

# Enhanced Pipeline Risk Assessment

## Part 2— Assessments of Pipeline Failure Consequences Rev 3

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*This document presents new material that is to be incorporated into the book: Pipeline Risk Management Manual, 4<sup>th</sup> 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 3<sup>rd</sup> edition text (and 4<sup>th</sup> edition, when available) for details and clarifications of concepts that are not fully developed in this document.*

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## Table of Contents

|  |    |
|--|----|
| I. Introduction .....                                  | 3  |
| II. Scope .....  | 3  |
| Simplified Relative Consequences .....                 | 5  |
| Probability Distributions .....                        | 6  |
| III. Expected Loss .....                               | 7  |
| IV. Hazard Zones .....                                 | 8  |
| Receptors.....   | 8  |
| Product Hazards .....                                  | 9  |
| Thermal and Overpressure Effects.....                  | 10 |
| Thresholds.....  | 11 |
| Distance From Leak Site.....                           | 12 |
| V. Estimating Hazard Zones .....                       | 14 |
| Using a Fixed Hazard Zone Distance .....               | 15 |
| V. Estimating Consequences .....                       | 16 |
| VI. Reduction Measures.....                            | 20 |
| VII. Example of Overall Expected Loss Calculation..... | 22 |
| VIII. Additional Modeling .....                        | 28 |
| IX. References.....                                    | 28 |
| X. Appendix A Damage Thresholds.....                   | 29 |

## ***I. Introduction***

Estimates of the potential consequences from a pipeline failure<sup>1</sup> must address the questions: What can be harmed by a pipeline failure? And how badly are ‘receptors’ likely to be harmed? The variables that will fully answer these questions include specifics of and interactions among receptors, product, spill size and dispersion. 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.

As with PoF, the designer of the CoF 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. 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 occurring, as a key ingredient in the assessment.
- 3 Characterize receptors and their potential damage rates within hazard zones

## ***II. Scope***

Especially in the case of a more detailed assessment, an infinite number of scenario permutations is 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 this narrowing of focus is to produce a manageable number of scenarios that fairly represent the range of possibilities.

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<sup>1</sup> For purposes here, “failure” is the unintended loss of pipeline contents.

Before scenarios are generated, an overall scope of the assessment must be established.

Defining the 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.

#### Scope Example 1

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 measured by the same means.

Analyses should be sufficient for regulatory compliance and segment ranking only—no monetizing of consequences is specified.

This scope should lead the modeler to a relatively narrow range of consequence potential, perhaps focusing solely on worst case scenarios. Meeting this scope would be establishment of only one hazard zone—for example, the US regulatory ‘PIR’ based on pressure and diameter—with some minimal characterization of receptors within the hazard zone.

#### Scope 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 toxic effects to

- the public, including human injuries and fatalities;
- property;
- environmental 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<sub>2</sub>S), 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 be relative with the potential for expressing results in absolute terms of dollars per mile year, where all 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.

## 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:

$$LIF = PH \times R \times S \times D$$

where

- Product hazard (PH);
- Receptors (R);
- Spill volume (S);
- Spread range or dispersion (D);

This equation shows that if any one of the four components is zero, then the consequence, or 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. 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 proportional to

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

The area impacted is shown (see ref 3) to be proportional to pressure (p) and diameter (d) of the pipe,  $A \sim pd^2$ . The ignition probability is loosely proportional to diameter. So the relationship simplifies to:

$$\text{Consequence} = \text{fctr} \times \text{pop} \times pd^3$$

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

## Probability Distributions

A limitation in the simpler approach 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 a number of fatalities (N)) show the range of possibilities and are powerful graphical tools. Such representations are more readily assimilated into decision-making when such curves are converted into point estimates that also capture the range of potential scenarios.

The suggestion here is to combine the range of possible consequence scenarios, and their respective probabilities of occurrence, into an 'expected loss' value. While the concept of expected loss is not a new concept in risk, especially in financial matters, it is perhaps unfamiliar to those practicing pipeline risk assessment.

The benefit of this approach is that, in 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. All scenarios are considered with appropriate 'weight' for more objective decision support.

### **III. Expected Loss**

In a more robust risk assessment—beyond relative results—potential consequence estimates are combined with the PoF estimates to arrive at final risk estimates. This approach 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
- 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. This is discussed more fully later.

When estimates from these 4 aspects are combined, the results will represent probability and value or cost (measured in units such as dollars) of consequences. These measurement units present the risk as a cost over time—dollars per year, for instance, for a particular location. Their combination is intended to embody all possible consequences (losses) with their respective likelihoods. This value can be viewed as the amount of potential loss that has been, created by the presence of the facility. 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.

Each point on a pipeline produces its own unique potential consequences and hence its own expected loss. Each point on the pipeline has a distribution of possible failure and consequence scenarios. This distribution is expressed as a single point estimate—the expected loss at that point.

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. These values suggest levels of appropriate risk management actions, as will be discussed later.

Annualizing all potential consequences is another modeling convenience. A \$100,000 loss event that occurs once every 10 years is mathematically equivalent to an expected loss of \$10,000 per year. In this representation, a uniform loss rate—X dollars of loss each period—is really not the expectation. However, the total expected losses over time, are 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 valid, other considerations challenge the notion of equivalency.

Theoretically, each possible dollar consequence scenario is multiplied by a probability of occurrence to arrive at a probability-adjusted consequence value (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 combined.

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 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.

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 represent a \$100K loss every ten years and an annual \$1K loss ( $\$100\text{K} / 10 \text{ yrs} + \$1\text{K/yr} = \$11\text{K/yr}$ ). It is therefore a point estimate representing a sometimes wide range of potential consequences.

#### ***IV. Hazard Zones***

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 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 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 combination of all possible scenarios results in the risk—expressed as expected loss.

### **Receptors**

As it is used here, a receptor is anything that can be harmed by a pipeline release. Some possible receptor types include: human fatality; human injury; property damage; environmental damage; service interruption costs.

Setting receptor valuations is a challenging aspect of risk modeling. Estimating potential damages in real terms requires 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. However, the ability to express risk in monetary terms is obviously a great advantage in many applications.

Receptor sensitivities are another aspect that can be included in the model. Receptor damage is dependent upon the nature of the event—acute versus chronic—as well as the intensity. 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 only simplified assumptions. For each receptor, such as population, environment, drinking water, waterways, key 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)
- 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 BLEVE's; soot and ash fallout; pollution; etc.

## **Product Hazards**

The types of hazards potentially produced by pipeline products are used to create estimates of hazard zone distances. Most products should be judged as having both acute and chronic consequence potential, even though in many cases, one or the other is a very remote possibility. For instance, natural gas presents an almost entirely acute consequence potential since an unignited release will dissipate so 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.

A full discussion of product hazards is available elsewhere in this text.

Thermal events are normally of prime interest for the hydrocarbon products typically moved by pipelines. The probability of a thermal event is a function of several product characteristics: heat of combustion, boiling point are good surrogates for a product's probability of ignition, 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), and the type of product.

## Thermal and Overpressure Effects

Hazards associated with the release of hydrocarbon gases and liquids include several flammability scenarios, an explosion potential, and the more minor hazard of spilled material displacing air and asphyxiating creatures in the oxygen-free space created.

The flammability 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**—not thought to be a potential for subsurface pipeline facilities, this is normally caused by boiling-liquid-expanding-vapor-explosions (BLEVE) episodes where a vessel, usually engulfed in flames, violently explodes creating a large fireball (but not blast effects of other types of explosions) with the generation of intense radiant heat.
- **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 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.

Toxicity is also a concern for some less commonly transported pipeline products.

## Thresholds

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 viewed as a threshold. Similarly, the resulting damage state from intensity of exposure can be viewed as a threshold. As used here, a threshold is a decision point, a point of interest, a point above which some certain impact is expected or some action will be taken. It is important to recognize that a hazard zone requires an associated threshold—thresholds define hazard zones. A threshold can either directly define the hazard zone—distance to a certain effect—or it can imply a damage state on which the hazard zone is based—10% mortality, if people are present. For discussion purposes, a distinction is made between threshold intensities and threshold damage states. Speaking of a hazard zone without knowing what threshold is expected at that distance, is not meaningful.

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 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. Losing the original exposure intensity of interest may result in modeling confusion as probabilities of thresholds are integrated with varying receptor characteristics.

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 exemplified.

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 directly upon some damage level such as 90% chance of at least one fatality or 50% chance of more than \$100K in property damage or any of countless other damage states. However, this would make the distance dependent upon the nearby receptors rather than upon the pipeline alone. Granted, the thresholds are themselves 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.

As an example of the creation and use of a threshold, consider the equation for natural gas “potential impact radius” (PIR) based on reference 1. This has been adopted by US regulations and is a mandatory consideration for determining HCA’s for US natural gas transmission pipelines. Since countless scenarios are possible and various types of damage can occur, some choices were made in determining a 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<sup>2</sup>).

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 from the heat.

According to this reference, a level of 5,000 BTU/(hr-ft<sup>2</sup>) “...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” (ref 1). These assumptions and choices have been deemed appropriate for US gas pipelines by US legislators and regulators. See also Appendix A for additional discussion of this hazard zone.

This illustrates the use of threshold intensities—5,000 BTU/(ft<sup>2</sup>-hr)—to establish a damage state based threshold—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 will 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 levels might be of interest.

## Distance 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 will have migrated some distance prior to ignition. This moves the origination point for the thermal effects. The cloud centroid or liquid pool center then become the point from which the hazard zone extends. The thermal effect can move back towards the leak site as the ‘trail’ of combustible spilled product is consumed. This creates a hazard zone along the ‘trail’.

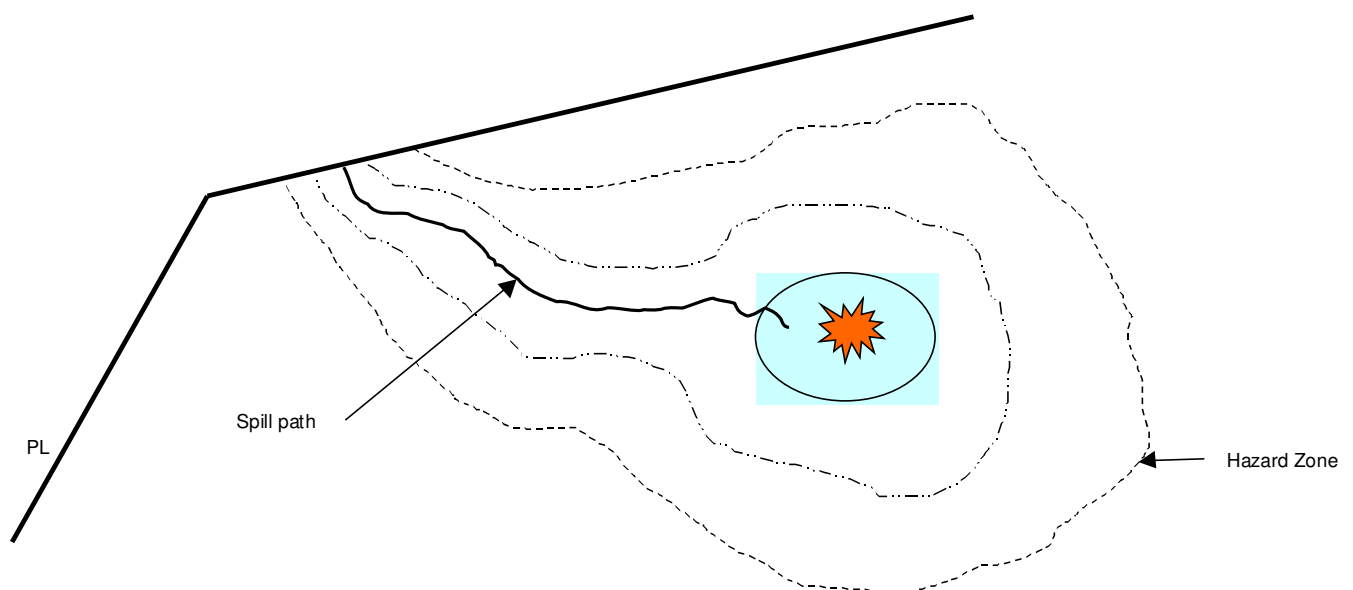
However, scenarios can be envisioned where the leak site experiences little or no damage while areas farther from the pipeline are damaged. Examples include a liquid spill where a ditch or sewer catches and moves the spilled product away from the leak; and an HVL ‘puff’ release where the cloud, fully 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 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. Of course, the assessment can always be supplemented with site-specific analyses that fully capture even the most rare possibilities.

Making a distinction between the path and the event centroid is useful. Centroid is used to refer to the center from which thermal or overpressure effects are emerging. 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.

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.

In the case of liquid spills, the distance estimate must always consider topography, making these scenarios more location-specific and difficult to model in some cases. Where the topography is relatively consistent, some ‘rules’ can be developed to facilitate assessment, adjusting estimates only when certain 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 hazard zone.



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 in 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.

## ***V. Estimating Hazard Zones***

A countless number of hazard distances can be created from possible failure scenarios of most hydrocarbon pipelines. Hazard zones based on threshold intensities such as heat, overpressure, and toxicity/contamination are a function of three general sets of release conditions:

- Pipeline / product characteristics
- Dispersion potential
  - Topography effects if liquid release
  - Meteorology effects if gaseous release

Product characteristics are grouped with pipeline characteristics since the operating conditions—pressure, temperature, flowrate—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 three plus a fourth:

- Receptor proximities and characteristics

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.

The 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.

Three aspects of hazard zones should be considered in building a simplifying model: distance from event; the threshold of interest; and probability of the threshold appearing at a certain distance. The objective is to model a manageable number of scenarios and, most importantly, have the chosen scenarios represent the full range of possibilities.

In this suggested approach, 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 (given ignition) or the probability of a certain damage state, given the manifestation of the hazard zone. Mathematically, the two are treated as identical. 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 100% property destruction; between 10% and 60% of maximum hazard zone produces no fatalities—injuries only, and 50% property destruction; etc.

The probability of the hazard distance and the probability of various damages states are both captured in the probability number assigned to the distance. So, a hazard zone distance of 1000 ft with a 1% probability embodies the belief that there is only a 1% chance of a threshold extending this far, and, if it does reach this distance, damages will only be 1% of what they would be immediately adjacent to the centroid.

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—thresholds—will decrease as distance from the event increases. When establishing threshold zones, the modeler should keep in mind that actual intensities of thermal events—usually the events of most interest—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 overland. The rate of drop in damage potential with increasing distance might be receptor- or threshold-dependent.

## 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 corresponding 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) injuries could occur in the event of a subsequent vapor cloud explosion. Sources of conservatism in this fixed 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 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 hazard zones for vast majority of pipeline release scenarios. 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 depressure 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.

## ***V. Estimating Consequences***

The key ingredients for the consequence assessment proposed here are:

1. Scope of assessment
2. Thresholds
3. Hazard zones
4. Receptor characterizations
5. Consequence reduction measures
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 along a pipeline are:

1. Estimate all possible threshold distances and associated probabilities.
2. Produce zones based on distances in step one.
3. Associate damage states with each distance zone
4. Characterize receptors within each zone.

### **Step 1**

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 9 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.

Depending on the PoF analysis, the entry point into this CoF analysis can be either the relative hole size distribution or an ‘absolute’ hole size distribution. The former is illustrated here—the hole size distribution representing 100% of all possible failures; the relative chance of a certain size hole, given that some hole is present. The latter implies that several hole



sizes have a specific probability of occurrence already estimated in the PoF assessment—there is a calculated probability of rupture, a calculated probability of a pinhole, and so forth.

## Step 2

Compile all distances and group them into categories. For example, suppose that threshold effect distance estimations using the 9 permutations in the example of step 1 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 groupings such as:

| 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. This implies no differences in potential damages at the closest and farthest point of the zone. So, 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.

In this 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 grouping or zone will have a probability comprised of the probabilities of all the individual scenarios that can produce a threshold distance that falls in the zone.

Each zone represents a collection of numerous potential damage thresholds. There are no sharp demarcations between possible zones. 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 graphical presentation of the various thresholds associated with various scenarios will help the modeler to establish zones and associated probabilities.

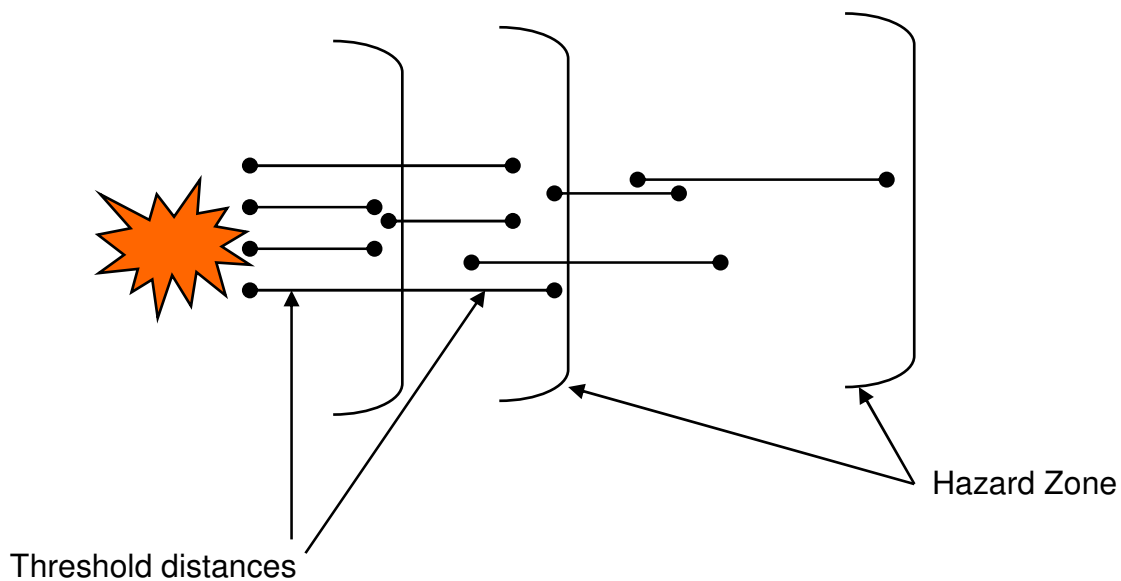


Figure 1 Visualizing Ranges of Thresholds and Setting Zones

This grouping of hazard distances is for 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.

As is illustrated in Figure 1 above, there are some scenarios in the farthest zone that produce no impacts in the closest zone. For instance, a scenario where leaked product moves 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.

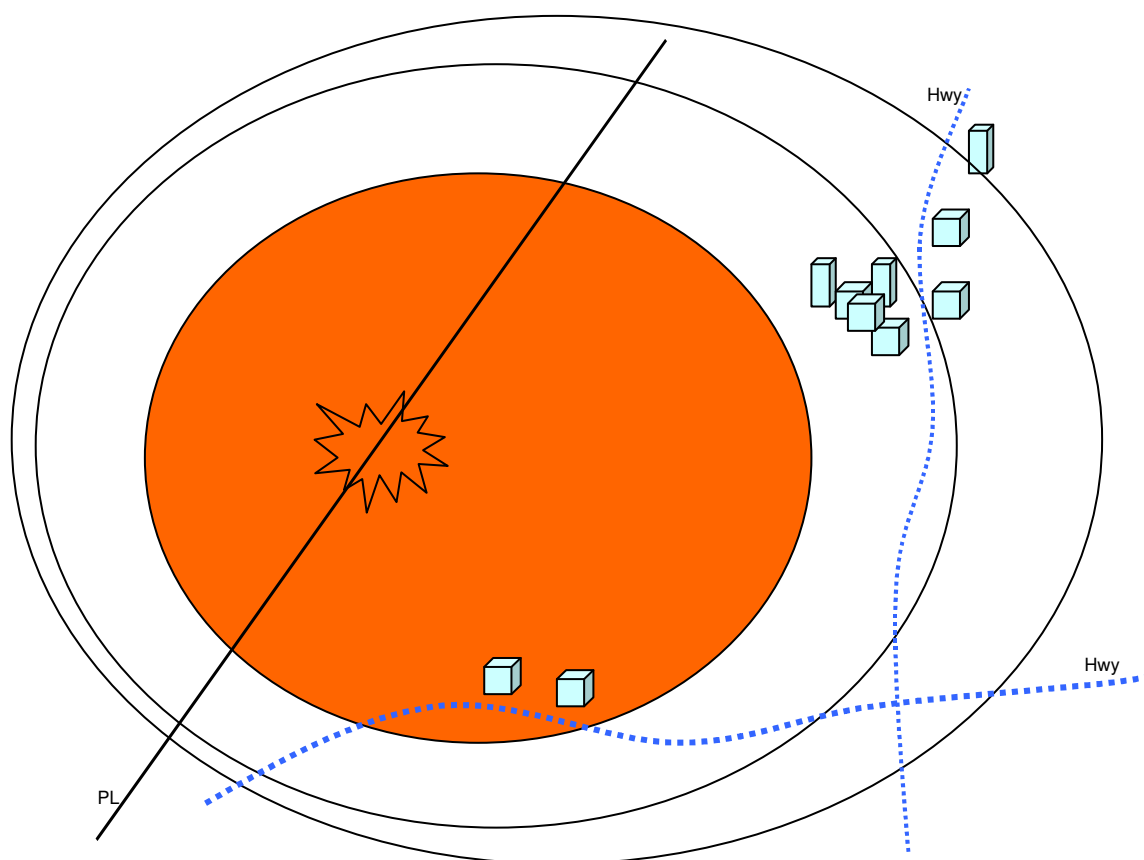
In many cases, a circular hazard area is a fair representation. However, given certain topographies and/or meteorological phenomena, ellipses or other shapes might be more representative of true hazard areas.

### Step 3

Characterize the types of damages to each receptor type that may occur in each zone. Characterization can be in terms of percentage of maximum damage 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.

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 at 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.



#### Step 4

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 or receptor damage state. A unit can be assigned a fixed dollar value—the cost of remediation 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—for some thresholds. 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.

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 an uncleanable aquifer at 15. A dollar value can be assigned to an environmental unit. These are value judgments best established by knowledgeable environmental specialists along with company managers.

Steps 3 and 4 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 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.

#### Step 5

Combine the results from previous steps into a 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.

## ***VI. 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. Most acute events offer little or no reduction opportunities since the largest hazard zones tend to occur immediately after release and then improve over time.

If a reduction measure can reduce the size of the hazard zone, then fewer receptors can be exposed and consequences will be lower. The hazard zone can often be reduced through changes such as pressure reduction, secondary containment, and/or changes to the product stream. Leak detection and emergency response can also play a role but usually cannot significantly change the size of a thermal hazard zone. In the case of chronic hazards, if a small release is detected before a contamination plume can become larger or migrate to additional sensitive receptors, the hazard zone is reduced. Additional opportunities, less common for pipelines, include fire suppression systems

Reduction measures are valued in the same way as mitigation measures in PoF. 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’?

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 should also be included. Shielding and reduction in exposure time (perhaps through rapid evacuation) are examples of protection opportunities for human

receptors. For example, an analysis that considers population mobility should probably 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.

## VII. 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.

|         |           |                     |                   |                                  |                           | Threshold Distances (ft) |                  |                      | Maximum Distance (ft) | Probability of Maximum Distance |
|---------|-----------|---------------------|-------------------|----------------------------------|---------------------------|--------------------------|------------------|----------------------|-----------------------|---------------------------------|
| Product | Hole Size | Probability of Hole | Ignition Scenario | Probability of ignition scenario | Distance from source (ft) | Thermal impact           | Overpress impact | Contamination Impact |                       |                                 |
| 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%                          |

Table 1 Establishing Hazard Zone Distances and Probabilities

|           |                   |                       |                                 |  |          | unit cost          | unit cost            |                 | unit cost            |  |
|-----------|-------------------|-----------------------|---------------------------------|--|----------|--------------------|----------------------|-----------------|----------------------|--|
|           |                   |                       |                                 |  |          | \$100,000          | \$3,500,000          |                 | \$ 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 2 Estimating Expected Loss from Hazard Zone Characteristics

*Table Notes*

*See Table 5 for expected loss per mile year*

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

Table 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. 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. They sum to 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  $1\text{E-}6$  per mile-year, then the probability of a rupture is estimated to be 8% of that value or  $0.08 \times 1\text{E-}6 = 8\text{E-}8 = 0.000008\%$  chance of rupture for each mile for each year. This also suggests  $8\text{E-}8$  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 hole 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 ignition site, 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, 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 will probably want 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, to arrive at an absolute probability of each scenario. In the example tables,



though, scenario probabilities assume that the pipeline failure has already occurred. Therefore, scenario probabilities sum to be 100%.

Table 2 repeats some information from Table 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 such as shown in Figure 2 can be helpful. This grouping into zones is a modeling convenience that avoids having to perform receptor characterizations at too many distances. In the example, PIR is set at 1500 ft and the zones are defined as “less than 100 ft”; “from 100 ft to 50% of PIR (or 750 ft)”; and “from 50% PIR to 100% PIR (or 750 ft to 1500 ft)”.

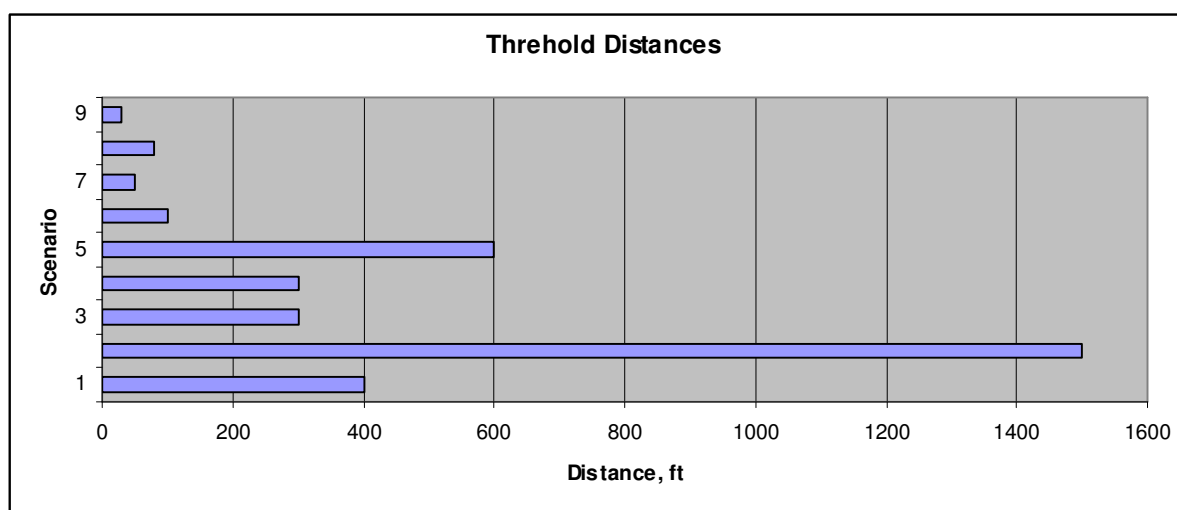


Figure 2 Visualizing Hazard Zone Distances

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 3.

| 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%                       |

Table 3 Damage State Estimates for Each Zone

Damage percentages are assumed to be 0% at distances beyond the 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 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 used 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, in this area, 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.

| 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                              |

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

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 should be carefully set and fully documented.

Information in tables 3 and 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) =  $4.8\% \times 5 \times 50\% \times 30\% \times \$100,000 = \$3,600$  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 expected loss from all pipeline 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 (\$166K per mile per year) x ( $10^{-3}$  failures per mile-year) = \$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 5.

| Expected Loss                               |  |  |  |
|---|--|--|--|
| Failure Rate<br>(failures per<br>mile-year) | Probability of<br>Hazard Zone <sup>1,2</sup> | Probability weighted<br>dollars <sup>2,3</sup> | Probability<br>weighted dollars<br>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  |
|   | <b>100.00%</b>                               | <b>\$165,660</b>                               | <b>\$54.59</b>                                   |

Table 5. Final Expected Loss Values

*Table Notes*

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

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 this segment can be combined with all other segments' expected losses to arrive at an expected loss for an entire pipeline or pipeline system. So, while \$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.

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 produced by this evaluation. The point estimates show the range of risks and can themselves be compiled into a single estimate for the entire range of possibilities.

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.

## **VIII. Additional Modeling**

### Recognized shortcuts

The consequence modeling at a more sophisticated level will include representations that go beyond simple point estimates. The range of possibilities for all pertinent variables must be understood and accounted for in producing the risk estimates.

A more robust assessment requires a full characterization of the receptors that could be damaged by a pipeline spill or release. For human population, this means knowledge of density of people at varying distances (and shielding scenarios) from the pipeline and perhaps even density of subgroups of that population; i.e. pregnant women; those with compromised immune systems, etc. The density would be a function of time of day, day of week, time of year, type of surroundings—workplaces, residential, shopping, roadways, etc. Shielding effects would ideally consider not only indoor versus outdoor exposure, but also type of buildings, availability of barriers when outdoors, and types of clothing normally worn.

Multiple dispersion scenarios are needed to fully characterize the hazard zones.

More rigorous hole-size distribution assessment based on factors such as pipe toughness, initiating mechanisms, stress level, material defects, rate of loading, etc.

## **IX. 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*, 3<sup>rd</sup> 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

## **X. Appendix A Damage Thresholds**

Reference 1 proposes a simple calculation to determine hazard zones from natural gas pipeline ruptures. These calculations are supported by empirical evidence and indicate that the hazard zone is directly proportional to release rate which in turn is a function of several factors including molecular weight and specific heat of the product.

The radiant heat intensity threshold of 5,000 BTUs/Ft/Hr was also established based on industry accepted release model results (ref 1). This heat intensity corresponds to a predicted 1% mortality rate for people, assuming they are exposed for 30 seconds while seeking shelter after the rupture, and no non-piloted ignition of wooden structures regardless of the exposure time.

Recognized thermal load vs. effect models estimate that a burn injury will occur within 30 seconds of exposure at a heat flux of 1,600 to 2,000 BTU/hr/ft<sup>2</sup> (5.0 to 6.3 kW/m<sup>2</sup>). At a radiant heat intensity of 5,000 BTU/hr/ft<sup>2</sup> (15.8 kW/m<sup>2</sup>) the likelihood of a fatal burn injury within this exposure period becomes significant (1%), where 1 in 100 people exposed would not survive.

Various wood ignition models have been used to estimate the steady-state effects of thermal radiation on property based on the duration of exposure required to cause piloted and spontaneous ignition. These models conservatively establish a radiant heat intensity threshold of 4,000 BTU/hr/ft<sup>2</sup> (12.6 kW/m<sup>2</sup>) for piloted wood ignition and a 10,000 BTU/hr/ft<sup>2</sup> (31.6 kW/m<sup>2</sup>) threshold for spontaneous wood ignition. At 8,000 BTU/hr/ft<sup>2</sup> (25.2 kW/m<sup>2</sup>) spontaneous ignition is very unlikely, but after 38 seconds in the presence of a pilot source there will be piloted wood ignition.

These wood ignition models are considered very conservative because an actual worst-case pipeline rupture would be a transient event with the highest radiant heat intensity being reached very shortly after ignition, then decaying with time due to the reduction in pipeline pressure. The initial release radiant heat intensity and decay time depends on the pipeline diameter, operating pressure, failure configuration, recognition time, response time, location of isolation valves and length of isolated segment.