

Pipeline Risk Modeling

Overview of Methods and Tools for Improved Implementation

Pipeline and Hazardous Materials Safety Administration

May 9, 2018 (Draft 1)



U.S. Department of Transportation
Pipeline and Hazardous Materials
Safety Administration

"To protect people and the environment by advancing the safe transportation of energy and other hazardous materials that are essential to our daily lives."

4



Table of Contents

Executive Summary.....	5
I. Definitions & Acronyms	9
II. Introduction	14
A. Purpose of Document	14
B. NTSB Recommendations.....	14
C. Definition of Risk.....	17
D. Background	18
E. Risk Model Categories.....	19
E.1 ASME B31.8S Risk Assessment Method Categorization	22
III. Overview Information for Use of Risk Model Types	23
A. Selecting an Appropriate Risk Model.....	23
A.1 Moving from Qualitative or Relative Assessment/Index Models to Quantitative System or Probabilistic Models.....	26
B. Understanding Uncertainty and Critical Model Parameters	27
C. Validating Risk Analysis Results	28
D. Configuration Control of Risk Models.....	29
E. PHMSA Key Recommendations – Overview Information for Use of Risk Model Types	30
IV. Likelihood Modeling.....	31
A. Pipeline Threats	32
B. Selection of Approach for Representing Likelihood	33
C. Single Approach or Threat-Specific Approach	35
D. Human Performance Modeling.....	37
E. Interactive Threat Modeling	38
F. Threshold for Threat Consideration.....	43
G. Application of Risk Models to Identify and Evaluate Preventive Measures	44
H. PHMSA Key Recommendations – Likelihood Modeling.....	46
V. Consequence Modeling	46
A. Selection of Approach.....	48
A.1 Hazard.....	49
A.2 Volume.....	50

May 9, 2018 - Draft 1

- A.3 Dispersion 51
- A.4 Receptors 52
- A.5 Expected Loss..... 52
- B. Operator and Emergency Responder Response 53
- C. Application to Identification of Mitigative Measures 55
- D. PHMSA Key Recommendations – Consequence Modeling 56
- VI. Facility Risk Modeling..... 57
 - A. Comparison with Line Pipe Risk 57
 - B. Application to Preventive Measures and Mitigative Measures..... 60
 - C. PHMSA Key Recommendations – Facility Risk Modeling..... 61
- VII. Risk Modeling Data 61
 - A. Relation of Data to Risk Model Types 64
 - B. Data Sources 65
 - C. Data Quality and Uncertainty 69
 - D. SME Input..... 71
 - E. PHMSA Key Recommendations – Risk Modeling Data 73
- Appendix A – Likelihood Models..... 75
 - A.1 Qualitative Models..... 75
 - A.2 Relative Assessment (Index) Models 76
 - A.3 Quantitative System and Probabilistic Models..... 78
 - A.4 Probabilistic Models..... 81
- Appendix B – Consequence Models..... 83
 - B.1 Gas Transmission Consequence Models..... 83
 - B.2 Hazardous Liquid Consequence Models 86
- Appendix C – Facility Risk Models..... 88
- Appendix D – Migration from Older Risk Analysis Methods to Quantitative Models 92
 - A-D.1 Introduction 92
 - A-D.2 Applicability..... 92
 - A-D.3 Level of Effort..... 92
 - A-D.4 Definitions 93
 - A-D.5 Units of Measurement 94
 - A-D.6 Input Data 94

May 9, 2018 - Draft 1

A-D.7 Risk Assessment Results..... 95

A.D-8 Weightings 96

A.D-9 Uncertainty 96

A.D-10 Data Conversion..... 97

 A.D-10.1 CoF Data Sub-Categories..... 99

A.D-11 Algorithms..... 99

 A.D-11.1 PoF..... 99

 A.D-11.2 Time Independent Failure Mechanisms..... 100

 A.D-11.3 Time Dependent Failure Mechanisms 100

 A.D-11.4 CoF 100

A.D-12 Example..... 101

 A.D-12.1 PoF Excavator Contacts..... 102

 A.D-12.2 PoF Corrosion..... 102

 A.D-12.3 Total PoF 103

Appendix E – Regulatory Drivers..... 104

 E.1 Requirements for Hazardous Liquid Pipelines 104

 E.2 Requirements for Gas Transmission Pipelines..... 106

Appendix F - Risk Modeling Work Group Mission Statement 109

References 110

Executive Summary

The Pipeline and Hazardous Materials Safety Administration (PHMSA) is issuing this report to support improvements in pipeline risk models.

Pipeline risk models are a foundational part of the assessment of operational pipeline risk. Federal pipeline safety integrity management (IM) regulations require pipeline operators to use risk assessments.¹ Based on the results of pipeline inspections and failure investigation findings, both the Department of Transportation's PHMSA and the National Transportation Safety Board (NTSB) have identified general weaknesses in the risk models used by pipeline operators in performing risk assessments for their IM programs.

To help address the varying levels of risk model implementation, PHMSA organized a Risk Modeling Work Group (RMWG) composed of representatives of state and federal pipeline regulators, pipeline operators, industry organizations, national laboratory personnel, and other stakeholders. The purpose of the RMWG was to gather information regarding state-of-the-art pipeline risk modeling methods and tools, the use of those methods and tools, and the resulting data in operator IM programs. This document provides an overview of methods and tools for improved implementation based on the results of the RMWG.²

This report considers the major types of pipeline risk models, and the effectiveness of each type in supporting risk assessments, as applied to pipeline operator decisions. The spectrum of risk models is divided into four major risk model categories: Qualitative, Relative Assessment/Index, Quantitative System, and Probabilistic. Each category can be characterized by the model's approach, inputs, outputs, and algorithms, and was evaluated according to its ability to support pipeline risk management decisions and regulatory requirements.

This overview document focuses on the applicability of the different risk model types to various risk management decisions required by the Federal pipeline safety IM regulations, including:

1. Risk Priorities for Baseline Integrity Assessments
2. Identification of Preventive Measures and Mitigative Measures
3. Evaluation and Comparison of Preventive Measures and Mitigative Measures
4. Consideration of Threats and their Interactions in Risk Assessments
5. Benefit-Cost Analysis for Risk Reduction Options³
6. Integrity Assessment Interval Determination

¹ 49 Code of Federal Regulations (CFR) Part 192, Subpart O (Gas Transmission Pipelines) and 49 CFR Part 195.452 (Hazardous Liquid Pipelines).

² Documentation of RMWG activities, including all technical presentations and meeting notes, can be viewed on PHMSA's Pipeline Technical Resources web site in tab RMWG at <https://primis.phmsa.dot.gov/rmwg/>.

³ The IM rules require operators to reduce risks to high-consequence areas (HCAs) by implementing preventive and mitigative measures (risk reduction actions) beyond those measures specifically required elsewhere in the pipeline safety regulations (49 CFR Parts 192 and 195). If limited operator resources require prioritization of measures that could be effective in reducing risk, then benefit-cost analysis, supported by the operator's risk model, provides an effective method of promoting efficiency as well as risk reduction.

7. Support of Continual Evaluation of Integrity and General Risk Management Decision Making

Conclusions

This report details discussions and technical recommendations related to the various aspects of pipeline risk modeling. PHMSA has derived the following summary conclusions:

1. The overriding principle in employing any type of risk model/assessment is that it supports risk management decisions to reduce risks.
2. While different risk models have different capabilities for evaluating risk reduction actions, Quantitative System model or Probabilistic models are more versatile and provide greater capabilities to provide risk insights and support decision making. Such models are not necessarily more complex or need more data than other types of risk models.
 - Small pipeline operators with limited (but highly knowledgeable) personnel resources will likely continue to use relative assessment/index models.
 - Pipeline operators who continue to use relative assessment/index models should seek to supplement personnel judgment with as much physical data as can reasonably be acquired over time.
 - Use of the most complete and accurate available data is needed for the application of all risk model types.
3. Pipeline operators should take on-going actions to improve and update data quality and completeness over time. However, the type of risk model to employ in pipeline risk analysis should not depend primarily on the perceived initial quality and completeness of input data, because all models utilize the available data. Instead, operators should select the best model approach and then populate the model with the best information currently available on risk factors or threats for each pipeline segment and improve that data over time.
4. It is important for risk models to include modeling of incorrect operations, which includes human interactions and human performance, that are significant to the likelihood of failure or have a significant effect on the consequences of a failure (e.g., inappropriate controller restart of pumps, realistic emergency response time scenarios).
5. It is important for pipeline risk models to include the potential for threat interactions in ways that can increase risk. Therefore, when risk analysis involves multiple threats, the effect of “interactive threats” or dependencies on likelihood of failure should be clearly evaluated.

May 9, 2018 - Draft 1

6. Varying levels of sophistication are possible in the analysis of the consequences of a failure. However, it is important to consider a full range of scenarios (even if they do not have a high probability of occurrence) to capture the full spectrum of possible consequences, including the high consequence outlier.
7. The characteristics of pipeline facilities that affect risk may be significantly different than those of line pipe, although the same basic risk assessment principles apply.

PHMSA recommends that pipeline operators develop and apply risk models consistent with these summary conclusions and the associated technical recommendations contained in this document. This should result in an improved understanding of the risks from pipeline systems and should improve critical safety information provided to the broader integrity and risk management processes.

RMWG Meeting Technical Presentations

The RMWG conducted several meetings during 2016 and 2017 to define, review, and document best practices in applying pipeline risk models. Pipeline operators may wish to consider these presentations when developing their own risk models. The below technical topics were presented at RMWG meetings and are available at: <https://primis.phmsa.dot.gov/rmwg/presentations.htm>.

Likelihood: August 9-11, 2016, Washington, DC

- USCAE Risk Assessment Methodologies
- Modeling for Optimized Safety Decisions
- Risk Analysis and Rare Events Data
- Bayesian Data Analysis
- Interactive Threats Discussion
- Probability Estimation
- ASMEB31.8S Risk Modeling Summary

Consequences & PHMSA R&D Projects: October 4-6, 2016, Houston, TX

- Emergency Planning & Response Performance Modeling
- GT QRA
- Risk Tolerance R&D Presentation
- Preventing Catastrophic Events R&D Project
- Pipeline Risk Assessment
- HL Consequence Overview
- Critical Review of Pipeline Risk Models R&D Project

Facility Risk: November 30-December 1, 2016, Washington, DC

- Facilities Risk Approaches
- GT Facilities Risk Management

May 9, 2018 - Draft 1

- Facility Piping Risk Assessment
- LNG Facility Risk Analysis Process

Data: March 7-9, 2017, Houston, Texas

- API Technical Report on Data Integration (TR 1178)
- Data Integration – Industry Practices and Opportunities
- Data Integration Using GIS Systems & Improved Risk Modeling
- Data Uncertainty in Risk Models
- HCA and Incident Statistics
- Overview of Partial Draft BSEE PRA Procedures Guide
- Performance Data Analysis for Nuclear Power Plants (Industry Data)
- PODS Data Management
- Relative Risk Model Applications at Southwest Gas
- Risk Acceptability Tolerance (Probabilistic Models)
- Using Data in Relative models with Respect to Decision Criteria

Index Models and Migration to Quantitative Models: June 15, 2017, Houston, Texas

- SME Input into Pipeline Risk Models
- Index Models and Applications (Vectren)
- Index Models and Applications (Dynamic Risk)
- Data Quality for Index Models and Migration to Quantitative Models
- Migration from Older Risk Analysis Methods to Quantitative Models (WKMC)

The RMWG and PHMSA thanks the individuals and groups that supported this effort by presenting materials at our meetings.

PHMSA thanks the members of the RMWG for their efforts and time spent in attending meetings, presentations, discussion, and commenting during the development of this document.

I. Definitions & Acronyms

The following lists specify how terms are used in this document. Some definitions are not consistently defined and/or used consistently across the pipeline industry.

Definitions		
Term	Definition	Principal Source
Terms Related to Defining Risk		
Consequence	Impact that a pipeline failure could have on the public, employees, property, the environment, or organizational objectives.	B31.8S-2004, ISO 31000:2009
Frequency	Number of events or outcomes per defined unit of time. Frequency can be applied to past events or to potential future events, where it can be used as a measure of likelihood / probability.	ISO 31000:2009
Hazard	Source of potential harm or potential consequences. [Used synonymously with “threat” by some references.]	Muhlbauer, 2004 ISO Guide 73-2009
Likelihood	The chance of something happening, whether defined, measured, or determined objectively or subjectively, qualitatively or quantitatively, and described using general terms or mathematically (such as a probability or frequency over a given time period).	ISO 31000:2009
Probability	(1) Likelihood, or (2) Measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty.	(1) numerous sources use the terms likelihood and probability interchangeably (2) ISO 31000:2009
Risk	Measure of potential loss in terms of both the likelihood or frequency of occurrence of an event and the magnitude of the consequences from the event.	B31.8S-2004 CSA Z662 Annex B
Terms Related to Defining Risk Assessment and Risk Assessment Models		
Risk analysis	Process of using available information to comprehend the nature of risk and estimate the level of risk.	ISO 31000:2009
Risk assessment	Systematic process in which hazards from pipeline operation are identified and the probability and consequences of potential adverse events are analyzed and estimated.	B31.8S-2004
Risk assessment model (Risk Model)	A set of algorithms or rules that use available information and data relationships to perform risk assessment. A model is a simplified representation of a pipeline system and represents the relation of important risk factors.	Muhlbauer, 2004
Risk management	Overall program consisting of identifying potential threats to a pipeline; assessing the risk associated with those threats in terms of incident likelihood and consequences; mitigating risk by reducing the likelihood, the consequences, or both; and measuring the risk reduction results achieved.	B31.8S-2004
Terms Related to Different Types of Risk Models		

Definitions		
Term	Definition	Principal Source
Index model	Scoring rules or algorithms that define how a risk index is calculated from input information. The scoring rules do not strictly adhere to the laws of probability, instead capture subject matter expert judgment of the relative importance of various risk factors. Output is a unit-less index score.	RMWG Discussion
Probabilistic model	Model with inputs that are quantities or probability distributions and with outputs that can be expressed as probability distributions. Model logic attempts to adhere to laws of probability.	RMWG Discussion
Qualitative	Expressible in descriptive terms, not quantitatively or numerically; measured as descriptive categories (e.g., high, medium, low), but not as numerical quantities or amounts.	RMWG Discussion
Qualitative model	Model with inputs and outputs that are descriptive or relational categories. Model logic defines output categories from combinations of input categories.	RMWG Discussion
Quantitative	Expressible in terms of numerical quantity or involving the numerical measurement of quantity or amount.	Dictionary (Merriam-Webster.com)
Quantitative model	A model with input that is quantitative and output that is quantitative. Model logic may or may not conform to laws of probability or to represent physical and logical relationships of risk factors (see definition of quantitative system model).	RMWG Discussion
Quantitative system model	A quantitative risk model with an algorithm that models the physical and logical relationships of risk factors to estimate quantitative outputs for likelihood and consequences and represents the outputs in standard units such as frequency, probability, and expected loss. This modeling approach is in contrast to index models that score and weight individual model inputs and calculate a unit-less index score.	RMWG Discussion
Relative assessment model	Synonymous term as a risk index model (see separate risk index definition).	RMWG Discussion
Risk index	Unit-less measure of risk derived from input information using ordinal scales.	ISO/IEC-31010-2009 – Risk management – Risk assessment techniques
Other Terms		
Data structure	A specialized format for organizing and storing data. A data structure is designed to organize data to suit a specific purpose so that it can be accessed and worked with in appropriate ways.	RMWG Discussion

Definitions		
Term	Definition	Principal Source
Facility	For the purposes of this document, “facility” refers to portions of a pipeline system other than line pipe: includes compressor units, metering stations, regulator stations, delivery stations, holders, fabricated assemblies, and underground storage facilities (gas); and pumping units, fabricated assemblies associated with pumping units, metering and delivery stations and fabricated assemblies therein, breakout tanks, and underground storage facilities (liquid).	49 CFR Part 192.3 49 CFR Part 195.2
Failure	(1) A part in service has become completely inoperable; is still operable while incapable of satisfactorily performing its intended function; or has deteriorated seriously, to the point that it has become unreliable or unsafe for continued use. (2) A structure is subjected to stresses beyond its capabilities, resulting in its structural integrity being compromised. (3) Unintentional release of pipeline contents, loss of integrity, leak or rupture.	B31.8S-2004 Muhlbauer, 2004 Muhlbauer, 2015
Gas pipeline	All parts of those physical facilities through which gas moves in transportation, including pipe, valves, and other appurtenance attached to pipe, compressor units, metering stations, regulator stations, delivery stations, holders, and fabricated assemblies.	49 CFR Part 192.3
Hazardous liquid pipeline	All parts of a pipeline facility through which a hazardous liquid or carbon dioxide moves in transportation, including, but not limited to, line pipe, valves and other appurtenances connected to line pipe, pumping units, fabricated assemblies associated with pumping units, metering and delivery stations and fabricated assemblies therein, and breakout tanks.	49 CFR Part 195.2
Line pipe	Linear “mileage” portions of a pipeline system that transport commodities from one point to another; i.e., the part of a pipeline system outside of any facilities.	49 CFR Part 195.2
Linear reference system	A systematic method of associating pipeline characteristics or other risk factors to specific positions on the pipeline.	RMWG Discussion
Mitigative measure	Risk reduction action to reduce risk by modifying the consequences of failure.	RMWG Discussion
Preventive measure	Risk reduction action to reduce risk by modifying the probability of failure.	RMWG Discussion
Risk factor	Pipeline characteristic or other input that is used by the model algorithm to determine model outputs; can be a data attribute input to a risk model.	RMWG Discussion

Definitions		
Term	Definition	Principal Source
Risk Modeling Work Group (RMWG)	A PHMSA-organized group composed of representatives of state and federal pipeline regulators, pipeline operators, industry organizations, national laboratory personnel, and other stakeholders. The purpose of the RMWG was to characterize state-of-the-art pipeline risk modeling methods and tools. RMWG members individually provided recommendations to PHMSA regarding the use of those methods, tools, and the resulting data in operator IM programs.	RMWG Discussion
Scenario	Sequence of events, when combined, result in a failure and consequence.	Muhlbauer, 2015
Segment	A contiguous length of pipeline or part of a pipeline in a specific geographic location.	RMWG Discussion
Threat	Potential cause of failure, failure mechanism.	B31.8S-2004 Muhlbauer, 2015
Time-dependent	Failure rate for threat tends to increase with time and is logically linked with a deterioration/aging effect.	Muhlbauer, 2015
Time-independent	Failure rate for threat tends to vary only with a changing environment; failure rate should stay constant as long as environment stays constant.	Muhlbauer, 2015

Acronyms	
Term	Definition
ALARP	as low as reasonably practicable
CD	construction damage
CFR	Code of Federal Regulations
CIS	close interval survey
CON	construction
CP	cathodic protection
CW	cold weather
DCVG	direct current voltage gradient
DEM	digital elevation model
DFW	defective fabrication weld
DGW	defective girth weld
DP	defective pipe
DPS	defective pipe seam
EC	external corrosion
EM	earth movement
ESD	emergency shut-down
EQ	equipment
GF	gasket failure
GIS	geographic information system

Acronyms	
Term	Definition
HCA	high consequence area
HRF	heavy rains and floods
HVL	highly volatile liquid
IEC	International Electrotechnical Commission
IC	internal corrosion
IM	integrity management
IO	incorrect operations
ISO	International Organization for Standardization
LIGHT	lightning
LRS	linear reference system
MAOP	maximum allowable operating pressure
MCRE	malfunction of control or relief equipment
MFR	manufacturing
MOP	maximum operating pressure
NTSB	National Transportation Safety Board
P&ID	pipng and instrument drawing
PDP	previously damaged pipe
PHMSA	Pipeline and Hazardous Materials Safety Administration
PODS	Pipeline Open Data Standard
QRA	quantitative risk assessment
RMWG	Risk Modeling Work Group
ROW	right-of-way
SCC	stress corrosion cracking
SME	subject matter expert
SPPF	seal or pump packing failure
TP	third party
TPD	third-party damage
TSBPC	stripped threads, broken pipe, or coupling failure
V	vandalism
VSL	Value of Statistical Life
WROF	weather related and outside force

II. Introduction

A. Purpose of Document

Risk models are a foundational part of the assessment of operational pipeline risk and an integral part of gas and hazardous liquid pipeline integrity and risk management. A risk model provides a representation of the risks throughout a pipeline system by combining inputs associated with both likelihood and consequence aspects of unintended pipeline releases. The model supports risk analysis, risk management decisions, and helps operators evaluate and quantify the effects of various risk mitigation activities and options.

This document provides an overview of methods and tools used for risk modeling in support of pipeline integrity and risk management. Broader topics such as integrity management systems, quality management systems, overall risk management, and safety management systems are not addressed within this document.

Federal gas and hazardous liquid pipeline safety integrity management (IM) regulations (see Appendix E) contain requirements for the uses of risk assessments by pipeline operators. Based on the results of pipeline inspections and failure investigation findings, both the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) and the National Transportation Safety Board (NTSB) have identified general weaknesses in the risk models used by pipeline operators in performing risk assessments for their IM programs. PHMSA has previously communicated findings and concerns regarding risk models at past public meetings.⁴

B. NTSB Recommendations

In 2015, NTSB published a safety study titled *Integrity Management of Gas Transmission Pipelines in High Consequence Areas* (<https://www.nts.gov/safety/safety-studies/Pages/SS1501.aspx>). The NTSB undertook this study because of concerns about deficiencies in the operators' integrity management programs and the oversight of these programs by PHMSA and state regulators. As a result of the study, the NTSB made three recommendations to PHMSA concerning the use of risk assessments:

- **Recommendation P-15-10:** Update guidance for gas transmission pipeline operators and inspectors on the evaluation of interactive threats. This guidance should list all threat interactions that must be evaluated and acceptable methods to be used.
 - This overview document discusses interactive threats in Section IV, Important Elements of Likelihood Modeling, Part E, Interactive Threat

⁴ See meeting records "Improving Pipeline Risk Assessments and Recordkeeping", Arlington, VA, July 21, 2011 (<https://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=70>) and "PHMSA Pipeline Risk Modeling Methodologies Public Workshop", Arlington, VA, September 9, 2015, (<https://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=104>).

Modeling. The section lists different threats that can potentially interact as well as methods for incorporating threat interactions into risk models and provides discussions of the completed PHMSA funded project DTPH56-14-H-00004 that provides tools and techniques for accounting for interacting threats in risk assessments

(<https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=557>).

- Applicable RMWG Presentations:
 - Discussion of Interactive Threats (https://primis.phmsa.dot.gov/rmwg/docs/Interactive%20Threats%20Discussion_RMWG0816.pdf) (August 9-11, 2016 Washington, DC)
 - Modeling for Optimized Safety Decisions (https://primis.phmsa.dot.gov/rmwg/docs/Modeling%20for%20Optimized%20Safety%20Decisions_RMWG0816.pdf) (August 9-11, 2016 Washington, DC)
- **Recommendation P-15-12:** Evaluate the safety benefits of the four risk assessment approaches currently allowed by the gas integrity management regulations; determine whether they produce a comparable safety benefit; and disseminate the results of your evaluation to the pipeline industry, inspectors, and the public.⁵
 - This overview document evaluates the four basic risk modeling approaches based on their suitability to support risk management decisions required by IM regulations in Section III, Overview Information for Use of Risk Model Types, Part A, Selecting an Appropriate Risk Model.
 - Applicable RMWG Presentations:
 - Risk Analysis and Rare Events Data (https://primis.phmsa.dot.gov/rmwg/docs/Risk%20Analysis%20and%20Rare%20Events%20Data_RMWG0816.pdf) (August 9-11, 2016 Washington, DC)
 - Probability Estimation (https://primis.phmsa.dot.gov/rmwg/docs/Probability%20Estimation_RMWG0816.pdf) (August 9-11, 2016 Washington, DC)
 - USCAE Risk Assessment Methodologies (https://primis.phmsa.dot.gov/rmwg/docs/USCAE_RiskAssessmentMethodologies_RMWG0816.pdf) (August 9-11, 2016 Washington, DC)
 - ASMEB31 8S Risk Modeling Summary (<https://primis.phmsa.dot.gov/rmwg/docs/ASMEB31%208S%20>

⁵ See Section II.D for discussion relating the NTSB-referenced risk assessment categories to the categories discussed in this document.

- [Risk%20Modeling%20Summary_RMWG0816.pdf](#) (August 9-11, 2016 Washington, DC)
 - Modeling for Optimized Safety Decisions
(https://primis.phmsa.dot.gov/rmwg/docs/Modeling%20for%20Optimized%20Safety%20Decisions_RMWG0816.pdf) (August 9-11, 2016 Washington, DC)
 - Critical Review of Pipeline Risk Models R&D Project
(<https://primis.phmsa.dot.gov/rmwg/docs/Skow-DTPH56-15-T00003%20-%20Final%20Project%20Presentation%20-%202005%20Sept%202016%20RiskWo....pdf>) (October 4-6, 2016 Houston, TX)
- **Recommendation P-15-13:** Update guidance for gas transmission pipeline operators and inspectors on critical components of risk assessment approaches. Include (1) methods for setting weighting factors, (2) factors that should be included in consequence of failure calculations, and (3) appropriate risk metrics and methods for aggregating risk along a pipeline.
 - This overview document discusses components of risk assessment approaches throughout, including weighting factors (Appendix A.D-8), factors for consequence failure calculations (Sections V.A.1 through V.A.5), and risk metrics/aggregation (Section VII, Appendix A.2, Appendix B.2).
 - Applicable RMWG Presentations:
 - Pipeline Risk Assessment
(https://primis.phmsa.dot.gov/rmwg/docs/Muhlbauer-PHMSA_committee_Oct_2016.pdf) (October 4-6, 2016 Houston, TX)
 - HL Consequence Overview
(https://primis.phmsa.dot.gov/rmwg/docs/Cavendish-PHMSA_RMWG_Liquid_Operator_Consequence_Presentation.pdf) (October 4-6, 2016 Houston, TX)
 - GT QRA (<https://primis.phmsa.dot.gov/rmwg/docs/NG-QRA-Working%20Group%20Rev.6.pdf>) (October 4-6, 2016 Houston, TX)
 - Emergency Planning & Response Performance Modeling
(<https://primis.phmsa.dot.gov/rmwg/docs/Westrick-Emergency%20planning%20and%20response%20performance%20modeling.pdf>) (October 4-6, 2016 Houston, TX)
 - Relative Risk Model Applications at Southwest Gas
(https://primis.phmsa.dot.gov/rmwg/docs/Relative_Risk_Model_Applications_at_Southwest_Gas_RMWG0317.pdf) (March 7-9, 2017 Houston, Texas)

- Using Data in Relative models with Respect to Decision Criteria (https://primis.phmsa.dot.gov/rmwg/docs/Using_Data_in_Relative_models_with_Respect_to_Decision_Criteria_RMWG0317.pdf) (March 7-9, 2017 Houston, Texas)
- Index Models and Applications (Vectren) ([https://primis.phmsa.dot.gov/rmwg/docs/IndexModels_and_Applications\(Vectren\)_RMWG0617.pdf](https://primis.phmsa.dot.gov/rmwg/docs/IndexModels_and_Applications(Vectren)_RMWG0617.pdf)) (June 15, 2017 Houston, Texas)
- Index Models and Applications (Dynamic Risk) ([https://primis.phmsa.dot.gov/rmwg/docs/IndexModels_and_Applications\(DynamicRisk\)_RMWG0617.pdf](https://primis.phmsa.dot.gov/rmwg/docs/IndexModels_and_Applications(DynamicRisk)_RMWG0617.pdf)) (June 15, 2017 Houston, Texas)
- Migration from Older Risk Analysis Methods to Quantitative Models (https://primis.phmsa.dot.gov/rmwg/docs/MigrationFromOlder_MethodsToQuantitativeModels_RMWG0617.pdf) (June 15, 2017 Houston, Texas)

To promote the development and application of improved pipeline risk models and to respond to these recommendations, PHMSA committed to organize and work with stakeholders in a Risk Modeling Work Group to help inform the development of this overview of methods and tools document.

The RMWG⁶ was organized with representatives from state and federal pipeline regulators, pipeline operators and industry organizations, national laboratories, and other stakeholders. This overview document incorporates information gathered from the presentations, meetings, and comments from members of the RMWG with respect to the state-of-the-art of pipeline risk modeling.

C. Definition of Risk

Risk is defined⁷ as a measure of potential loss in terms of both the likelihood (or frequency of occurrence) of an event and the magnitude of the consequences from the event. A standard conceptual definition of risk used to structure risk assessment is given by the equation:

$$Risk = Likelihood \times Consequence$$

For hazardous liquid and natural gas pipeline systems, the basic undesired event is the failure of any segment of a pipeline or pipeline system that results in a release of the gas or hazardous liquid. Likelihood is the probability or frequency of failure due to threats that affect the

⁶ The mission statement of the Risk Modeling Work Group (RMWG) that developed this document can be found at <https://primis.phmsa.dot.gov/rmwg/index.htm> along with other pertinent background information. See also Appendix F of this document for the RMWG mission statement.

⁷ See definitions used in Section I of this document.

pipeline, and consequence is the severity of impacts to different receptor categories (e.g., human safety, environment, property) because of a pipeline failure.

A risk analysis considers the likelihood of failure from all potential and existing threats at each segment along the pipeline. In addition, each receptor category may experience different consequence levels from a pipeline failure, depending on the failure mode (e.g., leak vs. rupture event) and location of the failure (e.g., proximity to receptors such as population and environmentally sensitive areas).

D. Background

Federal pipeline safety regulations include requirements for risk assessment and risk analysis in the hazardous liquid and gas pipeline integrity management (IM) rules. Gas transmission IM requirements are found in 49 Code of Federal Regulations (CFR) Part 192, Subpart O. Hazardous Liquid IM requirements are found in 49 CFR Part 195.452.⁸

Prior to issuance of the IM rules, the pipeline industry had begun to apply risk modeling to support risk assessment and decision support in planning maintenance and capital projects as early as the mid-1980s and worked to develop industry standards and recommended practices such as API Recommended Practice (RP) 1160 - Managing System Integrity for Hazardous Liquid Pipelines, and ASME B31.8S – Managing System Integrity of Gas Pipelines.

Initially, as part of IM rule implementation efforts, many pipeline operators implemented relative risk models to prioritize their performance of baseline integrity assessments and remediation of pipeline segment threats. This is at least partially due to their use by industry for simple prioritizations prior to the regulations. However, the application of risk analysis required by Federal pipeline safety regulations goes well beyond the simple prioritization of pipeline segments for baseline integrity assessments. Additional applications include the following broad areas of performance requirements:

- Identification (§ 195.452 (i)(1) and § 192.935(a)) and evaluation (§§ 195.452 (i)(2), 192.911(c), and 192.917(c)) of preventive measures and mitigative measures;
- Continual integrity evaluation process to identify the risks of integrity threats (§§ 195.452 (j)(2) and 192.937(b));
- Continual integrity assessment interval determination process (§§ 195.452 (j)(3) and 192.939(a)(1)(i));

PHMSA inspections of operator IM programs include operator risk assessment processes and the risk models employed in those processes; inspection experience indicates that operators' risk assessment approaches, primarily qualitative and relative risk models, have been

⁸ See Appendix E of this document for excerpts from these requirements that relate to risk assessment and risk models. Regulatory references are those in effect as of the date of this document.

inadequate in many cases to meet all IM requirements and provide meaningful insight into the risks in an operator’s unique operating environment.

The IM regulations also require operators to continuously improve their IM programs, and overall industry integrity performance has shown general improvement over time. However, the continuing occurrence of significant pipeline incidents points to a continuing need for operators to upgrade their tools for risk assessment and risk management. Upgrades to risk assessment processes using quantitative or probabilistic risk models is an important step for operators to take to improve IM programs, allowing better understanding of the risks on pipeline systems and better support for risk management practices.

PHMSA has communicated its findings and concerns regarding risk models at past public meetings⁹ and worked with the stakeholder participants in the RMWG to develop this overview document in support of improved pipeline risk models and their usage, as appropriate.

E. Risk Model Categories

Risk models employed in pipeline risk analysis can be categorized based on the nature of the model’s inputs, outputs, and the nature of the algorithms used to convert the inputs to outputs. This overview document evaluates each category for its suitability to support pipeline operator decision making.

Table II-1 below gives the breakdown of risk model categories:

**Table II-1
Risk Model Categories**

Model Category	Inputs	Outputs	Algorithms
Qualitative ¹⁰	Qualitative (descriptive and relational)	Qualitative	“Matrix” Mapping Inputs to Outputs
Relative Assessment/ Index	Qualitative and Quantitative	Quantitative – unit-less	Risk Index Scoring
Quantitative System	Quantitative ¹¹	Quantitative - with units (e.g., probability, frequency, expected loss)	Quantitative System Model
Probabilistic	Quantitative, including probability distributions	Probability distributions	Quantitative System Model

⁹ See meeting records “Improving Pipeline Risk Assessments and Recordkeeping”, Arlington, VA, July 21, 2011, (<https://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=70>) and “PHMSA Pipeline Risk Modeling Methodologies Public Workshop”, Arlington, VA, September 9, 2015 (<https://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=104>).

¹⁰ Includes “SME” approaches.

¹¹ These models can use qualitative inputs that have been converted to numerical equivalents for evaluation.

The **Qualitative** model uses qualitative inputs such as expert judgement, experience, and technical knowledge, and outputs. The model translates inputs into ranges or qualitative outputs (e.g., high, medium, low). The algorithm in this model is a direct mapping of inputs to outputs, often represented by a matrix.¹²

The **Relative Assessment** or **Index** model uses quantitative *or* qualitative inputs to derive numerical outputs using a scoring algorithm.¹³ Scores assigned to inputs are combined to obtain a unit-less quantitative output “index” score. The most common method of combining inputs and obtaining model outputs is to sum the individual and sometimes weighted risk factor scores.

The numerical outputs are not expressed in risk assessment units like probability, frequency, or expected loss. Instead, they are unit-less index scores for likelihood, consequence, and risk, having relevance only in comparisons to other scores. This method of combining risk factor inputs and producing outputs distinguishes this model from quantitative system or probabilistic models. Index models were used widely by pipeline operators to establish priorities for integrity assessments as part of the baseline integrity assessment requirements of the pipeline IM rules.

- The term “semi-quantitative” risk model is not used in this document, in part due to RMWG technical discussions that indicated a wide variance in how this term can be interpreted. ASME B31.8S also does not use the term semi-quantitative, however, in the description of the relative assessment model approach states “*Such relative or data-based methods use models that identify and quantitatively weigh the major threats and consequences relevant to past pipeline operations. These approaches are considered relative risk models, since the risk results are compared with results generated from the same model.*” Consistent with this treatment, risk models that have incorporated quantitative elements into their algorithms and retain the underlying relative model structure, are included in the Table II-1 “Relative Assessment/Index” model category.

The **Quantitative System** model also utilizes quantitative inputs and outputs. However, it is distinguished from Relative Assessment/Index models in significant ways, including:

- Use of quantitative inputs and outputs that are expressed in risk assessment units like probability, frequency, expected loss, etc. Usage of risk assessment units is an important distinction from numerical/quantitative values used in Relative Assessment/Index models that are unit-less values, and only can be used to compare if they are higher/lower than other values within the model. For example:¹⁴
 - In a Relative/Index Model, a threat input value of “8” for coating condition on one pipeline segment versus a value of “4” on a different segment does not mean it is twice as likely to cause a failure due to

¹² See Appendix A and ISO/IEC 31010:2009 – *Risk management – Risk assessment techniques* Annex B.29.

¹³ See Appendix A and ISO/IEC 31010:2009 – *Risk management – Risk assessment techniques* Annex B.28.

¹⁴ In these example, higher values imply higher threat likelihood and higher risk.

- poor coating, only that the segment with the higher value has relatively poorer coating than the segment with the lower value.
- In a Relative/Index Model, a risk output value of “70” for a pipeline segment does not represent “twice” the risk of a different segment with an output value of “35”; only that the segment with the higher value has been determined to be of higher risk relative to the segment that has a lower score.
- Algorithms that model the physical and logical relationships of the pipeline system risk factors, the threats to system integrity, and the potential consequences of a product release from the system. This approach aims to combine risk factors in ways that more directly reflect physical reality (e.g., corrosion rates applied to effective wall thicknesses). The outputs from these models are likelihood, consequence, and risk measures expressed in recognizable units, such as probability or frequency of failure and expected loss.

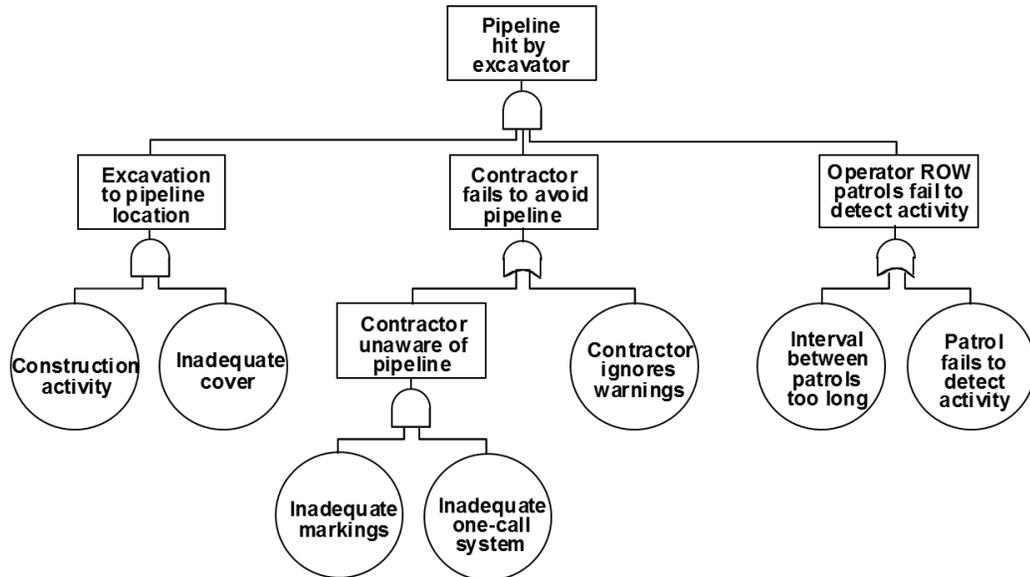
A minority of operators have employed models of this type in their IM programs.

As a simplified example of how Quantitative System models might model the relationship of risk factors in a pipeline system, consider part of a model of the probability of failure from third-party excavation damage. A failure from excavation damage may be modeled as the logical combination of factors such as the frequency of excavation activity in the area of the pipeline, one-call system effectiveness, depth of cover, probability of an excavator hitting the pipeline, pipe resistance to a hit, and the effect of pipeline rights-of-way (ROW) patrolling. Figure II-1 (also shown in Appendix A.3) is an illustration of such a model for developing the frequency of a pipeline hit by an excavator, in this case using a fault tree to model the relationship of the relevant risk factors.¹⁵ [Note: A fault tree approach is not always utilized for quantitative system models.] In this model, the frequency of a hit is calculated by evaluating the likelihood of the individual risk factors (frequency of construction activity, probability of inadequate cover, probability of inadequate one-call, etc.) and combining these likelihoods according to the logical relationships in the model. The model’s output likelihood is calculated in the units of frequency (per unit time) of a pipeline hit.¹⁶

¹⁵ See ISO/IEC 31010:2009 – *Risk management – Risk assessment techniques*, Annex B.14.

¹⁶ In contrast, an index model would have unit-less output values based on the (possibly weighted) sum of the individual risk factor scores.

Figure II-1
Simplified Example Fault Tree Model for Excavator to Hit Pipeline¹⁷



The **Probabilistic** model is a specific type of Quantitative System model. It is distinguished from other such models in that probability distributions can be used to represent uncertainties and variability in model inputs. Input distributions are then propagated through the model to obtain resultant probability distributions that can be used to represent uncertainty in model outputs, such as failure probability, severity of consequences given a failure, or expected loss.

See Appendix A for examples of these model types.

E.1 ASME B31.8S Risk Assessment Method Categorization

In choosing risk assessment approaches to evaluate, PHMSA chose the risk model categories listed in above Table II-1, Risk Model Categories, as they are applicable for both hazardous liquid pipelines and gas transmission pipelines and represented basic methods of modeling.

ASME B31.8S-2004¹⁸ presented four alternative approaches for gas transmission integrity management risk assessment:

1. Subject Matter Experts (SMEs)
2. Relative Assessment Models
3. Scenario-Based Models
4. Probabilistic Models

¹⁷ From Stephens, Mark, C-FER Technologies, *Methods for Probability Estimation*, presentation to PHMSA Risk Modeling Work Group, 2016.

¹⁸ ASME B31.8S-2004 is incorporated by reference in the gas transmission IM rule, 49 CFR Part 192, Subpart O.

While there is overlap between these and PHMSA’s four categories, the RMWG members noted that the ASME categories were not strictly risk models, but instead a mixture of both risk assessment tools and models.¹⁹

For example, Subject Matter Experts perform an important role in all types of pipeline risk modeling, and SME input is fundamental to both qualitative and quantitative model input. As a risk assessment method, the Table II-1 “Qualitative” category is comparable to the “Subject Matter Experts” B31.8S risk assessment approach category. To minimize potential confusion with the more general role of SMEs for all types of pipeline risk models, the term “Qualitative” risk model is used in this document instead of “Subject Matter Experts (SMEs).”

The RMWG members also noted that stand-alone scenario-based methods were utilized by some (mainly hazardous liquid) pipeline operators in the early phases of integrity management program development. These approaches look at specific failures and seek to identify events that could lead to that failure (e.g., HAZOP is a type of scenario model). In practice, this approach has proved to be difficult to apply to significant lengths of line pipe, and more recent applications have generally been limited to specialized cases (e.g., where a particular consequence is of concern).²⁰

In addition, the B31.8S description of the “Scenario-Based” risk assessment method notes that *“This method usually includes construction of event trees, decision trees, and fault trees.”* As noted previously in this section, these types of tools are often employed in both quantitative and probabilistic risk models as part of their model algorithms. For instance, fault trees²¹ may be used to break down failure due to threats into more specific constituent events that can lead to failure. Figure II-1 shows an example fault tree approach for excavation damage using a logical combination of contributing factors. The system can be modeled to the level of specificity where data and SME input can be applied to quantify the failure probability or frequency. Given that the application of this document is for both hazardous liquid pipelines and gas transmission pipelines, and that scenario-based tools can be used for various types of risk models, use of scenario-based tools has been folded into the quantitative system and probabilistic risk model categories of this document.

III. Overview Information for Use of Risk Model Types

A. Selecting an Appropriate Risk Model

Pipeline operators should select risk models capable of supporting risk management decisions required as part of pipeline IM programs as well as more general risk management decisions

¹⁹ Muhlbauer, *Pipeline Risk Assessment: The Definitive Approach and its Role in Risk Management*, 2015.

²⁰ PHMSA Risk Modeling Work Group, 08.09.16 Meeting Notes, Washington, DC (Likelihood).

²¹ See ISO/IEC 31010:2009 – *Risk management – Risk assessment techniques*, Annex B.14.

that may be required. Table III-1 characterizes and compares the suitability of the different risk model categories defined in Section II.D to for each decision type.

**Table III-1
Risk Model Types and Applicability to Decisions**

Decision Type	Model Category			
	A. Qualitative Model	B. Relative Assessment/Index Model	C. Quantitative System Model	D. Probabilistic Model
Risk Priorities for Baseline Integrity Assessment	A	A	A	BP
Preventive and Mitigative Measure Identification	A	A	A	BP
Preventive and Mitigative Measure Evaluation and Comparison	AI	AI	A	BP
Benefit-Cost Analysis for Risk Reduction Options	AI	AI	A	BP
Integrity Assessment Interval Determination	AI	AI	A	BP
General Risk Management Decision Making	AI	AI	A	BP

Key:

Can be Applicable with Additional Inputs to Risk Assessment Process	AI
Can be Applicable	A
Potential Best Practice	BP

Qualitative Models and Relative/Index Models (Model Category A and Category B)

The initial application of risk models required by the hazardous liquid and gas transmission IM rules was to establish risk-based priorities for baseline integrity assessments. Relative assessment/index models, and to some extent qualitative-oriented models, were widely used by pipeline operators to address this requirement. The application of these risk models allowed large numbers of pipeline segments to be ranked based on risk factors. [As indicated in Table III-1, the relative nature of assessment prioritization is an applicable application of these models.] In the event a situation arises that would require the prioritization of a several new pipeline segments for a baseline assessment, relative/index models would still be applicable.

In addition, a broad scope of pipeline accident likelihood and consequence factors are considered when using Qualitative and Relative Assessment/Index models. As such, they can be applied to the identification of preventive and mitigative measures by considering model inputs and measures that change these inputs to values that are estimated to reduce risk. This

application is essentially qualitative in nature, indicating the general effect proposed measures on the risk, so is appropriate for identifying P&M measures.

In general, application of Qualitative and Relative/Index models is invalid for applications where the degree of difference between different scenarios, options, etc., or the risk as compared to a quantitative risk criterion is important in addition to simply knowing a relatively higher or lower risk. Outputs from Qualitative and Relative Assessment/Index models may not be based on consistent units and cannot be assumed to be proportional to outputs like failure frequency, probability, or expected loss.

Risk models that produce consistent quantitative output in standard risk units (probability of failure, expected loss, etc.) provide an easier format for evaluating and comparing risk alternatives, particularly for larger multi-regional pipeline systems. For applications such as the comparison of alternative preventive or mitigative measures, or benefit-cost analysis, some form of a quantitative type of risk model output in standard risk units is generally needed.

In practice, continued use of qualitative and relative assessment/index models is better suited for small, less complex pipeline systems, where the effects of preventive and mitigative measures on risk can be reasonably be understood via changes to the model inputs²². These systems can be characterized by limited geographic extent and lower mileage; simple system configuration; uniform risk factors throughout the system; affected HCAs limited in extent and similar in nature; and single, small operating organization.

Operators planning to continue the use of Qualitative and Relative Assessment/Index models should seek to supplement personnel judgment with the highest degree of pipeline physical attribute data as can reasonably be acquired over time.

Quantitative System Models (Model Category C)

Quantitative System models can be applicable for all decision types. The algorithms and outputs of quantitative system models can produce quantitative estimates of overall risk, using consistent units. These models can be used to estimate the risk before and after risk reduction measures are implemented. Because a quantitative system model represents the physical and logical relationships of model inputs, the inputs can be varied to define alternatives and compare the risk reduction effects of each alternative. Candidate risk reduction measures at different locations along the pipeline can be compared via quantitative estimates using consistent input units. Quantified risk reduction benefits can be combined with data on implementation costs to perform benefit-cost analysis to further enhance decision making.

²² See ISO/IEC 31010:2009 – *Risk management – Risk assessment techniques*, Annex B, Section B.28, for additional discussion on the strengths and limitations of risk index models.

Probabilistic Models (Model Category D)

Probabilistic models are considered a best practice for supporting all decision types. Probabilistic models have the added feature of representing the uncertainty (i.e., realism) in model inputs by probability distributions, and the resulting ability to produce resultant distributions for model outputs. This allows a systematic representation of uncertainty and unique risk insights for decision making that does not usually accompany other model types.

An example of the application of both Quantitative System and Probabilistic models is the incorporation of integrity assessment results and associated defect anomaly findings and remediation. In these models, the probability of failure and an overall risk can be estimated using different integrity assessment intervals. Results can then be used to define optimal integrity reassessment intervals consistent with the operator's risk tolerance. A Probabilistic model with input and output distributions is particularly effective for identifying integrity assessment intervals through its ability to support evaluations of the uncertainty in the predicted probability of failure given actual integrity assessment results. Also, uncertainties due to tool tolerances and other risk model inputs, such as corrosion growth rates, excavation damage statistics, and equipment reliability can be represented by input probability distributions, which may be propagated through the risk model along with other inputs to give an output distribution for probability of failure that more accurately portrays risk.

It should be noted that the IM rules require operators to reduce risks to high consequence areas (HCAs) by implementing preventive and mitigative measures beyond those measures required elsewhere in Parts 192 and 195 of the pipeline safety regulations. If limited operator resources require prioritization of risk reduction measures, then benefit-cost analysis, supported by the application of an effective risk model, can optimize the prioritization results. [Note: In most cases, risk analysis results should not be used to defer/delay the normal process of pipeline system remediation of known deficient conditions.]

A.1 Moving from Qualitative or Relative Assessment/Index Models to Quantitative System or Probabilistic Models

Quantitative System and Probabilistic models are considered more robust and capable of supporting all risk reduction decisions. Operators should consider moving to these risk modeling categories, as appropriate.

Developing and implementing Quantitative System models does not necessarily require more resources than Relative Assessment/Index models, despite some perceptions to the contrary. The structure of Quantitative System models is not inherently more complex nor do they necessarily require more data than Index models, and may be developed and implemented with common tools such as spreadsheets.

Many Relative Assessment/Index and Qualitative risk models include relatively large numbers of inputs representing pipeline characteristics and other risk factors. These inputs can serve as a

starting point for development of a Quantitative System model that provides failure probability and risk in standard units. The inputs for Relative Assessment/Index models are often already quantified and can readily be incorporated in a Quantitative System model. PHMSA believes that operators using Relative Assessment/Index models should consider taking steps to evolve into Quantitative System models that utilize the inputs from their existing models. This would enhance the risk reduction decision making ability for those operators.

Probabilistic models are sometimes perceived as being excessively complex and requiring significant additional data. While it is true that quantifying a Probabilistic model involves more than a basic “spreadsheet” type of calculation, applying probabilistic analysis to basic quantitative system models can be a more powerful use of available data. Other benefits of using Probabilistic models include a more accurate representation of uncertainties than those provided by models that use point estimates of the same data as inputs.

A pragmatic approach is to evolve from the use of Relative Assessment/Index risk models to Quantitative or Probabilistic models over time. Organizational experience in developing and implementing quantitative system models for a limited number of threats can then be applied in a way that maximizes the benefits and optimizes the level of resources needed as the quantitative system model and probabilistic approaches are applied to an increasing number of threats.²³ Appendix D outlines one process for evolving Relative Index models to more of a Quantitative system modeling approach.

B. Understanding Uncertainty and Critical Model Parameters

The output of any risk model is an estimation of actual risk, so it is important to consider how much uncertainty may be involved with the model outputs. Variations in risk model inputs impact results, and different parameters have different influences on the results.

For Quantitative System models, input parameters can be represented by ranges of possible values, and the effect on the output of varying each input can be calculated (e.g., “sensitivity analysis”). For probabilistic models, the uncertainty in model inputs can be represented by probability distributions.

It is important to review the impact of input uncertainty to identify which uncertainties should be reduced by obtaining additional information. For example, the operator’s SMEs may assign input variables a wide range of values given a lack of data or lack of SME agreement. If the range has a significant impact on the risk model results, efforts to obtain better data to reduce that uncertainty may be appropriate, particularly if the additional information could improve the evaluation of alternative risk reduction measures.

²³ Section IV.C addresses the potential for employing threat-specific risk models instead of a single modeling approach for all threats.

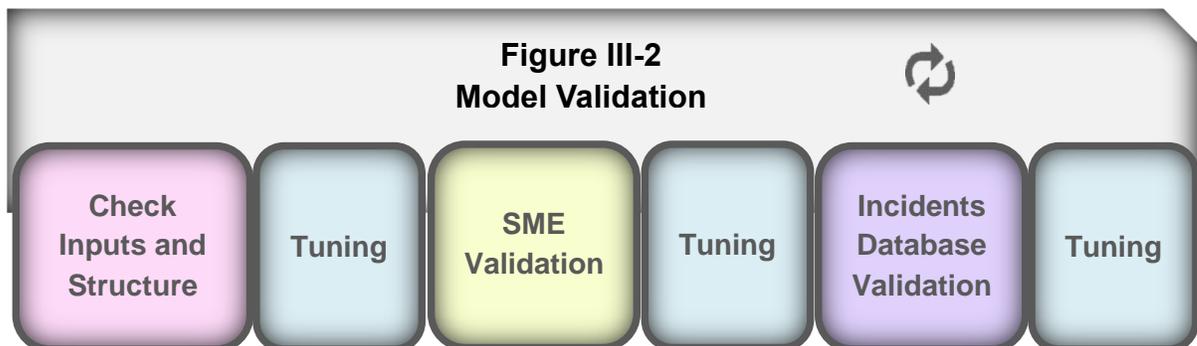
Inputs, and their variability with the biggest impact on risk model output results are sometimes referred to as the “risk drivers.” It is important when reviewing the risk drivers for a segment of line pipe or a pipeline facility, to determine if the model output results make basic technical sense. Examples are: risk model results are as expected by SMEs, no errors in the risk model or the inputs, or SME expectations are incorrect. (See Section III.C, Model Validation.)

Investigation of risk drivers can also suggest potential preventive and/or mitigative measures, by indicating the factors that could lead to the greatest reduction in risk if changed. Risk models should include risk factors that will be affected because of the potential preventive measures and mitigative measures. If evaluated risk reduction measures do not result in differences in the model outputs, then analysts should ensure that this is not merely because the model does not include the applicable risk factors.

The relative importance of risk factors depends on the particular risk model output(s) of interest. Inputs may be important risk drivers over specific pipeline segments, although not significant system-wide or operator-wide. For example, the risk of failure due to a landslide might be negligible for the large majority of pipeline segments but could be the single most important risk factor for some segments with certain topography and soil conditions. The risk assessment model should accurately account for segment-specific parameters that are critical to the segment of pipeline being evaluated versus overall line-averaged values.

C. Validating Risk Analysis Results

Risk model development requires the review of risk assessment results and validation of the model input and output data, both periodically and whenever significant changes are made to the model or its inputs (e.g., if operational experience demonstrates that input data needs to be revised). Figure III-2 depicts typical risk model validation steps to ensure quality and the most accurate representation of pipeline risk.



Validation of model **inputs** typically includes:

1. Model inputs should be validated against existing data/operational history and SME estimates, including inputs to both the likelihood and consequence analyses.

2. Model inputs need to represent the most accurate available information on each pipeline location (including default values). To accomplish this, input data should be continuously reviewed and updated, as appropriate, by trained and qualified personnel. Management of risk model input datasets should include clearly defined requirements, definitions, process owners, process maps and governance structures. This clear definition of roles and responsibilities also applies if portions of the work are contracted to external organizations.
3. Model inputs also apply to consequence variables such as response times, conditions affecting dispersion, and the locations of receptors. These need to cover the range of possibilities to ensure a representative selection of outcomes, particularly so that high-consequence outcomes are identified and can be selected for the potential application of specific risk reduction activities.
4. The structure of the risk model and algorithm(s) used to calculate risk measures should be checked to ensure the relationships of risk inputs are appropriately represented. The structure, analytical functions, analytical content, and technical computing structure detailed within the model should be continually reviewed and updated, as appropriate, by applicably trained and qualified personal.

Validation of model **outputs** typically includes:

1. Model outputs should be validated against SME (peer) review. The review includes operator-specific knowledge to ensure results are appropriate for operator-specific risks. The highest frequency sources of risk predicted by the model and risk drivers should be consistent with applicable historical data.
2. Model results should be consistent with historical failure data. If operating history of the analyzed pipeline or similar pipelines include failures or consequences that are not captured by the model, then changes to the model should be considered to include factors related to such historical events.
3. If model results vary sharply from SME expectations or operating history, the model and input values involved should be examined to identify the source(s) of the variance. It is possible that the discrepancy points to a need for data correction or modification to the model to accurately represent risk. It is also possible that the risk model results will yield new insights that are not consistent with SME expectations, so there may be variance in the operator's understanding of risk-important characteristics and what is produced by the model. These new insights into risk drivers are a valuable benefit of a risk model.

D. Configuration Control of Risk Models

As with other analytical tools supporting safe pipeline operation, risk models should be reviewed and updated on a regular, defined basis to assure they continue to accurately reflect the pipeline system's configuration and operation. A structured management of change process also applies to pipeline risk models. For example, data about the pipeline system is constantly

being acquired, and updates to risk model inputs should be performed routinely to incorporate the latest information.

While the details of achieving management of change will vary for differing aspects of a risk model, the process for control and update of the model should assure that risk estimates provided to decision makers are accurate and incorporate the latest system information. For example, information on the population near the pipeline may change less frequently than cathodic protection information and may need less frequent updating in the model.

E. PHMSA Key Recommendations – Overview Information for Use of Risk Model Types

- The overriding principle in employing any type of model to support risk assessment is that it be capable of supporting risk management decisions.
 - A quantitative system or probabilistic model utilizes many of the same inputs as a relative assessment/index model. However, quantitative system and probabilistic models have algorithms that represent the physical relationships of model inputs, and model outputs that are risk measures in standard units. Consequently, the outputs from quantitative system models or probabilistic models are directly relatable to the evaluation and comparison of preventive measures. In general, a quantitative system or probabilistic model is more versatile for such an evaluation, with greater capabilities to provide risk insights and support decision making.
 - Outputs for qualitative and relative assessment/index models are not risk measures in standard units that are easily comparable for different segments or different preventive measures. Therefore, additional processing and interpretation of the results is required to apply model risk evaluations to decision making. This additional processing and interpretation may take place outside of the risk model as part of the operator’s overall risk assessment and risk evaluation process.
- Identification and evaluation of preventive measures is an important application of risk assessment and required by IM regulations. This application can be supported by a risk model that has the following characteristics:
 - The model can indicate the change in risk from implementation of the risk reduction measure.
 - The model includes all threats to the pipeline segment that can be addressed by preventive measures.
 - Model inputs represent the pipeline characteristics, consequence receptors, and other risk factors affected by the preventive measures, so that the effect of each measure can be evaluated through changes in inputs or changes to the structure of the model.

IV. Likelihood Modeling for Line Pipe

This section²⁴ on line pipe covers important characteristics of the likelihood part of the risk definition and formula.²⁵ Likelihood represents the chance of an unwanted event occurring. In the context of pipeline risk modeling, the primary “unwanted event” for hazardous liquid and natural gas pipelines is the failure of a pipeline system to contain the gas or hazardous liquid product. The likelihood part of a pipeline risk model encompasses the scenarios for failure and uses the model input variables in those scenarios and the interrelationships among inputs to estimate an overall likelihood of failure. To accomplish this, the model should specify:

1. Input variables representing characteristics of a pipeline segment and the environment around the segment, representing all factors important for estimating the likelihood of failure for the segment: They represent the prevalence of threats, the resistance of the pipeline system to threats, and the effectiveness of existing preventive measures. These variables may include pipe condition, coating condition, cathodic protection (CP) effectiveness, operating pressure, operating stress level, depth of cover, excavation activity around the pipeline, landslide potential, product transported, etc.
2. How to combine the model inputs in the overall evaluation of the likelihood of failure. The model should accurately represent threat interactions that could increase the likelihood of failure and whether an input variable can cause failure on its own or would only occur in combination with other factors.

Different model types have different output likelihood measures. Output likelihood measures from different model types²⁶ can be qualitative categories, relative indexes, or quantitative measures of probability or frequency in standard units. Output measures in standard units, such as failures per unit distance per unit time (e.g., failures per mile per year) are the most flexible and widely applicable model outputs, allowing a consistent measure of failure likelihood for a pipeline segment, specifying *time* and *distance* (length):

1. The likelihood of failure varies depending on the time interval being considered. For example, the likelihood of failure for a specific pipeline segment is higher over a 10-year period than during a single year. Therefore, likelihood measures are typically expressed as frequencies (e.g., failures per year, failures per mile-year, etc.).
2. The likelihood of failure also varies depending on which portion of a pipeline system is being evaluated. As a system that can extend over long linear distances, a pipeline has different likelihoods of failure at different locations, as risk factors vary

²⁴ Sections IV and V of this document consider modeling of likelihood and consequences primarily for line pipe segments. Risk modeling for pipeline facilities (e.g., pump and compressor stations, tank facilities) is considered in Section VII.

²⁵ See Section II.C of this document for definitions and formula.

²⁶ See Section II.D of this document.

at different locations. A pipeline risk model should be able to evaluate the likelihood of failure for specifically defined segments.

Sections IV.A through IV.H below provide additional information on risk model treatment of likelihood.

A. Pipeline Threats

The likelihood of pipeline failure is derived from the collective likelihood of all threats acting on the pipeline and leading to pipeline failure. Pipeline risk models break down broad threat categories into more specific inputs that can be quantified using data or judgment and combined by a model algorithm to obtain the likelihood estimate.

Pipeline integrity management regulations (see Appendix E) require identification and evaluation of preventive measures to reduce the likelihood of failure. Most preventive measures implemented by pipeline operators attempt to reduce the likelihood of failure due to a single threat or a subset of threats. Evaluation of these measures will require the evaluation of the effect on the likelihood of failure due to each threat (also accounting for interacting or dependent threats) and summing up overall affected threats to obtain the total effect on failure likelihood.

Historical pipeline failure experience has resulted in a generally consistent scheme for categorizing threats. Different sources employ similar categorization of threats that should be considered for a complete evaluation of pipeline failure likelihood. The Risk Modeling Work Group considered the threat categorization from four sources:

- a. ASME Standard B31.8S-2004 identified threats²⁷
- b. Muhlbauer identified failure causes²⁸
- c. Canadian incident reporting failure causes²⁹
- d. U.S. DOT accident and incident report causes³⁰

PHMSA compared and integrated the categories from these four sources to develop the following categories of threats recommended for the likelihood portion of risk models:

1. External Corrosion
2. Internal Corrosion
3. Environmental Cracking (including SCC)
4. Structural/Material Degradation (non-steel pipe)

²⁷ ASME B31.8S-2004, *Managing System Integrity of Gas Pipelines*, 2005. Although developed specifically for application to gas pipelines, the threat categories in this document are applicable to hazardous liquid pipelines.

²⁸ Muhlbauer, *Pipeline Risk Assessment: The Definitive Approach and its Role in Risk Management*, 2015.

²⁹ CAN/CSA-Z-662-15, *Oil and Gas Pipeline Systems*, Annex H.

³⁰ PHMSA F 7000-1-Accident Report Form, F 7100.1-Incident Report Form, and F 7100.2-Incident Report Form can be accessed on PHMSA's web site at: <https://www.phmsa.dot.gov/pipeline/library/forms>.

5. Manufacturing-related Defects (includes defective pipe and seam acted on by fatigue or other failure mechanisms)
6. Construction-, Installation-, or Fabrication-related Defects (includes defective girth weld, fabrication weld, wrinkle bend or buckle, stripped threads, broken pipe, coupling failure acted on by fatigue or other failure mechanisms, improper equipment installation)
7. Equipment Failure (includes failure of control/relief equipment, pump, compressor, seal/pump packing failure, threaded or non-threaded connection, tubing or fitting, gasket O-ring, equipment body)
8. Excavation Damage (includes damage by operator, contractor, or third party; includes immediate failure or damage that results in later failure)
9. Other Accidental Outside Force Damage (includes causes such as vehicles, other fire or explosion, electric arcing)
10. Intentional Damage / Vandalism / Sabotage
11. Incorrect / Improper Operation (includes human errors such as tank overfull, valve misalignment, over-pressurization, improper equipment installation)
12. Geohazards / Weather / Natural Force Damage
13. Other / Uncategorized / Emerging Threat

Models should include all applicable threats, including any emerging threats found by pipeline operators that do not fit easily into the categories listed above. Even threats that have a low likelihood of causing a pipeline failure at a given location should be considered in the model (e.g., if the potential consequences due a failure from a low likelihood threat at the location could be high, the overall risk might be significant).

B. Selection of Approach for Representing Likelihood

The development of algorithms for assessing likelihood using a quantitative system model can employ a variety of approaches. The overall likelihood of failure is built threat by threat, by considering the factors affecting the likelihood of failure for each threat.³¹ The structure and approach to estimating the likelihood of failure due to different threats can vary widely in Quantitative System models. The choice of approach may also differ for different threats within the same model, based on the available data and information. Some different likelihood modeling approaches include:³²

1. **SME opinion** – SME opinion is converted into quantitative probabilities.
2. **Historical data** – Historical failure rates from available databases are used to estimate baseline failure rates, which are modified to reflect system specific attributes.

³¹ Including accounting for threat interactions; see Section IV.E of this document.

³² This list of approaches is taken from Skow, J., C-FER Technologies, Inc., *Critical Review of Candidate Pipeline Risk Models*, presentation at Pipeline Risk Modeling Methodologies Public Workshop, September 2015. See also Koduru, et al., C-FER Technologies, *Critical Review of Candidate Pipeline Risk Models*, 2016.

3. **Reliability Analysis Methods** – Detailed engineering models are used to estimate probability and consequence.

Another method for assessing the likelihood of failure for different threats is the “triad” approach recommended by Muhlbauer.³³ This approach envisions the modeling of pipeline failure mechanisms as assessing “exposure,” “mitigation,” and “resistance,” defined as:

“...Exposure (attack) –...defined as an event which, in the absence of mitigation, can result in failure, if insufficient resistance exists...”

Mitigation (defense) –...type and effectiveness of every mitigation measure designed to block or reduce an exposure.

Resistance – measure or estimate of the ability of the component to absorb the exposure force without failure, once the exposure reaches the component...”

The application of relative assessment/index models in IM programs led to questions regarding “weights” for likelihood scores of individual and interacting threats and their relative contributions to failure likelihood. This issue arose because some models treated the likelihood contributions from all threats equally in the total risk estimates, and did not consider interacting threats. This created a distortion because, historically and logically, different threats have and will cause failures with different frequency. [For example, past failure history indicates threats like corrosion and third-party damage have been the cause of failures with greater frequency and impact than other threats.]

To correct this distortion, some models apply fixed numerical weights as multipliers to each threat’s likelihood score and add the weighted scores to obtain a total likelihood score. However, the weights are often based on historical averages using data from diverse pipelines. Applying such averaged weights introduces additional distortion in the likelihood estimates intended to represent specific segments on specific pipelines with location-specific risk factors. To represent risk in the most accurate way possible, the risk assessment model should accurately account for segment-specific parameters of each segment of the pipeline being evaluated.

This is an issue primarily affecting relative assessment/index models or qualitative models, as Quantitative System models do not usually use fixed weights to normalize threat-specific likelihood of failure estimates for specific segments (although the quantitative estimates may use historical data as an input to the model). However, Quantitative System models that use “adjustment factors” to modify historical frequency data may also introduce inappropriate bias into the assessment.

³³ Muhlbauer, *Pipeline Risk Assessment: The Definitive Approach and its Role in Risk Management*, 2015. The reference includes examples of the modeling approach for different threats.

C. Single Approach or Threat-Specific Approach

When considering different modeling approaches, it is important to keep the overall purpose of risk modeling in mind – to understand the likelihood of threats to and consequences of a failure for a pipeline segment, and to identify measures to reduce and manage the risks. When a single approach is applied to all threats, the detail needed to model more complex threats adequately will necessarily be applied to other threats, even if a simpler approach is sufficient. Some operators may choose a threat-specific approach to risk modeling rather than a single approach for all threats to optimize available resources and reduce model complexity.

In practice, pipeline operators, particularly for smaller systems, often select approaches to risk modeling with the primary consideration of resource availability. Some modeling approaches are viewed as overly complex and costly, whereas other approaches may not be detailed enough to adequately model risk for specific threats. In addition, there can be a natural tendency for analysts to seek a single measure to characterize the overall risk for a pipeline segment. This can lead to the assumption that only a single approach should be taken to model pipeline risk.

A single risk value is of interest when evaluating the relative level of risk between different parts of a pipeline system, or when an absolute estimate of risk is needed. However, different threat-specific risk modeling approaches may be preferable, even if they do not result in a singular measure of likelihood or risk. For example, if one threat is thought to require a more detailed evaluation than others (e.g., stress corrosion cracking), operators should not feel like they must treat all threats with the same level of heightened sophistication if it is not needed. Less sophisticated models may be sufficient for the other threats.

Finding an appropriate balance of granularity, complexity, cost, and applicability of results is a challenge unique to each pipeline being analyzed. Figures IV -1 and IV-2 show the general outlines of two differing approaches – a “single” modeling approach for all threats, and another model approach where different modeling approaches are applied to different threats (the multiple arrows in Figure IV-2 indicate threat-specific modeling approaches vs. the singular modeling approach shown in Figure IV-1).

One challenge to a threat-specific approach is the comparison of output results from the different approaches when different modeling approaches (with potentially different risk units) have been applied. The ability to compare results is important to evaluating which risks are the most important to address and promoting the efficient use of resources for implementing preventive measures across the pipeline operator’s assets. One way to address this challenge is to extend the threat-specific analysis to include consequences, and then comparing threat-specific risk estimates, combining likelihood and consequences. Comparison of consequence estimates is generally more straightforward, as consequence estimates can be characterized by a common output such as expected loss.

Figure IV-1
Threat Category Modeling (Single Approach)

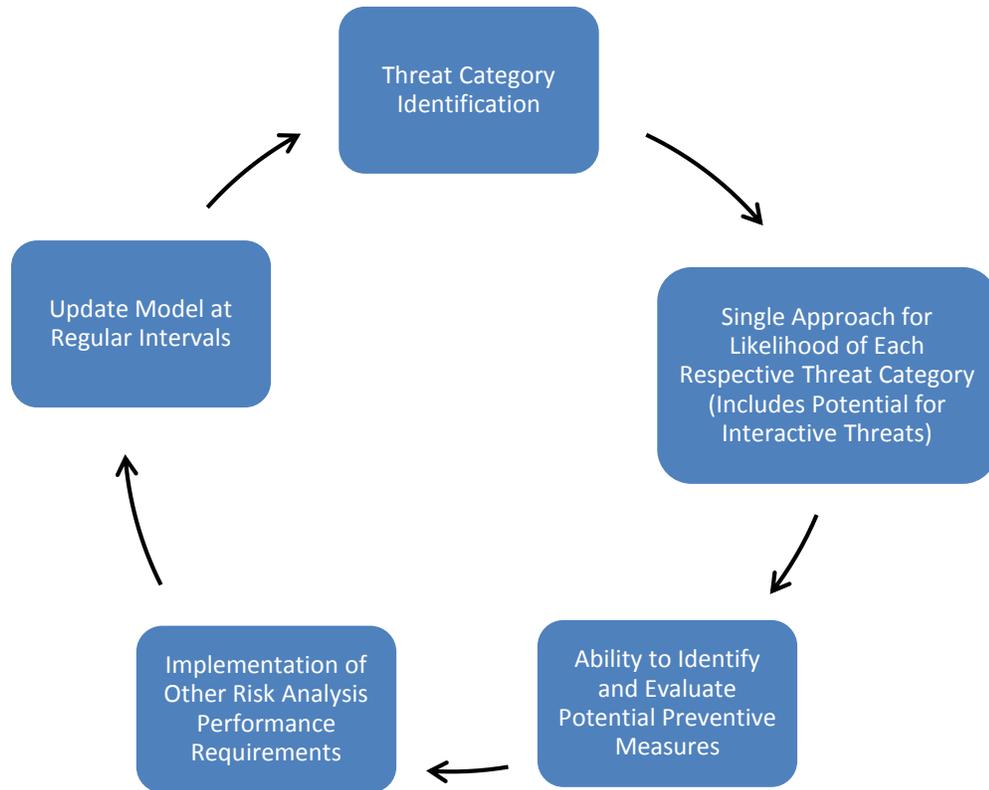
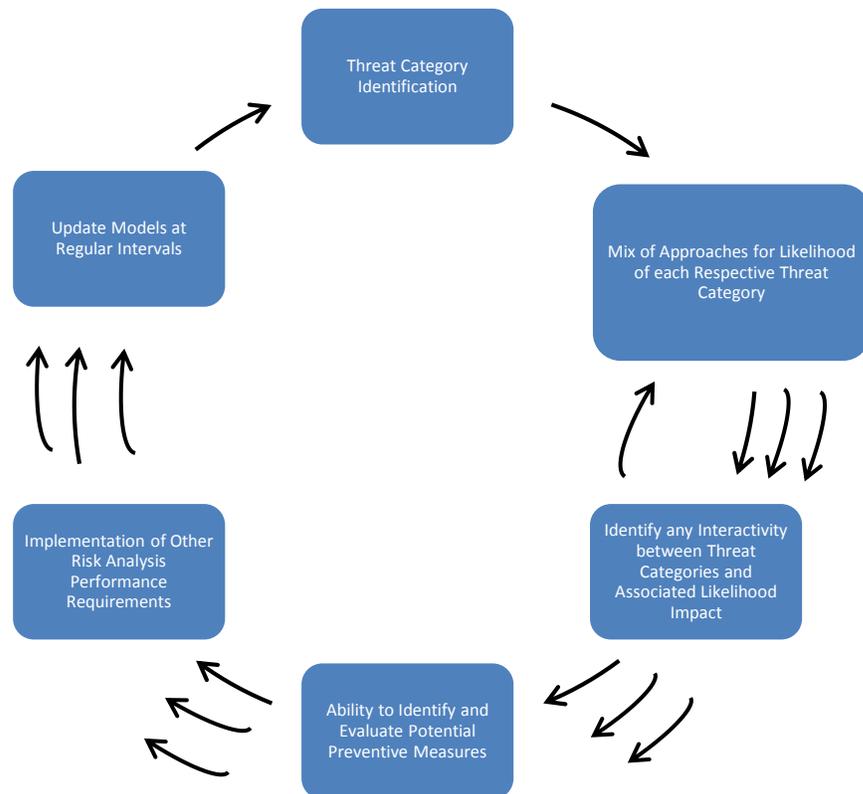


Figure IV-2
Threat Category Modeling (Threat-Specific Approach)



D. Human Performance Modeling

Historical failure experience shows that pipeline operator actions can have a significant effect on the likelihood of failure and the level of consequences following a pipeline failure. PHMSA has observed that these risk factors may be underrepresented in operator risk models. To fully represent the likelihood of failure, a risk model should include inputs related to human performance, and the model algorithms should include the relationship of these factors to other risk factors in the overall evaluation of risk. Risk modeling of human errors can be accounted for in various ways for likelihood estimates, including:

1. A threat category that represents operator actions that are the apparent cause of failures, e.g., “incorrect operation.” While PHMSA incident and accident data often list “small” percentages for “incorrect operation” as an apparent cause,³⁴

³⁴ <https://www.phmsa.dot.gov/pipeline/library/data-stats/pipelineincidenttrends>

probable and root cause analyses commonly find human performance as a leading contributory cause and cause of incidents and accidents as well as exacerbating the consequences of the failure.

2. Failures in other threat categories may stem from human errors. For example, “equipment failure” may result from maintenance, or design and construction human errors.
3. Consideration of interactive threats includes interactions between threats due to operator actions. For example, the threat category “incorrect operation” has potential interaction with threats in multiple categories. [One example is a combination of improper pressure control in combination with internal corrosion leading to failure of a pipeline segment.³⁵]
4. Potential human errors added to the uncertainty in the likelihood of failure given integrity assessment results, i.e., assessment results are subject to mischaracterization and misidentification of repair conditions.

Operator actions, or lack of actions, often influence and overlap both likelihood and consequence aspects of pipeline risk modeling. Actions taken in response to failures can affect the severity of consequences. Operator actions can also directly impact likelihood modeling when differing characteristic of pipeline releases is involved (e.g., likelihood of small vs. medium vs. large releases). Dependencies of potential release levels on operator actions should be considered in the model to more correctly characterize risk.

E. Interactive Threat Modeling

The threats represented in a pipeline risk model may be interactive, because mechanisms that drive the likelihood of failure from one threat may be intensified by mechanisms driving the likelihood of failure from another threat. The interaction of the mechanisms driving both threats increases the total likelihood of failure from the combined threats. Multiple threats may also interact and result in an otherwise premature failure at a location on the pipeline. A study sponsored by PHMSA³⁶ uses a similar concept to define interacting threats as “two or more threats acting on a pipe or pipeline segment that increase the probability of failure to a level greater than the effects of the individual threats acting alone.”

This study further points out that “...In order for threats to be interacting, they must act to cause a condition or situation that is more severe than that created by individual threats. It is important to note that threats are not necessarily interacting simply because they exist at the same location on a pipe or pipeline.”

To provide an appropriate likelihood of failure estimate, the risk model should account for the interaction of multiple threats. In addition, identification of effective preventive measures and

³⁵ See Section IV.E, Table IV-1 of this document.

³⁶ Munoz and Rosenfeld, *Improving Models to Consider Complex Loadings, Operational Considerations, and Interactive Threats*, Kiefner and Associates, U.S. DOT / PHMSA DTPH56-14-H-00004, 2016.

evaluation of the effect of preventive measures on reducing the likelihood of failure should include consideration of interacting threats.

One example of threat interaction is external corrosion or cracking on pipe damaged by denting. If the pipe damage caused external coating damage or coating shielding in an area of ineffective cathodic protection, then the pipe is more susceptible to external corrosion and cracking and the resulting likelihood of failure is increased. Another example is earth movement around a pipeline that exacerbates construction-related imperfections such as wrinkle-bends or certain vintages of girth welds.

The likelihood of failure from each threat includes a portion that involves that threat alone and a portion that involves interaction with other threats. To evaluate the likelihood of failure from multiple threats, the risk model should appropriately account for both portions. To illustrate, consider the following example of two threats. The likelihood of failure (probability) from the two threats can be expressed as:

$$P_T = P_1 + P_2 + P_i$$

Where P_1 = failure probability from threat 1 individual factors
 P_2 = failure probability from threat 2 individual factors
 P_i = increased failure probability from threat 1 and threat 2 interactions (see Appendix K of U.S. DOT PHMSA DTPH56-14-H-00004³⁷)

P_i in this expression is evaluated by considering the increased conditional probability of failure from threat 2, given the interactive factors from threat 1. In this example, the increased likelihood of failure from external corrosion due to ineffective CP combined with the existing coating damage from previous pipe damage will be higher than the likelihood of failure from external corrosion if no coating damage is present. Accordingly, that will increase the probability P_i in the above expression³⁸ used to evaluate the probability of failure from either threat.

Defining the interactions between different threats is an important activity in pipeline risk model development. It enhances the accuracy of the model as a representation of the risk of the pipeline. Additionally, the process of investigating and defining potential threat interactions can uncover failure causes that may not be immediately apparent. For a complete risk analysis, the definition of risk factors and assignment of values to model inputs for a pipeline segment should involve consideration of threat interactions. Both historical data and SME input should be employed to define potential threat interactions. Analysis of historical failure data may point to failures resulting from interactive threats where pipe characteristics are similar to the

³⁷ Munoz and Rosenfeld, *Improving Models to Consider Complex Loadings, Operational Considerations, and Interactive Threats*, Kiefner and Associates, U.S. DOT / PHMSA DTPH56-14-H-00004, 2016, Appendix K.

³⁸ The expression for the probability of failure from either threat is simplified by assuming the multiplied terms of the probability expression ($P_1 \times P_2$, $P_1 \times P_i$, $P_2 \times P_i$, etc., are small relative to the probabilities P_1 , P_2 , and P_i .

pipeline being modeled. SMEs with local knowledge can identify segments with characteristics that make them susceptible to interacting threats.

As an example of one way of analyzing available industry information, Munoz and Rosenfeld³⁹ identified combinations of threat types that could potentially interact. The study, based on a literature search, SME surveys, and analysis of accident/incident historical data, identified 98 threat interactions considered “reasonably possible” and depicted these threat interactions in a matrix, shown below in Table IV-1.⁴⁰ Interacting threats are indicated by a “1” in the matrix entry for each pair of threats that interact. Footnotes to the table give conditions when the threats might interact.

**Table IV-1
Interacting Threat Matrix**

		Time-Dependent			Stable								Time-Independent								
		EC	IC	SCC	MFR		CON		EQ				IO		TPD			WROF			
		EC	IC	SCC	DP	DPS	DFW	DGW	CD	MCRE	TSBPC	GF	SPPF	IO	TP	PDP	V	EM	HRF	LIGHT	CW
EC	EC			1	1	1		1	1 ¹	1	1 ³	1		1	1	1		1	1		1
	IC				1	1		1		1		1		1		1					
SCC	SCC				1	1	1	1	1 ⁴	1				1		1		1	1		
	MFR																				
CON	DP					1	1	1	1	1 ²					1 ⁷	1 ⁷	1 ⁷				
	DPS								1 ⁵	1 ²				1 ⁶	1 ⁷	1 ⁷	1 ⁷	1			
	DFW										1			1	1			1	1		1
	DGW									1	1				1	1		1	1		1 ⁸
	CD										1 ²	1						1	1		
	MCRE											1	1	1	1	1			1	1	1
	TSBPC													1	1			1	1		1
	GF													1	1		1	1	1	1	
	SPPF															1					
	IO	IO																			
TP															1	1	1	1	1	1	
PDP																		1	1		
V																					
EM																					1
WROF	HRF																				1
	LIGHT																				
	CW																				

Table IV-1 Footnotes:

1. A 1 applies unless the history of the segment indicates the construction damage has not contributed significantly to corrosion.
2. A 1 applies if the segment has not been subject to a pressure test to at least 1.25 times MAOP.
3. A 1 applies if the Dresser-coupled segment has no CP or has CP but no bonds across the Dresser couplings.
4. A 1 applies unless it can be shown either that little or no coating damage exists or that the segment is not susceptible to SCC.
5. A 1 applies if the pipe is seam-welded and was installed with wrinkle bends
6. A 1 applies if the pipe was manufactured with low-frequency welded ERW seam or flash welded seam.
7. A 1 applies unless it is known that the pipe material exhibits ductile fracture behavior under all operating circumstances.
8. A 1 applies only to pipe joined by acetylene girth welds or girth welds of known poor quality.

³⁹ Munoz and Rosenfeld, *Improving Models to Consider Complex Loadings, Operational Considerations, and Interactive Threats*, Kiefner and Associates, U.S. DOT / PHMSA DTPH56-14-H-00004, 2016.

⁴⁰ Munoz and Rosenfeld, *Improving Models to Consider Complex Loadings, Operational Considerations, and Interactive Threats*, Kiefner and Associates, U.S. DOT / PHMSA DTPH56-14-H-00004, 2016, Table 1.

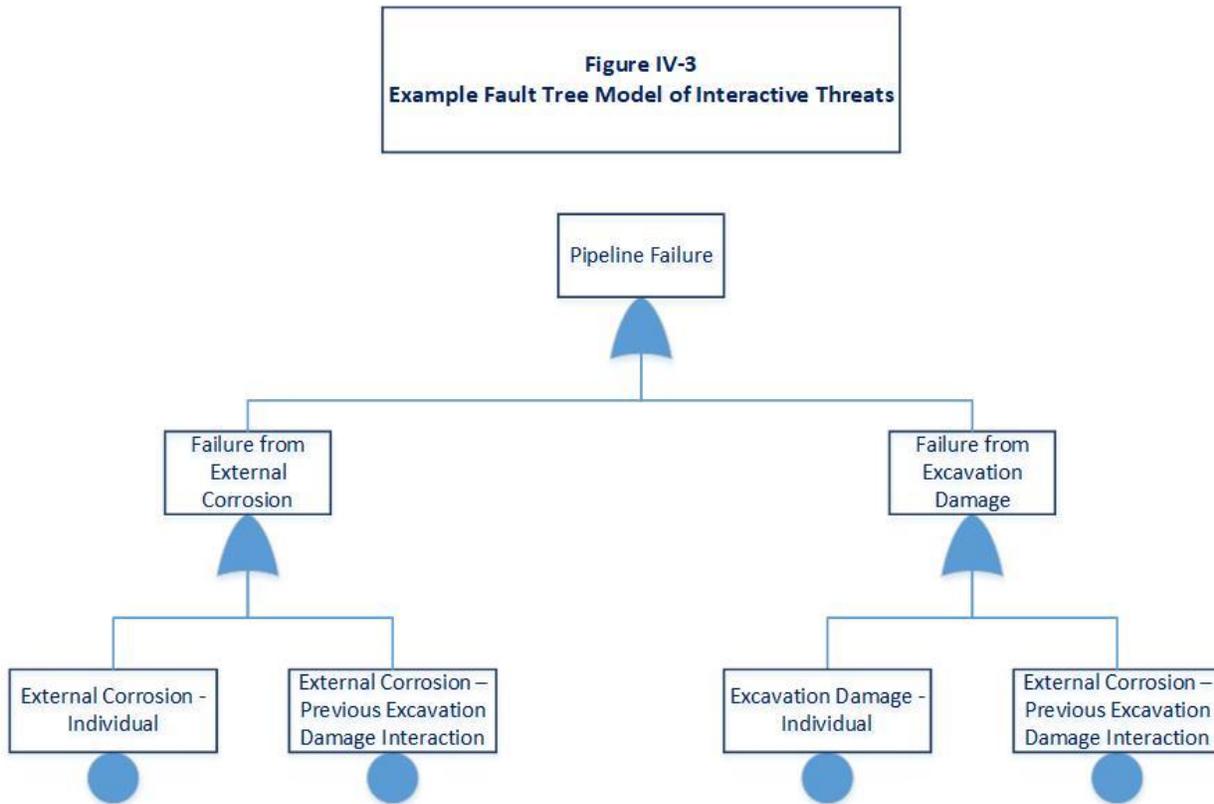
The codes used in the matrix to represent different threats are:

- External Corrosion (EC)
- Internal Corrosion (IC)
- Stress Corrosion Cracking (SCC)
- Manufacturing Related (MFR)
- Defective Pipe (DP)
- Defective Pipe Seam (DPS)
- Construction Related (CON)
- Defective Fabrication Weld (DFW)
- Defective Girth Weld (DGW)
- Construction Damage (CD)
- Equipment Related (EQ)
- Malfunction of Control or Relief Equipment (MCRE)
- Stripped Threads, Broken Pipe, or Coupling Failure (TSBPC)
- Gasket Failure (GF)
- Seal or Pump Packing Failure (SPPF)
- Incorrect Operations (IO)
- Third Party Damage (TPD)
- Third Party (includes First and Second Parties) (TP)
- Previously Damaged Pipe (PDP)
- Vandalism (V)
- Weather Related or Outside Force (WROF)
- Earth Movement (EM)
- Heavy Rains and Floods (HRF)
- Lightning (LIGHT)
- Cold Weather (CW)

Threat interactions such as shown in Table IV-1 should be incorporated in risk models at locations where they are found applicable.

As another example, fault trees may be used to model interacting threats explicitly by representing shared failure mechanisms as the same basic event in the models for each of the interacting threats. When the likelihood of failure due to the interacting threats is quantified using the fault tree logic, then the combined likelihood of failure from the threats will more correctly represent the contribution of the interactions. This is shown in Figure IV-3 below, using the example of external corrosion and excavation damage. [Note that the threat

interaction event under both external corrosion and excavation damage is identical but is not over-counted when the fault tree logic is properly quantified.]



Threats that act on pipelines independently (e.g., external and internal corrosion) may also act simultaneously at the same location on a pipeline. If such conditions are identified, by integrity assessment methods or otherwise, then this would impact the evaluation of the likelihood of failure at the location where both threats are impacting the pipeline. For a valid estimate of likelihood of failure, the risk model should reflect the composite effect of both threats, based on the identified condition of the pipe.

In another approach, Muhlbauer⁴¹ states that threat interactions are automatically considered in the “triad” approach to failure modeling (see Section IV.B and Appendix D of this document). By modeling changes in “resistance” and then overlaying changes in failure mechanisms at all points along a pipeline all types of potential interactions are considered. In the external corrosion / excavation damage interaction example discussed previously, this would mean that the reduced resistance of the pipeline due to external corrosion damage limits the pipeline’s ability to survive excavation contact (or other failure mechanisms).

⁴¹ Muhlbauer, *Pipeline Risk Assessment: The Definitive Approach and its Role in Risk Management*, 2015.

F. Threshold for Threat Consideration

Screening threats can have a distinct impact on risk analysis results. As part of IM rule requirements, operators must determine the applicability of specific threats to pipeline segments for the purposes of conducting integrity assessments⁴² and repairing applicable anomalies. However, PHMSA has noted in pipeline inspections and failure investigations that operators are applying the threat screening criteria for integrity assessments to risk models, causing threats deemed insufficiently significant to require an integrity assessment to be inappropriately excluded from risk models.

IM regulations require pipeline integrity assessment and repairs of identified pipe anomalies for pipeline segments that could affect HCAs. Operators may also carry out integrity assessments beyond the HCA-affecting segments. Integrity assessment methods are employed for specific threats of concern (corrosion, cracking, mechanical damage). Operators base decisions on which integrity assessment methods to apply on an evaluation of the susceptibility of pipeline segments to specific threats. If a particular threat is not considered significant on a segment, then an integrity assessment method associated with that threat is not specifically required.

However, when a threat is eliminated from consideration for integrity assessment, the threat must not be eliminated from inclusion in a risk model used to evaluate other risk reducing measures. In other words, if a threat is not deemed significant enough to warrant application of a specific integrity assessment method, it does not necessarily mean that threat can be discarded from the likelihood analysis in the overall risk model nor can data stop being collected on that threat. To exclude threats may lead to an incomplete risk evaluation and erroneous determinations of risk reduction measures. Many threats do not warrant that a unique integrity assessment technique be applied but are nonetheless valid for the consideration of risk reduction measures. The basis for screening out threats from consideration for integrity assessment must be documented and maintained for the useful life of the pipeline (in accordance with §§ 192.947 and 195.452 (I)).

The pipeline risk model should represent all relevant threats. It is important that the threats included in the model are not limited only to those that have caused pipeline failure historically. Rather, the model should include other threats that have caused failures within the pipeline industry and could do so in the future because of pipe characteristics and changing conditions affecting the pipeline. On some segments, pipeline characteristics may result in the model estimating a negligible likelihood of failure for one or more threats (e.g., several orders of magnitude lower than higher likelihood threats). Such a result can be justification for reduced

⁴² “Integrity assessment” refers to method(s) used to assess the integrity of the line pipe for identified threats. More than one method may be required to address all the threats to a pipeline segment (49 CFR Part 192, Subpart O). Current pipeline code sections can be accessed at the U.S. Government Printing Office web site at: https://www.ecfr.gov/cgi-bin/text-idx?SID=1d49a3b137cb1b6fc45251074e634b44&c=ecfr&tpl=/ecfrbrowse/Title49/49cfrv3_02.tpl.

priority of additional measures to prevent failures from the negligible threats. However, such decisions must be made carefully to ensure a complete and accurate risk analysis. Additional considerations include:

1. Threat screening should consider the severity of consequences, as threats presenting a low likelihood of failure may be risk-significant if the failure modes could result in especially severe consequences.
2. If measures are taken to reduce the likelihood of failure from other threats, then the likelihood of failure from the screened-out threats should be reconsidered to determine if they are significant for a segment.
3. Interactions with other threats should be evaluated. Threats with low risk when considered individually may still interact with other threats and result in a significant risk.
4. Uncertainties in the assumptions and basis for model parameter values should be examined to determine if the likelihood of failure from a threat could be higher with small changes. If the uncertainties indicate that the likelihood of failure from the threat could be considerably higher, then evaluation of the threat should be included in the model. Understanding the shape of probability distributions for inputs can provide important insights into the effect of uncertainty and identify when actions to reduce uncertainty can impact decisions and yield significant risk reductions.

G. Application of Risk Models to Identify and Evaluate Preventive Measures

Integrity Management regulations require risk assessment to support identification of risk reduction measures to prevent and mitigate the consequences of a pipeline failure that could affect a high consequence area⁴³ and evaluation of the likelihood of a pipeline release occurring and how a release could affect the high consequence area.⁴⁴ Section 192.935(a) requires that an operator take additional measures beyond those already required by Part 192 to prevent a pipeline failure and to mitigate the consequences of a pipeline failure in a high consequence area. Section 195.452(i) requires that an operator must take measures to prevent and mitigate the consequences of a pipeline failure that could affect a high consequence area. “Preventive” measures reduce the likelihood of failure through additional protection against threats.

The effectiveness of different types of models in supporting risk-based decisions, including decisions on preventive measures, was discussed in Section III.A. A risk model can support *identification* and *evaluation* of preventive measures. To assist *identification*, sensitivity analysis can be conducted to help examine which threats and model inputs are driving the risk results. Preventive measures can be defined to address the most important risk drivers.

⁴³ 49 CFR §§ 195.452 (i)(1) and 192.935(a).

⁴⁴ 49 CFR §§ 195.452 (i)(2), 192.911(c), and 192.917(c).

There are various ways to identify and evaluate potential preventive measures. One method involves performing such a sensitivity analysis by reducing the value assigned to each model input variable one-by-one by a fixed percentage (e.g., 25-50 percent), leaving the other variables fixed at their best estimated values. The risk is then reevaluated using the revised input value. After this is repeated for all variables, the results can be compared. The variables that drive the biggest changes in the likelihood of failure could represent the risk factors with the best potential for risk reduction by preventive measures.

This evaluation can be performed on the entire pipeline or on specific pipeline segments. If considering the entire pipeline, the analysis results would show risk factors that have the greatest overall potential for risk reduction. If conducted separately for specific pipeline segments, the results indicate the factors that have greatest potential for risk reduction on those segments. If relatively few segments dominate the risk of the entire pipeline, then concentrating on the risk factors and potential preventive measures for the high-risk segments may present an efficient path to reducing risk.

Once risk drivers are identified, preventive measures may be defined to reduce the likelihood of failure. The risk reduction that may be achieved by implementing a measure is estimated by evaluating the baseline risk (i.e., *without* the preventive measure), evaluating the risk assuming the preventive measure is implemented, and calculating the difference as the estimated risk reduction. When this evaluation is performed for each preventive measure under consideration, the estimated effectiveness of all individual preventive measures are compared, necessary resources to complete each measure are calculated, and the most effective set of measures given available resources will be shown.

When estimating the significance of risk factors or the risk reduction achieved by preventive measures, the effects of interacting threats should be evaluated (see Section IV.E above). In addition, although the analysis may include *preventive* measures, the analysis to evaluate the potential benefit of a preventive measure should also include consequences to determine the overall risk reduction (versus just the reduction of likelihood). Any dependencies between likelihood and consequences should also be included, since these can affect the overall risk estimates.

For example, reducing the likelihood of failure from a particular threat may affect the distribution of failure modes (e.g., rupture vs. leak), which may then affect the distribution of release volume or the likelihood of different operator actions to limit a release. If a threat is reduced that has a higher than average proportion of failure by leak rather than rupture (e.g., corrosion), then the remaining distribution of failure modes will have a higher proportion of

failure by rupture, and the consequence aspects of the risk model will need to be adjusted accordingly.⁴⁵

H. PHMSA Key Recommendations – Likelihood Modeling

- The use of fixed numerical weights applied to risk factors and/or categories can introduce distortions in the likelihood of failure estimates for specific pipeline segments. These distortions should be avoided/corrected as part of the necessary adjustments to apply the output from these models to the evaluation of risk reducing measures affecting specific segments.
- Uncertainties in the values of model variables can be important to the conclusions of a risk analysis and should be carefully evaluated. The likelihood of failure due to a threat should be evaluated in the context of uncertainties and the potential for consequences given the threat.
- Estimates of the likelihood of failure should be periodically validated, including evaluation of model inputs and outputs, to ensure the risk model accurately represents pipeline system risks.
- Identification of the most important model inputs or risk “drivers” is critical to understanding if the model outputs are technically valid. Risk model factors found to be important to the output risk levels should be reasonable when reviewed by SMEs or compared with historical data (both industry-wide and operator-specific).
- When risk analysis involves multiple threats, the effects of threat interactions or dependencies on the likelihood of failure should be evaluated. The threat interactions shown in Table IV-1 represent one recommended approach for inclusion where applicable. Other interactions found to be applicable at specific locations or in unique operating environments should also be evaluated.
- The risk assessment should include modeling of human interactions that are significant to the likelihood of failure or have a significant effect on consequences following a failure.
- Different modeling methods may be applied to assessing the likelihood of failure due to different threats. Threat-specific modeling methods may necessarily vary and may not always be amenable to characterize risk as one composite risk value.

V. Consequence Modeling

This section provides information on important characteristics of consequence, the second fundamental part of the risk definition and formula.⁴⁶ In the general risk definition, consequence represents and evaluates the severity and loss associated with an unwanted event. In pipeline risk modeling, the unwanted event is failure (where failure is usually a leak or rupture) of a pipeline system or portion of a

⁴⁵ While the leak to rupture threshold has been historically set at operating pressures of 30% SMYS (specified minimum yield strength), it is important to note that recent work by Kiefner and Associates and Kleinfelder has demonstrated that ruptures occur below 20% SMYS when interacting threats are present (see http://kiefner.com/wp-content/uploads/2013/05/Study_of_pipelines_-_that_ruptured_at_stress_below_30pct_SMYS_PPIM_2013_paper.pdf). Operators should be aware of threat interactions when minimizing the consequence of a failure based on their assumption that the failure will only leak and not rupture.

⁴⁶ See sections I and II.B of the document above.

pipeline system. The consequence portion of a pipeline risk model encompasses the scenarios following a pipeline failure. The risk model uses the factors driving those scenarios and the interrelationships among risk factors to estimate the overall consequence of failure to potential receptors. Depending on the release characteristics, receptors may be at the point of failure of the segment or may be some distance away. To estimate consequences, the model should therefore include input variables representing important characteristics of a pipeline segment, including the product being transported and the location of the segment, and the potential paths of release dispersion between the segment and consequence receptors. These variables represent all factors needed to estimate the consequences of failure for all points along the segment.

The consequence analysis begins with consideration of a pipeline failure at a specific location and ends with estimates of the impacts that could occur from a release following the failure at that location. To evaluate the consequences of failure, the model includes and estimates the following dependent elements of a release⁴⁷:

1. **Product Hazard:** What kind of damage could the pipeline's transported product cause to receptors (e.g., flammability, toxicity)?
2. **Release rate and volume:** How much gas, liquid, or vapor could be released?
3. **Release dispersion characteristics:** Where, how, and when could the released product travel?
4. **Receptors:** Who or what could be impacted negatively by the release given the product hazard, volume, and dispersion?
5. **Expected Loss:** What is the estimated worth to the operator and other stakeholders of avoiding impacts to receptors and direct losses from a release?
 - a. Receptors of a release may be diverse (e.g., the public, operator personnel, the environment, private and public property). Consequences can be measured individually for the different types of receptors, but optimal decision making can be facilitated if consequences can be translated into a single value equivalent that represents total loss from the consequences (e.g., dollars). If a unified measure of consequence is needed for risk assessment or decision-making, then a consistent and defensible method to measure the magnitude of consequences to different receptors is needed.

The first four⁴⁸ elements are estimated based on data and information on the objective characteristics of the pipeline and its location. However, "Expected Loss" is a more subjective measure that ultimately represents the realities, attitudes and preferences of the operator organization and other stakeholders. For example, respective pipeline operators conduct operations in widely varying population densities,

⁴⁷ Approaches can vary as to whether commodity release/dispersion modeling is part of the same software used to quantify pipeline risk or is estimated separately and then integrated into the quantification model. For the purposes of this report, both approaches are considered to be part of the same overall risk model.

⁴⁸ Muhlbauer, *Pipeline Risk Assessment: The Definitive Approach and its Role in Risk Management*, 2015.

physical environments, regulatory environments, have varying levels of ability to cope with accident costs, and have organization-specific levels of risk tolerance.

Conceptually, the evaluation of consequences is a function of these elements, with the estimates for each element dependent on previous elements:

$$\text{Consequence of Pipeline Failure} = f(H, Q, D, R, L(R))$$

Where:

H = Product Hazard to Receptors

Q = Release Rate and Volume

D = Release Dispersion Characteristics

R = Receptors Impacted by the Release

L(R) = A Measure of the Loss given the Impacts to all Receptors

Sections V.A through V.D of this document provide additional information on risk model treatment of consequence.

A. Selection of Approach

Consequences of pipeline failures can differ widely because of a variety of factors, including the differences in hazards and dispersion characteristics of different commodities. Table V-1 shows the names of commercially available consequence analysis models that have been used to estimate safety consequences for different commodities.⁴⁹ These models cover different elements of the consequence analysis described in Sections V.A.1 through V.A.4.

**Table V-1
Safety Consequence Models for Different Commodities**

Commodity	Hazard	Model Type	Models
Natural Gas	Jet Fire, Flash Fires, Blast Pressure, Thermal Radiation	Simplified Models	PIR calculation
		Detailed Proprietary Models	PIPESAFE DNV PHAST
HVL	Flash Fires, Jet Fires, Pool Fires, Fireballs, Toxic Effects, Blast Pressure	Hazard Area Estimate	API RP 581
		Proprietary Software	CANARY DNV PHAST EFFECTS (TNO) TRACER (Safer Systems)

⁴⁹ Presentation by J. Skow, C-FER Technologies to Risk Modeling Work Group, *Critical Review of Candidate Pipeline Risk Models*, October 5, 2016. This presentation can be accessed on the internet at: <https://primis.phmsa.dot.gov/rmwg/meetings.htm>.

		CFD ⁵⁰ Modelling	IOGP (2010) Norwegian Standard NORSOK Z-13 Annex F (NORSOK 2010)
Refined Product and Crude Oil	Pool Fires, Fireballs, Toxic Effects	Proprietary Software	
		CFD Modelling	

A consequence analysis approach should address all relevant elements of a product release following a pipeline failure, including hazards of the released product, release rate and volume, dispersion characteristics, and receptor impacts. Exclusion of any element results in an incomplete analysis and unreliable results. Sections V.A.1 through V.A.5 below provide information on each of the consequence analysis elements, the inputs and outputs of each element, and the needs from risk models to support each element.

A.1 Hazard

Input: Pipeline commodity properties.

Output: Hazards to consequence receptors.

The analysis should consider acute hazards of the released products such as flammability, toxicity, and mechanical effects of a release, as well as chronic hazards such as environmental contamination. Acute thermal hazards can include effects from immediate or delayed ignition.

For a complete analysis, all relevant hazards of all commodities that are transported in the pipeline should be included in the risk model. If multiple commodities are transported, then the hazards of all of them should be included. For example, a hazardous liquid pipeline could transport different types of HVLs, crude oil pipelines can carry sour crude and non-sour crude, refined products pipelines can carry jet-A fuel and high-octane gasolines, and natural gas pipelines can carry high BTU gas as well as lower BTU gas and some natural gas condensates. Each product that a pipeline transports comes with distinct hazards to humans and the environment and distinct dispersion characteristics over land, water, and air.

Even if the pipeline transports a single commodity type, release of the commodity could result in multiple hazards. Limiting the scope of the consequence analysis to only the most frequently transported commodity or the “most significant hazard” could result in excluding risk-significant scenarios from the risk analysis. Often, the consequences of

⁵⁰ “CFD” stands for “Computational Fluid Dynamics.”

one hazard will dominate some locations, but for other locations, multiple hazards will each have an important contribution to risk⁵¹.

A.2 Volume

Input: Pipeline characteristics, location characteristics, failure modes, and commodity properties.

Output: Release volumes at each location following a failure.

For a complete risk assessment, the consequence analysis should include consideration of a wide range of scenarios to estimate the volume of commodity that might be released following a pipeline failure. Volume is an uncertain quantity, so a complete analysis may require consideration of multiple scenarios to estimate the range of volumes that could be released. Volume estimate scenarios are defined by input variables that affect release volumes, including the leak or rupture size, the flow rate through the pipe failure, the time required to detect the leak or rupture, the effect and timing of operator actions, the location of valves that could be used to isolate and limit the release, commodity vapor pressure (as applicable), and the elevation profile of the pipeline. Considering a range of possible scenarios, including both large and small failure sizes, better ensures that the highest risk scenarios are covered. Concentrating on only one scenario (e.g., largest rupture) may not result in the highest release volume or the highest risk level.

At each potential release location, the range and distribution of failure sizes is dependent on the distribution of failure modes (leak vs. rupture). The distribution of failure modes is dependent on the distribution of the likelihood of failure from different threats, because threats have varying frequencies of failure in different modes. For example, corrosion failures on pipe with higher toughness properties tend to have a lower likelihood of rupture than seam and cracking failures or excavation damage. Therefore, the range of release volumes at each location is dependent on the distribution of threats at the location. For an accurate consequence estimate, the risk model algorithm should preserve this dependency.

To properly represent risk, the volume estimate should encompass the range of possibilities experienced in applicable historical releases. As applicable, historical data beyond the specific pipeline being analyzed should be included when considering the range of possible release volumes. If historical releases are considered inapplicable, the analysis should explain exclusion of these scenarios from consideration.

⁵¹ For example, the 1999 Olympic Pipeline / Bellingham, WA accident caused three fatalities, two resulting from fire and one from fumes causing loss of consciousness. Document can be accessed at: (<https://www.nts.gov/investigations/AccidentReports/Reports/PAR0202.pdf>).

It may be useful for an operator to consider a fixed set of hole sizes based upon types of expected failures (e.g., pinhole, corrosion hole, small rupture, etc.) Release rates can then be calculated for each size and used as the basis for determine release volumes while incorporating other information, such as estimated response times.

A.3 Dispersion

Input: Release rate and volume, commodity properties, location and dispersion path characteristics, emergency response to spill.

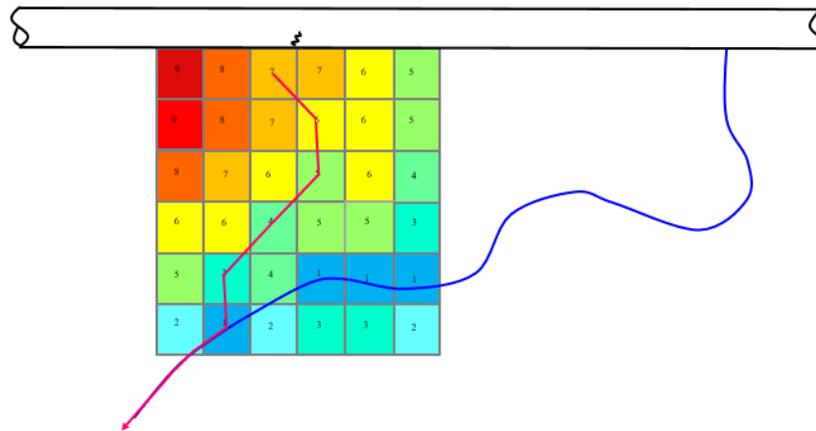
Output: Locations where receptors are subject to hazards from released commodities.

To support a complete consideration of potential consequences, the analysis should consider all dispersion methods and pathways that could result in adverse consequences to receptors, recognizing that pathways and magnitudes of dispersion are uncertain. The consequences of a pipeline release to impact potential receptors depend on the extent and direction of release dispersion. Dispersion depends on the product characteristics, volume released, geographic features around the pipeline, and environmental conditions. Depending on the released commodity and location characteristics, the release may disperse by air, soil, or water. Variable atmospheric and waterway conditions (e.g., wind direction and speed, water flow velocity) should be considered to include the full range of possible dispersion of the released commodity. Consideration of both high-likelihood and high-consequence dispersion scenarios is essential to a full evaluation of risk. It may also be that the most likely scenario is not the highest-risk scenario.

For released liquids, dispersion by land and water is frequently modeled using a digital elevation model (DEM) to trace potential spill flow paths, along with stream locations integrated in a GIS (see example in Figure V-1). Dispersion by water is particularly important to analyze, since waterways provide paths for the spill to reach more receptors further from the spill location. For very small spill volumes that occur away from waterbodies, detailed dispersion modeling may not be warranted, if the spill is unlikely to disperse beyond the immediate vicinity of its origin.

To initiate integrity management programs, pipeline operators were required to identify which of their pipeline segments could affect high consequence areas. Operators continue to update those analyses as an ongoing part of their IM programs. The analyses may involve use of elements of consequence models that include hazard identification, spill volume estimates, and dispersion estimates.

Figure V-1: Spill Plume Dispersion over Model of Relative Elevation Near Pipeline



A.4 Receptors

Input: Locations subject to hazards following release.

Output: Receptors in locations subject to hazard after release and dispersion.

The magnitude and direction of release dispersion defines the areas subject to release hazards, the potential receptors of release consequences in the hazard areas, and the severity of impacts. Depending on the hazards involved, potential receptors may be near the failure location on the pipeline, or they may be some distance away (particularly in scenarios where the released commodity may be transported by water). Potential receptors include:

- Persons occupying the hazard area (homes, workplaces, schools, hospitals, etc.) that could be injured or killed
- Features of the natural environment (water resources, flora and fauna, etc.) that could be damaged or contaminated
- Structures and other property that could be damaged or destroyed.

A.5 Expected Loss

Input: Consequences to receptors from a release.

Output: Expected loss due to consequences.

A measure of loss is needed to allow comparison of the expected loss from a pipeline failure to the resource expenditure of risk reduction measures, to help evaluate their relative effectiveness. Some consequences, such as the direct monetary costs of a release, including property damage, relocation costs, environmental cleanup costs, and paid civil and legal penalties, are directly comparable to the increased capital and operating costs required to implement risk reducing measures. However, release consequences could include additional impacts that are not readily measured by direct

monetary costs, including human casualties, ecological damage, damage to company reputation with regulators or the public, and product supply problems. If the analysis includes only monetary costs, it could understate the total loss from releases. Depending on the type of pipeline and the release, the societal impacts of such consequences could far exceed the direct monetary costs to the operator.

A common method for establishing a single-valued measure of the loss from diverse consequences is to convert all consequences to monetary equivalents. Operators are often reluctant to express losses due to fatalities and injuries in monetary terms. However, if human safety consequences are not included in the calculation of expected loss from failures, then the loss will be understated and the benefits of potential risk reducing measures will be undervalued. To fully characterize the loss from pipeline failure consequences, operators should include the cost of human casualties, along with other non-monetary costs, in the overall measure of consequences. The U.S. Department of Transportation has provided guidance⁵² on the value of avoiding human casualties, prescribing a Value of Statistical Life (VSL) figure of \$9.6 Million (2015 dollars) for DOT analyses.

In some applications, operators may choose one type of consequence, such as potential human casualties or environmental damage, and set decision criteria based on risk measures of this consequence only (e.g., expected fatalities per year). An example of this approach is given in Appendix B.1, which uses “FN” curves⁵³ as a guide for evaluating consequences based on human impacts. If a single consequence type is used to evaluate risk reduction measures, then the benefits of the risk reduction measures could be understated, because risks in other categories that are not included in the decision criteria may also be reduced by the risk reduction measures being considered.

Risk models may use an alternative to monetary equivalents to combine different types of consequences in a common measure of loss. If so, the method chosen should reflect the organization’s relative valuation of the types of consequences involved. Scales used to measure loss for different receptors (e.g., human casualties, environmental damage, economic) should be internally consistent, so that the same values are assigned to loss levels that are valued equivalently for all receptors.

B. Operator and Emergency Responder Response

The responses of operator and emergency responders during an event are key factors in the severity of consequences from pipeline releases. Failure detection capability and the speed and

⁵² U.S. DOT, *Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses – 2016 Adjustment*, 2016. Document can be accessed at: (<https://cms.dot.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20a%20Statistical%20Life%20Guidance.pdf>).

⁵³ See ISO/IEC 31010:2009 – *Risk management – Risk assessment techniques*, Section B.27.

efficacy of the emergency response can significantly impact the severity of the consequence of a release.

Consequence analysis should consider ability to detect leaks of various sizes as well as time to respond and shut down and isolate the pipeline. Overly optimistic expectations and assumptions about leak detection capabilities will likely lead to underestimating spill volumes and the associated consequences.

Operators have often used spill response plan assumptions in risk models to estimate spill volume and dispersion direction and distance as the basis for consequence estimates. Accident history indicates that although most pipeline accidents do not involve “maximum” or worst-case release estimates, in some cases, the anticipated level of consequences can be significantly underestimated. For a balanced assessment of consequences, operators should include the full range of released volume assumptions or estimates regarding spill response actions.

For example, the NTSB pipeline accident report for the July 25, 2010 Marshall, Michigan, crude oil pipeline rupture⁵⁴ stated “During interviews, first responders said that they were unaware of the scale of the oil release; this lack of knowledge contributed to their poor decision-making.” In addition, NTSB concluded “that although Enbridge quickly isolated the ruptured segment of Line 6B after receiving a telephone call about the release, Enbridge’s emergency response actions during the initial hours following the release were not sufficiently focused on source control and demonstrated a lack of awareness and training in the use of effective containment methods.”

The NTSB pipeline accident report for the September 9, 2010 San Bruno, California incident⁵⁵ concluded “...that the 95 minutes that PG&E took to stop the flow of gas by isolating the rupture site was excessive. This delay, which contributed to the severity and extent of property damage and increased risk to the residents and emergency responders, in combination with the failure of the SCADA center to expedite shutdown of the remote valves at the Martin Station, contributed to the severity of the accident.”

While not typical, historical high-consequence releases such as the Marshall, MI, and San Bruno, CA, incidents illustrate that variability in human actions in response to a failure can compound other factors to significantly affect the consequences of the failure. Emergency response time variation can depend on factors such as procedural complexity, logistical challenges, and the experience/training level of responders. Identification of the actual release location and the ability to isolate the release can vary widely depending on pipeline location and configuration,

⁵⁴ NTSB Accident Report NTSB/PAR-12/01 PB2012-916501, Enbridge Incorporated Hazardous Liquid Pipeline Rupture and Release, Marshall, Michigan, July 25, 2010.

⁵⁵ NTSB Accident Report NTSB/PAR-11/01 PB2011-916501, Pacific Gas and Electric Company Natural Gas Transmission Pipeline Rupture and Fire, San Bruno, California, September 9, 2010. This document can be accessed on the internet at: <https://www.nts.gov/investigations/AccidentReports/Reports/PAR1101.pdf>.

and surrounding population density. Therefore, it is important for a complete and valid modeling of consequences that the model:

1. Identify and incorporate all key human actions or decision points that can have a substantial impact on the level of consequences following a failure. Even complex responses can generally be broken out into a relatively few major steps that should be accomplished to minimize the consequence of a release.
2. Estimate the range of time that may be required to perform the key actions. The estimate should include a sufficient range to cover the full uncertainty in response time. Using a single point estimate for potentially important parameters such as the time to stop stream flow spill migration is not appropriate without substantial justification and can potentially skew consequence calculations.
3. Estimate the key parameters that have a substantial impact on spill volume and dispersion given the range of possible response times and the effectiveness of the response.

Given the uncertainty in response times, it may be useful to develop best-estimate, minimum, and maximum estimates (or a probability distribution for key response times) to more fully define the range of expected consequences for the releases being analyzed. Consideration of a range or distribution of impacts from emergency response allows more insight on the range of risks than reliance on point estimates that might have originally been developed for other purposes.

C. Application to Identification of Mitigative Measures

Integrity management regulations require risk assessment to support identification⁵⁶ and evaluation⁵⁷ of risk reducing (preventive and mitigative) measures. Section 192.935(a) requires that an operator must take additional measures beyond those already required by Part 192 to prevent a pipeline failure and to mitigate the consequences of a pipeline failure in a high consequence area. Section 195.452(i) requires that an operator must take measures to prevent and mitigate the consequences of a pipeline failure that could affect a high consequence area. “Mitigative” measures reduce the consequences of failure, through actions that reduce the product hazard, release volume, the dispersion of the release, or the exposure of receptors to the release (and may also reduce likelihood in some cases).

Risk models can support *identification* and *evaluation* of mitigative measures. The effectiveness of different types of models in supporting decisions, including decisions on mitigative measures, was discussed in Section III.A. To assist *identification*, sensitivity analysis can be conducted to

⁵⁶ 49 CFR §§ 195.452 (i)(1) and 192.935(a). Current pipeline code sections can be accessed at the U.S. Government Printing Office web site at: https://www.ecfr.gov/cgi-bin/text-idx?SID=1d49a3b137cb1b6fc45251074e634b44&c=ecfr&tpl=/ecfrbrowse/Title49/49cfrv3_02.tpl.

⁵⁷ 49 CFR §§ 195.452 (i)(2), 192.911(c), and 192.917(c). Current pipeline code sections can be accessed at the U.S. Government Printing Office web site at: https://www.ecfr.gov/cgi-bin/text-idx?SID=1d49a3b137cb1b6fc45251074e634b44&c=ecfr&tpl=/ecfrbrowse/Title49/49cfrv3_02.tpl.

examine which consequence analysis inputs are driving the risk results. Risk reduction measures can then be defined to address the most important risk drivers and mitigate the consequences of failure. Consequences may be reduced by actions, such as:

1. Reducing potential release volumes by:
 - a. Installing new emergency flow restriction devices, remote control valves, or automatic shutoff valves
 - b. Improving leak detection systems or operator response to rupture indications
 - c. Installing more SCADA measurement points to allow for more precise monitoring and quicker determinations of pressure, flow, or temperature data reflective of pipeline operating conditions at specific locations.
2. Reducing the potential for spill dispersion through such measures as secondary containment, pre-positioning emergency equipment, or improving emergency response.
3. Relocating receptors or relocating the pipeline to lower the potential for receptor impacts.

These measures have varying levels of practicality and potential effectiveness.

For a risk model to adequately support an analysis of the effects of additional mitigative measures, the model's consequence evaluation should be capable of reflecting changes due to the projected mitigative measures and showing the differences in risk due to the changes, whether they be changes to the pipeline, operations, dispersion pathways, or location of potential receptors. Changes can be represented in the model by changing the values assigned to variables or by making changes to the model structure.

The potential risk reduction from implementing a measure is estimated by evaluating baseline risk (i.e., *without* the measure), evaluating risk assuming the measure is implemented, and calculating the difference as the estimated risk reduction. The results can then be fit into a benefit-cost analysis of the risk reducing measures under consideration. When this evaluation is performed for each measure under consideration, the estimated effectiveness of all measures are compared, necessary resources to complete each measure are calculated, and the most effective set of measures given available resources will be shown.

D. PHMSA Key Recommendations – Consequence Modeling

- To support decision making and the identification and evaluation of mitigative measures, the consequence analysis should encompass the five elements of hazard, release volume, dispersion, receptors, and estimated loss. The impact of operator response actions and timing on these elements should be appropriately evaluated.
- Varying levels of sophistication are possible in the consequence analysis, while still allowing for useful results, but it is important to consider a range of scenarios, defined by a range of values for key consequence variables, to capture the spectrum of possible consequences. Also, it is important to consider high-consequence scenarios, even if they have a low probability of occurrence.

- The quantitative information in the consequence analysis should represent the operator's best current understanding of important variables that affect estimates of hazards, release volume, and dispersion. Equally important is a consistent and complete measure of losses from estimated consequences. If index scores, monetary equivalents, or other measure are used to represent the cost of consequences to diverse receptors, then the relative values assigned to different consequence levels should be internally consistent and represent the values of the operator organization or values used in societal decision making.
- The risk analysis should include modeling of human interactions that have a significant effect on consequences following a failure.

VI. Facility Risk Modeling

Pipeline facility risk assessment can appear to be different from line pipe risk assessment, because facilities have different component types with different failure mechanisms and failure modes. Consequence assessment can also look different because facilities are most often located on property controlled by the pipeline operator and not on public rights-of-way (ROW). In general, facility risk models will measure the likelihood of failure for the facility location (or specific areas within a facility), rather than a likelihood per mile. However, the basic failure mechanisms and consequence considerations are the same as for the modeling of line pipe risk.

Gas Transmission Facilities include:

- Compressor stations
- Regulator and Metering Stations

Hazardous Liquid Transmission Facilities include:

- Tank Facilities
- Pump Stations
- Metering Stations

The liquid and gas IM regulations require HCA identification, risk assessment, and evaluation of preventive measures and mitigative measures for facilities as well as line pipe. The IM regulations require integrity assessments for line pipe only.

A. Comparison with Line Pipe Risk

The same basic principles apply for risk assessment of facilities as for risk assessment of line pipe. Risk assessment models for facilities should model likelihood and consequence. All threats to integrity at the facility should be considered in the likelihood assessment. All product hazards, dispersion paths, and receptors should be considered in the consequence assessment.

Risk assessment of facilities includes consideration of the failure modes considered for line pipe as well as additional failure modes introduced by the inclusion of other components, such as motive equipment (e.g., pumps, compressors).

Some important aspects of facility risk include:

- The concentration of complex equipment at facilities can result in a higher likelihood of failure due to threats like equipment failure and incorrect operation (as shown in historical incident data).
- Equipment failure can be a more significant threat for facilities. Factors such as vibration, excessive and varying temperatures, start-ups and shut-downs, wear, design and construction errors, and other aging/cycling effects affect motive equipment like compressors and pumps and can cause failures of equipment or associated piping.
- Because of the complexity of most pipeline facilities, their failures represent a higher likelihood of service interruption. Standard designs and regulations for facilities include alarms systems, emergency shut-down systems (ESD), site grading for control of lost product, and facility evacuation planning. Most operators employ reliability engineering practices and predictive maintenance schemes to manage facility risk. These factors should be included in the inputs of the facility risk model, as appropriate.
- Facilities that are above ground may be more susceptible than buried assets to some outside force damage threats.
- The operator's analysis should consider the difference between risks for manned and unmanned facilities.

Overall, facilities may have a smaller risk "footprint" than line pipe, and the geographic extent of consequences may not be as widespread. Exceptions include facilities that store large quantities of commodities, such as tank farms. Many facility components are above ground and accessible for inspection and maintenance activities, in contrast to mainly underground line pipe.

To support improved facility operation, operators sometimes perform facility reliability analyses. The data and models for such analyses may be used as the basis for facility risk assessments, if they are augmented to include evaluation of consequences to receptors (e.g., human safety and environmental protection) both on and off the facility site. Operators may use tools often applied to analyze the failure of facilities, such as HAZOP, FMEAs, fault trees, LOPA, or "bow-tie" analysis,⁵⁸ as a starting point, expanding the analysis to consider failures that have offsite consequences and evaluating the risk of those failures. Operators may also be able to apply the data sets developed for risk assessment for those other tools and analyses.

⁵⁸ ISO/IEC 31010:2009 – *Risk management – Risk assessment techniques*, Sections B.13, B.14, B.18, B.21.

The following are other examples of threats and related risk factors for consideration in a facility risk assessment model:⁵⁹

- Equipment Malfunction
 - Effect of Preventive Maintenance Program
 - Effect of Routine Inspections
 - Effect of Secondary Containment
 - Valve Releases
 - Pump Releases
 - Automation
- Pipe Corrosion
 - External Corrosion
 - External Corrosion Monitoring Program
 - Cathodic Protection Systems
 - Soil/air Interface
 - Historic Releases from External Corrosion
 - Internal Corrosion
 - Internal Corrosion Monitoring Program
 - Product Type
 - Low Flow/Dead Legs Piping
 - Historical Releases from Internal Corrosion
 - Atmospheric Corrosion
 - Facility Proximity to Coastal Area
 - Previous Atmospheric Corrosion Issues
 - Effect of Routine Inspections
- Pipe Outside Force Related failures
 - Existence of Underground Pipe Markings
 - Existence of Underground Pipe Maps
 - Effect of Monitoring of Excavations
 - Historic Outside Force Damage Failures
- Incorrect Operation⁶⁰
 - Inadequate Procedures
 - Human Error
 - Quality of Station Documentation
 - Inadequate Training
 - Debris from Pigging and Hydrotesting
- Natural Force Damage

⁵⁹ Examples from RMWG presentation by M. LaMont, Integrity Plus, *Pipeline Facilities Risk Management*, November 30, 2016. This presentation can be accessed on the internet at: <https://primis.phmsa.dot.gov/rmwg/meetings.htm>.

⁶⁰ Incorrect Operation threat and related risk factors taken from the Appendix C facility risk example.

- Whether Located in Hurricane / Storm Prone Area
- Whether Located in Earthquake Prone Area
- Historic Natural Force Damage

Appendix C contains an example qualitative risk model used for facility risk assessment.

B. Application to Preventive Measures and Mitigative Measures

IM requirements for identification and evaluation of preventive measures and mitigative measures apply to facilities as well as line pipe. These regulations require operators take additional measures to prevent a pipeline failure and to mitigate the consequences of a failure that could affect a high consequence area.⁶¹ The same model types (Section II.D) are available for facility risk assessment as line-pipe risk assessment, with the same capabilities to support decision making (Section III.A), although the threats and consequences evaluated using the models will be somewhat different for facilities.

As an example, one hazardous liquid pipeline operator uses a relative assessment (index) model to assess risk at tank facilities. The model includes a likelihood index and leak impact factor (consequence) index. The likelihood index scores factors in the following categories:

- Design and Materials
- Incorrect Operations
- Corrosion
- External Forces

The design and materials category includes scores for such factors as:

- material operating stress and cyclic stress,
- material vibration,
- safety systems predictive and preventive maintenance program, and
- failure history of equipment like pumps, valves, tubing, and control and instrumentation

The leak impact factor index scores factors for product hazard, receptors, and spill size.

The design of many facilities includes telemetry, monitoring, and automatic shutdown and isolation systems. These instrument and control systems continuously monitor for leakage, explosive gas mixtures, fire, vibration, component temperature, intrusion, operating pressure, etc., and automatically isolate the system when alarm thresholds are exceeded. The required maintenance for these facilities often follows manufacturer's recommendations along with reliability engineering concepts to develop preventive actions to assure system availability,

⁶¹ 49 CFR §§ 192.935 and 192.452(i)(1). Current pipeline code sections can be accessed at the U.S. Government Printing Office web site at: https://www.ecfr.gov/cgi-bin/text-idx?SID=1d49a3b137cb1b6fc45251074e634b44&c=ecfr&tpl=/ecfrbrowse/Title49/49cfrv3_02.tpl.

reducing the risk of failure. Risk models should support the evaluation of enhancements to equipment design, maintenance, inspection, and operation and the effects of such enhancements on risk.

With a risk model, changes in the likelihood of failure of different equipment can be made to represent reliability enhancements from changes to design, maintenance, testing, or operating practices. The risk model's algorithm can be altered to represent design changes that add redundancy or introduce automation. The risk model can be used to evaluate the likelihood of failure with and without the improvements to estimate the resulting changes in risk. The changes in risk values can be compared to the cost of implementing the enhancement if alternative risk reduction measures are being compared or benefit-cost analysis is being conducted to evaluate the measures.

C. PHMSA Key Recommendations – Facility Risk Modeling

- Facility characteristics that affect risk may be significantly different than those for line pipe. Different failure causes may be important, and failures may have different consequences than nearby line pipe. However, the same basic principles apply for risk assessment of facilities as for risk assessment of line pipe and the same types of models may be applied.
- Incorrect operation, human error, and equipment failure can be important failure threats for facility risk and should be represented thoroughly in facility risk models.
- Existing operational approaches to assess facility reliability can often be adapted for evaluation of risk and off-site consequences and should be utilized where possible.

VII. Risk Modeling Data

Previous sections of this document concentrated on the structure of risk models and their use in supporting decisions on operator activities to control risks. This section discusses developing the values for input variables to risk models.

Model inputs should represent the best currently available information on risk factors for both the likelihood and consequences of pipeline failures. Inputs should draw data from both pipeline system records and the knowledgeable and informed opinion of subject matter experts (SMEs). Both data from records and SME input should be validated to ensure applicability as risk model inputs.

Using pipeline records to develop risk model inputs can be a large-scale effort, because of the wide variety of records involved and because pipeline characteristics can change considerably over the length of the pipeline. The operational and inspection history of pipeline segments can also vary significantly over the length of the pipeline. Other model inputs related to the environment in which the pipeline operates (e.g., terrain, soil types, and area characteristics around the pipeline) can also change significantly over the entire pipeline route. SME information should be used to fill gaps in information for model inputs as data from records is being assembled and validated and when inputs cannot be derived from any available records. Operators should revise field data acquisition forms to capture the

May 9, 2018 - Draft 1

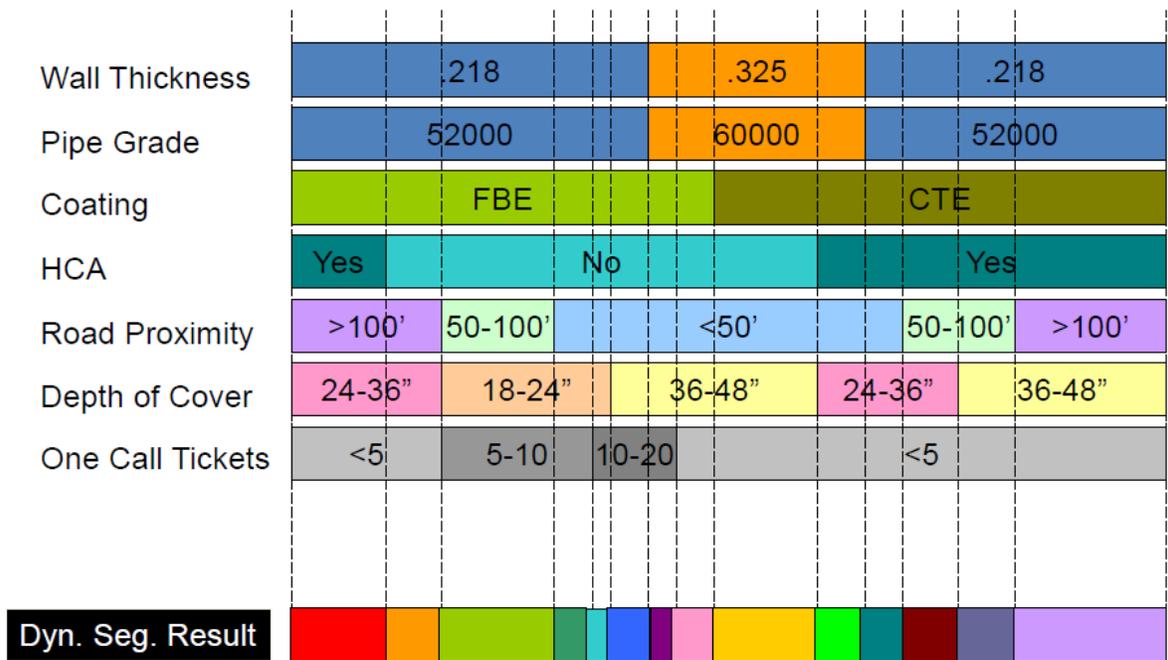
data and information required to support their risk assessment and any associated Geospatial Information Systems (GIS). Staff responsible for completing field data acquisition forms should be trained on the forms' requirements to meet the data quality expectations of the groups relying on this data to make decisions.

An important feature of input data for a pipeline risk model is a method such as a "Linear Reference System" (LRS) to tie risk factors to specific points or segments on the pipeline. Factors can be "linear" (e.g., pipe segments, HCA-affecting segments, class locations, inline inspection (ILI) ranges, MAOP/MOP, test pressure) or single "points" (e.g., facilities, valves, crossings, features or anomalies identified by ILI, girth welds). The reference system that specifies risk factor locations along the pipeline is integrated with a "geographical" location system to tie points and segments on the pipeline with the location of specific features around the pipeline (e.g., HCAs, buildings, bodies of water, elevation changes). In the context of risk models, this is necessary to align risk factors, affecting both the likelihood and consequences of a release, so that each location on the pipeline is appropriately represented by inputs to the risk model. This allows the risk model outputs to reflect the unique combination of risk factors representative at each location.

A GIS is useful to house data on the locations of pipeline characteristics and geographical features. If the operator does not use a GIS, then other methods should be used to accurately assign risk factors to the correct locations along the pipeline. SME knowledge on the relative location of pipeline-related factors and geographic features may be necessary to align these factors for input to the risk model.

Operators should define criteria for defining pipeline segments that have sufficiently different risk characteristics as to need segment-specific risk estimates. Segmentation can be achieved "dynamically" rather than manually if the operator stores risk data within a "linear Reference System" approach. Under this approach, illustrated in Figure VII-1, a model would estimate risk separately for each segment where risk factors are distinct. In the figure, the distinct segments are indicated by the dashed vertical lines. For example, the first (leftmost) segment extends to where the "HCA" factor changes from "Yes" to "No"; the second segment extends from this point to where the "Road Proximity," "Depth of Cover," and "One-Call Ticket" factors all change value.

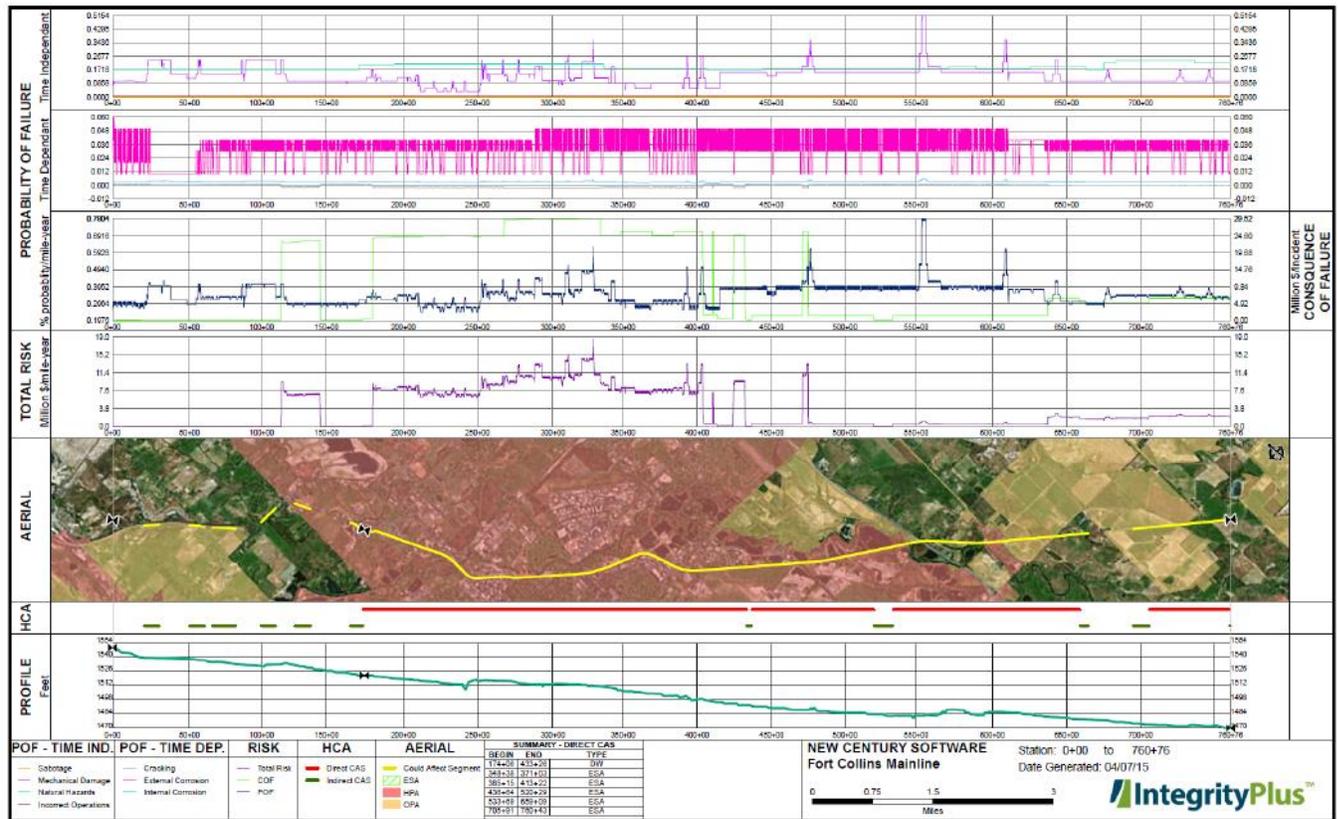
Figure VII-1: Dynamic Segmentation⁶²



Observing the change in multiple risk factors along the pipeline route can suggest locations where preventive measures and mitigative measures to reduce risk could be most effective. Figure VII-2 depicts an example of a “risk alignment sheet,” where changing risk model outputs along a pipeline route are shown in a visual form. As risk factor data changes and is used to generate estimates of likelihood, consequences, and risk, these outputs fluctuate.

⁶² Both Figures VIII-1 and -2 are taken from a RMWG presentation by R. Brush, New Century Software, *PODS Data Management*, March 7, 2017. This presentation can be accessed on the internet at: <https://primis.phmsa.dot.gov/rmwg/meetings.htm>.

Figure VII-2: Sample “Risk Alignment Sheet”



A. Relation of Data to Risk Model Types

The most important reasons to choose specific risk model types include: 1) how the models relate to and represent the pipeline system, 2) the output risk measures provided by each model type, and 3) the capabilities of model types to support decision making (see section III.A). While the type and quality of data that are available as model inputs are discriminating factors for applying different types of models, they should not be the primary factor. All model types can employ a combination of location-specific data from records, industry or operator averages, and SME-sourced information. PHMSA does not believe that any specific model type is preferable simply based on the level of data quality available to support the model inputs.

A quantitative system model, if it represents the logical and physical combination of risk factors to produce likelihood and consequence estimates, can produce useful results even if uncertainties exist in the input data. Although optimal results are obtained with a high degree of accurate location-specific data, system risk insights and support for decisions can be achieved with different levels of data quality and completeness, including situations when significant reliance is placed on SME input or generic data.

B. Data Sources

Operator records of segment-specific characteristics are the primary source of data used for risk model inputs. Operators collect data from routine operating, maintenance, and inspection activities. For example, operating logs record pressures, indicative of stresses on the pipeline, and transients to which the pipeline may be subjected. Exposed pipe reports record data about the condition of the pipeline that is gathered whenever the pipeline is exposed by excavation for other reasons. Records of patrols and surveillance show nearby construction activities that could pose threats to the pipeline, and evidence of changes in local flora that may be indicative of changes in soil conditions. Data sets from in-line inspection and other integrity assessments also provide information about pipeline integrity.

Operators should ensure that their data acquisition forms are collecting the data needed for their risk model inputs. Construction, operations, maintenance, and inspection personnel (both employees and contractors) responsible for completing data acquisition forms should be trained on requirements for completing forms with the needed data quality and completeness.

Table VII-1 lists typical data elements that apply to risk model inputs. Table VII-2 lists important sources for these data elements. Both tables were duplicated from ASME B31.8S (in some operating environments, operators may need to add additional data elements). Further information on data sources for risk model inputs may be found in ASME B31.8S, section 4.3.

Table VII-1: Data Elements⁶³

CATEGORY	DATA
ATTRIBUTE DATA	Pipe wall thickness
	Diameter
	Seam type and joint factor
	Manufacturer
	Manufacturing date
	Material properties
CONSTRUCTION	Equipment properties
	Construction Year of installation
	Bending method
	Joining method, process and inspection results
	Depth of cover
	Crossings/casings
	Pressure test
	Field coating methods
	Soil, backfill
	Inspection reports
Cathodic protection (CP) installed	
Coating type	
OPERATIONAL	Gas quality
	Flow rate
	Normal maximum and minimum operating pressures
	Leak/failure history
	Coating condition
	CP system performance
	Pipe wall temperature
	Pipe inspection reports
	OD/ID corrosion monitoring
	Pressure fluctuations
	Regulator/relief performance
	Encroachments
	Repairs
	Vandalism
	External forces
INSPECTION	Pressure tests
	In-line inspections
	Geometry tool inspections
	Bell hole inspections
	CP inspections (CIS)
	Coating condition inspections (DCVG)
Audits and reviews	

⁶³ ASME B31.8S-2004, *Managing System Integrity of Gas Pipelines*, Table 1.

Table VII-2: Typical Data Sources⁶⁴

Process and instrumentation drawings (P&ID)
Pipeline alignment drawings
Original construction inspector notes/records
Pipeline aerial photography
Facility drawings/maps
As-built drawings
Material certifications
Survey reports/drawings
Operator standards/specifications
Industry standards/specifications
O&M procedures
Emergency response plans
Inspection records
Test reports/records
Incident reports
Compliance records
Design/engineering reports
Technical evaluations
Manufacturer equipment data

Merging large amounts of data from diverse sources is facilitated by a consistent structure for storing and retrieving the data. Although methods and techniques are evolving, one example the pipeline industry has developed is the “Pipeline Open Data Standard” database architecture for organizing pipeline data (see <http://www.pods.org>). Figure VII-3 depicts the top-level structure of PODS. Figure VIII-4⁶⁵ shows an example of the data structure for a PODS module, showing the structure for data items such as CP type, CP Criteria, Nominal Wall Thickness, Outside Diameter, Pipe Grade, and Pipe Long Seam. The full scope of PODS modules may be found at <http://www.pods.org/wp-content/uploads/2015/06/PODS-6.0-Logical-Models1.pdf> and a depiction of the full architecture showing relationships among modules may be found at <http://www.pods.org/wp-content/uploads/2015/08/PODS-6.0-ERD1.pdf>.

⁶⁴ ASME B31.8S-2004, *Managing System Integrity of Gas Pipelines*, Table 2.

⁶⁵ Figures VII-3 and -4 are taken from <http://www.pods.org/pods-model/model-diagrams/>.

Figure VII-3: PODS Top-Level Module Organization

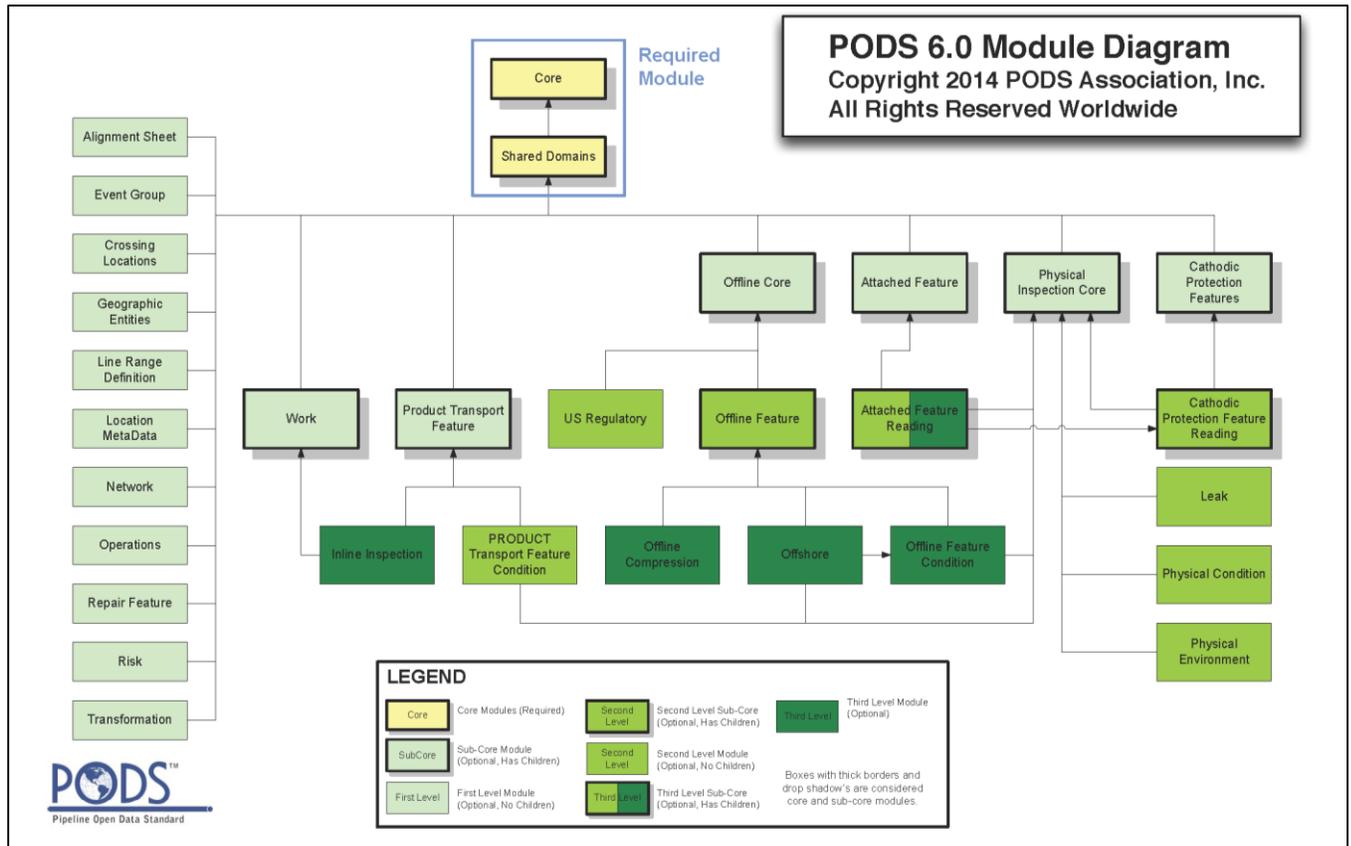


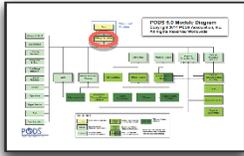
Figure VII-4: Example PODS Module



PODS™
Pipeline Open Data Standard

Shared Domains Module

(page 1 of 2)



PODS 6.0
Copyright 2014 PODS Association, Inc.
All Rights Reserved Worldwide

<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><th colspan="2">Cathodic_Protection_Type_CL</th></tr> <tr><td>Code</td><td>varchar(16) <pk></td></tr> <tr><td>Description</td><td>varchar(254)</td></tr> <tr><td>Name</td><td>varchar(50)</td></tr> <tr><td>Active_Indicator_LF</td><td>char(1)</td></tr> <tr><td>Source_CL</td><td>varchar(16) <fk></td></tr> </table>	Cathodic_Protection_Type_CL		Code	varchar(16) <pk>	Description	varchar(254)	Name	varchar(50)	Active_Indicator_LF	char(1)	Source_CL	varchar(16) <fk>	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><th colspan="2">County_CL</th></tr> <tr><td>State_CL</td><td>varchar(16) <pk/fk1></td></tr> <tr><td>FIPS_Code</td><td>char(3) <pk></td></tr> <tr><td>Description</td><td>varchar(254)</td></tr> <tr><td>API_Code</td><td>char(3)</td></tr> <tr><td>Name</td><td>varchar(50)</td></tr> <tr><td>Active_Indicator_LF</td><td>char(1)</td></tr> <tr><td>Source_CL</td><td>varchar(16) <fk2></td></tr> </table>	County_CL		State_CL	varchar(16) <pk/fk1>	FIPS_Code	char(3) <pk>	Description	varchar(254)	API_Code	char(3)	Name	varchar(50)	Active_Indicator_LF	char(1)	Source_CL	varchar(16) <fk2>	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><th colspan="2">CP_Criteria_CL</th></tr> <tr><td>Code</td><td>varchar(16) <pk></td></tr> <tr><td>Description</td><td>varchar(254)</td></tr> <tr><td>Name</td><td>varchar(50)</td></tr> <tr><td>Active_Indicator_LF</td><td>char(1)</td></tr> <tr><td>Source_CL</td><td>varchar(16) <fk></td></tr> </table>	CP_Criteria_CL		Code	varchar(16) <pk>	Description	varchar(254)	Name	varchar(50)	Active_Indicator_LF	char(1)	Source_CL	varchar(16) <fk>	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><th colspan="2">CP_Reading_Type_CL</th></tr> <tr><td>Code</td><td>varchar(16) <pk></td></tr> <tr><td>Description</td><td>varchar(254)</td></tr> <tr><td>Name</td><td>varchar(50)</td></tr> <tr><td>Active_Indicator_LF</td><td>char(1)</td></tr> <tr><td>Source_CL</td><td>varchar(16) <fk></td></tr> </table>	CP_Reading_Type_CL		Code	varchar(16) <pk>	Description	varchar(254)	Name	varchar(50)	Active_Indicator_LF	char(1)	Source_CL	varchar(16) <fk>
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C. Data Quality and Uncertainty

It is important to evaluate the quality of the current data supplied to a risk model. For many pipeline risk models, improving the scope and quality of input data is a long-term process. The operator should understand the overall characteristics of the risk model data set and implement actions to ensure needed data quality and seek continuous improvement in the data gathered and input to the model. Data quality issues can increase uncertainty in the results from the risk model. If the results are used to support decision making, then the results should be interpreted in light of those uncertainties.

There are many ways to measure data quality,⁶⁶ but, in the context of risk models, two central aspects can be identified:

1. Data Completeness

For any model, there may be input variables that are not always known, or verified to be accurate. Often in these cases, generic default values based on general industry information or SME knowledge and experience are applied. Accounting for this, a simple measure of data quality is the “unavailability” of pipeline-specific data in situations where default or generic average values are being used. This data quality measure can be further refined by considering the relative importance of the respective input data elements according to their impact on the risk model results.

The lack of pipeline-specific data does not imply that certain model types should not be used and the results should not be applied to support decisions. If a model is thought to be a better representation of the pipeline system but input data is incomplete, then informed default inputs can be used as an interim step, and data needs can be prioritized as familiarity with the model, model results, and real-world application to pipeline integrity management develop.

If a probabilistic model is being used, priorities for additional data collection may be developed systematically using a value-of-information analysis. This analysis estimates how additional data collection is expected to affect risk assessment results and thereby potentially change decisions on risk reducing measures. If the analysis finds that collecting specific additional information could change decisions significantly, then risk reduction could be significantly enhanced by collecting the additional information.

2. Data uncertainty

In addition to data completeness, it is also important to understand the uncertainty in data inputs to a model, regardless of the modeling approach. It is straightforward to estimate the basic statistical attributes for each model input (e.g., mean, variance). Bayesian updating⁶⁷ (a technique where a set of existing information – e.g., industry level component failure rate – can be updated by additional pipeline-specific data) is one approach to providing updated statistical estimates as additional data for a variable are obtained. Applying methods to estimate input variable uncertainty is especially important for risk models that apply only point estimates as input values rather than probability distributions. Applying a point estimate to represent a variable’s underlying data is convenient, but if the data is spread over a wide range, this should be understood and handled in a deliberate

⁶⁶ For example, see “Dimensions of Data Quality: *Toward Quality Data by Design*”; Wang, Guarascio (1991) (<http://web.mit.edu/smadnick/www/wp2/1991-06.pdf>), cited in presentation by P. Westrick, *Using Data in Relative models with Respect to Decision Criteria*, March 8, 2017.

⁶⁷ See *Probabilistic Risk Assessment Procedures Guide for Offshore Applications (DRAFT)*, BSEE-2016-xxx (Draft), October 25, 2016, and presentation by R. Youngblood, Idaho National Laboratory, *Bayesian analysis approaches to risk modeling*, August 9, 2016.

manner (e.g., sensitivity analysis). This is particularly important for the input variables that have the largest effect on model results.

If SME input is used, then the uncertainty associated with this input should be understood, particularly for the most important input variables. Applying point values for SME-based input variables with little attention to the uncertainty in those inputs can introduce substantial bias into risk results.

A persistent issue often mentioned by pipeline operators is data loss during new construction and during asset acquisition. To ensure complete and accurate data for risk model, operators should ensure that records are preserved and retrievable after construction and acquisition events.

D. SME Input

Accurate records of pipeline characteristics (including operational, maintenance, and inspection history) and the geographic features in the pipeline vicinity should be the primary source of risk model inputs. However, complete and accurate records are not always available for every pipe segment, and some risk model inputs may not be obtainable from records. In some cases, operator or industry average values may be available as inputs where segment-specific data are not available. In other cases, operators are dependent on the knowledge and experience of personnel who are familiar with the pipeline and important risk factors. Although accurate data from records may be a preferable source, SMEs are a valuable source for significant portions of the information used as risk model inputs.

For greatest effectiveness, a structured process is needed to integrate and balance personnel knowledge on risk factors to ensure consistency and minimize bias. As an example, steps in the process may resemble:⁶⁸

1. Establish members of the SME group that will provide data estimates.
Each SME should be an actual “expert,” in that the individual has authoritative or unique knowledge on the risk factors being evaluated. Criteria for SME status include factors such as credentials demonstrating expertise (not just years in a job or longevity at a company), certificates and training records, industry recognition, professional/ongoing education, etc.
2. Identify SME group facilitator and information integrator.
The facilitator should be familiar with the risk model, know how to interpret and calibrate expert opinion accounting for individual biases, and know how to integrate the information to obtain useful inputs for the risk model.
3. Define each variable or model input that is being estimated by expert opinion.

⁶⁸ The basic steps given here are adapted from Ayyub, B., *A Practical Guide on Conducting Expert Elicitation of Probabilities and Consequences for Corps Facilities*, U.S. Army Corps of Engineers, IWR Report 01-R-01, 2001.

All quantities should be precisely defined so that the experts clearly understand the scope and boundaries of what is being estimated. All relevant records and maps should be available to the SME group to help clarify the variable definitions and guide the evaluations.

4. Define specific criteria for SME evaluation of variables.

Specific rules should be established for how SMEs assign input values to ensure consistent application by different SMEs and consistent application across all pipeline segments covered by the risk model. For example, if “external coating condition” is being evaluated on a segment, then SMEs need specific criteria for what constitutes “good,” “medium,” “poor,” “disbonded,” or “shielding” coating conditions, so that the process can be consistently applied across the operator’s pipeline assets. Quantitative criteria are preferable where practicable.

5. Elicit SME information to obtain values for variables.

The process should involve a facilitated discussion to elicit risk factor inputs from the SME group. The facilitator should train the SMEs on the objectives of the evaluation, the process for eliciting SME input, and the evaluation criteria.

Group discussion should be facilitated and opinions obtained and made available to the entire SME group for consideration before a conclusion is reached. Although knowledgeable, SMEs can still have biases that influence their estimates of variables. A discussion should endeavor to draw out any biases⁶⁹ and correct for them. Any available applicable data (including information on pipeline characteristics, operational history, or inspection history) that can be used for comparisons is useful for this purpose.

6. Aggregate and present results.

The SME evaluations should be assessed for internal consistency and aggregated. The process should have documented rules for handling differences of opinion among SMEs⁷⁰ and methods for evaluating uncertainties in the inputs that are based on SME information. SME input should always include measures of uncertainty that capture the range of possible values estimated by the expert for each variable and the relative weighting of the values in the range. Probability distributions are a convenient way to capture information on uncertainty and can be used as direct input to probabilistic risk models. One method for expert elicitation⁷¹ involves

⁶⁹ Muhlbauer, W., *Pipeline Risk Management Manual*, 2004, Table 1.2, for a list of biases that can affect expert evaluations. See also Ayyub, 2001, Appendix C.

⁷⁰ Ayyub, B., *A Practical Guide on Conducting Expert Elicitation of Probabilities and Consequences for Corps Facilities*, U.S. Army Corps of Engineers, IWR Report 01-R-01, 2001. Different methods for combining expert opinions are summarized in Appendix C of Ayyub, 2001.

⁷¹ S. Kaplan, 'Expert information' versus 'expert opinions.' *Another approach to the problem of eliciting/combining/using expert knowledge in PRA, Reliability Engineering and System Safety*, 35 (1992).

assembling the evidence that each expert has used to formulate estimates, and deriving probability distributions for each variable consistent with that evidence.

7. Review and revise results.

The aggregated results should be presented to the SMEs for review, additional discussion, and potential revision. SMEs should be given the opportunity to revise their assessments after presented with the aggregated evaluation results. Any revised estimates should be incorporated in the aggregated results and Step 6 repeated.

Further details on processes for obtaining information from SMEs may be found in the following references:

1. Ayyub, B., *Methods for Expert-Opinion Elicitation of Probabilities and Consequences for Corps Facilities*, U.S. Army Corps of Engineers, IWR Report -00-R-10, 2000.
2. Ayyub, B., *A Practical Guide on Conducting Expert Elicitation of Probabilities and Consequences for Corps Facilities*, U.S. Army Corps of Engineers, IWR Report 01-R-01, 2001.
3. Unal, R., Keating, C., Conway, B., and Chytka, T., *Development Of An Expert Judgement Elicitation Methodology Using Calibration And Aggregation For Risk Analysis In Conceptual Vehicle Design*, Old Dominion University, NASA, 2004.

E. PHMSA Key Recommendations – Risk Modeling Data

- An operator’s choice for the type of risk model to employ in pipeline risk analysis should not primarily depend on factors related to quality and completeness of input data. Operators should take actions to improve data quality and completeness over time, but risk model inputs should represent the best currently available information on risk factors for each pipeline segment and operators should endeavor to employ segment-specific and location-specific data whenever possible to develop risk model inputs.
- Field data acquisition forms should be consistently checked against the data needs in the risk assessment and the GIS processes to assure the data that is needed to support these processes is being collected in the formats and quality expected. Personnel responsible for completing data acquisition forms should be trained on requirements for completing forms with the needed data quality and completeness.
- Risk models that rely on generic estimates or SME information for a significant portion of input data can be useful to gain insight on risk issues and support decisions. This is especially so if the model algorithm reflects the physical and logical relationships of the input variables and the model output risk measures are expressed in standard units.
- Risk model results should be generated using dynamic segmentation to account for changes in characteristics of the pipeline and its operating environment along the

pipeline route, so that the results best reflect the segment-specific and location-specific combinations of risk factors.

- SME input should be elicited carefully to best reflect expert knowledge on risk factors. A structured process should be employed to systematically obtain estimates from SMEs. All SME estimates should include a measure of the uncertainty in the estimates and effort should be made to minimize bias in the estimates.

Appendices

Appendix A – Likelihood Models

A.1 Qualitative Models

In qualitative models, inputs and outputs are developed as qualitative categories rather than numerical scores. In processes that use such models, the likelihood, consequence, and output risk levels are obtained by consideration of pipeline risk factors and assignment to a qualitative risk level. These models should have a defined logic for assigning risk levels.

Risk levels may be assigned via an SME discussion. If so, a structured process is needed to integrate and balance the panel’s knowledge on risk factors (see section VII.D).

A simplified example of the representation of qualitative results is given in Figure A-1. In the matrix shown, the different shaded regions represent areas of equivalent risk based on different combinations of likelihood and consequence.

Figure A-1
Example Qualitative Model

Consequence	Likelihood		
	High	Medium	Low
High	Red	Red	Yellow
Medium	Red	Yellow	Green
Low	Yellow	Green	Green

Qualitative Risk Scale



High

Medium

Low

A.2 Relative Assessment (Index) Models

Relative Assessment (index) model inputs represent the major risk factors for failure of a pipeline segment, including characteristics of pipeline segments and the surrounding area. These inputs are assigned numeric scores that represent the relative effects on failure likelihood of a pipeline characteristic. Each input may also be assigned a numerical weight, which reflects a subjective assessment of the importance to the potential for a pipeline failure represented by the input. The weighted scores are then combined to calculate an index or score representing the risk presented by each segment. Weights are commonly applied to threat scores to account for the pipeline segment's or operator's failure cause history. Typically, a likelihood index score and consequence index score are calculated separately. They are then combined to obtain a total risk index score. The most common method of combining a likelihood and consequence index to calculate a risk score is by multiplying them.

The index model algorithms often combine likelihood factors according to categories representing major threats to pipeline integrity. For example, index model likelihood categories might include:

- External Corrosion
- Internal Corrosion
- Stress Corrosion Cracking
- Manufacturing Related Defects
 - Defective pipe seam
 - Defective pipe
- Welding/Fabrication Related
 - Defective pipe girth weld
 - Defective fabrication weld
 - Wrinkle bend or buckle
 - Stripped threads/broken pipe/coupling
 - failure
- Equipment
 - Gasket O-ring failure
 - Control/Relief equipment malfunction
 - Seal/pump packing failure
 - Miscellaneous
- Third Party/Mechanical Damage
 - Damage inflicted by first, second, or third parties (instantaneous/immediate failure)
 - Previously damaged pipe (delayed failure mode)
 - Vandalism
- Incorrect Operations
 - Incorrect operational procedure
- Weather Related and Outside Force

- Cold weather
- Lightning
- Heavy rains or floods
- Earth Movements

The models typically include several inputs in each threat category. As noted above, each input is assigned a numerical score based on the characteristics or “attributes” of the pipeline segment or the area surrounding the section and is weighted according to its importance. The attribute information is stored in a pipeline risk database. Individual likelihood and consequence indexes can be calculated for each threat, using only the scores and weights of inputs included for the threat category.

For example, a risk index algorithm used by one pipeline operator includes the input “Construction Activity” under the category of “Third-Party Damage”. This input has four possible levels, or “attributes”, corresponding to different levels of construction activity along a pipeline segment. A numerical score is associated with each attribute so that the variable can be assessed on a consistent basis from pipeline segment to pipeline segment. The attributes and their associated scores for “Construction Activity” are as follows:

Construction Activity	
Attribute	Score
High	10
Medium	7
Low (“typical”)	5
Very Low or None	1

Specific rules should be established for assigning attributes to ensure consistent application of the process across different SME groups. SMEs need specific guidance on what constitutes “high”, “medium”, “low”, and “very low”, so that the process can be consistently applied across the operator’s pipeline assets.

Continuing the example, the weight for “Construction Activity” within the third-party damage threat category would be assigned a value (e.g., perhaps “13%”). In this algorithm, the attribute score for the “Construction Activity” variable is multiplied by this weight and summed with the weighted attribute scores for all other inputs in the third-party damage category to calculate a likelihood index score for the relative probability of pipeline damage due to third-party damage. This threat-specific index score is weighted and summed with the weighted index scores developed for the other cause categories to obtain the total likelihood index. The likelihood index is multiplied by the consequence index to obtain the total risk score for the pipeline segment.

Some operators use one of the “standard” risk-index models that have been developed by various industry consultants, while other operators have developed their own in-house index

models. One commonly used industry model is the model, presented in the Muhlbauer *Pipeline Risk Management Manual*.⁷²

Significant differences exist among index models in the specific input variables that are included in the quantification of the likelihood index; how scores are assigned to these variables; how the scores are weighted; and how the weighted scores are combined to provide an overall index. In the most common approach, the likelihood index is calculated simply as a weighted sum of the variable scores. Each variable weight is multiplied by the corresponding variable score for a segment and the products of the variable weights and scores are summed to calculate the likelihood index. If any interacting threats were applicable, an additional score would be added to the likelihood index to reflect the additional likelihood of pipeline failure (i.e., the “ P_i = failure probability from threat 1 and threat 2 interactions” discussed in Section IV.E).

In the Muhlbauer⁷³ approach, an index model algorithm calculates the likelihood index as a weighted sum of variable scores. The Muhlbauer *Pipeline Risk Management Manual* provides a set of nominal variable scores and weights that are intended to be starting points for the incorporation of segment-specific data. Additional variables can be defined by the operator.

In-house models developed by operators have been similar in nature to these two models. In some models, the algorithm that translates the individual variable scores into the likelihood index is more complex than a simple weighted sum.

A fundamental characteristic of index models is that the quantitative output is not an actual estimate of the likelihood of failure, consequence of failure, or risk. Instead, it is a numerical index that represents these measures. In most cases, a higher index value is meant to indicate higher likelihood, consequence, or risk and a lower index value is meant to indicate lower values. Thus, the indexes provide a relative measure of risk that has been useful for comparison between different segments or sections of the pipeline (e.g., for setting integrity assessment priorities). Relative model risk results can be challenging to use for applications requiring absolute estimates of likelihood or risk.

A.3 Quantitative System and Probabilistic Models

In this category of risk model, the characteristics of segments of the pipeline and the surrounding area are used to derive an actual estimate of the risk for each segment. Likelihood is estimated as the frequency of failure along each segment over a year’s time (or over some other relevant period). Expected levels of consequences in different categories (e.g., human health and safety, the environment, or the potential for economic losses) are estimated. The various consequence measures may be combined using some common units, such as equivalent

⁷² Muhlbauer, W. Kent, *Pipeline Risk Management Manual*, 2004.

⁷³ Muhlbauer, W. Kent, *Pipeline Risk Management Manual*, 2004.

dollar cost. If so, this requires consequences such as human deaths and injuries and adverse environmental impacts to be represented by dollars in the risk equation.

The total risk for the segment is estimated as the product of the likelihood of failure and the expected consequences given failure. If the model calculates the likelihood of different pipeline failure modes (i.e., small leak, large leak, rupture), then the likelihood and consequences corresponding to each failure mode would be estimated as well. The total risk would be estimated as the sum of the product of the likelihood of failure in each failure mode and the expected consequences, given failure in that mode.

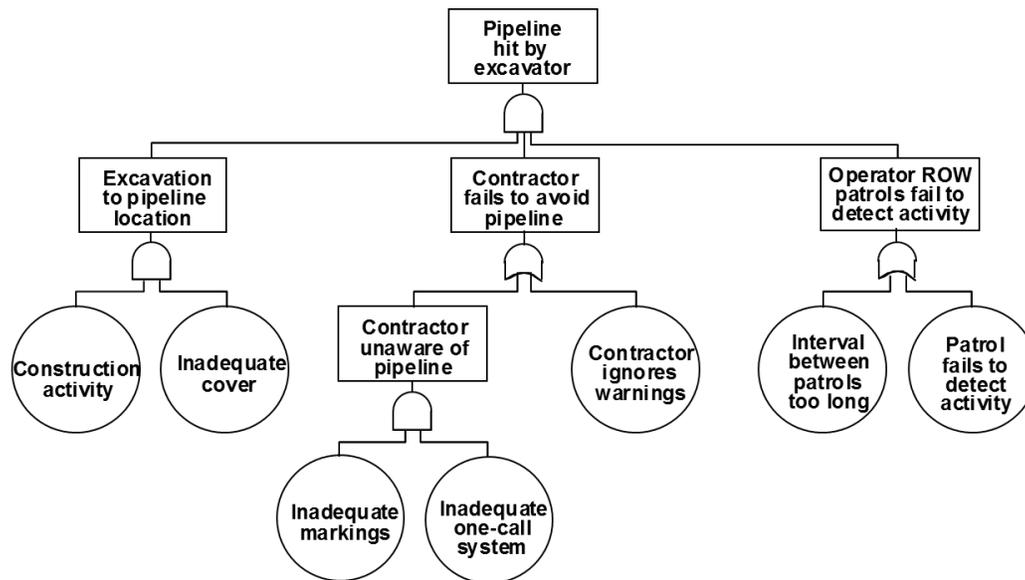
Quantitative System models calculate the likelihood and consequences of a failure along each pipeline segment using the same types of information on pipeline segment characteristics and the surrounding area that relative assessment (index) models use. Like index models, they can use a combination of data and SME judgment to evaluate inputs in categories corresponding to important threats and consequences.

The algorithm for a Quantitative System model typically includes numerous calculations based on the physical and logical relationships that translate pipeline segment characteristics into estimates of failure likelihood and consequences.

In one model of this type, a nominal or base likelihood estimate is provided based on historical failure rates for the cause categories. This nominal failure rate is modified according to segment-specific characteristics to estimate a segment-specific failure rate (i.e., the expected number of failures for each of the different failure modes per year). The algorithm for modification of the base failure rate may be based on statistical analysis of incident data or on analytical models (e.g., fault tree models or structural reliability models). In addition, the estimate for likelihood of failure may be modified by assumptions about the inspection and maintenance history and practice along the segment. For example, segments that have had recent integrity assessment and repair of discovered defects would typically have different failure likelihood estimates than other segments whose characteristics would otherwise be similar. In addition, as shown in previous Figure IV-3, the additional threat potential from interacting threats can be explicitly accounted for in quantitative system and probabilistic models.

As an example of how an analytical tool is utilized to estimate the likelihood of pipeline failure for one threat category, see Figure A-2, which is a simplified fault tree that models the likelihood of an excavator hit on a pipeline. This model would be part of the model used to estimate the likelihood of failure from excavation damage.

Figure A-2
Simplified Example Fault Tree Model for Excavator to Hit Pipeline⁷⁴



The frequencies or probabilities of the basic events of this fault tree (construction activity, inadequate cover, etc.) are model inputs that would be evaluated based on data or SME inputs. These quantities would be combined according to the model logic to estimate the probability of a pipeline hit by an excavator. This estimate would be combined with an estimate of pipe failure probability, given a hit, to obtain the estimated failure likelihood due to excavation damage. The failure probability, given a hit, is estimated using the probability of a hit imposing specific loads on the pipe and the probability of pipe failure to maintain integrity given those loads (based on pipe characteristics).

For time-dependent threats (e.g., corrosion), a similar “load vs. resistance” approach may be taken that includes evaluation of operating pressure, pipe properties, identified defect characteristics, and the likelihood of failure given pipe, defect, and operating characteristics. For these threats, however, defects grow over time, so the likelihood of failure is time dependent.

Consequences in some risk estimation models are estimated using analytical models to derive quantities such as economic loss and fatalities.

The CFER PIRAMID model is an example of a risk estimation model that has been employed by some pipeline operators.

Because Quantitative System model outputs are actual estimates of probability, consequences, and risk in standard units, they can be applied appropriately to IM program areas requiring

⁷⁴ From Stephens, Mark, C-FER Technologies, *Methods for Probability Estimation*, presentation to PHMSA Risk Modeling Work Group, 2016.

absolute measures of risk, as well as when relative measures are needed. They may also be used in other applications that require absolute quantitative estimates of risk.

A.4 Probabilistic Models

Probabilistic models are distinguished from other quantitative system models by the use of probability distributions, rather than single point value estimates, to represent model inputs. The model algorithms combine the distributions according to the system model and obtain output distributions for standard risk measures such as probability of failure, and expected loss from consequences. The difference between a Quantitative System model and a Probabilistic model is not necessarily in the logic of the model algorithm, but a probabilistic model should utilize tools (e.g., Monte Carlo simulation⁷⁵) that allow probabilistic input, in the form of distributions, to be processed and derive output.

Some important inputs to pipeline risk models, such as integrity assessment results and consequences to receptors, can be highly uncertain. Allowing probabilistic input is an advantage when the input values are uncertain, so that the model output can reflect the input uncertainties. The output risk measures then give a fuller representation of the range of possible values, including potential high-consequence outcomes.

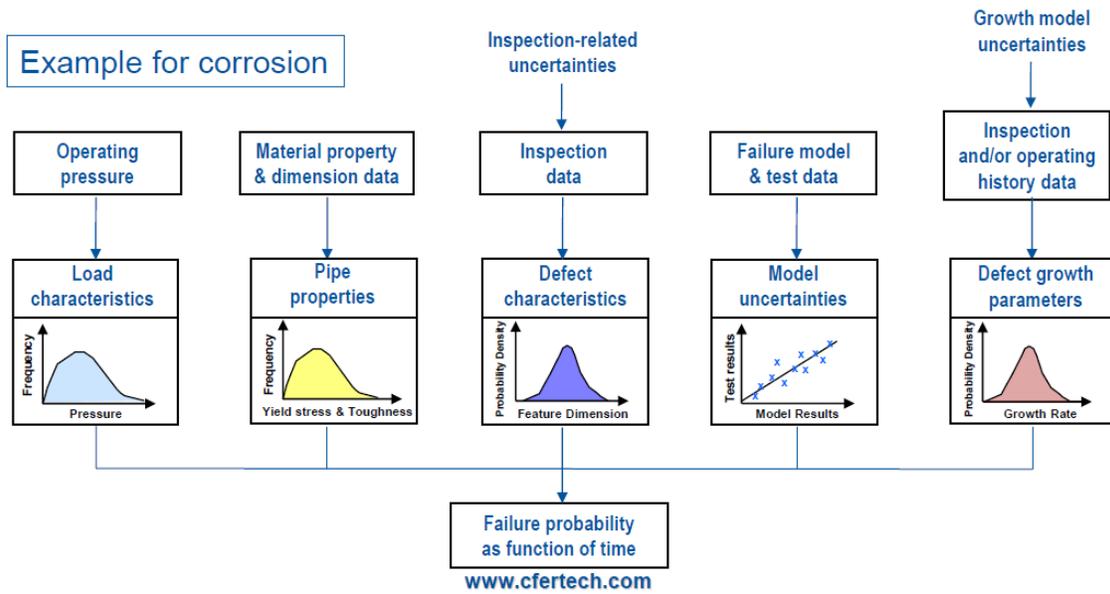
Figure A-3⁷⁶ depicts an example of distributions to represent uncertainties for inputs to a model for the time-dependent probability of failure due to corrosion. Uncertain inputs that are assigned distributions include operating pressure, pipe yield strength and toughness, defect characteristics from ILI, and defect growth. The model calculates a failure probability as a function of time, given these distributions.

Input distributions should be chosen by considering the range of possible values for the inputs and how the possible values are distributed over the range. Statistical methods, such as Bayesian analysis, may be used to choose distributions given data or SME estimates for an input.

⁷⁵ See ISO/IEC 31010:2009 – *Risk management – Risk assessment techniques*, Section B.25.

⁷⁶ Presentation by M. Stephens, C-FER Technologies, *Methods for Probability Estimation*, August 9, 2016.

Figure A-3
Example of Distribution Input to a Probabilistic Model



Appendix B – Consequence Models

B.1 Gas Transmission Consequence Models

Example of Use of FN Curves and “ALARP” by a Gas Pipeline Quantitative Risk Model

One scheme that has been used in application of the *PipeSafe*⁷⁷ quantitative risk model for a natural gas pipeline operator is a combination of the ALARP (As Low As Reasonably Practicable) principal with three societal risk bands on a frequency vs. number of fatalities (“FN”) scale⁷⁸.

Three risk bands for societal risk are defined to determine the relative value of measures to reduce risk at a location on the pipelines:

- At the top end of the scale there are risks that judged to be so great that they are not acceptable/tolerable. [Region above the red line in Figures B-1 and B-2.]
- At the bottom end are situations where the risk is, or has been made, so small that no further precaution is necessary - a ‘broadly acceptable’ region. [Region between the red line and blue line in Figures B-1 and B-2.]
- In between these two extremes is a region where risks are tolerable only if their level has been reduced to one which is ALARP (As Low as Reasonably Practicable). [Region below the blue line in Figures B-1 and B-2.]

See the Figure B-1 below for an illustration of an FN curve representing the societal risk of fatalities at a specific location on the pipeline. In this example, a portion of the risk curve is in the “ALARP” region, so risk reduction measures were sought to reduce risk at the location.

Figure B-2 shows FN curves for proposed preventive measures for the location with the risk illustrated in Figure B-1. Multiple risk-reducing measures are shown to move the entire FN curve into the “broadly acceptable” risk band.

⁷⁷ M. Acton, K. Dimitriadis, T. Manns, S. Martin, DNV GL; D. McCollum, S. Potts, National Grid, *Development of a Risk Based Asset Management Tool for Gas Transmission Pipelines*, 2015; and M. Acton, P. Baldwin, T. Baldwin, BG Technology; E. Jager, NV Nederlandse Gasunie, *The Development of the PIPESAFE Risk Assessment Package for Gas Transmission Pipelines*, 1998.

⁷⁸ See ISO/IEC 31010:2009 – *Risk management – Risk assessment techniques*, Section B.27.

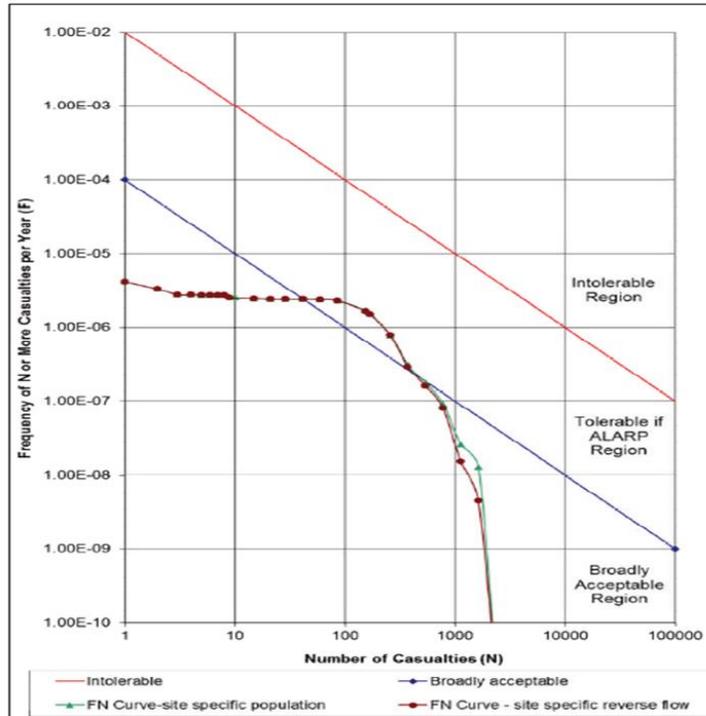


Figure B-1. FN Curve for a 1-mile section of natural gas pipeline

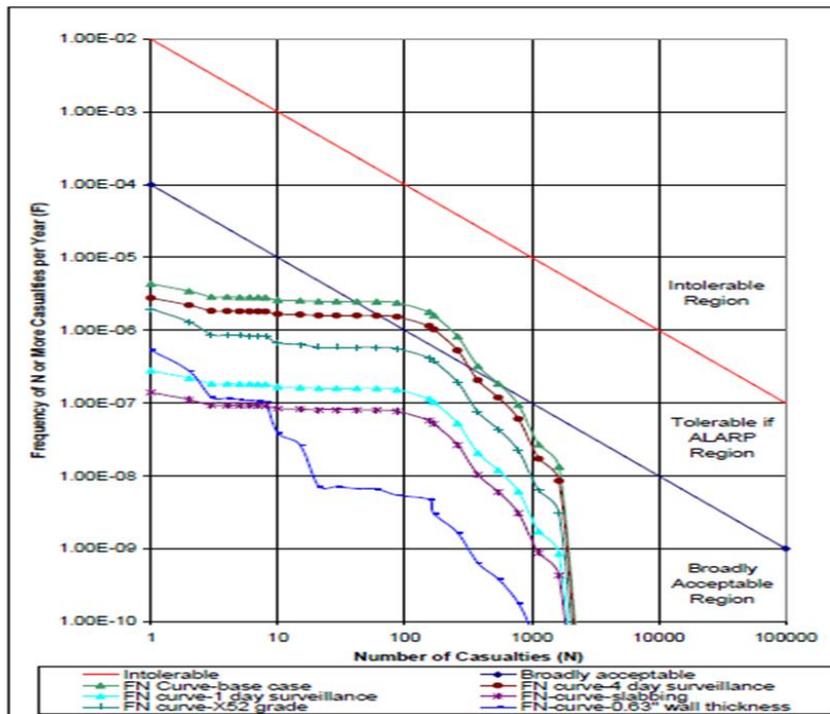


Figure B-2. FN Curves preventive measures for a 1-mile section of natural gas pipeline

An alternative application of FN curves is shown in Figure B-3. In this application, the black dashed lines indicate different risk bands. Differences with the previous example include:

1. A different upper limit is used to define the border between the intolerable risk region and the "ALARP" region.
2. There is no "broadly tolerable" risk region where risk is considered low enough so that ALARP criteria are not applied.
3. There is a separate region at the lower right end of the FN graph to indicate low probability, high consequence outcomes. Risks in this area are noted for special scrutiny and application of ALARP

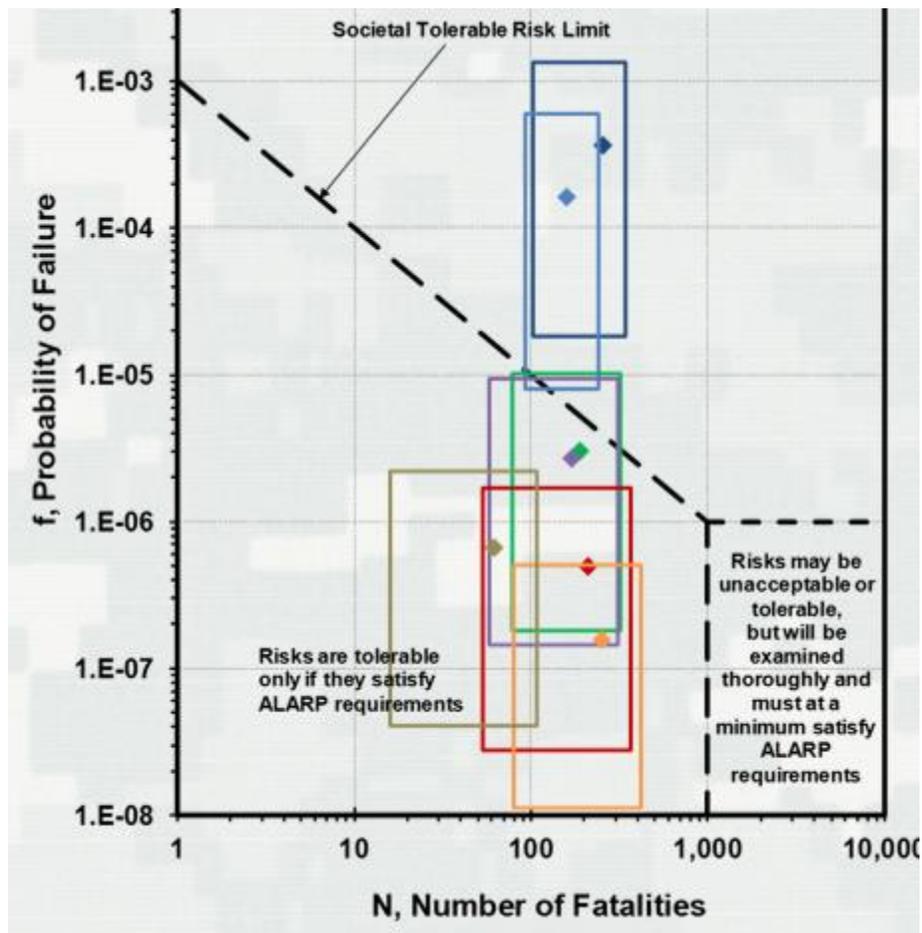


Figure B-3. Alternative Application of FN Curves

B.2 Hazardous Liquid Consequence Models

Example: Relative Risk Model Consequence Model

A risk index model, developed by Dynamic Risk⁷⁹, and used by an operator for pipelines with diverse hazardous liquid commodities calculates hazard areas for multiple hazards posed by a potential pipeline failure:

- Flammability
- Toxicity (based on H₂S content)
- Overpressure

For flammability and toxicity, the size of the hazard area is based on equations from API RP 581 for different commodities, considering estimated release rates, likelihood of ignition, liquid or gas release, and instantaneous or continuous release. For overpressure, the hazard area calculations use estimated release rates and "...TNT equivalent Equation for Hard radius..."⁸⁰ Estimated release rates are based on an average of assumed hole sizes assumed for failure from different threats and equations for sonic and subsonic flow.

The largest hazard area of the three hazards considered for each location is chosen to estimate consequences. Human safety consequences are derived from the product of the estimated hazard area and the assumed population density within the hazard area (units are the estimated number of persons impacted). Different population densities are assumed based on which HCA types (High-Population, Other Populated, No HCAs, etc.) are within the hazard area.

Environmental consequences are estimated as the cost to clean up spills, which is considered applicable to commodities released as liquids (including some HVLs). Different costs per gallon to clean up spill are assumed for liquids and HVLs and for different HCA types. Total costs are estimated by applying this cost per gallon to the estimated spill volume, which is based on leak detection and shut down time, volume in line between valves, and drain down factor. The units are estimated total clean-up costs in dollars.

The human safety impact measured in estimated number of persons impacted and environmental impact measured in estimated total clean-up costs are weighted to obtain a total consequence score (Figure B-4 below). Note that safety and environmental consequence scores are assigned the same weight in the overall consequence score and economic consequences are assigned zero weight.

⁷⁹ MacFarlane, Trevor (Dynamic Risk), *Index Models and Applications An Industry Perspective*, June 15, 2017. Document can be accessed at:

[https://primis.phmsa.dot.gov/rmwg/docs/IndexModels_and_Applications\(DynamicRisk\)_RMWG0617.pdf](https://primis.phmsa.dot.gov/rmwg/docs/IndexModels_and_Applications(DynamicRisk)_RMWG0617.pdf).

⁸⁰ "TNT equivalence" is a common technique for equating properties of an overpressure impact to that from the standard TNT explosive – e.g., see <https://www.science.gov/topicpages/t/tnt+equivalent+explosive>.

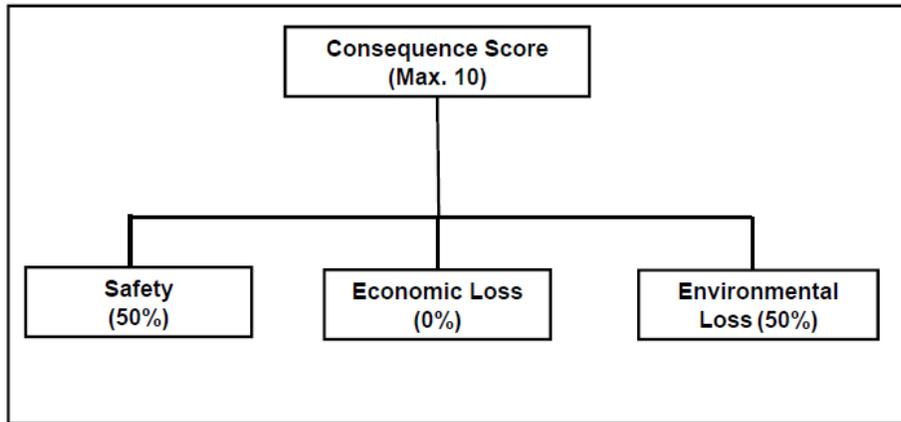


Figure B-4 Relative Risk Model Consequence Score

Appendix C – Facility Risk Models

*Example Tools for Gas Facility Risk Assessment*⁸¹

Three examples are shown of risk assessment tools used by an operator for facility risk assessment. These examples indicate threats and risk factors that should be included in facility risk models.

Figure C-1 shows an example “threat matrix” indicating threats and risk factors for a qualitative gas system facility risk assessment. Note that this process includes threats to facility reliability and emergency response as well integrity threats. The figure shows candidate preventive measures for each threat.

Figure C-2 shows an example table of threats and failure causes to be considered in a gas facility risk assessment process.

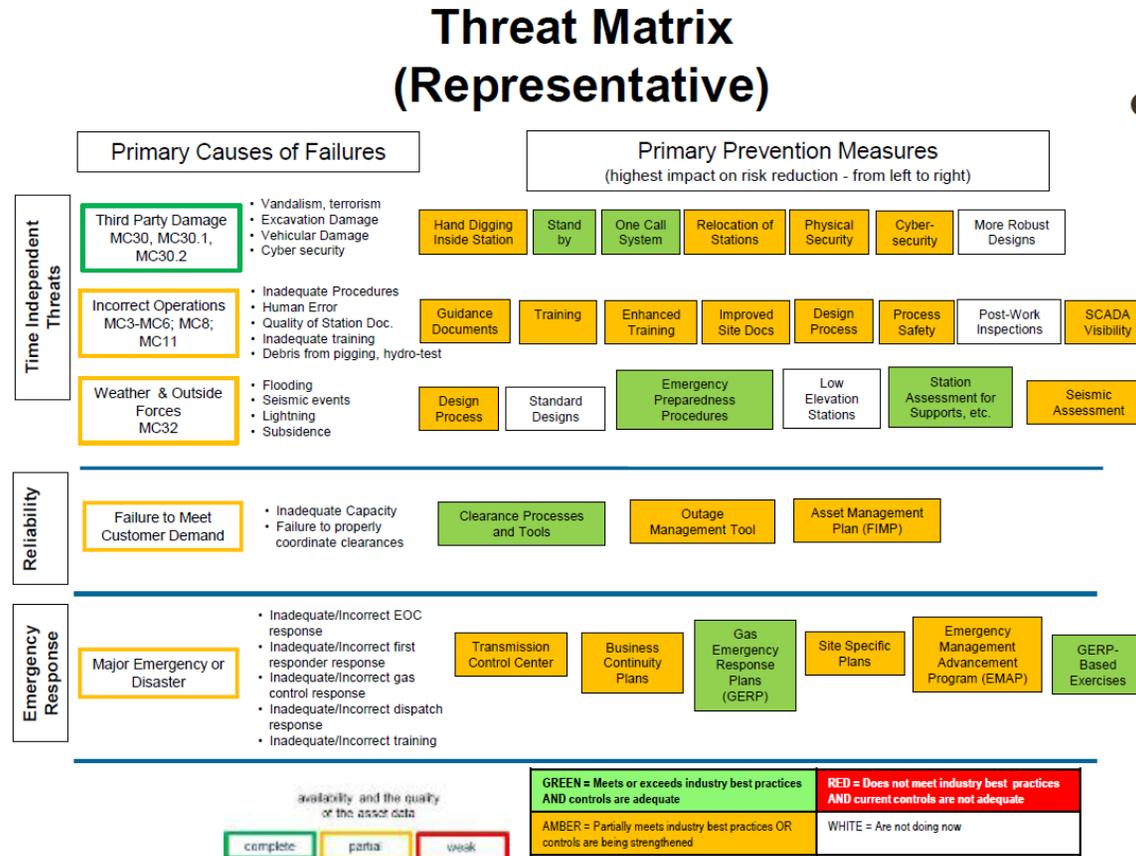
Figure C-3 shows a portion of a “risk register” used as a qualitative risk assessment model. The model includes:

- Seven frequency levels (the highest 2 are shown), from “Common” (>10 times per year), down to “Remote” (once every 100+ years)
- Seven impact (consequence) levels (highest 2 shown), from “Catastrophic” down to “Negligible
- Impact levels are defined for six categories (two are shown), including:
 - Safety
 - Environmental
 - Compliance
 - Reliability
 - Reputational
 - Financial

⁸¹ All examples from RMWG presentation by T. White and T. Rovella, PG&E, *PG&E Facilities Risk Management*, November 30, 2016.

Figure C-1⁸²

Example Threat Matrix for a Gas Facility Risk Assessment



⁸² Figures C-1, C-2, and C-3 from RMWG presentation by T. White and T. Rovella, PG&E, *PG&E Facilities Risk Management*, November 30, 2016.

Figure C-2

Example Threats and Failure Causes for a Gas Facility Risk Assessment

	Time-Dependent Threats <i>"The threat level may grow over time if unchecked"</i>			Stable Threats <i>"The threat is inherent but does not grow over time unless acted upon by pressure or external load"</i>			Time Independent Threats <i>"The threat exists outside of the continuum of time"</i>		
	External Corrosion	Internal Corrosion	Stress Corrosion Cracking	Manufacturing Related Defects	Welding / Fabrication Related	Equipment	Third Party / Mechanical Damage	Incorrect Operations	Weather Related & Outside Forces
Primary CAUSES	<ul style="list-style-type: none"> 1) Transitions 2) Inadequate coating 3) Atmospheric conditions 	<ul style="list-style-type: none"> 1) Liquids 2) Sulfur 3) Erosion 	Not a high risk for asset family	<ul style="list-style-type: none"> 1) Poor quality manufacture 2) Inadequate specifications 3) Strength test documentation 	<ul style="list-style-type: none"> 1) Poor construction practices 2) Inadequate QC/inspection 	<ul style="list-style-type: none"> 1) Age, Obsolescence 2) Incorrect sizing/design 3) Maintenance related 4) Sulfur 5) Liquids entering the system 6) Vault flooding (LP) 	<ul style="list-style-type: none"> 1) Vandalism 2) Excavation Damage 3) Vehicular Damage 4) Cyber Threat 	<ul style="list-style-type: none"> 1) Inadequate procedures 2) Human error 3) Quality of station documentation 4) Inadequate training 5) Debris from pigging & hydrotesting 	<ul style="list-style-type: none"> 1) Flooding 2) Seismic events

Figure C-3

Portion of Example “Risk Register” for Gas Facility Risk Assessment

Frequency Description	Frequency per Year	Frequency Level	Impact Level	Safety	Environmental
> 10 times per year	F = > 10	Common (7)	Catastrophic (7)	<ul style="list-style-type: none"> Fatalities: Many fatalities and life threatening injuries to the public or employees. 	<ul style="list-style-type: none"> Duration: Permanent or long-term damage greater than 100 years; or Hazard Level/Toxicity: Release of toxic material with immediate, acute and irreversible impacts to surrounding environment; or Location: Event causes destruction of a place of international cultural significance; or Size: Event results in extinction of a species.
1 - 10 times per year	F = 1 - 10	Regular (6)	Severe (6)	<ul style="list-style-type: none"> Fatalities: Few fatalities and life threatening injuries to the public or employees. 	<ul style="list-style-type: none"> Duration: Long-term damage between 11 years and 100 years; or Hazard Level/Toxicity: Release of toxic material with acute and long-term impacts to surrounding environment; or Location: Event causes destruction of a place of national cultural significance; or Size: Event results in elimination of a significant population of a protected species.

Appendix D – Migration from Older Risk Analysis Methods to Quantitative Models

A-D.1 Introduction

This appendix discusses an example “risk model type” conversion of an index/scoring-type pipeline risk assessment into a Quantitative System type of model that better quantifies risks. While there are certainly many approaches to this type of migration, the benefits of such an upgrade are numerous, as is discussed in Section III.A.

This model conversion process is intended to salvage and utilize previously-collected data wherever practical. When the underlying scoring assessment is robust – i.e., includes all or most of the needed data – only a few new data sources will need to be added.

This conversion process involves 4 general steps:

1. Convert data currently expressed as scores into data with verifiable measurement units;
2. Establish risk estimation equations that utilize this measurement data;
3. Produce risk assessment results using the converted data and the appropriate algorithms; and
4. Perform QA/QC on results.

A-D.2 Applicability

This information applies to risk assessments performed on pipeline systems, facilities, and all related components or collections of components. Components include pipe, fittings, valves, appurtenances, tanks, pumps, compressors, etc. Collections of components includes typical groupings such as all types of pipeline systems (gathering, transmission, distribution, offshore, onshore, etc.), and all types of facilities (tank farms, pump or compressor stations, etc.), or to specific components such as tanks, pumps, and compressors when such equipment are assessed based on their sub-components.

A-D.3 Level of Effort

Performing the basic conversion process will take a varying level of effort, depending on factors such as those shown below. However, experience has shown that the level of effort is not as significant as some may think, and the benefits to safety and reduced consequences of a failure have been shown to significantly outweigh the costs.

- Knowledge and skills of personnel performing upgrade
 - General pipeline knowledge
 - Risk knowledge
 - Software skills
- Data previously collected for previous risk assessments
 - Data quantity
 - Data condition

- Correctly aligned to common centerlines
- Consistent formatting
- Level of modifications previously done for scoring purposes
- Level of QA/QC performed

The data conversion portion of the upgrade will often require the majority of the effort. Performing the subsequent QA/QC on the assessment results will require on going attention, with more effort at initial stages as practitioners become accustomed to the upgrades.

A-D.4 Definitions

The following definitions are offered to clarify how the terms are used specifically in this appendix.

Algorithm: An equation that calculates some aspect of risk for a component of a pipeline system. Calculation are typically done using location-specific input data describing characteristics and conditions.

CoF: Consequence of failure. Multiple CoF scenarios are generally possible for each failure event.

Exposure, Mitigation, Resistance: These are essential components of a calculation of PoF for each potential failure mechanism. Synonyms for these terms are, respectively, attack, defense, and survivability. They measure:

- Exposure or attack: a measure of the aggressiveness of each failure mechanism, either 1) the frequency of integrity-threatening events or 2) the degradation rate associated with a time-dependent failure mechanism (corrosion or cracking).
- Mitigation: a measure of the effectiveness of all mitigation measures that serve as barriers, preventing or reducing the effect of the exposure.
- Resistance: a measure of the ability of the component to absorb the exposure without failing.

Mpy: Mills-per-year of pipeline degradation.

PoD (or FoD): Probability of Damage (or Frequency of Damage): a part of the PoF estimate that shows the likelihood of a component being damaged by a failure mechanism.

PoF (or FoF): For purposes of this appendix, failure means loss of integrity; i.e., a leak or rupture.

PXX: A point in a distribution of possible values, where the distribution takes into account uncertainty.

QRA: Quantitative Risk Analysis, expressing risk in numerical units of measure such as “failures per mile-year”, “dollars per year”, etc.

Receptor: Anything that can be harmed – receive damage – from a spill/release. Examples include people, property, soil, groundwater, etc.

Risk, Expected Loss (EL): An estimate of the losses associated with possible failure-and-consequence pairings on a component or collection of components (e.g., a pipeline system) over a specific time period. EL units are usually \$/year or \$/mile-year. Risk = PoF x CoF.

Time to Failure (TTF): An estimate of remaining life, based on a definition of ‘failure’, obtained by algorithm calculation performed on input data. For purposes of this appendix, ‘failure’ means loss of integrity (i.e., a leak or rupture). Considerations for either a leak or a rupture are included in the TTF value, with the one resulting in earlier failure normally dominating the final estimate of TTF.

A-D.5 Units of Measurement

In order to overcome many of the limitations of scoring type assessments, and to better understand and communicate risks, all input data and subsequent risk assessment results should be expressed in verifiable measurement units.

Verifiable measurement data is always expressed in common units of measurement. Data is obtained by either direct measurement or by estimation. These values are distinct from assigned values such as points or scores since they can be replicated without the need of a translation tool (e.g., a scoring, indexing, or point factor assignment system).

Ensuring a consistent and appropriate set of verifiable measurement units is simply ensuring that the measurement units of all inputs combine algebraically to arrive at the desired risk estimate units of measurement.

A-D.6 Input Data

Examples of typical input data with verifiable and non-verifiable units of measure, include:

Risk Issue Measured	Measurement/Verifiable Example Units	Not Deemed Verifiable Units
Pipe specification as indicator of strength	24 inches diameter, 1440 psi operating pressure, 42,000 psi allowable stress	Diameter = “large” Stress level = 7 risk points
The frequency of excavator damage potential at a specific location	2 excavations per mile-year	Excavator activity level = ‘high’ = 9 risk points
Soil Corrosivity	8.2 mil-per-year pitting corrosion rate	“medium” = 4 risk points
Benefits of additional depth of cover	15% reduction in excavator contact events per foot	-11 risk points
CoF	\$87,000/incident, 0.0001 fatalities/failure	‘low’ = 2 on risk matrix

There are multiple measurement units that can support the CoF estimates. The units used for input data will be determined by the desired units in which the final CoF will be expressed. Whichever set of units are chosen, the algebra used to combine the information (see algorithm discussion below) should result in the desired units of CoF. For example, if units of dollars per failure are sought, units of measure might be:

$$\text{CoF} = \text{hazard zone} \times \text{receptors} \times \text{damage rate} = (\text{ft}^2 \text{ of hazard zone generated per failure}) \times (\text{number of receptors per ft}^2) \times (\text{damage rate per receptor, } \$ / \text{receptor}) = \text{Dollars per failure}$$

May 9, 2018 - Draft 1

In this example, simply adding an estimate of ‘failures per year’ to this chain of calculations results in risk units of ‘dollars per year’:

$$\text{Risk} = \text{EL} = \text{PoF} \times \text{CoF} = (\text{failures/year}) \times (\$/\text{failure}) = \$ / \text{year of expected loss}^{83}$$

A-D.7 Risk Assessment Results

Since all data input into the risk assessment carry verifiable measurement units, the risk assessment results also are expressed in verifiable measurement units. For instance, units of events per year, incidents per mile-year, dollars per incident, TTF, expected loss per mile year, etc. are all verifiable and appropriate outputs for a QRA, as shown below.

Risk, Expected Loss (EL)

$\text{Risk} = \text{PoF} \times \text{CoF}$. Common units of measure include dollars per year, fatalities per mile-year, and overlap units used in PoF when the consequence is defined as the failure, as was defined for PoF. For example, failures per mile-year can be a measurement unit for both FoF and Risk⁸⁴. When risks are fully monetized, risk can be expressed as an annualized EL where $\text{EL} (\$/\text{year}) = \text{PoF} (\text{failures/year}) \times \text{CoF} (\$/\text{failure})$. EL values are applicable measures of risk for all collections of components, from single items to entire pipeline systems.

PoF (or FoF)

Common measurement units include: chance of failure per year, failures per year, failures per mile-year, incidents per year, ruptures per mile-year, etc. For time-degradation failure mechanisms, TTF in units of time (often ‘years’) is an intermediate calculation of the PoF estimation.

PoF Components

Only two sets of units are needed to describe all possible failure mechanisms. When time-independent failure mechanisms are involved, units are, for example:

$$\text{PoF} (\text{failures/year}) = \text{Exposure} (\text{number of potential failure-causing events/year}) \times \text{Mitigation} (\text{fraction of potential failure-causing events that are not avoided}) \times \text{Resistance} (\text{fraction of potential failure-causing events failure})$$

When time-dependent failure mechanisms are involved, units are, for example:

$$\text{PoF} (\text{failures/year}) = f[\text{TTF} (\text{years to failure})] \text{ where } \text{TTF} (\text{years to failure}) = \text{Resistance} (\text{inches of effective wall thickness}) / [\text{Exposure} (\text{mpy}) \times \text{Mitigation} (\text{fraction of exposure not mitigated})]$$

⁸³ This example uses \$ / year for expected loss. Other risk units could also be utilized.

⁸⁴ However, this does not acknowledge the differences in consequences associated with various types of failures.

May 9, 2018 - Draft 1

Alternate measurement units are also possible. The user should ensure that, algebraically, the units combine to result in the units of the final risk value being estimated. See overall examples in Attachment A for numerical examples using these units of measure.

CoF:

Common measurement units include: dollars of loss per incident, fatalities per incident, \$ per failure, \$ per leak, \$ per rupture, consequence units per failure, etc.

A.D-8 Weightings

Weightings introduce inappropriate bias into a risk assessment and are to be avoided. Weightings should not be used in the updated risk assessment methodology. The use of verifiable measurement data will automatically address all concerns that were previously attempted to be addressed by using weightings, thereby negating the need for weightings of any kind in a modern risk assessment.

When upgrading a previous risk assessment that used weightings, the intent of those weightings should be understood. The intent of weightings was typically to compensate for limited mathematical capabilities of the scoring models (e.g., limited range of possible point values with inability to capture real world orders of magnitude differences). If the intent is valid, then the intended effect of the weighting should automatically be captured either in the conversion of the previously collected data or in the set-up of algorithms. A QA/QC process should be established to confirm this.

A.D-9 Uncertainty

Every risk assessment representing real world phenomena will have at least some amount of uncertainty. This is due to natural variability in all phenomena, the probabilistic nature of the real world, and simple lack of complete information. Consideration of uncertainty results in a range of possible answers. Every risk assessment should document how it is taking uncertainty into account.

There are several ways to deal with this uncertainty in a risk assessment. A rigorous option is to generate a distribution of possible values for each input, including considerations for both lack of information and 'natural' variation in each input. All input distributions are then combined using the risk assessment algorithms. This generates distributions of all calculation results and ensures that uncertainty is accounted for in final risk estimates. [This would fit the Probabilistic Model approach discussed previously in this document.] Practitioners pursuing this option should seek background and information from the fields of statistics, engineering, and pipeline-specific materials science, design, operations, and maintenance practices.

A less rigorous, but usually sufficient approach is discussed here⁸⁵ – Since an understanding of the range of possible answers is sought, treating uncertainty in terms of conservatism is an efficient option to avoid the complexities of combining numerous distributions. A risk assessment can document its consideration of uncertainty by declaring the target level of conservatism used in producing its risk estimates. For regulatory compliance as well as practical utility, the recommendation is to not exclude input values that are thought to be “rare,” thereby erring on the side of overstating the actual risks. By instead including all input values and specifying their perceived rarity used in the assessment, the role of uncertainty is acknowledged and the entire range of risk is more readily understood. This “range of risk” concept is important for decision makers to understand when managing pipeline integrity.

“PXX” terminology, taken from probability theory, can be used to convey the way in which uncertainty/conservatism is being handled in a specific risk assessment. PXX refers to a point in a distribution of possible values, where the distribution takes into account uncertainty. The values assigned for various conservatism levels – i.e., PXX levels – arise from a known or posited distribution of all possible actual values.

A higher PXX means more conservatism – tending to overstate actual risk – is being incorporated into the risk assessment. P50 normally means the value most likely to occur⁸⁶ is being used, so zero conservatism accompanies this value. P90 means a rare value, erring on the side of overstating actual risk, is being used, thereby ensuring conservatism (tending to overstate actual risk) is being used. Numerically, P90 suggests that risk is being overstated 9 times out of ten – a negative surprise occurs once time out of ten when a P90 value is used. A P99 value means that risk has been underestimated only one time out of a hundred – i.e., actual risk will be lower 99 times out of a hundred.

Specifying the level of conservatism that is being employed in the choice of input data effectively turns distributions of possible values into point estimates of possible values. Different levels of conservatism support different intended uses of the risk assessment. The risk assessor declares the level of conservatism used in each assessment, often performing two or more assessments to show the range of possible results. A common strategy is to produce risk estimates at a high (P90 or P99) level of conservatism, for use in location-specific risk management and also to produce a P50 risk assessment for use in communications with outside stakeholders.

A.D-10 Data Conversion

The objective of this phase of the upgrade is to create a new database of converted information, where each entry in the new database carries units of verifiable measurements. The ‘rules’ and processes used to create the new database should be documented and preserved since they memorialize this aspect of the risk assessment upgrade.

⁸⁵ While this discussed approach requires at least an approximation of the range and frequency of possible values (a distribution), similar to the more rigorous option, that distribution can often be simply approximated rather than be derived from rigorous analyses.

⁸⁶ The mode of the distribution; also the mean and median, if the distribution is ‘Normal’.

May 9, 2018 - Draft 1

Since a pipeline is an engineered structure placed in an often constantly changing natural environment, numerous sets of data are normally required to fully assess risk. This is true for any risk assessment methodology. Therefore, previously-collected information used in a scoring type risk assessment can often be readily upgraded for use in a quantitative risk assessment (QRA).

The first step is to identify data that is already captured in absolute terms – i.e., in verifiable units of measure. This includes all data in measurements units such as inches, feet, psi, mills-per-year (mpy), counts, frequency, etc. This data generally requires no conversion.

Next, data whose underlying measurement units can be easily extracted from its expression as a ‘score’ should be returned to those units. For example, if depth of cover of 24-inches was previously assigned a value of 7 points in a scoring system, all values of ‘7’ in the old risk database should generate a record showing 24” in the new database.

The next step is to assign each piece of input data to one of four categories, based on the risk information that is contained in the data.

Data Category	Examples of Data/Information	Example Units of Measure
PoF: Exposure	excavator activity, mpy external corrosion, mpy fatigue cracking, human error rates, etc.	events/mile-year
PoF: Mitigation	depth of cover, patrol, signage, coatings, procedures, training, etc.	% reduction in damage potential
PoF: Resistance	wall thickness, SMYS, toughness, weaknesses (dents, gouges, seam issues, etc.), etc.	% of damage resisted without leak/rupture OR ⁸⁷ effective wall thickness (inches)
CoF	population density, thermal radiation distance, dispersion distances, explosion potential, overland flow distances, soil permeability, etc.	Ft2, Count/ft2, value per unit (remediation costs), cost per incident, etc.

This categorization adds much clarity to the risk assessment since the role of each piece of information is understood and its use in the risk assessment is transparent. This illustrates how a single piece of data can inform many different aspects of risk.

Most data will fit logically and uniquely into just one category, although it might impact several aspects within that category. Some data has application in more than one category. As an example of both, the input variable ‘flow rate’ can influence risk estimates of four different PoF exposures: surge potential, fatigue, internal corrosion, and erosion. Flow rates also influence CoF estimates of spill size, dispersion, leak detection, and others.

Some data might be more efficiently converted using a risk assessment algorithm, rather than a data conversion algorithm. Recall the previous example of restoring a depth of cover ‘score’ to the actual depth – “score of 7 is 24 inches”. The record showing 24-inches of cover is important. But the risk assessment should also ‘understand’ the benefits of the 24-inches of cover. This can be done either by

⁸⁷ Two types of units are commonly used, depending on whether the failure mechanism is time dependent (corrosion or cracking) or time-independent (third party damage, geohazards, etc.).

storing the risk-reduction-value of 24-inches of cover in another database or by using an algorithm that translates 24-inches into a risk reduction value⁸⁸. The risk assessment algorithms are discussed in the next section. Either option – building a separate database of values ready to be used in the risk assessment or equating ‘raw’ data into risk terms using an algorithm – is viable and the choice is a matter of preference for the model designer.

A.D-10.1 CoF Data Sub-Categories

As with PoF data to be used as risk assessment inputs, previously collected data for CoF will generally fall into one of only a few categories. Those categories, and sample data inputs for each, are

1. Spill/Release size: the volume or mass released in a failure, as a function of hole size, product characteristics, operational parameters (e.g., flow rates, pressures, elevation, etc.), detection time, reaction time,
2. Dispersion: the distance traveled by the spill/release, as a function of product characteristics, terrain, atmospheric conditions, detection time, reaction time, surface flow resistance, etc.
3. Hazard area estimates: the footprint or area of the leak/rupture, in which damages to one or more receptors may occur
4. Receptors: the types and counts of receptors that are potentially damaged by a leak/rupture.

Consequence-related data elements are discussed in the main body (Section V) of this report.

A.D-11 Algorithms

The objective of the algorithm upgrade is to have a set of calculations that makes correct and efficient use of all relevant input information and produces complete and verifiable estimates of risk in terms of PoF, CoF, and TTF.

Algorithms should quantify all aspects of risk at all locations along each pipeline system being assessed. Algorithms to calculate risk in a modern QRA should ensure that measurement units of all inputs combine appropriately to express risks in units that are also verifiable. The upgrade algorithms should be intuitive and easily established in any calculating software platform.

This section discusses algorithm set-up concepts.

A.D-11.1 PoF

Algorithms supporting a modern QRA’s PoF estimate should use or produce values for exposure, mitigation, and resistance, for each potential failure mechanism. That is, each failure mechanism should have values assigned to exposure, mitigation, and resistance at all points along each pipeline system being assessed.

⁸⁸ Note that translating 24” of cover into a risk reduction benefit is not the same as scoring. The understanding that equates 24” into a mitigation benefit is a measurement, can be verified, and has meaning beyond a relative comparison. The understanding underlying this translation can arise from anywhere in a range of rigor: from a detailed analysis to a simple estimate provided by a knowledgeable individual.

Exposure, mitigation, and resistance combine to provide estimates of both PoD and PoF for each failure mechanism. However, the initial step of measuring each independently is critical. Measuring exposure independently generates knowledge of the 'area of opportunity' or the aggressiveness of the attacking mechanism. Then, the separate estimate of mitigation effectiveness shows how much of that exposure will likely be prevented from reaching the component being assessed. Finally, the resistance estimate shows how often the component will failure, if contact with the exposure occurs.

In risk management, where decision-makers contemplate possible additional mitigation measures, additional resistance, or even a re-location of the component (often the only way to change the exposure), this knowledge of the three key factors will be critical.

The PoF algorithms will differ slightly depending on which of the two types of failure mechanisms are being assessed.

A.D-11.2 Time Independent Failure Mechanisms

Each time independent failure mechanism, including excavation damages, impacts of any other kind, geohazards, human errors, sabotage, etc., that contributes to an overall PoF should have its specific PoF estimated. That estimate is made from combining the three aspects of PoF as discussed previously.

A.D-11.3 Time Dependent Failure Mechanisms

Quantifying PoF for time-dependent failure mechanisms can be more challenging than for time-independent failure mechanisms. The additional challenge arises from 1) the need to produce an intermediate estimate of TTF and 2) the need to assess the effectiveness of commonly used mitigation measures.

As a modeling convenience that generally produces PoF estimates of sufficient accuracy, each time-dependent failure mechanism can be modelled in terms of:

- Exposure expressed as mils-per-year (mpy)
- Mitigation expressed as a probability that, at a specific location, some amount of mpy degradation is occurring.
- Resistance expressed as the effective wall thickness that experiences the mpy degradation.

These terms produce an estimate of TTF. That estimate should then be expressed also as an equivalent PoF. A simple and conservative relationship to do this could be simply: $PoF = 1/TTF$. More accuracy is achieved when expanded relationships are used, capturing, for example, instances where failures early in the TTF time range are virtually impossible.

A.D-11.4 CoF

Consistent with the categorization of CoF input data (previously discussed), the CoF algorithms will use those same categories to produce estimates of direct CoF resulting from leak/rupture.

Many sophisticated analyses routines are available to model hydrocarbon releases and potential thermal events associated with leaks/ruptures. A review of these is beyond the scope of this appendix.

May 9, 2018 - Draft 1

Critical to the risk assessment upgrade recommended here, is the estimation of a hazard area that could arise from a leak/rupture. The hazard area estimate should include considerations of spill/release size and duration, dispersion (travel from origination point), ignition potential, potential thermal events (fire/explosion), contamination/toxic effects.

Once a hazard area has been estimated, an accounting should be made of the types, quantities, and sensitivities of the various receptors within the hazard area. Receptors typically include human populations, property, and environmental resources.

Multiple scenarios of CoF are generally required in order to properly assess CoF at all points along a pipeline. Scenarios are generated by varying aspects of each of the four CoF categories. Spill size and dispersion are varied by varying the underlying factors such as hole size, detection time, response time, ignition potential, and terrain. Likelihoods of the respective scenarios should also be considered and reflected in the risk assessment.

See details related to Consequences in the main body of the report (Section V).

A.D-12 Example

Modern QRA includes units of measurement for all risk assessment inputs and outputs that are transparent and intuitive. The following example illustrates this.

In common applications of the exposure, mitigation, resistance triad, units are as follows:

Each exposure is measured in one of two ways – either **in units of ‘events per time and distance’**, i.e., events/mile-year, events/km-year, etc. or **in units of degradation** – metal loss or crack growth rates, i.e., mpy, mm per year, etc. An ‘event’ is an occurrence that, in the absence of mitigation and resistance, will result in a failure. To estimate exposure, we envision the component completely unprotected and highly vulnerable to failure (think ‘tin can’ wall thickness). So, an excavator working over a buried pipeline is an event. This is counted as an event regardless of type of excavator, excavator reach, depth of burial, use of one-call, signs/markers, etc.

Mitigation and Resistance are each measured in units of %, representing ‘fraction of damage or failure scenarios avoided’. A mitigation effectiveness of 90% means that 9 out of the next 10 exposures will not result in damage – mitigation has blocked 90% of the exposures that would otherwise have occurred. Resistance of 60% means that 40% of the next damage scenarios will result in failure, 60% will not.

For assessing PoF from time-independent failure mechanisms—those that appear random and do not worsen over time – the top-level equation can be as simple as:

$$\text{PoF}_{\text{time-independent}} = \text{exposure} \times (1 - \text{mitigation}) \times (1 - \text{resistance})$$

With the above example units of measurement, PoF values emerge in intuitive and common units of ‘events per time and distance’ such as events/mile-year, events/km-year, etc.

A.D-12.1 PoF Excavator Contacts

As an example of applying this to failure potential from third party excavations, the following inputs are identified for a hypothetical pipeline segment:

- Exposure (unmitigated) is estimated to be 3 excavation events per mile-year.
- Using a mitigation effectiveness analysis, experts estimate that 1 in 50 of these exposures will not be successfully kept away from the pipeline by the existing mitigation measures. This results in an overall mitigation effectiveness estimate of 98%.
- Of the exposures that result in contact with the pipe, despite mitigations, experts perform load/stress analyses to estimate that 1 in 4 will result in failure, not just damage. This estimate includes the possible presence of weaknesses due to threat interaction and/or manufacturing and construction issues. So, the pipeline in this area is judged to be 75% resistive to failure from these excavation events, if mitigation fails and contact occurs.

These inputs result in the following assessment:

$$(3 \text{ excavation events per mile-year}) \times (1 - 98\% \text{ mitigated}) \times (1 - 75\% \text{ resistive}) \\ = 0.015 \text{ failures per mile-year}^{89}$$

This suggests an excavation-related failure about every 67 years along this mile of pipeline.

This is a very important estimate. It provides context for decision-makers. When subsequently coupled with consequence potential, it paints a valuable picture of this aspect of risk.

Note that a useful intermediate calculation, probability of damage (not failure) also emerges from this assessment:

$$(3 \text{ excavation events per mile-year}) \times (1 - 98\% \text{ mitigated}) = 0.06 \text{ damage events/mile-year}$$

This suggests excavation-related damage occurring about once every 17 years.

This damage estimate can be verified by future inspections. The frequency of new top-side dents or gouges, as detected by an ILLI, may yield an actual damage rate from excavation activity. Differences between the actual and the estimate can be explored: e.g., if the estimate was too high, was the exposure overestimated, mitigation underestimated, or both? This is a valuable learning opportunity.

A.D-12.2 PoF Corrosion

This same approach is used for other time-independent failure mechanisms and for all portions of the pipeline.

⁸⁹ [Exposure vents/mile-yr.] x [damage events/exposure event] x [failures/damage events] = failures/mile-yr.

May 9, 2018 - Draft 1

For assessment of PoF for time-dependent failure mechanisms – those involving degradation of materials – the previous algorithms are slightly modified to yield a time-to-failure (TTF) value as an intermediate calculation en route to PoF.

$$\text{PoF}_{\text{time-dependent}} = f(\text{TTF}_{\text{time-dependent}})$$

$$\text{TTF}_{\text{time-dependent}} = \text{resistance} / [\text{exposure} \times (1 - \text{mitigation})]$$

As an example, experts have determined that, at certain locations along a pipeline, soil corrosivity creates a 5 mpy external corrosion exposure (unmitigated). Examination of coating and cathodic protection effectiveness leads experts to assign a mitigation effectiveness of 90%⁹⁰. Recent inspections, adjusted for uncertainty, result in an 'effective' pipe wall thickness estimate of 0.220" (resistance). This includes allowances for possible weaknesses or susceptibilities, modeled as equivalent to a thinning of the pipe wall⁹¹.

Use of these inputs in the PoF assessment is shown below:

$$\text{TTF} = 220 \text{ mils} / [5 \text{ mpy} \times (1 - 90\%)] = 440 \text{ years.}$$

Next, a relationship between TTF and PoF for the future period of interest, is chosen. For example, a simple and conservative relationship yields the following.

$\text{PoF} = 1 / \text{TTF} = [5 \text{ mpy} \times (1 - 90\%)] / 220 \text{ mils} = 0.23\% \text{ PoF}$. Since the exposure and mitigation estimates underlying the TTF value are based on a 'per mile' assessment, this value of PoF has units of 'per mile-year'.

A.D-12.3 Total PoF

In this example, an estimate for PoF from the two failure mechanisms examined – excavator damage (see Section A.D-12.1) and external corrosion (see Section A.D-12.2) – can be approximated by 1.5% + 0.2% = 1.7% per mile-year. If risk management processes deem this to be an actionable level of risk, then the exposure-mitigation-resistance details lead the way to risk reduction opportunities.

The exposure-mitigation-resistance analyses is an indispensable step towards full understanding of PoF. Without it, understanding is incomplete. Full understanding leads to the best risk management practice – optimized resource allocation – which benefits all stakeholders.

⁹⁰ This is not necessarily a trivial estimate, often requiring significant analyses

⁹¹ This also can be a complex calculation and captures 'threat interaction' as noted in a previous column.

Appendix E – Regulatory Drivers⁹²

E.1 Requirements for Hazardous Liquid Pipelines

The requirements for hazardous liquid pipelines are found in §195.452 (Pipeline integrity management in high consequence areas):

§195.452 (f) What are the elements of an integrity management program?

An integrity management program begins with the initial framework. An operator must continually change the program to reflect operating experience, conclusions drawn from results of the integrity assessments, and other maintenance and surveillance data, and evaluation of consequences of a failure on the high consequence area. An operator must include, at minimum, each of the following elements in its written integrity management program: ... (3) An analysis that integrates all available information about the integrity of the entire pipeline and the consequences of a failure (see paragraph (g) of this section); ...

§ 195.452 (g) What is an information analysis?

In periodically evaluating the integrity of each pipeline segment (paragraph (j) of this section), an operator must analyze all available information about the integrity of the entire pipeline and the consequences of a failure. This information includes:

- (1) Information critical to determining the potential for, and preventing, damage due to excavation, including current and planned damage prevention activities, and development or planned development along the pipeline segment;
- (2) Data gathered through the integrity assessment required under this section;
- (3) Data gathered in conjunction with other inspections, tests, surveillance and patrols required by this Part, including, corrosion control monitoring and cathodic protection surveys; and
- (4) Information about how a failure would affect the high consequence area, such as location of the water intake.

§ 195.452 (h) What actions must an operator take to address integrity issues? —

... (4) Special requirements for scheduling remediation—

... (iv) Other conditions. In addition to the conditions listed in paragraphs (h)(4)(i) through (iii) of this section, an operator must evaluate any condition identified by an integrity assessment or information analysis that could impair the integrity of the pipeline, and as appropriate, schedule the condition for remediation.

⁹² Regulatory references are those in effect as of the date of this document.

§ 195.452 (i) What preventive and mitigative measures must an operator take to protect the high consequence area? —

(1) *General requirements.* An operator must take measures to prevent and mitigate the consequences of a pipeline failure that could affect a high consequence area. These measures include conducting a risk analysis of the pipeline segment to identify additional actions to enhance public safety or environmental protection.

(2) Risk analysis criteria. In identifying the need for additional preventive and mitigative measures, an operator must evaluate the likelihood of a pipeline release occurring and how a release could affect the high consequence area. This determination must consider all relevant risk factors, including, but not limited to:

- (i) Terrain surrounding the pipeline segment, including drainage systems such as small streams and other smaller waterways that could act as a conduit to the high consequence area;
- (ii) Elevation profile;
- (iii) Characteristics of the product transported;
- (iv) Amount of product that could be released;
- (v) Possibility of a spillage in a farm field following the drain tile into a waterway;
- (vi) Ditches along-side a roadway the pipeline crosses;
- (vii) Physical support of the pipeline segment such as by a cable suspension bridge;
- (viii) Exposure of the pipeline to operating pressure exceeding established maximum operating pressure.

§ 195.452 (j) What is a continual process of evaluation and assessment to maintain a pipeline's integrity? —

... (2) Evaluation. An operator must conduct a periodic evaluation as frequently as needed to assure pipeline integrity. An operator must base the frequency of evaluation on risk factors specific to its pipeline, including the factors specified in paragraph (e) of this section. The evaluation must consider the results of the baseline and periodic integrity assessments, information analysis (paragraph (g) of this section), and decisions about remediation, and preventive and mitigative actions (paragraphs (h) and (i) of this section).

(3) Assessment intervals. An operator must establish five-year intervals, not to exceed 68 months, for continually assessing the line pipe's integrity. An operator must base the assessment intervals on the risk the line pipe poses to the high consequence area to determine the priority for assessing the pipeline segments. An operator must establish the

assessment intervals based on the factors specified in paragraph (e) of this section, the analysis of the results from the last integrity assessment, and the information analysis required by paragraph (g) of this section.

E.2 Requirements for Gas Transmission Pipelines

The requirements for gas transmission pipelines are found in respective portions of 49 CFR Part 192, Subpart O (Gas Transmission Pipeline Integrity Management):

§ 192.911 What are the elements of an integrity management program?

An operator's initial integrity management program begins with a framework (see § 192.907) and evolves into a more detailed and comprehensive integrity management program, as information is gained and incorporated into the program. An operator must make continual improvements to its program. The initial program framework and subsequent program must, at minimum, contain the following elements. (When indicated, refer to ASME/ANSI B31.8S (incorporated by reference, see § 192.7) for more detailed information on the listed element.)

(c) An identification of threats to each covered pipeline segment, which must include data integration and a risk assessment. An operator must use the threat identification and risk assessment to prioritize covered segments for assessment (§ 192.917) and to evaluate the merits of additional preventive and mitigative measures (§ 192.935) for each covered segment.

§ 192.917 How does an operator identify potential threats to pipeline integrity and use the threat identification in its integrity program?

(a) *Threat identification.* An operator must identify and evaluate all potential threats to each covered pipeline segment. Potential threats that an operator must consider include, but are not limited to, the threats listed in ASME/ANSI B31.8S (incorporated by reference, see § 192.7), section 2, which are grouped under the following four categories:

- (1) Time dependent threats such as internal corrosion, external corrosion, and stress corrosion cracking;
- (2) Static or resident threats, such as fabrication or construction defects;
- (3) Time independent threats such as third party damage and outside force damage; and
- (4) Human error.

(b) *Data gathering and integration.* To identify and evaluate the potential threats to a covered pipeline segment, an operator must gather and integrate existing data and information on the entire pipeline that could be relevant to the covered segment. In performing this data gathering and integration, an operator must follow the requirements in

ASME/ANSI B31.8S, section 4. At a minimum, an operator must gather and evaluate the set of data specified in Appendix A to ASME/ANSI B31.8S, and consider both on the covered segment and similar non-covered segments, past incident history, corrosion control records, continuing surveillance records, patrolling records, maintenance history, internal inspection records and all other conditions specific to each pipeline.

(c) *Risk assessment.* An operator must conduct a risk assessment that follows ASME/ANSI B31.8S, section 5, and considers the identified threats for each covered segment. An operator must use the risk assessment to prioritize the covered segments for the baseline and continual reassessments (§§ 192.919, 192.921, and 192.937), and to determine what additional preventive and mitigative measures are needed (§ 192.935) for the covered segment.

§ 192.935 What additional preventive and mitigative measures must an operator take?

(a) *General requirements.* An operator must take additional measures beyond those already required by Part 192 to prevent a pipeline failure and to mitigate the consequences of a pipeline failure in a high consequence area. An operator must base the additional measures on the threats the operator has identified to each pipeline segment. (See § 192.917) An operator must conduct, in accordance with one of the risk assessment approaches in ASME/ANSI B31.8S (incorporated by reference, see § 192.7), section 5, a risk analysis of its pipeline to identify additional measures to protect the high consequence area and enhance public safety. Such additional measures include, but are not limited to, installing Automatic Shut-off Valves or Remote Control Valves, installing computerized monitoring and leak detection systems, replacing pipe segments with pipe of heavier wall thickness, providing additional training to personnel on response procedures, conducting drills with local emergency responders and implementing additional inspection and maintenance programs....

§ 192.937 What is a continual process of evaluation and assessment to maintain a pipeline's integrity? ...

(b) *Evaluation.* An operator must conduct a periodic evaluation as frequently as needed to assure the integrity of each covered segment. The periodic evaluation must be based on a data integration and risk assessment of the entire pipeline as specified in § 192.917. For plastic transmission pipelines, the periodic evaluation is based on the threat analysis specified in § 192.917(d). For all other transmission pipelines, the evaluation must consider the past and present integrity assessment results, data integration and risk assessment information (§ 192.917), and decisions about remediation (§ 192.933) and additional preventive and mitigative actions (§ 192.935). An operator must use the results from this evaluation to identify the threats specific to each covered segment and the risk represented by these threats.

(c) *Assessment methods.* In conducting the integrity reassessment, an operator must assess the integrity of the line pipe in the covered segment by any of the following methods as appropriate for the threats to which the covered segment is susceptible (see § 192.917), or by confirmatory direct assessment under the conditions specified in § 192.931.

§ 192.939 What are the required reassessment intervals?

An operator must comply with the following requirements in establishing the reassessment interval for the operator's covered pipeline segments.

(a) *Pipelines operating at or above 30% SMYS.* An operator must establish a reassessment interval for each covered segment operating at or above 30% SMYS in accordance with the requirements of this section. The maximum reassessment interval by an allowable reassessment method is seven years. If an operator establishes a reassessment interval that is greater than seven years, the operator must, within the seven-year period, conduct a confirmatory direct assessment on the covered segment, and then conduct the follow-up reassessment at the interval the operator has established. A reassessment carried out using confirmatory direct assessment must be done in accordance with §192.931. The table that follows this section sets forth the maximum allowed reassessment intervals.

(1) *Pressure test or internal inspection or other equivalent technology.* An operator that uses pressure testing or internal inspection as an assessment method must establish the reassessment interval for a covered pipeline segment by—

(i) Basing the interval on the identified threats for the covered segment (see § 192.917) and on the analysis of the results from the last integrity assessment and from the data integration and risk assessment required by § 192.917; or

(ii) Using the intervals specified for different stress levels of pipeline (operating at or above 30% SMYS) listed in ASME B31.8S (incorporated by reference, see § 192.7), section 5, Table 3.

Appendix F - Risk Modeling Work Group Mission Statement

Preamble

PHMSA has identified a need to provide technical guidance on

- Methods, and tools to be used in pipeline risk modeling, and
- Application of these methods and tools in pipeline risk management.

PHMSA's technical guidance needs to be based on the state of the art of pipeline risk modeling, as reflected in the views of the technically informed community of practice.

Risk Modeling Work Group Mission Statement

The mission of the Risk Modeling Work Group is to:

- **Characterize the state of the art of pipeline risk modeling** for gas transmission and liquid pipelines,
- **Identify** and, if necessary in specific areas, develop **a range of state-of-the-art methods and tools capable of addressing the spectrum of pipeline risk management applications**, and
- **Provide recommendations** to PHMSA regarding the use of these methods, tools, and data requirements.

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May 9, 2018 - Draft 1

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⁹³ Cited presentations may be found at <https://primis.phmsa.dot.gov/rmwg/presentations.htm>

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