Probabilistic Risk Assessment (PRA) for Natural Gas Assets

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Abstract: Probabilistic Risk Assessment (PRA) techniques are widely used in highly regulated environments such as aerospace and nuclear. Decades of risk management in the nuclear industry have brought the industry to the development of tools and programs aimed at assuring safety and to efficiently manage operation at the plant, with risk-informed programs aimed at optimization of test, inspection, maintenance and outages.

PRA failure metrics are re-envisioned to expand applicability to other industries and PRA techniques can be applied to quantify different kinds of risk that addresses high to low consequence events and high to low frequency events. For example a natural gas distribution system might be concerned with accidents that may lead to a number of undesirable outcomes such as Degradation of Assets, Loss of Inventory, Loss of Service to Customer and Loss of Life or Injury.

PRA models can be developed to quantitatively address any and all of these potential end states important to the customer. Once quantified, insights can be obtained to enable risk management of these undesirable end states.

Piping is a critical component in natural gas systems and assets. Typically, pipe break data is available and broken down by a failure mechanism (Corrosion, manufacturing defects, excavation), but the mapping of the piping systems does not quantitatively relate piping conditions/history with a revised failure frequency, nor is there a consistent means of evaluating the probabilistic risk impacts of piping segment and component failures. While some level of knowledge of which pipe conditions lead to more adverse outcomes exists, many approaches are employed to quantify risk insights. Mapping the drivers for piping segment and component failures to consequences and ranking those consequences on a consistent basis would help natural gas companies obtain more useful insights from their risk modeling and prioritize activities based on defined risk or performance metrics.

Keywords: Non-Nuclear, Natural Gas, Pipe Break, Piping, Maintenance Optimization

1. INTRODUCTION

Natural gas utilities route tens of millions of gas lines throughout the United States. While these gas lines provide a valuable energy supply to meet heating and cooking needs of millions of Americans, not unlike many industries, the generation, transport/delivery and distribution of the natural gas poses risks. However, unlike other hazardous plants, the transmission pipelines carrying natural gas are not only within secure industrial sites, but are often routed across publicly accessible land not owned by the pipeline company. Many of these sites are in heavily urbanized areas. Consequently, risks resulting from natural gas events can affect users and non-users alike. Analyses demonstrate that should natural gas be accidentally released

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and ignited, the hazard impact radius can vary under 20 meters for a smaller pipeline at lower pressure, up to over 300 meters for a larger one at higher pressure. The human and economic impact of such events can be devastating. Therefore, pipeline operators and regulators send considerable resources in addressing the associated public safety issues.

While the gas utility has a wealth of information in understanding risks of generation, delivery and distribution and many programs to limit/control risks, accidents continue to occur. Many events occur in rural areas with minimal collateral damage, and some random events are unpredictable and unavoidable. However, the authors believe that experience suggests that a number of events could have been avoided or potentially have consequences mitigated given the proper integration of system design, distribution and human factor insights.

This paper focuses on a conceptual design of natural gas system consequence assessment tool. The intent of the tool is to integrate analysis process to collect data and manage operational activities in a "risk-informed" manner to both improve company economic business metrics while reducing public risks. The concept of "risk-informed" system management is largely taken from the nuclear industry. In the natural gas operational environment it is envisioned that such a system would integrate utility operations, risk important equipment and instrument reliability, the utility Pipeline Open Data Standard (PODS) system for piping conditions/leak integrity and conditions and population density and economic data in the Graphical Information System (GIS) with a risk assessment module. The intent of such a system is to introduce a planning and event management tool that can be used to prioritize company maintenance activities and potentially optimize installation/repair and optimization teams in a "risk-informed" manner.

2. RISK INFORMED OPERATION IN THE NUCLEAR INDUSTRY

Risk Informed regulation has been evolving in the United States and worldwide nuclear industry as a means of improving the regulatory and industry decision making process involved in safety. In the nuclear industry the risk informed approach aims to integrate in a systematic manner quantitative and qualitative, deterministic and probabilistic safety considerations to obtain a balanced decision. In particular, this process includes explicit consideration of both the likelihood of events and their potential consequences together with such factors as good engineering practice and sound managerial arrangements.

The transition from deterministic regulations to a risk informed strategy has contributed to a reduction in initiating events and risk metrics (see Figure 2-1) as well as improvements in plant availability and reduction operating costs. In the nuclear industry the primary tool supporting the risk informed environment is the probabilistic risk assessment (PRA). This tool integrates plant design and operational information and human reliability assessments in a manner to quantitatively track plant risks. Most nuclear plants in the United States include on-line plant PRA models to manage risk on a contemporaneous basis.

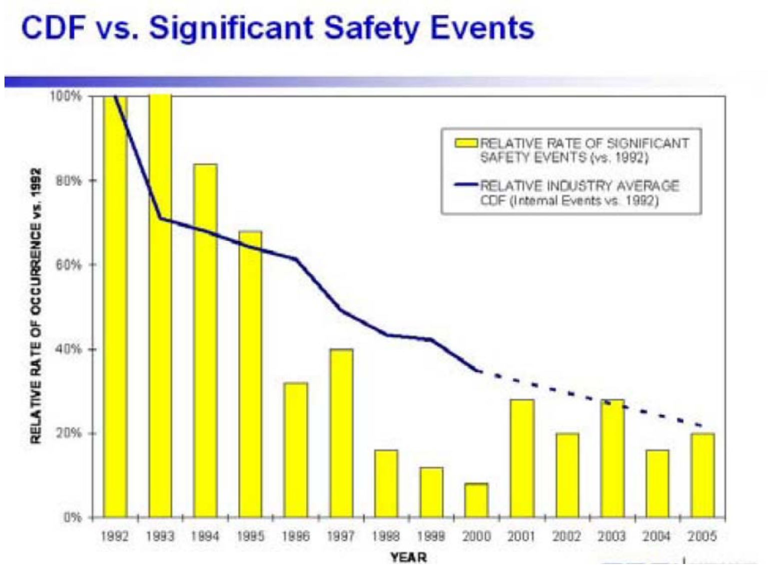

Figure 2-1: CDF vs. Significant Safety Events

While natural gas systems are less complex than nuclear units, risk informing system-wide operations can, over time, provide similar benefits to the utility, consumer and the public-at-large. The authors believe that analogous, but simpler on-line models can help realize similar benefits with modest investment and limited scope safety-focused applications.

3. OVERVIEW OF CONSEQUENCE ANALYSIS TOOL

Gas utilities programs consider risk at various levels. However, for the most part these programs are not integrated and do not benefit from a consistent framework. In the proposed framework the utility piping network as identified in PODS and the regional demographic and socio-economic data as capture in GIS are integrated with a risk module.

Figure 3-1 provides a high-level overview of the Gas System consequence assessment tool (CAT). The overall CAT consists of three basic constituents: PODS piping data, GIS framework and a gas event consequence assessment module (GECAM). PODS and GIS are already in use by many gas utility companies.

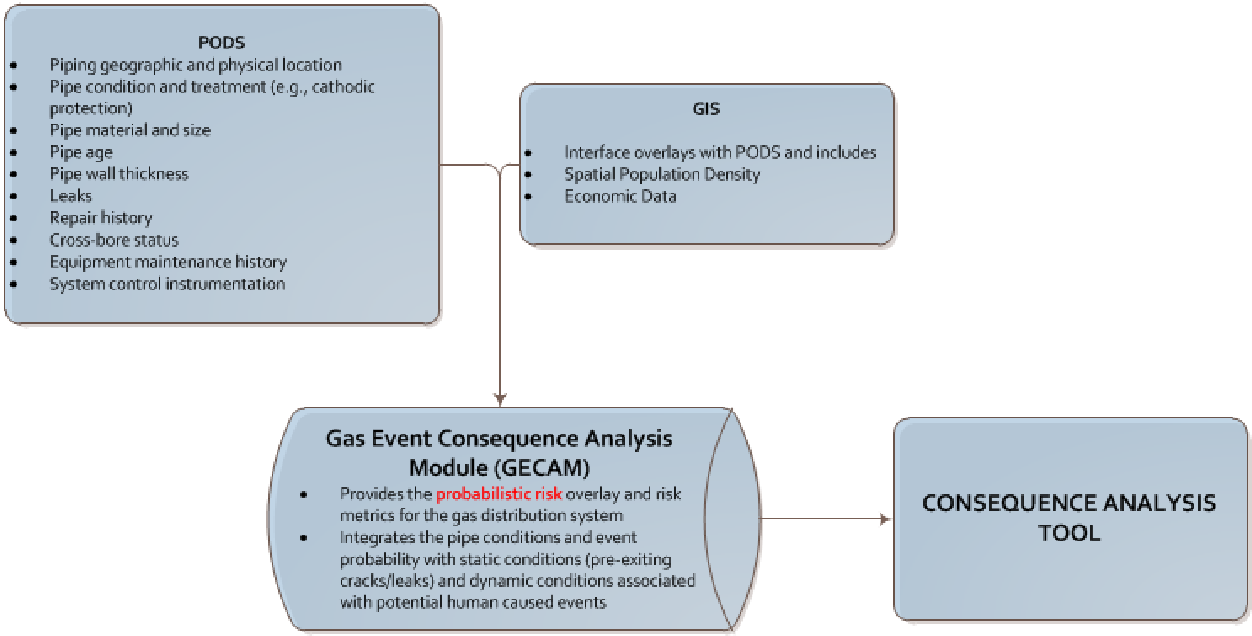

Figure 3-1: Consequence Analysis Tool Overview

3.1 Pipeline Open Data Standard (PODS)

The PODS is a data structure that allows for compiling and storing various pipeline parameters. PODS is presented as a database schema for use in both proprietary and open source SQL architecture.

The information of interest stored in PODS includes:

1. Piping geographic and physical location
2. Pipe condition and treatment (e.g., cathodic protection)
    a. Pipe material and size
    b. Pipe age
    c. Pipe wall thickness
    d. Leaks
    e. Repair history
    f. Cross-bore status
3. Equipment maintenance history
4. System control instrumentation
5. Regulatory Compliance information
6. Neighboring Physical Infrastructure Information including:
    a. Bridge Crossings
    b. Major transportation arteries
    c. Water and Waste Infrastructure

3.2 Graphical Information System (GIS)

GIS is comprised of geospatial layers, that contain various parameters tagged to their geolocation, that are layered to generate advanced geo-metrics for sample locales. GIS is comprised of an analysis engine (ESRI's ARC, QGis, etc.) connected to a database housing spatial information in tabular format (SQL).

A GIS project is comprised of base maps (showing state, county, and town, etc. delineations), to which any other information may be tied down to their location (e.g., tying population to geographic locations, or identifying proximity between pipelines and road ways, etc.). Using these tied information layers, spatial analyses can be generated.

Within the CAT GIS is used as the repository of PODS, such that PODS features (pipeline, valve, crossing, etc.) are tied to specific locations within GIS.

The GIS interface includes:

1. Spatial population density
2. Economic data
3. Physical Infrastructure
4. Governmental delineations (state, town etc., boundaries)

3.3 Gas Event Consequence Analysis Module (GECAM)

The purpose of the GECAM is to provide the probabilistic risk overlay and risk metrics for the gas distribution system on either a static or dynamic (contemporaneous) basis. To accomplish this the GECAM integrates the pipe conditions and event probability with static conditions (pre-exiting cracks/leaks) and dynamic conditions associated with potential human caused events with a consequence tool characterizing potential event outcomes (i.e., fireball, vapor cloud explosion, detonation). These models and a discussion of GECAM potential risk metrics are discussed below.

3.3.1 Static Risk Model

3.3.1.1 Approximation of Pipe Failure Probability

The static pipe failure module includes conditional pipe failure probabilities and failure impact assessments. This module establishes the likelihood and physical consequences of a pipe segment. Data supporting these models is presently based on generic analyses. Pipe failure frequency information used in the present model is based on information presented in Reference [1] and illustrated in Figure 3-2. This information may be updated by reference to other pipe failure studies and Bayesian updated by utility specific experience regarding pipe leaks.

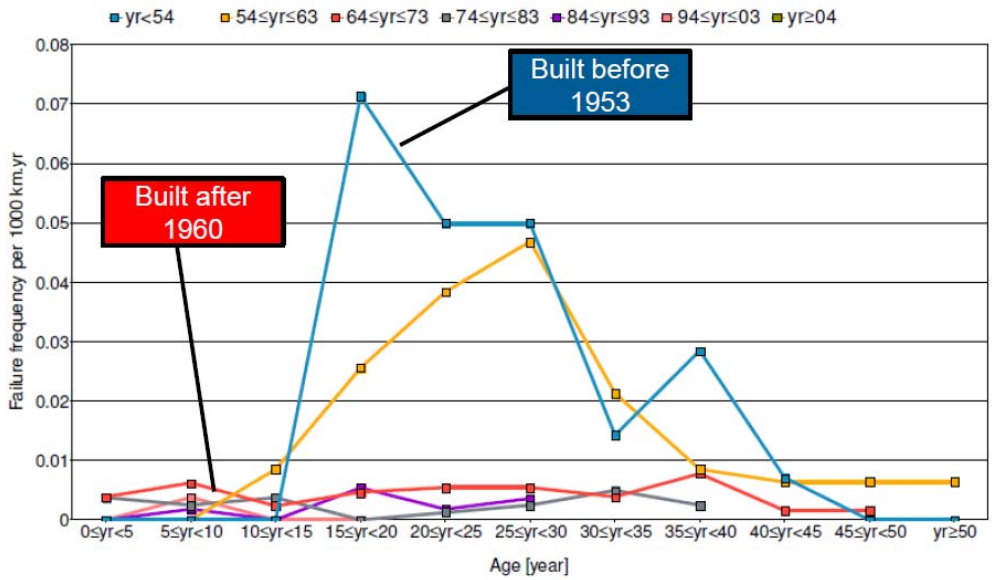

Figure 3-2: Pipe Failure rate for representative large diameter piping

To simply analysis in the example product the following is assumed in Table 3-1.

Table 3-1: Representative Pipe Failure Rates

Pipe Initially installed (year)	**Failure Frequency per 1000 Km/yr.**
Prior to 1953	0.030
Between 1953 and 1963	0.008
Between 1964 and 1983	0.005
After 1983	0.002

Reference [2] Tables 10, 14, 19 and 22 were used to derive the pipe failures associated with various failure mechanisms, summarized below in Table 3-2.

Table 3-2: Fraction of Pipe Failures Associated with Various Failure Mechanisms

Failure Mechanism	**Pipe Diameter (mm)**			
	<203	**203< 305**	**305<405**	**>406**
Mechanical Failure	0.043478	0.043478	0.026087	0.026087
Corrosion	0.017391	0.06087	0.06087	0.026087
Ground Movement	0	0.008696	0.026087	0.008696
Third Party Activity (TPA)	0.121739	0.365217	0.078261	0.086957

The overall local failure probability due to natural causes and random mechanical /corrosion failures is defined as:

$$P_f(I,J,K,M) = \lambda_D(I,J,K,M) * F(M,I,J) * L(I,J,K) * \Delta T(I)$$

Where,

$P_f(I,J,K,M)$ is the probability of failure of pipe segment *I* of pipe with an age in category *K* and diameter range *J* and Failure mode *M*,

$\lambda_D(I,K)$ = the failure rate of pipe in segment *I* and age range *K* (see Table 3-1) (per km/per year),

F(M,J) = failure contribution due to failure mode, *M*, and pipe diameter range *J* (see Table 3-2),

L(I,J,K) is the length of the pipe in segment *I* with diameter range *J* and age range, *K* (km),

and ΔT is the duration in years from the last inspection (years).

Given the Pipe failure defined above, Table 3-3 can be used to estimate gas release during a failure. Analyses also indicate that given a failure the effective consequences can be established by noting an approximate ignition probability of the release for < 406 mm diameter leaks is ~0.1 and for pipe ruptures the ignition probability is on the order of 0.33 coupled with the gas release event tree presented in Figure 3-3.

Within each category of pipe failure, the size category of the pipe failure may be estimated from the following Table 3-3 as S (N,M,I,J), where *N* represents the failure pipe range according to the following:

N=1: pinhole leak; N=2: small leak; N=3: large leak; N=4: Rupture (catastrophic)

Thus, the probability of failure of pipe segment *I*, resulting in leak of size category *N* due to failure mode *M* becomes:

$$P_f(I,M,N) = \sum_{\substack{K=1 \\ J=1}}^{\substack{K=3 \\ J=4}} \lambda_D(I,J,K,M) * F(M,I,J) * L(I,J,K) * \Delta T(I) * \mathrm{I}(J,K)$$

In the above *I*(*J,K*) is an indicator function which equals 1 for all positive entries of *L*(*I,J,K*) and 0 otherwise.

Table 3-3: Leak/Rupture Distribution Given Pipe Failure (Derived from Reference [2])

Failure Mechanism	**Pipe Diameter (mm) <203**			
	Pinhole Leak	**Small Leak**	**Large Leak**	**Rupture**
Mechanical	0.2	0.4	0.4	0
Corrosion	1	0	0	0
Ground Movement	0	0	0	0
TPA	0.357143	0.321429	0.321429	0
Failure Mechanism	**Pipe Diameter (mm) 203<D<305**			
	Pinhole Leak	**Small Leak**	**Large Leak**	**Rupture**
Mechanical	0.2	0.3	0.3	0.2
Corrosion	0.142857	0.357143	0.357143	0.142857
Ground Movement	0	0.5	0.5	0
TPA	0.142857	0.392857	0.392857	0.071429
Failure Mechanism	**Pipe Diameter (mm) 305<D<406**			
	Pinhole Leak	**Small Leak**	**Large Leak**	**Rupture**
Mechanical	0	0.5	0.5	0
Corrosion	0.285714	0.357143	0.357143	0
Ground Movement	0	0.166667	0.166667	0.666667
TPA	0.333333	0.222222	0.222222	0.222222
Failure Mechanism	**Pipe Diameter (mm) D>406**			
	Pinhole Leak	**Small Leak**	**Large Leak**	**Rupture**
Mechanical	0.666667	0	0	0.333333
Corrosion	0.333333	0.333333	0.333333	0
Ground Movement	0	0.5	0.5	0
TPA	0.3	0.15	0.15	0.4

3.3.1.2 Impact of Gas Release

Section 3.3.1.1 provides a means to estimate the probability of a pipe failure of size category *N* in the utility gas distribution/transmission system. In order to assess the impact of the failure, it is useful to know the likelihood of the consequential event and the approximate area that can be affected by the various release consequences. Figure 3-3 provides a simple event tree illustrating the impact of various gas release end states. In this simple model four (4) end states are defined: fire ball (FB)/jet fire, flash fire (FF), vapor cloud explosion (VCE) and no hazard.

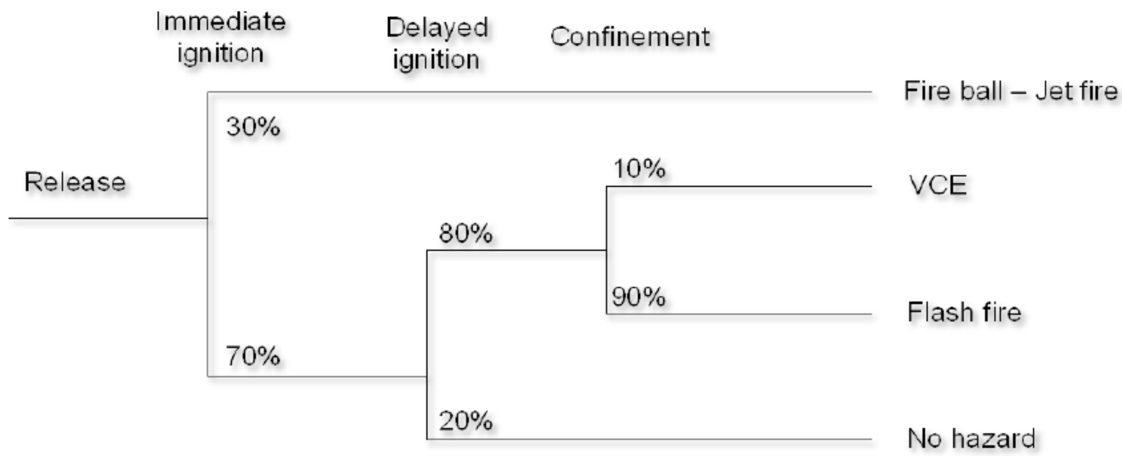

Figure 3-3: Natural Gas Pipeline Event Tree

In the above event tree, immediate ignition would result in a fire ball or jet fire. A delayed ignition can result in a VCE or Flash fire depending on if the release is confined and if there is no ignition source then there is no hazard in this example. The fire ball and flash fire end states *f* result in high flux radiative sources causing burns and fatalities to nearby individuals and fire and radiative damage to surrounding areas. A VCE causes both pressure induced and fire related challenges to both people and property. VCE loads can be severe causing potentially devastating damage.

The physical impact of the various events have varying impact radii based on pipeline gas pressure and type of challenge. Radiation fluxes of these events are significant and the impact is likely affected by event duration. An example estimate of the impact of various fire is presented in Figure 3-4. Fireballs typically have little impact beyond 500 feet from the release. Flash fires are more substantial and can have a significantly greater impact radius.

VCEs vary in impact based on the amount of energy in the vapor cloud. The energy content of the vapor cloud can be approximately estimated in pounds of TNT. A typical impact chart for a VCE is included in Figure 3-5. Note that the radius of the VCE is also influenced by contemporaneous weather conditions which can affect gas cloud transport. Estimates for the impact distance of vapor cloud explosions is captured in various regulatory environments. Regulations in the nuclear industry estimate the impact distance of explosions in accordance with Regulatory Guide 1.91, [3]. Which relates the blast impact distance of a vapor cloud explosion to an effective TNT equivalent of a vapor cloud. Typically, this results in an equation for the blast radius of a VCE of the form:

$$R = KW_{TNT}^{\frac{1}{3}}$$

Where,

R is the distance to the blast overpressure defined at a specific pressure (typically 1 psi)

W_{TNT} is the equivalent effective energy in the vapor cloud available for explosion (evaluated in accordance with Reference [3])

K is the constant associated with stipulation of the blast distance.

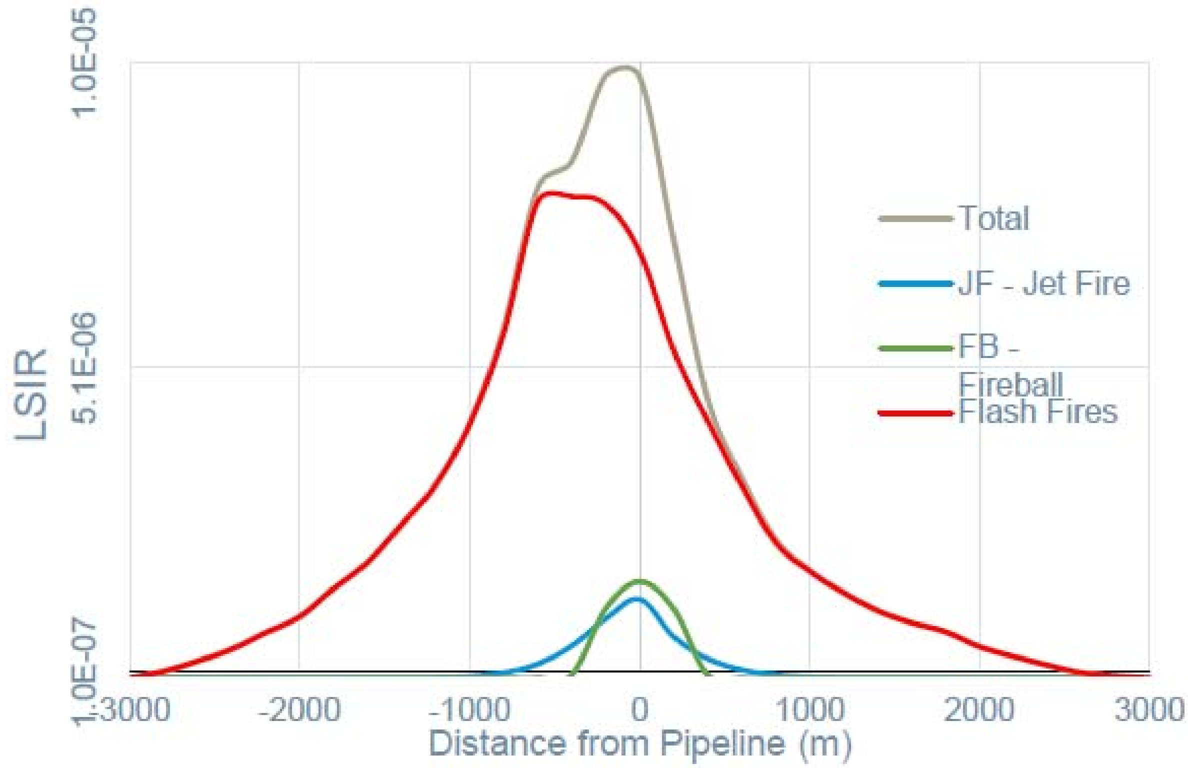

Figure 3-4: Location Specific Individual Risk (LSIR) for Various Fire End States

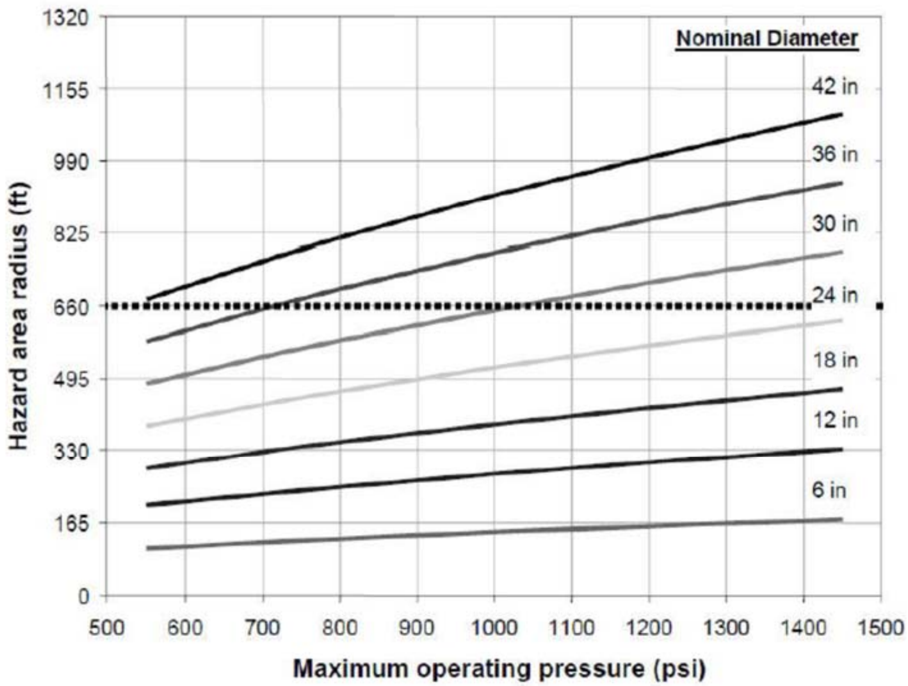

Figure 3-5: Example Chart for High Consequence Areas for Natural Gas Pipelines Operating Above 500 psig (Reference [4])

Overall, the above strategy can estimate the risk of pipe failure throughout the utility gas network. As the impact is not tied to actual activities, the risk matrix is generally static and may evolve over time as piping is replaced and new transmission and distribution lines installed and surveillance processes change.

3.3.1.3 Discussion of Impact Radius

The impact radius determined from the above relationships and graphs reflect a point source event. In that circumstance the impact area is simply estimated as πR^2. For the point estimate to be meaningful, the length of pipe involved in the probability risk calculation should be small compared to the overall impact distance.

3.3.1.4 Example Ranking Metric

The above estimates may be used to overlay the impact area on the distribution system grid and regional demographics. To complete this assessment, it is useful to estimate the real consequences of a natural gas event in terms of number of fatalities, number of individuals with serious burns, and surrounding economic impact in damage to buildings, contents and adjacent infrastructure. These estimates can be quite complex. Such assessments may be available from the insurance industry. In this example a simplified metric is used which reflects event severity, population density and high-level local economics subject to the illustrative assumptions in Table 3-4.

Table 3-4: Illustrative Assumptions for a Simple Economic Metric(Note 1)

Impact/Consequence	Jet/Fireball	Flash Fire	VCE 1	VCE 2
Fatalities	[1E-06]*ρ*A_{impact}	[1E-05]* ρ*A_{impact}	[1E-04]* ρ*A_{impact}	[1E-04]* ρ*A_{impact}
Serious Burns	[1E-05]* ρ*A_{impact}	[1E-04]* ρ*A_{impact}	[1E-03]* ρ*A_{impact}	[1E-03]* ρ*A_{impact}
Real Estate Damage ($)	[0.05]*V1(RFB)	[0.1]*V1(RFF)	[0.75]*V1(RVCE)	[0.9]*V1(RVCE)
Economic Activity/Business ($)	[0.0005]*V2(RFB)	[0.005]*V2(RFF)	[0.25]*V2(RVCE)	[0.50]*V2(RVCE)
Cost of Interruption per hour (CPH) per client ($/HR)	$[0.5]	$[0.5]	$[0.5]	$[0.5]
HRS_SERVICE Interruption (HRS_INT)	12	24	48	48
Service Interruption cost	CPH*HRS_INT*Nc	CPH*HRS_INT*Nc	CPH*HRS_INT*Nc	CPH*HRS_INT*Nc
Reputation Impact	[x1] if burn victims; [x2] if fatalities	[x1] if burn victims; [x2] if fatalities	[x3] if burn victims; [x4] if fatalities	[x3] if burn victims; [x4] if fatalities
Cost per Fatality ($)	[1E+06]			
Cost per Burn Victim ($)	[1E+05]			
Nc-Number of Clients affected by loss of Service	Variable			
x1,x2,x3,x4	[$100,000; 500,000; $1 x 10^6; $5 x 10^6]			
Incremental pipe length for point analysis	Variable			

Note 1: The values within brackets are provided as an representative example for the conceptual application of the tool. Note that actual values will be specific to the utility, region and situation being assessed and these will change for future and actual applications of the tool.

Where,

P = population density per square mile
A_{impact} = impact area
V1 (X) - Real Estate Value in Radius X
V2 (X) - Business Activity per year in Radius X
RFB/RFF/RVCE = effective impact radii of gas ignition events
X = RFB = 250 ft; RFF = 1000 ft; RVCE1 = 1500 ft; RVCE2 = 2500 ft
CPH = lost revenue per hour due to interruption of service

3.3.2 Dynamic Risk Model

The above model is intended to reflect the static risks of the utility piping system. In addition to static risks, maintenance, repair and installation activities include additional risks to the interruption of services and public risks. These risks are considered transient and have a dynamic character. In evaluating these risks, one needs to assess the risk of these utility operations. This includes a risk assessment of utility procedures and implementation and training practices.

The dynamic model follows the same structure as the static model with the following exceptions:

1. A failure modes and effects analysis is performed on activities to ensure all potential failure modes and consequences are identified.

2. Failure modes will be assessed on a utility specific basis to include risks related to utility field activities. Experience in the nuclear industry indicates that risks of potentially risk sensitive activities should consider:
    a. Staff experience
    b. Complexity of task/use of heavy equipment
    c. Procedure quality
    d. Level of oversight/crew size
    e. Condition of system in need of repair
    f. Ability to isolate system during repair
3. Human factor insights will be used to establish human error probabilities. These techniques are well established in the nuclear industry and various process industries.
4. Industry/utility experience with past events.
5. Potential for creating hazardous conditions.
6. Availability of recovery actions.

While the function of the static tool is to identify high consequence areas to prioritize repairs, the dynamic tool is focused on identifying risk issues in advance and ensuring teams performing high risk actions in high consequence areas have appropriate pre-briefs, procedures, training and resources to minimize risk.

Given an assessment of the above, each field operation can be quantified with respect to the probability of an adverse failure modes. Such adverse failure modes may include a confined or unconfined gas release, or interruption of service to one or more individual clients. Using that as an initiating event and knowledge of the pipe size being maintained the base model should be able to estimate property damage at some level, injury to utility team member, injury to one or more or more members of the public, or one or more fatalities to public. An example maintenance risk table could look like the following as shown in Table 3-5.

Table 3-5: Risk of Field Operations per 1000 Km

File Operation Risk	Pipe Replacement Utility Team	Pipe Replacement Third Party Team
Unconfined Gas release-small	1×10^{-7}	1×10^{-6}
Unconfined Gas release-large	1×10^{-8}	1×10^{-7}
Confined Gas Release-small	1×10^{-10}	1×10^{-9}
Confined Gas Release-large	1×10^{-11}	1×10^{-10}
Loss of Service	1×10^{-5}	1×10^{-4}

4. CONCEPTUAL APPLICATION: RISK INFORMING PIPELINE REPLACEMENT

4.1 Segment Maintenance Prioritization

In the consequence analysis tool, US pipeline routing is overlaid with population and property value data from PODS and GIS. Then, industry probabilities and after effects can be applied from the GECAM estimates and this information can be used to postulate property loss and fatalities. Based on the output, maintenance activities can be prioritized.

The following example is for Flash Fires brought about by all types of leaks for natural gas pipelines in Massachusetts.

In this example, approximately 20,000 points along the pipeline is postulated. Each points radius is defined by type of emission (flash fire in this example). All population or property value within each point's radius is summed and then is multiplied by the appropriate multiplier from Table 3-4. Figure 4-1 presents a heat map for postulated fatalities from a flash fire for a given point on the map. Figure 4-2 presents another heat map but this time for total (building, land and other) property value loss. Note that because a total property loss was considered, these values have been scaled for more realistic impact values.

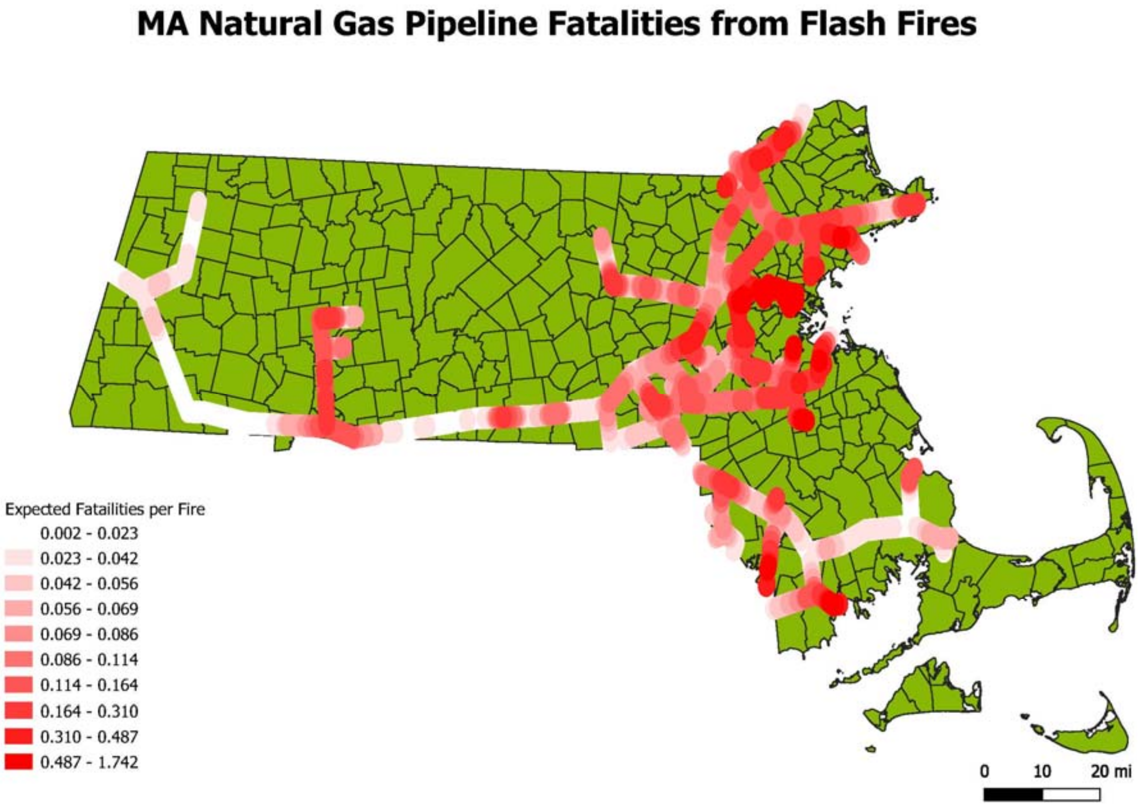

Figure 4-1: Massachusetts Natural Gas Pipeline Fatalities from Flash Fires

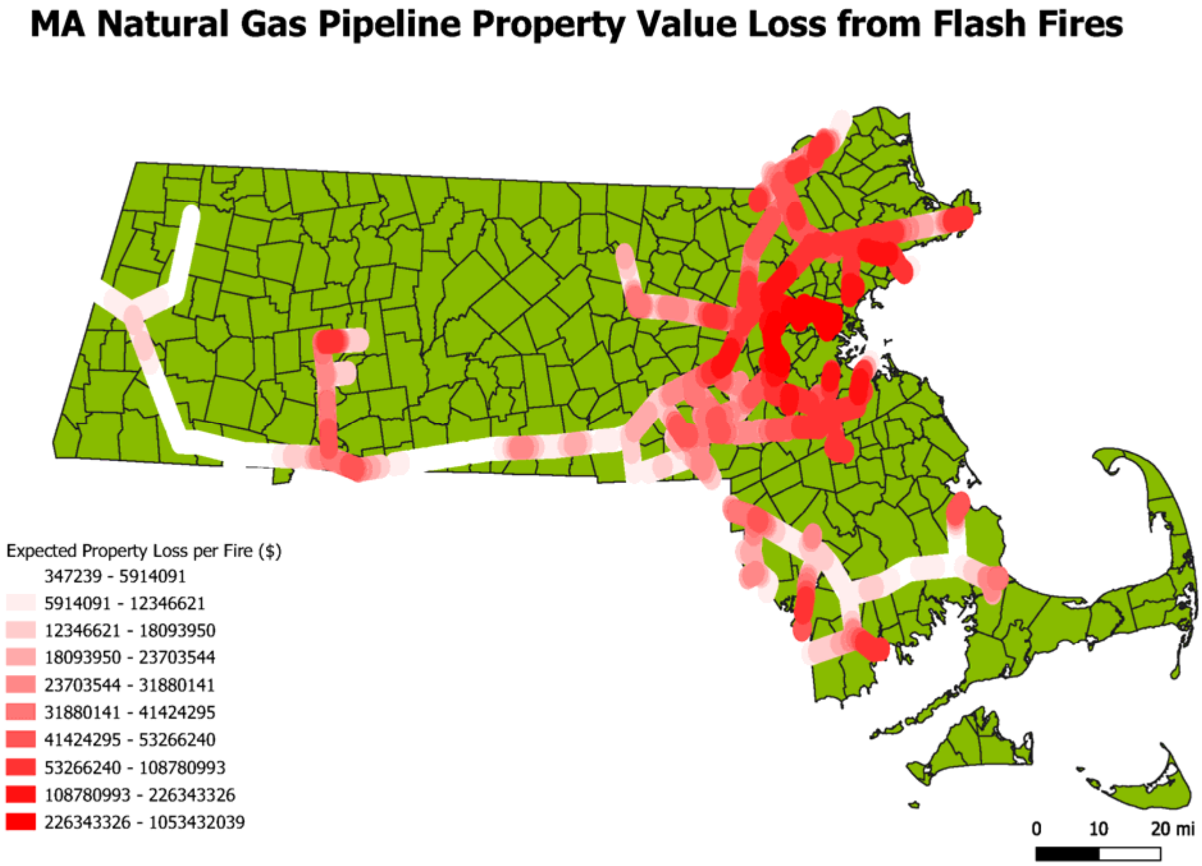

Figure 4-2: Massachusetts Natural Gas Pipeline Property Value Loss from Flash Fires

4.2 The Human Factor

Based on nuclear industry experience risk related planning of activities can substantially reduce maintenance risks by optimizing size, experience level and training of team for higher risk activities as well as conducting Pre-Job briefs to increase the attention to high risk steps, factoring in lessons learned, and enhancement of procedure quality.

When used in a proactive mode the tool provides the risk information useful in allocating company maintenance/repair resources and prioritizing system-wide maintenance and repair activities. For example, priority in maintenance for piping with pre-conditions would be given to those areas with the highest consequence based on the heat map figures developed by the tool. Similarly, use of third parties or less experience crews could be dedicated to areas with lower consequences. In addition, a basis for quantifying and ranking absolute and relative activity risks can be established and "high risk" activities can be identified at the planning stage, thereby providing potential to employ mitigating strategies prior to maintenance on the pipelines.

5. CONCLUSION

Natural gas utilities have available information in understanding risks of generation, delivery and distribution and many programs to limit/control risks accidents continue to occur. However, some of the events could have been avoided or potentially have mitigated consequences with risk-informed and human factor insights.

This paper discussed the development of a consequence analysis tool for use in the natural gas industry, specifically for management of their pipeline network assets. The consequence analysis tool includes static and dynamic management tools. The intent of the consequence analysis tool is to introduce a planning and event management tool that can be used to prioritize and improve company maintenance activities and potentially optimize installation/repair and optimization teams in a “risk-informed” manner to minimize undesired consequences. Maintenance activities can be optimized with respect to service interruptions and maintenance activities can be focused on components with high risk impact (public safety) and high impact on delivery services (economic). Reducing risk of an event improves utility image and reduces economic exposure from preventable hazards. The tool has been developed conceptually and data needs can vary and be modified based on the objectives of an individual utility. Additional specific information can include event history including near misses, system condition assessments for safety related equipment, procedures/training strategies, and economic models tied to corporate objectives.

6. REFERENCES

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