade-off is some measure of accuracy since compromises are made in setting the zones. All event scenarios occurring within a zone are treated equally, even though some occur at either extreme of the zone.

6.4 Step 5

Characterize the types of damages to each receptor type that may occur in each zone. Recall that, as a modeling convenience, the probability of a certain hazard zone occurring is considered to also capture the diminished damage potential at the increasing distance. Receptors within farther hazard zones produce lower expected losses since their probabilities of damage are lower. They are lower for two reasons: lower chance of that hazard distance happening, and lower intensities resulting in less damage to the receptor at farther distances.

Characterization can be in terms of fraction of maximum damage possible or percentage chance of the maximum damage. For instance, in a zone close to the ignition point and following a very high consequence event, the damage state to humans might be 2% fatality and 100% injury. A more distant zone might be characterized as a damage state to humans of 0.1% fatality and 20% chance of injury. In the case of non-absolute damage states such as injuries or property damage, the percentage can be thought of as either x% chance of any damage, or a 100% chance of a damage that is x% of the maximum possible damage. Both conceptualizations are supported since the mathematical approach would be the same for each.

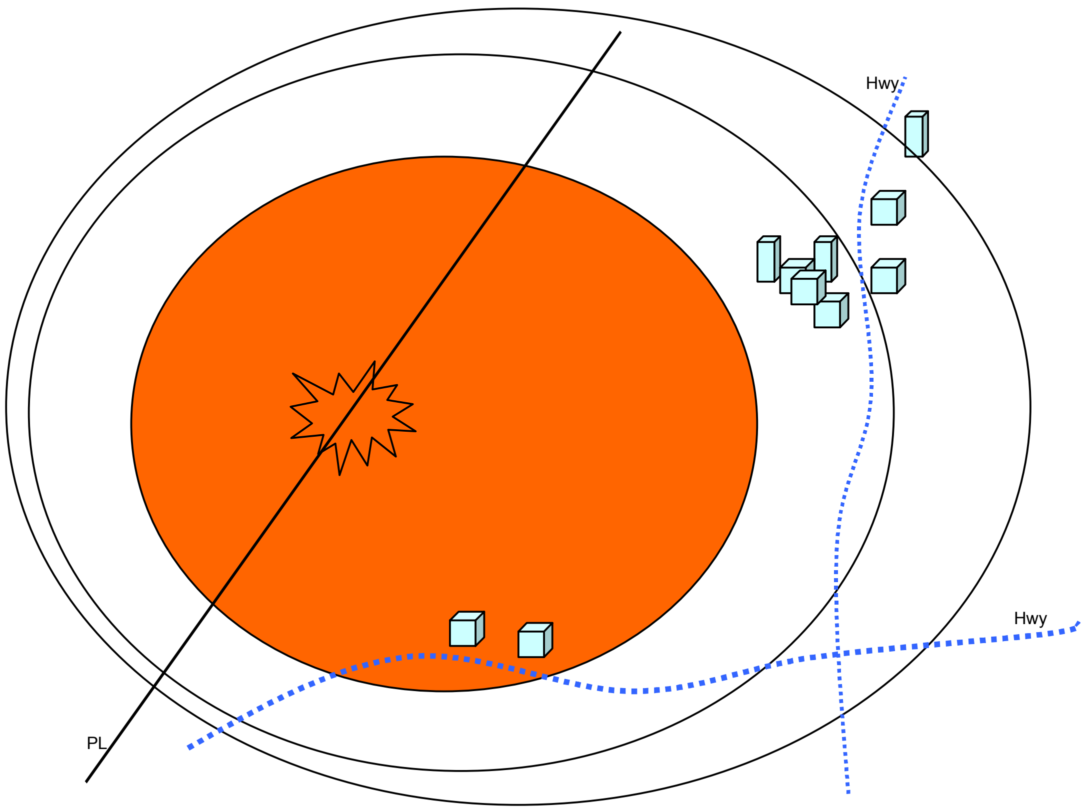

Figure 6.4-1. Receptor Characterization within Hazard Zones

6.5 Step 6

Characterize the receptors within each hazard zone. Characterization includes count and type. Receptors can be efficiently quantified in terms of "units" where each unit represents a pre-determined receptor damage state such as "human fatality", "human injury," "destruction of one residence," "contamination of one acre of herbaceous wetland," etc. So, a certain hazard zone might have the expectation of damages of 4 injury units and 7 wetland contamination units. A unit can be assigned a fixed dollar value—the cost of remediation and/or compensation to injured parties.

The receptor characterization will be determined by the scope of the assessment, with more robust assessments requiring more detailed characterization. For instance, some models will make distinctions among human populations—age, mobility, etc. Environmental damages can be quantified in "environmental units," where the evaluator sets some equivalencies among possible scenarios. For instance, an acre of "old growth forest" may be set as 1 environmental unit, while a T&E species is set at 10 and aquifer contamination at 15. A dollar value can be assigned to an environmental unit. These are value judgments possibly established through knowledge of remediation costs or some other metric of valuation. Figure 6.4-1 shows a very simplistic characterization where only buildings and roads within three hazard zones are noted.

Consideration of shielding is another possible variable. Shielding of almost any kind is an effective reduction to radiant heat, minimizing damages or allowing more escape time. It can be incorporated into the receptor characterization or used as a stand-alone variable—a factor to reduce potential damages.

Steps 5 and 6 will have produced characterizations of possible receptor damages in each zone. Ideally, the risk evaluator will now have the ability to answer, at least generally, questions such as:

- How many people are typically in each zone?
- What is the potential rate of injuries, fatalities in each zone?
- What is the potential rate or % of other damages in each zone?
- How much property damage is likely in each zone?
- How much and what type of environmental damage is possible in each zone?

He will also have gained the ability to answer these questions in somewhat quantitative terms, although many assumptions and uncertainties are usually embedded in such quantifications.

6.6 Step 7

Combine the results from previous steps into an expected loss value for each scenario. Each scenario has an associated probability of occurrence, produces a certain hazard zone, and contains certain numbers and types of receptors with associated dollar values. Multiplying these values together and then summing the results for each hazard zone produces the expected loss for the pipeline segment. See the following example of this overall process.

7. Example of Overall Expected Loss Calculation

An example of the overall consequence estimation process is laid out in the following tables and discussion. Values shown are to illustrate the process only—they will not be realistic values for most pipelines and should not be used as a basis for any other estimates.

Table 7-1. Establishing Hazard Zone Distances and Probabilities

						Threshold Distances (ft)				
Product	**Hole Size**	**Probability of Hole Size**	**Ignition Scenario**	**Probability of ignition scenario**	**Distance from source (ft)**	**Thermal Impact**	**Overpress Impact**	**Contamination Impact**	**Maximum Distance (ft)**	**Probability of Maximum Distance**
propane	rupture	8%	immediate	60%	0	400	0	0	400	4.8%
			delayed	20%	300	400	800	0	1500	1.6%
			no ignition	20%	300	0	0	0	300	1.6%
	medium	12%	immediate	15%	0	300	0	0	300	1.8%
			delayed	15%	100	300	200	0	600	1.8%
			no ignition	70%	100	0	0	0	100	8.4%
	small	80%	immediate	10%	0	50	0	0	50	8.0%
			delayed	10%	30	50	0	0	80	8.0%
			no ignition	80%	30	0	0	0	30	64.0%
		100%								100.0%

In this example, hazard zone distances are related to PIR, under the assumption that the PIR distance is the maximum extent of damages.

Table 7-2. Estimating Expected Loss from Hazard Zone Characteristics

						unit cost $100,000	*unit cost* $3,500,000		*unit cost* $ 50,000	Expected Loss
Hole Size	**Ignition Scenario**	**Maximum Distance (ft)**	**Probability of Maximum Distance**	**Hazard Zone Group**	**# people**	**Human injury costs**	**Human fatality costs**	**# environ units**	**Environ Damage Costs**	**Probability weighted dollars per failure**
rupture	immediate	400	4.8%	100'-50% PIR	5	$ 3,600	$ 12,600	1	$ 720	$ 16,920
	delayed	1500	1.6%	50% -100% PIR	10	$ 960	$ 3,360	1	$ 80	$ 4,400
	no ignition	300	1.6%	100'-50% PIR	5	$ 1,200	$ 4,200	1	$ 240	$ 5,640
medium	immediate	300	1.8%	100'-50% PIR	5	$ 1,350	$ 4,725	1	$ 270	$ 6,345
	delayed	600	1.8%	100'-50% PIR	5	$ 1,350	$ 4,725	1	$ 270	$ 6,345
	no ignition	100	8.4%	100'-50% PIR	5	$ 6,300	$ 22,050	1	$ 1,260	$ 29,610
small	immediate	50	8.0%	<100'	1	$ 1,920	$ 6,720	0.5	$ 1,000	$ 9,640
	delayed	80	8.0%	<100'	1	$ 1,920	$ 6,720	0.5	$ 1,000	$ 9,640
	no ignition	30	64.0%	<100'	1	$15,360	$ 53,760	0.5	$ 8,000	$ 77,120
			100.0%	Total expected loss per failure at this location						$165,660

Table Notes

1. *Not shown is the Shielding factor: estimated as a percentage, this adjusts the damage estimate by considering protective benefits of all shielding opportunities including clothing, buildings, etc. in each hazard group and for each receptor type. In this example, 30% shielding factor is used.*

Table 7-1 shows how the hazard zone distances are estimated for this example. For the nine scenarios shown, maximum threshold distances range from 30' to 1500'. 1500' is considered to be the maximum impact distance for this location on the examined pipeline.

The analysis begins with estimates of hole size probabilities. Depending on the PoF analysis, the entry point into this analysis can be either the relative hole size distribution or an "absolute" hole size distribution. The hole size distribution in this example represents 100% of all possible failures; the relative chance of a certain size hole, given that failure has already occurred. Alternatively, the PoF analysis might have already estimated a specific probability of occurrence for various hole sizes—a calculated probability of rupture, a calculated probability of a pinhole, and so forth.

For this example, these probabilities simulate a distribution of all possible hole sizes with their associated probabilities of occurrence. Such a distribution would be influenced by pipe material, stress level, and failure mechanism, as well as other considerations. In the table above, three relative hole size occurrence percentages are shown, with a cumulative occurrence percentage of 100%. Each will be multiplied by the PoF of all possible leak sizes—a very small number for most pipelines—to get absolute probabilities of occurrence. For instance, if the overall failure probability (all holes sizes) was estimated to be 1E-6 per mile-year, then the probability of a rupture is estimated to be 8% of that value or 0.08 x 1E-6 = 8E-8 = 0.000008% chance of rupture for each mile for each year. This also suggests 8E-8 ruptures per mile per year as an estimated frequency of occurrence.

Next, three ignition scenarios are modeled: "immediate," "delayed," and "no" ignition. The probability of each scenario is estimated for each hole size scenario. In this sense, hole size is being used as a surrogate for leak size. Larger holes imply larger leaks and greater ignition potential. The three holes sizes and the three ignition possibilities will produce nine scenarios, thought to sufficiently represent the possibilities in this example.

The "distance from source" column represents the possible migration distance of spilled product from the leak source. It is based on dispersion modeling—vapor cloud drift—in the case of gaseous releases and overland flow modeling in the case of liquids. This distance is additive to thermal effects distances and contamination distances. The leaked product might travel some distance, ignite, and produce thermal damages from the point of ignition, sometimes far from the leak site. In the contamination damage scenario, envision a pool of spilled liquid that accumulates some distance from the leak location and only then begins a more aggressive subsoil migration, causing a groundwater contamination plume spreading from the pool. Since propane—a highly volatile liquid—is the product in this example and will be released almost entirely as a gas, no contamination impacts are foreseen.

Several thresholds are selected for production of hazard distance estimates. Shown are one thermal effects threshold, one overpressure threshold, and one contamination threshold. These must be defined in terms of some intensity level or some probable damage state before distances could be assigned. The evaluator may wish to include multiple thermal and contamination thresholds to ensure that the full range of possibilities is portrayed.

The distance for each threshold is estimated from appropriate models for the product released. A gaseous release might base the threshold on flame jet thermal radiation (as in reference 3, for example); an HVL release threshold might be based on overpressure distance as well as fireball or jet thermal radiation; and a liquid release is often based on pool fire thermal radiation or contamination level. In this example, the longest distance occurs with a delayed ignition scenario, allowing the vapor cloud to migrate before ignition initiates a thermal event, including overpressure, if the release is sufficiently large.

The relative probability of each scenario is calculated as the product of the hole size probability times the ignition scenario probability. These values can be multiplied by the overall PoF for the pipeline at this location, to arrive at an absolute probability of each scenario. In the example Tables 7-1 and 7-2 though, scenario probabilities assume that the pipeline failure has already occurred. Therefore, scenario probabilities sum to be 100%.

Table 7-2 repeats some information from Table 7-1 and then shows how the scenarios are further developed. The evaluator has grouped the threshold distances into three zones. This was done by setting some logical breakpoints. A simple plotting of distances can be helpful. Similar to Figure 6.3-1, Figure 7-1 shows the nine scenario-generated distances. This graphic was used to better visualize logical break points for establishing hazard zones. This establishment of zones is a modeling convenience that avoids having to perform receptor characterizations at too many distances. In the example, maximum PIR is set at 1500 ft and the zones are defined as

1. "less than 100 ft,"
2. "from 100 ft to 50% of PIR (or 750 ft)," and
3. "from 50% PIR to 100% PIR (or 750 ft to 1500 ft)."

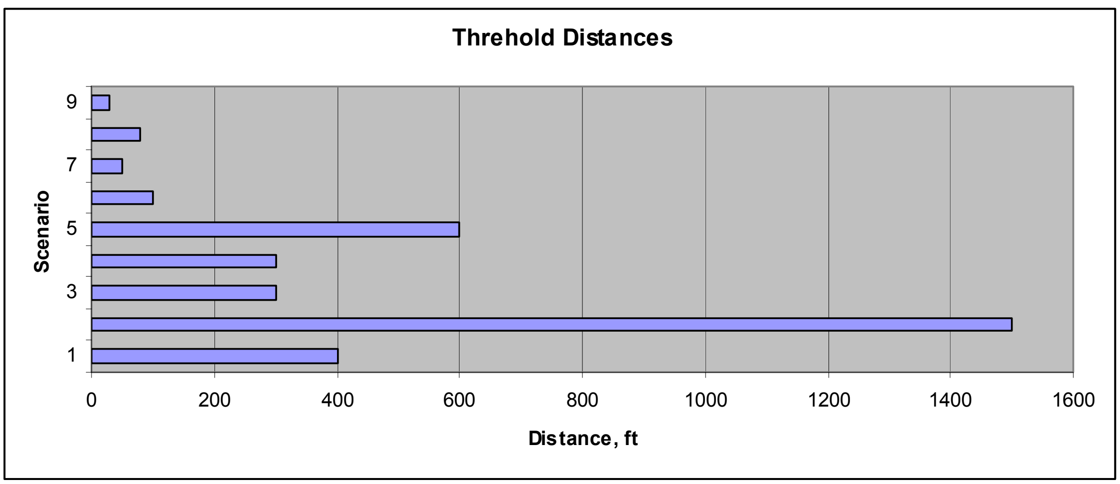

Figure 7-1. Visualizing Hazard Zone Distances

Each zone is assigned receptor damage rates based on the damages that would likely occur. For example, where very high heat radiation thresholds occur, higher fatality rates and higher property damage rates would be expected. The estimated damage rates are shown in Table 7-3.

Table 7-3. Damage State Estimates for Each Zone

Hazard Zone	Injury Rate	Fatality Rate	Environ Damage Rate	Service Interruption Rate
<100'	80%	8%	50%	100%
100'-50% PIR	50%	5%	30%	90%
50% -100% PIR	20%	2%	10%	80%

Damage percentages are assumed to be 0% at distances beyond the maximum PIR. The percentages will be used to calculate expected losses. They should be relatively conservative, reflect the modelers' experience and beliefs, and should be fully documented.

Next, receptors are characterized within each hazard zone as is shown in Table 7-4. At three distances from the pipeline (maximum hazard distance divided into 3 zones), all receptors are characterized in terms of their number and types within each zone. Three types of receptor-damages are examined in this example: fatalities, injuries, and environmental damages. Other common receptors/damages include service interruption costs and property damages.

Not shown in this table but used in the calculations, is a benefit from shielding. The evaluator estimates that, at this location, shielding from buildings, trees, etc; the amount of clothing normally worn; and the emissivity (heat movement through the atmosphere), a reduction factor of 30% should be applied to the injury and fatality rates. This assumption could also have been embedded in the overall damage rate estimates, but in this example, the modeler keeps this variable separate so that it can be a distinguishing factor when shielding conditions change along the pipeline.

Table 7-4. Characterization of Receptors Within Each Zone at a Particular Pipeline Location

Hazard Zone	# of people	# of environ units	# of service interruption units
<100'	1	0.5	1
100'-50% PIR	5	1	5
50% -100% PIR	10	1	10

More detailed receptor characterizations are of course possible and supported by this approach. For instance, the population might be divided into groups based on increased susceptibility to injury or death, such as: "limited mobility;" "unshielded;" "weakened immune systems;" etc. Similarly, the environmental units could be categorized into many different subgroups. As with many aspects of modeling, the evaluator must make decisions involving tradeoffs between robustness and simplicity.

As another modeling convenience, receptors are measured in terms of units. A higher quantity or sensitivity of receptor type is captured in terms of more units. A dollar value is assigned to a unit of each type. In this example, an injury is valued at $100K, a fatality at $3.5M, and an environmental unit at $50K. Such valuations are controversial, difficult to establish, and should be carefully set and fully documented.

Information in Tables 7-3 and 7-4 are used along with occurrence probabilities and valuations to arrive at expected losses for each receptor in each scenario. For instance, in the case of the first scenario, the human injury cost is estimated as the product of (scenario probability, over some time period) x (# of people) x (injury rate in zone "100' to 50% PIR") x (30% shielding benefit factor) x (cost of injury) = 4.8% x 5 x 50% x 30% x $100,000 = $3,600 per scenario. If the scenario frequency is estimated to be once every 10 years, then the expected loss is $360 per year at this location.

The total expected loss per failure at this location on the pipeline is estimated to be ~$166K. This is the sum of the expected loss from the nine pipeline failure scenarios thought to fairly represent all failure scenarios. The annual expected loss is obtained by multiplying this value by the annual leak rate. If that value is 10^{-3} failures per mile-year and this "location" on the pipeline represents one mile, then the expected loss is (average failure costs of $166K per mile per year) combined with (scenario distribution based on overall rate of 10^{-3} failures per mile-year) leading to $55 per year. Therefore, over long periods of time, the cost of pipeline failures for this one mile of pipe is expected to average about $55 per year, as is shown in Table 7-5.

Table 7-5. Final Expected Loss Values

Expected Loss			
Failure Rate (failures per mile-year)	Probability of Hazard Zone[1,2]	Probability weighted dollars[2,3]	Probability weighted dollars per mile-year
0.001	4.80%	$16,920	$0.81
	1.60%	$4,400	$0.07
	1.60%	$5,640	$0.09
	1.80%	$6,345	$0.11
	1.80%	$6,345	$0.11
	8.40%	$29,610	$2.49
	8.00%	$9,640	$0.77
	8.00%	$9,640	$0.77
	64.00%	$77,120	$49.36
	100.00%	**$165,660**	**$54.59**

Table Notes

1. *after a failure has occurred*
2. *from Table 7-2 above, per event*
3. *(damage rate) x (value of receptors in hazard zone), per event*

Note that in this example, costs are dominated by the very conservative assumption of an 8% human fatality rate even though the hazard zone distance is only 30' and involves only contamination (probably only debris and hydrocarbon liquid sprays). If this is thought to be unnecessarily conservative, the establishment of different damage rates for different thresholds—perhaps <0.5% fatality rate for contamination-only scenarios—would yield more reasonable results. Nonetheless, the conservatively-estimated cost of failures is still low in this example.

8. Extrapolation of EL Estimates

The expected loss values can be viewed as part of the cost of operations. They can be used in decision-making regarding appropriate spending levels. The expected loss for the example segment above can be combined with all other segments' expected losses to arrive at an expected loss for an entire pipeline or pipeline system. So, while the example of $55 per year appears very low, a 500-mile pipeline with the same estimates as this segment, suggests an expected loss from failures of over $27,000 per year. Modern pipeline operations can quickly accumulate high total exposure levels depending on exposures per unit length and total lengths.

This example illustrates the representation of risk as a frequency distribution of all possible damage scenarios, including their respective probabilities and consequence costs. The distribution is characterized by a representative number of point estimates of failure consequences. The point estimates show the range of risks and can themselves be compiled into a single estimate for the entire range of possibilities.

Note that while this example includes extremely rare, higher consequence scenarios, it did not quantify the worst possible case independently. When risk aversion—disproportionate costs for higher consequences—is also considered, the overall expected loss value should not be used in isolation. The very rare, but very consequential scenarios, are obscured when all scenarios are compiled into a single point estimate. The more consequential events might warrant further consideration independent of the final risk estimates.

Upon completion of a risk assessment, various roll ups of the risk estimates will be useful. Decision-makers will often need to see and compare risks presented by entire pipe systems as well as by individual pipeline segments. Since risk itself is a complex topic, comparisons will also present some complications. Consider the example shown in Table 6 where 3 fictitious pipeline systems are compared. Note the subtleties emerging from the comparisons:

- The system presenting the highest risks has the smallest risk rate (EL per mile-year)
- The system with the most consequential possible events also has the smallest event frequency, making its risks lower.
- The system with the least consequential possible events has the highest event frequency—more failures but less consequential.
- Length effects can overshadow and obscure risks unless normalized values are also considered.

Table 8-1. Sample Roll Up of EL Values

System	Product	Length	Risk	Risk	PoF	CoF
		miles	Total Annual Exposure	Expected Loss $/mi-yr	Incident Rate, failures per mi-yr	Loss Exposure, Probability-weighted $/failure
Elvira	gasoline	120	$ 142,080	$ 1,184	0.001	$ 1,184,000
Scaramonga	crude oil	408	$ 342,720	$ 840	0.0015	$ 560,000
Perseus	natural gas	23	$ 33,810	$ 1,470	0.007	$ 210,000

9. References

1. GRI-00/0189: A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines Topical Report, Prepared by: Mark J. Stephens of C-FER Technologies; Edmonton, Alberta T6N 1H2, Canada. C-FER Report 99068. Prepared for: Gas Research Institute, Contract No. 8174.
2. Muhlbauer, W. Kent. *Pipeline Risk Management Manual, 3rd edition*. Houston, Texas: Gulf Publishing Co, 2004.
3. Nessim et al. Target Reliability Levels for Design and Assessment of Onshore Natural Gas Pipelines. International Pipeline Conference, Calgary, Alberta, 2004.