C-FER Technologies

200 Karl Clark Road
Edmonton, Alberta
Canada T6N 1H2
Tel 780.450.3300
Fax 780.450.3700

www.cfertech.com

Final Report

Critical Review of Candidate Pipeline Risk Models

Prepared by
Smitha Koduru, PhD, PEng
Riski Adianto, MSc, PEng
Jason Skow, PEng

Reviewed by
Maher Nessim, PhD, PEng

Copyright © 2016
C-FER Technologies

December 2016
M172

PROJECT TEAM

Critical Review of Candidate Pipeline Risk Models	C-FER Project: M172
Name	**Responsibility**
Jason Skow, PEng	Project management/guidelines development
Smitha Koduru, PhD, PEng	Data compilation/literature review/guidelines development/report preparation/conclusions and recommendations
Riski Adianto, MSc, PEng	Literature review for LNG facilities
Brent Ayton, EIT	Literature review for aviation industry
Maher Nessim, PhD, PEng, FCAE	Project Advisor and Report review

REVISION HISTORY

Critical Review of Candidate Pipeline Risk Models		C-FER Project: M172			
Revision	**Date**	**Description**	**Prepared**	**Reviewed**	**Approved**
1	September 27, 2016	Internal Draft	SDK	MAN	--
2	November 15, 2016	Draft	SDK	--	MAN
3	December 13, 2016	Draft Final	SDK	--	MAN

NOTICE

1. This Report was prepared as an account of work conducted at C-FER Technologies (1999) Inc. ("C-FER") on behalf of Pipeline and Hazardous Materials Safety Administration ("PHMSA"). All reasonable efforts were made to ensure that the work conforms to accepted scientific, engineering and environmental practices, but C-FER makes no other representation and gives no other warranty with respect to the reliability, accuracy, validity or fitness of the information, analysis and conclusions contained in this Report. Any and all implied or statutory warranties of merchantability or fitness for any purpose are expressly excluded. Any use or interpretation of the information, analysis or conclusions contained in this Report is at PHMSA's own risk. Reference herein to any specified commercial product, process or service by trade name, trademark, manufacturer or otherwise does not constitute or imply an endorsement or recommendation by C-FER.

2. Pursuant to the terms of the Other Transaction Agreement No. DTPH5615T00003 dated September 28, 2015, any confidential and proprietary information contained in this Report is owned solely by PHMSA. C-FER confirms that PHMSA is entitled to make such additional copies of this Report as PHMSA may require, but all such copies shall be copies of the entire Report. PHMSA shall not make copies of any extracts of this Report without the prior written consent of C-FER. C-FER further confirms that PHMSA is entitled to distribute copies of this Report for Government purposes only, as detailed in the Other Transaction Agreement.

3. Any authorized copies of this Report distributed to a third party shall include an acknowledgement that the Report was prepared by C-FER and shall give appropriate credit to C-FER and the authors of the Report.

4. Copyright C-FER 2017. All rights reserved.

TABLE OF CONTENTS

Project Team and Revision History i
Notice ii
List of Figures and Tables viii
List of Acronyms x
Executive Summary xii

1. INTRODUCTION 1

1.1 Terms of Reference 1
1.2 Background and Objective 1
1.3 Scope 2
1.4 Organization of the Document 2

2. INDUSTRY SURVEY 4

2.1 Introduction 4
2.2 Survey Objectives and Methodology 4
2.3 Summary of Survey Results 5
2.4 Key Learnings from Survey Results 9

3. LITERATURE REVIEW – PIPELINE INDUSTRY 11

3.1 Search Methodology and Data Collection 11
3.2 Risk Analysis Process 11
3.2.1 Overview 11
3.2.2 Purpose 12
3.2.3 System Definition 12
3.2.4 Threat Identification 13
3.2.5 Risk Estimation 13
3.2.5.1 Failure Modes 13
3.2.5.2 Frequency versus Probability 14
3.2.5.3 Risk Measures 15
3.2.5.4 Segmentation 15
3.3 Failure Frequency Estimation Models 16
3.3.1 Introduction 16
3.3.2 Subject Matter Expert (SME) Opinion 16
3.3.3 Historical Data 17
3.3.4 Analytical Models 19
3.4 Consequence Estimation Models 21
3.4.1 Overview 21
3.4.2 Hazard Scenarios 21

3.4.3 Quantification of Consequences 23
3.4.3.1 Life Safety 23
3.4.3.1.1 General 23
3.4.3.1.2 Natural Gas 23
3.4.3.1.3 Flammable Liquids 24
3.4.3.2 Environmental Impact 24
3.4.3.3 Financial Impact 26
3.5 Summary and Conclusions 27

4. LITERATURE REVIEW - OTHER INDUSTRIES 28

4.1 Introduction 28
4.2 Nuclear Industry 28
4.2.1 Overview of the Risk Assessment Approach 28
4.2.2 Risk Assessment Guidelines 31
4.2.2.1 Types of Risk Assessments 31
4.2.2.2 Selected Components of Risk Assessments 31
4.2.3 Key Learnings 33
4.3 Offshore Industry 33
4.3.1 Risk Assessment Guidelines 33
4.3.2 Risk Assessment Techniques 38
4.3.3 Key Learnings 39
4.4 Aviation Industry 39
4.4.1 Risk Assessment Guidelines 39
4.4.2 Operational Safety Risk Assessment 40
4.4.2.1 Hazard Identification 40
4.4.2.2 Risk Assessment Approach 41
4.4.3 Aircraft Structural Integrity Risk Assessment 41
4.4.4 Key Learnings 42
4.5 Power Transmission Industry 42
4.5.1 Risk Assessment Guidelines 42
4.5.2 Risk Modelling Approaches 44
4.5.3 Key Learnings 45
4.6 Summary and Conclusions 45

5. GUIDELINES FOR QUANTITATIVE RISK MODEL DEVELOPMENT 47

5.1 General 47
5.2 Scope of the Guidelines 47
5.3 Framework 47
5.4 The QRA Process 49
5.4.1 Objectives 49
5.4.2 Model Selection 50

5.4.2.1 Failure Frequency Estimation Models 50
5.4.2.1.1 Introduction 50
5.4.2.1.2 Level 1 – SME Opinion 50
5.4.2.1.3 Level 2 – Historical Data 52
5.4.2.1.4 Level 3 – Probabilistic Models 54
5.4.2.2 Failure Consequence Estimation Models 55
5.4.2.2.1 Life Safety 55
5.4.2.2.2 Environmental Impact 56
5.4.2.2.3 Financial Impact 59
5.4.3 Data Collection 60
5.4.3.1 Data Requirements 60
5.4.3.2 Data Quality 60
5.4.3.3 Data Gaps 61
5.4.3.4 Data Management 61
5.4.4 Risk Analysis 62
5.4.4.1 Overview 62
5.4.4.2 System Definition 62
5.4.4.3 Threat Identification 63
5.4.4.4 Risk Estimation 64
5.4.4.4.1 General 64
5.4.4.4.2 Failure Modes 64
5.4.4.4.3 Risk Measures 65
5.4.4.4.4 Granularity 66
5.4.4.4.5 Risk Aggregation 67
5.4.5 Documentation 67
5.4.6 Risk Model Validation 69
5.4.6.1 General 69
5.4.6.2 Component Verification 69
5.4.6.3 Hindcasting 69
5.4.6.4 Error Bounds 69
5.4.6.5 Benchmarking 70
5.4.6.6 Sensitivity Analysis 70
5.5 Risk Evaluation and Decision Making 70

6. COMMENTARY ON OTHER FACILITIES AND LNG PLANTS 74

6.1 Objective and Scope 74
6.2 Review of Risk Models 76
6.2.1 Models 76
6.2.2 Risk Analysis Process 78
6.2.3 System Definition 78
6.2.4 Threat Identification 78

6.2.5 Failure Frequency Estimation 78
6.2.5.1 Overview 78
6.2.5.2 Historical Data 79
6.2.5.3 Probabilistic and Engineering Models 80
6.2.6 Consequence Estimation 80
6.2.6.1 Overview 80
6.2.6.2 Hazard Scenarios 81
6.2.6.3 Life Safety 82
6.2.6.4 Environmental Impact 83
6.2.6.5 Financial Impact 83
6.2.7 Risk Estimation 84
6.2.8 Domino Effect 84
6.3 Comparison with Pipeline Models 85
6.3.1 Model Comparison 85
6.3.2 Integration of Pipeline and Facility Risks 87
6.4 Summary 88

7. SUMMARY AND RECOMMENDATIONS 89

7.1 Summary 89
7.2 Future Work 91

8. REFERENCES 92

8.1 References – Pipeline Industry 92
8.2 References – Nuclear Industry 98
8.3 References – Offshore Industry 99
8.4 References – Aviation Industry 99
8.5 References – Power Transmission Industry 100
8.6 References – Guidelines 101
8.7 References – Other Facilities and LNG Plants 103
8.8 References – Summary and Recommendations 107

APPENDICES

Appendix A – Glossary

Appendix B – Industry Survey Questionnaire

Appendix C – Aggregated Responses from Industry Survey

Appendix D – Bibliography – Pipeline Industry

Appendix E – Bibliography – Other Industries

LIST OF FIGURES AND TABLES

Figures

Figure 2.1 Summary of Model Uses from the Industry Survey

Figure 2.2 Averaged Scores for Attributes of an Ideal Quantitative Risk Model

Figure 2.3 Averaged Scores for Obstacles to the Use of Quantitative Risk Models

Figure 2.4 Averaged Scores for Areas of Standardization

Figure 3.1 Risk Management Process

Figure 3.2 Event Tree for a Natural Gas Pipeline Failure Adapted from IGEM/TD/2 (IGEM 2013)

Figure 3.3 Event Tree for a Rupture of a Hazardous Liquid Pipeline Adapted from BS PD 8010-3 (BSI 2013)

Figure 4.1 Example of a PRA Process

Figure 4.2 Risk-Related Decision Support Framework (UKOOA 1999)

Figure 4.3 Overview of the Risk Assessment Process (ABS 2000)

Figure 4.4 Sources of Risk Assessment Uncertainty (HSE 2006)

Figure 4.5 Risk Modelling Approaches Based on Event Severity (NERC 2010)

Figure 5.1 Framework for the QRA Process

Figure 5.2 Example of F-N Curve for a Pipeline Segment

Figure 5.3 Example of an Individual Risk Contour at a Given Location

Figure 5.4 Example of a Risk Profile Along a Pipeline Segment

Figure 5.5 Example of a Risk Matrix

Figure 5.6 Example of Risk Variation with Time

Figure 6.1 Gas Pipeline System Schematic

Figure 6.2 Oil Pipeline System Schematic

Figure 6.3 API 581 Level 1 Consequence Analysis for Instantaneous-Type Release Event Tree

Tables

Table 6.1 Types of Facilities in a Pipeline Transmission System and Their Typical Components

Table 6.2 List of Applicable Threats in a Pipeline Code and Two Facility Risk Models

LIST OF ACRONYMS

ABS	American Bureau of Shipping
AEP	American Electric Power
BLEVE	Boiling Liquid Expanding Vapor Explosion
BOSCEM	Basic Oil Spill Cost Estimation Model
CAA	Civil Aviation Authority
CAPP	Communication, Assessment and Prioritization Program
CFD	Computational Fluid Dynamics
DOE	U.S. Department of Energy
DOS	U.S. Department of State
EASA	European Aviation Safety Agency
EEI	Edison Electric Institute
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Industry
FAA	Federal Aviation Authority
FERC	Federal Energy Regulatory Commission
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes and Effects Criticality Analysis
FORM/SORM	First- and Second-order Reliability Methods
HAZID	Hazard Identification Studies
HAZOP	Hazard and Operability Study
HEART	Human Error Assessment and Reduction Technique
HRA	Human Reliability Analysis
HSE	U.K. Health and Safety Executive
HSSM	Hydrocarbon Spill Screening Model

List of Acronyms

HVP	High Vapour Pressure
JHEDI	Justification of Human Error Data Information
LNG	Liquefied Natural Gas
NERC	North American Electric Reliability Corporation
NRC	U.S. Nuclear Regulatory Commission
PIR	Potential Impact Radius
PRA	Probabilistic Risk Assessment
QRA	Quantified Risk Assessment
RAMCAP	Risk Analysis and Management for Critical Asset Protection
RAM-D	Risk Assessment Methodology for Dams
RAM-T	Risk Assessment Methodology for Transmission
RAWG	Risk Assessment Working Group
RIVM	National Institute of Public Health and the Environment (The Netherlands)
ROW	Right-of-way
SCC	Stress Corrosion Cracking
SME	Subject Matter Expert
SMS	Safety Management System
SPCC	Spill Prevention, Control, and Countermeasure
SWIFT	Structured What-If Checklist Technique
THERP	Technique for Human Error Rate Prediction
VCE	Vapour Cloud Explosion
VRAP	Vulnerability Risk Analysis Program

EXECUTIVE SUMMARY

A critical review of quantitative risk analysis (QRA) models used in the pipeline industry was conducted as part of a project titled "Critical Review of Candidate Pipeline Risk Models", which was carried out for the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) under Agreement No. DTPH5615T00003. Additionally, QRA methods used in the nuclear, offshore, aviation and power transmission industries were reviewed, and a commentary on the application of QRA to pipeline facilities and LNG plants was developed. Guidelines for the development and application of pipeline QRA models were developed on the basis of the review findings, responses to an industry survey carried out as part of the project, and C-FER's prior experience. The project was carried out under the guidance of a Technical Advisory Committee consisting of six risk experts from the pipeline industry and in coordination with two other related projects carried out by Kiefner & Associates and the Gas Technology Institute.

In the context of pipeline systems, risk is a measure of the expected adverse consequences of a product release due to a failure. It is generally quantified as the product of the failure frequency and failure consequences. Key learnings from the pipeline risk model review and industry survey include the following:

- QRA models are extensively used in the industry to estimate threat-specific risk due to corrosion and mechanical damage for natural gas pipelines.
- While analytical probability models are being used to estimate failure frequencies due to corrosion and mechanical damage, SME opinion and historical data are typically used to estimate failure frequencies due to other threats.
- Well-established risk measures are available for life safety but not for environmental impact.
- Consequence quantification models are well-established for natural gas releases but are less well established for hazardous liquids pipelines.
- Standardization of the list and definitions of relevant interacting threats is required to facilitate their inclusion in QRA models.

The review of QRA methodologies used in the nuclear, offshore, aviation and power transmission industries, and for pipeline facilities and LNG plants has shown that failure frequency estimation methods are similar across these industries, whereas failure consequence estimation models are specific to risk measures established in each industry. Key learnings from other industries that can be adapted to pipeline QRA models are:

- *Nuclear*: The adoption of a probabilistic risk assessment methodology in the nuclear industry has shown that:
    - Well-established risk acceptance criteria and standardization of risk model components enables wider application of QRA models.

- Less conservative probabilistic acceptance criteria can be used for components with well-defined failure modes and recognized failure probability calculation models, whereas more conservative risk acceptance criteria need to be used if large uncertainties are associated with the consequence models used to estimate risk from the failure probabilities.
- Formal methods are required to address knowledge uncertainties, such as model uncertainties, and their influence on the decision-making process.

- *Offshore*: Offshore guidelines emphasize the use of QRA as a decision-making tool based on cost-benefit analyses and lifecycle economic trade-offs. Also, structured approaches for threat identification are recommended, which can be either qualitative based on checklists, or quantitative based on the analysis of data on incidents, near-misses, and operational parameters.
- *Aviation*: Qualitative methods are used to address operational risks while QRA is employed for structural integrity risks. The collection of safety-related data is incorporated into operational processes rather than being treated as a separate activity. Adoption of this approach reduces the effort required for data collection during QRA.
- *Power Transmission*: The guidelines emphasize the selection of risk measures that could be benchmarked against reality as the lack of realistic and standardized risk measures deters the use of QRA. While component risk estimation is well-established, system-wide risk estimation considering component interdependencies and domino effects is more challenging.

The methodologies used for facility QRAs are similar to those used for pipelines, and therefore, integration of QRA results for pipelines and facilities risk is possible. However, integration of risk results for different facilities should be undertaken with caution as the underlying models may have different assumptions, purposes and levels of detail.

Based on the learnings from the review, a guideline document was developed to facilitate the development and verification of quantitative pipeline risk models. The guidelines address the QRA process for a system-wide risk assessment, as well as more narrowly-focused QRA studies such as those carried out to address individual failure threats (e.g. corrosion) or individual consequence components (e.g. life safety). The steps involved in conducting a QRA are also addressed, including a definition of objectives, model selection, data collection, risk analysis, documentation and validation. Levels of analysis described in the guidelines enable the development of simplified subjective risk models and provide the tools to facilitate incremental improvements toward more detailed and objective models. Guidance is also provided on the use of risk results in risk evaluation and decision-making.

Future work recommended to enhance the value of the guidelines and QRA models in the pipeline industry includes the following:

- Model development is required to address the technology gaps identified in this project. These gaps include:

  - a standardized list of interacting threats similar to the individual threat list in ASME B31.8S;
  - standardized risk measures for environmental impact similar to the individual risk and societal risk measures used for life safety; and
  - simplified life safety models for hazardous liquids pipelines similar to the potential impact radius (PIR) model for natural gas pipelines.

- Guidance for defining risk model input parameter distributions and addressing model uncertainties is required.
- A pilot study is recommended to demonstrate the application of the guidelines developed in this project for the evaluation of an existing quantitative risk model.
- Development of a suite of benchmark problems will facilitate independent third-party risk model validation.

ACKNOWLEDGEMENTS

C-FER would like to acknowledge members of the Technical Advisory Committee for their advice and guidance during the project and their comments on the project deliverables. The Technical Advisory Committee consisted of Brandon Cavendish and Mark Piazza of Colonial Pipeline Co., Tom Zimmerman (formerly) of Enbridge Energy Inc., Zachary Cater-Cyker of ExxonMobil Research & Engineering, Shahani Kariyawasam of TransCanada Pipelines Ltd., and Juli Tatafu of Williams Co.

C-FER would also like to acknowledge the benefit of the interactions with industry that occurred during the Risk Model Workshop conducted by PHMSA in September 2015 and the Risk Model Working Group initiated by PHMSA. These interactions informed our understanding of industry needs and the status of risk model usage.

1. INTRODUCTION

1.1 Terms of Reference

This document is one of the deliverables for a project titled "Critical Review of Candidate Pipeline Risk Models" that was carried out by C-FER Technologies (1999) Inc. ("C-FER") for the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration ("PHMSA") under Agreement No. DTPH5615T00003 entered into on September 30th, 2015. This project is one of three projects initiated by PHMSA to address the gaps identified in the application of quantitative risk models during the Pipeline R&D Forum in August 2014. The other two concurrent projects are: "Paper Study on Risk Tolerance" by Kiefner & Associates, and "Approaches for Preventing Catastrophic Events" by Gas Technology Institute. This project was carried out under the guidance of a Technical Advisory Committee consisting of six risk experts from the pipeline industry, who provided input throughout the project and review comments on the final project deliverables.

1.2 Background and Objective

Quantitative risk assessment is a systematic, comprehensive analysis methodology for evaluating the risks associated with engineering systems. It is used as a tool for making cost-effective decisions that achieve specified acceptable safety levels. The quantitative approach has been used in the pipeline industry over the past three decades and some of its elements have been adopted in international transmission pipeline standards and regulations. Probabilistic quantitative risk approaches can include varying levels of detail and rigor, and the benefits that can be realized from the methodology depend on the approach used. As the rigor of the models increases, more of the benefits of quantitative risk models can be realized; however, the data requirements and the implementation effort increases. The selection of an appropriate model depends on the desired features and available resources.

The primary objective of the project was to conduct a critical review of the quantitative risk analysis approaches used in the pipeline industry and to review approaches used in the nuclear, offshore, aviation, and power transmission industries. A commentary on the risk analysis approaches used for facilities and LNG plants and a discussion of their similarities to the risk models used in the pipeline industry is provided.

A secondary objective was to produce guidelines for developing and validating quantitative pipeline risk models. The guidelines were based on the following:

- key findings of the literature review of risk models used both in the pipeline and other industries; and
- desirable model attributes with respect to accuracy, verifiability, transparency, practicality and fit within the decision-making processes used by operators and regulators. These were

identified from an industry survey conducted for the project and using C-FER's prior experience.

The guidelines can be used by operators to select, develop or evaluate their own risk models. They can also be used by regulators to evaluate risk models and by standards committees as a basis for defining requirements for the development of risk models.

1.3 Scope

The risk assessment process consists of two elements: risk estimation, which involves quantifying system risks; and risk evaluation, which involves comparing the estimated risks to quantitative risk criteria to determine acceptability. The risk estimation process requires risk analysis, which involves: defining the system being considered, identifying the threats that can lead to failure, estimating the frequency of failure, estimating the consequences of failure and estimating the risk as the product of failure frequency and failure consequences.

The review performed in this project focused on the following two components of the quantitative risk analysis (QRA) process:

- quantifying the failure frequency, typically expressed as events per mile-year (or km-year); and
- quantifying the failure consequences in measurable units, such as the number of casualties, the spill volume or the dollar value, for safety, environmental, and financial consequences respectively.

As part of the literature review, quantitative risk estimation models were evaluated based on the ideal model attributes identified from the industry survey and from the project advisory committee's input. Available models in the pipeline and other industries were used as a basis to categorize models based on the level of analysis detail and to identify the benefits and limitations of each level.

The project scope does not include developing, improving, or validating any particular risk analysis model. Similarly, risk criteria and the identification of rare-event threats are addressed by the other two concurrent research projects PHMSA-sponsored, mentioned in Section 1.1, and are not within the scope of this project.

1.4 Organization of the Document

The document is organized into the following sections:

- Industry Survey: Describes an industry survey and follow-up discussions with selected operators, regulators and SMEs that were conducted to identify the key attributes of an

effective quantitative risk model and the types of decisions made by operators based on risk model results.

- Literature Review – Pipeline Industry: Describes the critical review conducted to identify available failure frequency and failure consequence estimation models. The review addressed available risk estimation models as well as risk analysis processes used by operators.
- Literature Review – Other Industries: Describes the review of QRA models and guidelines in the nuclear, offshore, aviation, and power transmission industries. For each industry, the review included an overview of commonly used risk analysis processes and techniques, as well as key learnings that could be transferred to the pipeline industry.
- Guidelines for Quantitative Risk Model Development: Includes the standalone guideline document that was developed to assist operators in selecting or developing a risk model and to assist regulators in evaluating operator-specific models.
- Commentary on Other Facilities and LNG Plants: Describes the types of risk models currently used for pipeline facilities including LNG plants, and includes a commentary on the potential use of elements of pipeline risk models to improve facility risk modelling. The potential for developing integrated asset risk models that address both pipelines and facilities is also discussed.
- Summary and Recommendations: Summarizes the project findings and lists recommendations for future work required to address gaps in risk models that were identified in the literature review. This section also presents recommendations to enhance the value of the guidelines developed as part of the project.

2. INDUSTRY SURVEY

2.1 Introduction

An industry survey was conducted to collect information on current applications of risk models and to identify desirable model attributes. The survey was conducted through an online questionnaire (see Appendix B for the survey questions). Requests for survey participation were sent to 17 pipeline operators and consultants through a web-based link. A total of eight responses were received from six different operating companies. Some pipeline companies provided information on multiple risk models. As a result, descriptions of 13 risk models were received. All survey responses are anonymized and summarized in Appendix C.

2.2 Survey Objectives and Methodology

The purpose of the industry survey was to:

- learn about risk models not available in the published literature;
- determine risk model attributes that industry stakeholders consider important; and
- evaluate the readiness of the industry as a whole to adopt quantitative risk models.

The survey questions addressed the following topics:

- type of risk assessment used, i.e. qualitative or quantitative;
- applications of risk model results;
- desirable attributes of an ideal quantitative risk model;
- perceived obstacles to the adoption of quantitative risk models in the industry; and
- importance of risk model standardization.

The survey included the following definitions for 'Quantitative Risk Models' and 'Qualitative Risk Models':

- *Qualitative*: Model results are represented on a subjective scale either as risk indices or as verbal descriptions, e.g. severe, high, medium, and low.
- *Quantitative*: Model results are represented in terms of measurable units, e.g. expected dollar values for risk of damage.

Respondents were invited to describe their risk model if it did not conform to the definitions provided. Model descriptions were requested as free-form comments. The uses of the risk models were requested both as free-form comments and as selections from a list of options.

Industry Survey

To determine the attributes of an ideal quantitative risk model, participants were asked to rate attributes in a pre-defined list with respect to importance. The list of attributes was as follows:

- *Inputs* - considers all forms of evidence available to operators (e.g. incident/failure data, assessment results, or mechanistic understanding)
- *Defaults* - suggests appropriate defaults when information is missing
- *Transparency* - has clear documentation on algorithms, models and approach
- *Flexibility* - considers pipeline-specific factors
- *Repeatability* - produces consistent results upon repeated analysis by different analysts
- *Threats* - quantifies the risk associated with the standard threats
- *Rare threats* - quantifies the risk associated with interacting threats and rare threats
- *Validation* - has been validated with respect to model framework and model outputs and has an open model structure that facilitates further validation by a third party
- *Output type* - produces results that can be compared against a risk criteria or against other asset risk
- *Resolution* - identifies risk by location and by threat
- *Decision-making* - produces results that form a basis for decision-making.
- *Uncertainty* - estimates the uncertainty in the results based on the level of uncertainty in the inputs
- *Value of new data* - assesses the value of collecting new information

In addition to the ideal model attributes, the respondents were asked to rate obstacles to risk model usage and model standardization options. The response options for these questions are listed in Figure 2.3 and Figure 2.4. For the questions related to ideal model attributes, obstacles to using risk models and model standardization options, a score between 1 and 5 was requested, where 5 indicates high importance and 1 indicates low importance. For questions that required scoring, an option to provide free-form comments was also included.

2.3 Summary of Survey Results

Of the thirteen risk models reported, nine were quantitative and four were qualitative. No responses included an alternative characterization of the risk model in terms of being quantitative or qualitative. This confirms that the survey definitions were clear to the respondents.

Industry Survey

Figure 2.1 shows risk model applications ranked according to the survey results. All the qualitative models and most of the quantitative models are used for segment ranking and identification of significant failure threats at specific locations. The next most common use for all risk models is the identification of high-risk locations.

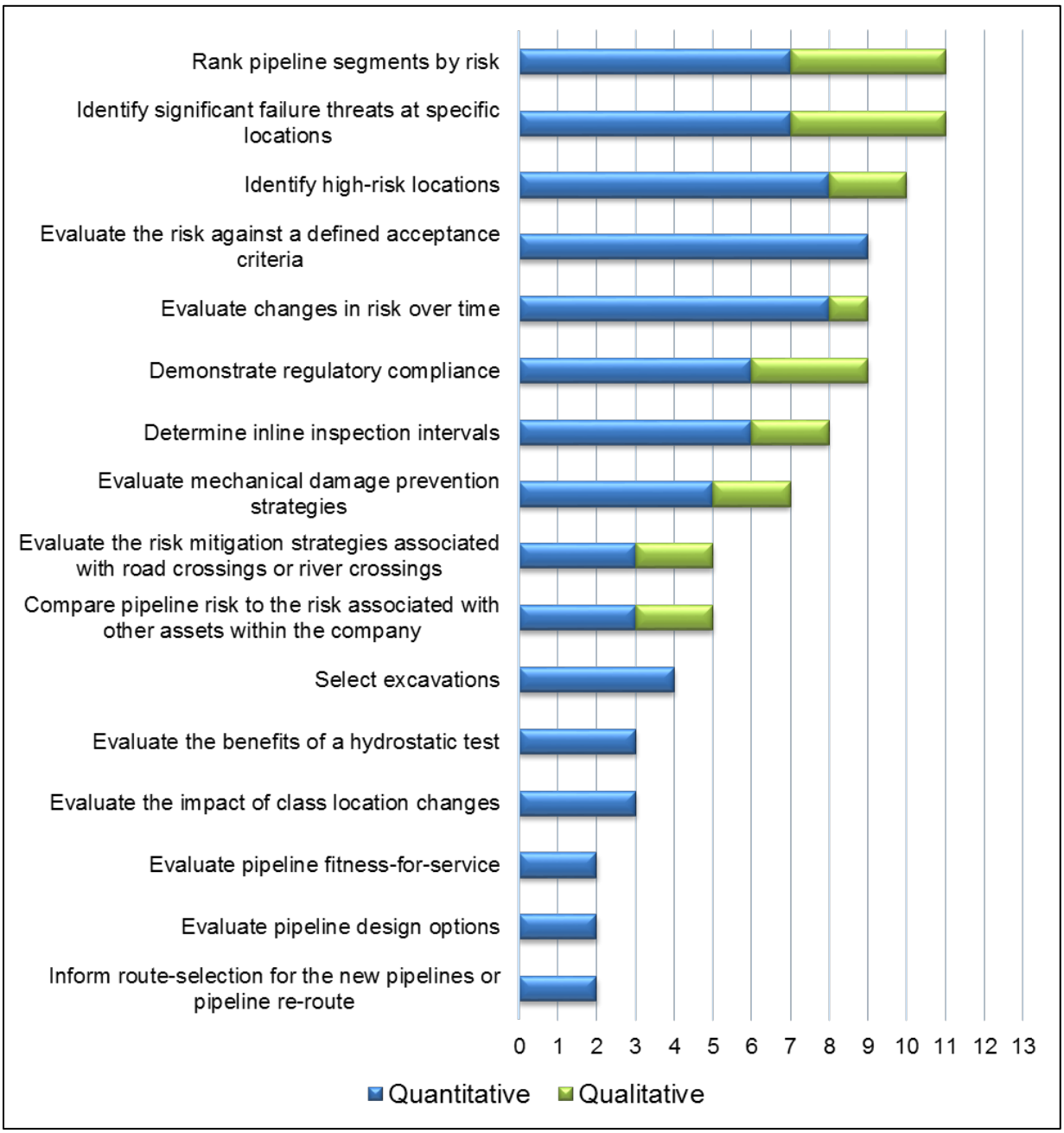

Figure 2.1 Summary of Model Uses from the Industry Survey

Industry Survey

All quantitaive risk models are used to evaluate the risk against defined acceptance criteria. This is an interesting finding in light of the fact that evaluation against acceptance criteria is not typically required to demonstrate regulatory compliance. Most quantitative models are also used to evaluate changes in risk over time; however, only one qualitative risk model was used for that purpose. The next most common risk model application is to demonstrate regulatory compliance.

Both quantitative and qualitative risk models are used to determine inline inspection intervals, plan for mechanical damage prevention and mitigate risk at crossings. Only quantitative models are used for excavation program planning and hydrostatic test interval evaluations. Quantitative risk models were also used to evaluate class location changes, assess fitness-for-service, compare design options, and optimize route selection. These survey responses indicate that risk models are primarily used as a decision-making tool for integrity management.

Figure 2.2 shows a ranked list of the ideal quantitative risk model attributes, where the ranking is based on the average score defined on a scale of 1 to 5.

Figure 2.2 Averaged Scores for Attributes of an Ideal Quantitative Risk Model

Ability to utilize all forms of available evidence was chosen by the respondents as the most important attribute. The next highest ranked attributes were a model resolution that supports a

review of risk by location and by threat, and model results that are usable for decision-making. These choices reflect the current uses of the risk models listed in Figure 2.1.

The ability to quantify the risk associated with the standard threats (listed in ASME B31.8S) was ranked higher than the ability to address rare and interacting threats. In the follow-up discussions, the survey respondents indicated that well-established quantitative risk methods are not yet available for all the standard threats and that it is a higher priority to address all the standard threats in a meaningful way before addressing rare and interacting threats. Other risk model attributes, such as validation, repeatability, and transparency, were also identified as important but were not ranked as highly as the attributes related to model inputs, resolution and threat identification. The average scores shown in Figure 2.2 vary from 3.25 to 4.86. These high average scores indicate that respondents considered all the options provided to be desirable and that none of the attributes were considered to be redundant.

Figure 2.3 shows the ranking of the perceived obstacles to a wider implementation of quantitative risk models based on the average of the scores received from the survey. Data collection effort ranks as the highest obstacle, which is consistent with 'consideration of input from all sources' being the highest-ranking attribute in Figure 2.2.

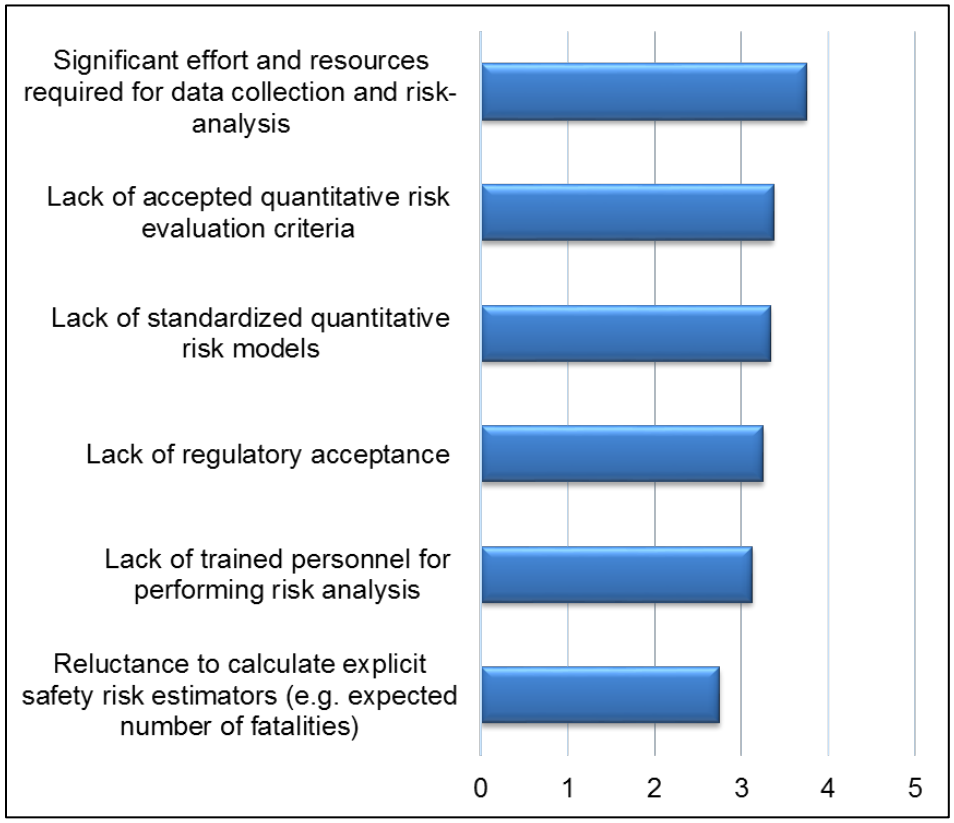

Figure 2.3 Averaged Scores for Obstacles to the Use of Quantitative Risk Models

The lack of accepted evaluation criteria and the standardization of risk models are ranked higher than the reluctance to quantify risk in explicit measurable units. This implies that the industry may be ready for quantitative risk analysis but lacks the standardized tools and models to implement the methodology. The lack of regulatory acceptance ranks higher than the lack of trained personnel, which further supports the need for regulatory acceptance of quantitative risk analysis.

In Figure 2.4, a standardized list of threats was ranked highest among the standardization options provided. Standardization of calculation methods for consequences ranks higher than calculation methods for probability, which indicates that there is a greater consensus on probability models than consequence models. No free-form comments were received regarding standardization options, indicating that the list provided in the survey covered all significant areas.

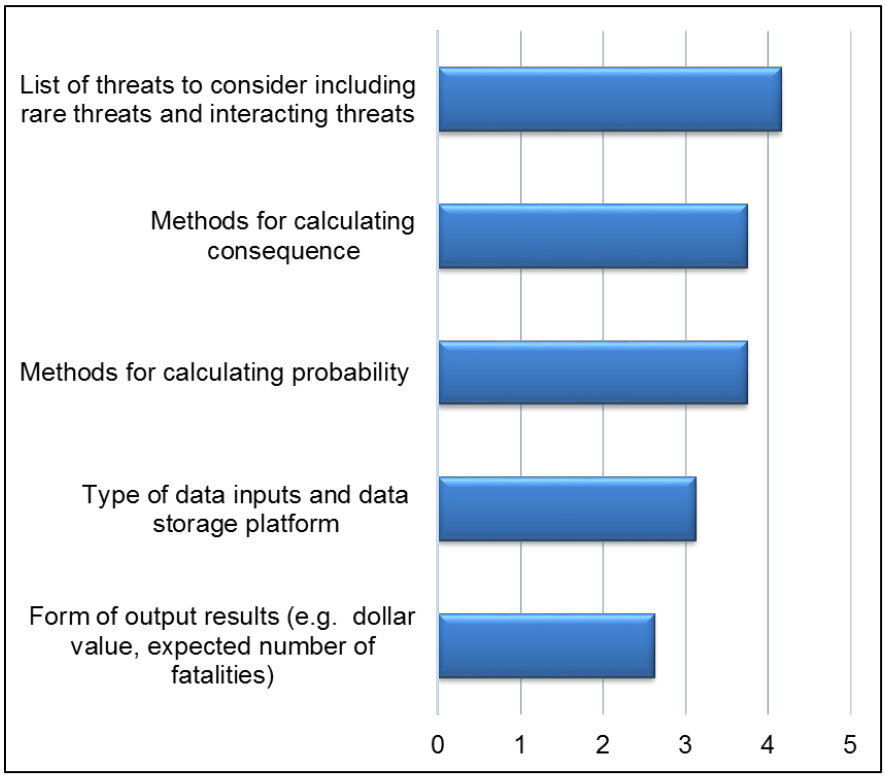

Figure 2.4 Averaged Scores for Areas of Standardization

2.4 Key Learnings from Survey Results

The industry survey indicated that several quantitative risk models are already in use in the pipeline industry. The key learnings from the responses received from pipeline operators regarding their experience in using both qualitative and quantitative risk models are as follows:

- Quantitative risk models have not replaced the use of qualitative models for risk-based ranking of pipeline segments and for identifying high-risk segments. Instead, quantitative risk models

are used when qualitative models are inadequate for specific purposes, such as selection of excavations, hydrostatic test simulation, evaluation of class location changes, fitness-for-service assessments, and pipeline design and route selection.

- All of the desirable quantitative risk model attributes suggested in the survey were assigned high scores by the respondents, indicating that the operators have high expectations from the risk models. They are not willing to compromise on model functionality and features.
- While the lack of universal quantitative risk criteria was ranked as the second highest obstacle to the use of quantitative risk models, all of the respondents using quantitative risk models evaluate the results against company-specific acceptance criteria. This suggests that the main obstacle in the area of quantitative risk evaluation is the lack of universally recognized criteria rather than a general reluctance to use explicit criteria.
- There was little interest in standardizing data inputs and data storage platforms, even though such standardization can reduce the level of effort required to identify appropriate data sources and develop data collection protocols. The use of existing data in all available formats was preferred instead, which suggests that users place more value on the flexibility to use operator-specific data and select an appropriate data platform.

3. LITERATURE REVIEW – PIPELINE INDUSTRY

3.1 Search Methodology and Data Collection

Relevant references were collected by searching 34 Engineering and Technology databases. The search concentrated on three databases, namely, Ei Compendex, Inspec and SciSearch, which catalogue peer-reviewed scientific publications from a wide range of science and engineering subject areas. In addition, C-FER's background expertise was used to fill in gaps identified in the literature collected. In addition to models that are fully described in the publications reviewed, proprietary models referenced in QRA applications by operators or in European or North American standards are also included as viable model options.

A total of 70 publications were reviewed. Eight publications described system-wide applications of quantitative risk models for either liquid or gas pipelines. Twenty-nine publications focused exclusively on quantifying the consequences of failure. The thirty-three remaining publications were related to quantifying the pipeline failure frequency for different threats using a wide range of probabilistic and statistical methods. In addition to the critical review presented in this section, a summary of each publication reviewed is included in Appendix D.

3.2 Risk Analysis Process

3.2.1 Overview

A flowchart of the risk management process is shown in Figure 3.1. Within the risk management process, *risk analysis* is defined as a sub-process that involves system definition, threat identification, failure frequency estimation, failure consequence estimation, and risk estimation.

A detailed review of the failure frequency and consequence estimation models is presented in Sections 3.3 and 3.4. The remaining components of the risk analysis process are addressed in the following sub-sections.

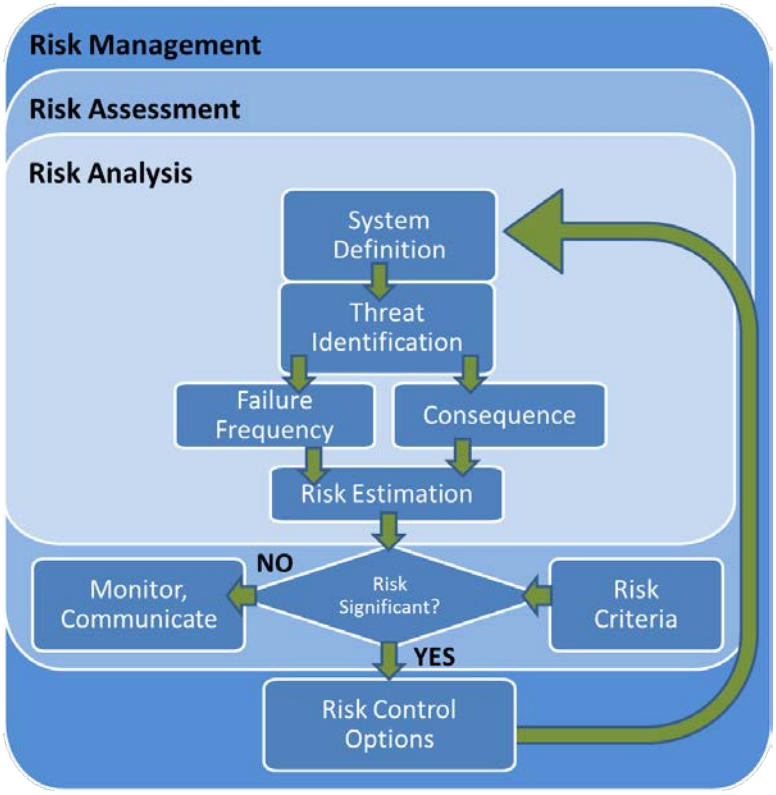

Figure 3.1 Risk Management Process

3.2.2 Purpose

Most of the risk models reviewed were used either as part of a pipeline integrity management process or to demonstrate regulatory compliance. Examples of models used in pipeline integrity management are described in Stephens and Nessim (1996), Cicansky and Yuen (1998), Sutherby et al. (2000), Mora et al. (2002), Wickenhauser and Playdon (2004), Esford et al. (2004) and Kariyawasam et al. (2014). Examples of models used to demonstrate regulatory compliance are described in Cicansky and Yuen (1998), McCallum et al. (2004), Francis et al. (2006), Mitchell et al. (2014), Mangold et al. (2014) and Solis et al. (2014).

3.2.3 System Definition

In most of the papers reviewed, the physical system analyzed included only the line pipe (i.e. excluding attachments or appurtenances). Exceptions to this were the models described by Mangold et al. (2014), which included valves and appurtenances, and the study by Worley Parsons (2012) of the proposed Northern Gateway pipeline, which addressed non-pipe components and other equipment, such as pumps, seals, valves, and flanges.

3.2.4 Threat Identification

Threat identification in most models was based on the list of threats in the ASME B31.8S (ASME 2014) Standard. For example, Perez et al. (2014), Worley Parsons (2012), and Kariyawasam et al. (2014) initially considered the nine threat categories in ASME 31.8S. In each of these studies, a screening process based on historical data and/or SME opinion was used to eliminate non-applicable threat categories (e.g. manufacturing defects, equipment failures) and to add system-specific threats not included in ASME B31.8S (e.g. theft and sabotage).

In addition to the standardized list of threats, Kariyawasam et al. (2014) evaluated the potential for three types of threat interactions between any two threat categories. These were classified as: interacting coincident defects that occur simultaneously at a given location (e.g. corrosion on dent-gouge), interacting activating threats that trigger or exacerbate a coincident threat (e.g. circumferential SCC with ground movement), and interacting common-mode conditions that indicate multiple threats occurring due to the same underlying conditions (e.g. coating holidays leading to external corrosion and SCC).

Solis et al. (2014) considered the list of threat categories provided in the Mexican Standard for integrity management NOM-027-SESH-2010 (NOM 2010) and modified it based on system-specific factors. Martinez and Rodriguez (2000), and Esford et al. (2004) considered threat lists that are based on historical failure rates. While identifying threats based on historical information provides a valid basis for risk analysis, using this approach as the sole basis for threat identification can lead to underestimation of risk as all of the potential threats may not have been observed in the past.

3.2.5 Risk Estimation

3.2.5.1 Failure Modes

Sutherby et al. (2000) estimated the failure frequencies for small leaks, large leaks and ruptures. Kariyawasam et al. (2014) estimated the failure frequencies based on an “equivalent rupture ratio”, which equates 20 leaks to a rupture. Worley Parsons (2012) estimated the frequency of leaks and ruptures as a fraction of the total failure frequency. Mitchell et al. (2014) reported only the frequencies of full-bore ruptures for the threats considered. Mangold et al. (2014) and Perez et al. (2014) estimated the total failure frequency and did not separate the failure frequencies for leaks and ruptures.

In the papers reviewed, the distinction between leaks and ruptures was made where failure frequency estimates were based on engineering models that define mathematical relationships to distinguish leaks from ruptures. Where SME opinion and historical data were used, the failure frequency estimate was often not divided between leaks and ruptures.

Since the consequences associated with leaks and ruptures are significantly different, calculating separate failure frequencies for each failure mode is preferred. Considering all failure events as ruptures leads to an overestimation of the total risk due to an overestimation of failure consequences. On the other hand, ignoring leak events and considering only rupture events leads to an underestimation of the total risk, particularly for hazardous liquids where leaks can have a significant environmental impact.

3.2.5.2 Frequency versus Probability

Failure frequency is typically computed annually (over a time period of one year) for each pipeline segment and for each threat category. Normalizing the failure frequency over a unit length results in a *failure rate* expressed as events per mile-year or events per km-year, e.g. Perez et al. (2014) and Kariyawasam et al. (2014). The total failure frequency for a given segment is estimated as the summation of the failure frequencies associated with different failure causes, e.g. Martinez and Rodriguez (2000), Sutherby et al. (2000), and Mangold et al. (2014). It is expressed as

$$F_t = \sum F_i \qquad [1]$$

where

F_t is the total failure frequency of the segment, and

F_i is the failure frequency of the segment due to threat i.

Some risk models in the literature have replaced the segment failure frequency by the total segment probability of failure, P_t, which is given by

$$P_t = 1 - \prod(1-P_i) \qquad [2]$$

where

P_i is the probability of failure of a segment due to a threat, i.

Solis et al. (2014) used this approach to estimate the total risk associated with all threat categories. Mora et al. (2002) used Equation [2] to estimate the total probability of failure due to metal loss based on the probabilities of failure of each detected metal loss feature, i, identified by in-line inspection.

Some references (e.g. Mihell and Rout 2012) incorrectly use the failure frequency and the failure probability interchangeably. It is recognized that the failure frequency and the failure probability are approximately equal for small values of the failure frequency. For example, the difference between the two quantities is less than 5% for a failure frequency of 10% or less. For large failure

frequencies (e.g. for a long segment), a significant underestimation error is introduced into the risk estimate by using the failure probability instead of the failure frequency.

The failure frequency can be related to the failure probability based on the assumption that failures follow a Poisson process. A Poisson process assumes that failures are independent events. Under this assumption, the relationship between the annual probability and the annual failure frequency is given by

$$P_t = 1 - e^{(-Ft)} \qquad [3]$$

Using Equation [3], a failure frequency of 1.0 events per-year equals an annual failure probability of 63%. In this example, QRA using probability instead of failure frequency underestimates the risk by 37%.

3.2.5.3 Risk Measures

In most of the literature reviewed, risk measures are evaluated in terms of monetary units by converting the consequences related to safety, environmental sensitivity and financial impact to a dollar value. Some example applications of this approach are available in Martinez and Rodriguez (2000), Mangold et al. (2014), Solis et al. (2014), and Perez et al. (2014).

Other measures of life safety risk include ‘individual risk’ and ‘societal risk’. Societal risk has been expressed as an F-N plot, which is a plot of the frequency (F) of incidents causing N or more of fatalities (Tomic et al. 2014), or casualties (i.e. fatalities and injuries) (Sutherby et al. 2000). Societal risk has also been expressed in terms of the expected number of fatalities per km-year (Wickenhauser and Playdon 2004).

Environmental risks have been quantified in terms of a sensitivity score (Worley Parsons 2012) and in terms of an effective spill volume (Nessim et al. 2014), which is defined as the spill volume, adjusted by a factor that accounts for the environmental sensitivity of the spill site.

Using consistent units for all consequences facilitates decision-making and allows for a consistent comparison between assets. However, as noted in Perez et al. (2014), the conversion of life safety consequences to a dollar value requires a realistic and current valuation of a statistical life. However, this conversion is controversial in some societies where assigning a monetary value on human life opens the operators up to the risk of litigation and public outrage.

3.2.5.4 Segmentation

Pipelines are typically segmented into sections with uniform attributes so that each segment has a uniform risk estimate. This is referred to as dynamic segmentation. This approach was adopted in all papers reviewed, e.g. Wickenhauser and Playdon (2004), Worley Parsons Report (2012), Mangold et al. (2014), Perez et al. (2014), Kariyawasam et al. (2014), and Solis et al. (2014).

3.3 Failure Frequency Estimation Models

3.3.1 Introduction

Based on the literature reviewed, failure frequency estimation methodologies are categorized into three groups:

1. subject-Matter Expert (SME) opinion;
2. historical data; and
3. analytical models

The results of the review of these three groups of methods are described in the following sections.

3.3.2 Subject Matter Expert (SME) Opinion

SME opinion was often employed to estimate failure frequencies for the following threats:

- geohazards (Esford et al. 2004, Perez et al. 2014);
- incorrect operations (Worley Parsons 2012, Perez et al. 2014, Cicansky and Yuen 1998); and
- theft and sabotage (Perez et al. 2014, Solis et al. 2014).

The following approaches were used to estimate failure frequencies based on SME opinion:

- identifying parameters that influence failure and estimating the failure frequencies based on a qualitative assessment of these parameters (e.g. Cicansky and Yuen 1998 and Perez et al. 2014);
- converting a qualitative risk index score to a quantitative failure frequency (e.g. Mangold et al. 2014);
- using a structured questionnaire to elicit SME scores and converting the scores to failure frequencies through a consistent set of rules (e.g. Esford et al. 2004) and Worley Parson 2012); and
- using the “Analytical Hierarchical Process”, in which SMEs perform systematic pairwise comparisons to assign a proportion of the total failure frequency to each threat category and then using a quantitative estimate of failure frequency for one threat category to estimate the failure frequencies for all other threats (e.g. Dawotola et al. 2009).

Using SME opinion is advantageous in the following circumstances:

- When data gaps exist in the model, this approach can be used to fill these gaps based on the system-specific knowledge of the SMEs (e.g. Cicansky and Yuen 1998, Perez et al. 2014, Solis et al. 2014 and Mangold et al. 2014).
- For threats that are not well represented in the historical data and are not amenable to analytical modeling, structured questionnaires can be employed to convert SME-defined scores into failure frequency estimates (e.g. Esford et al. 2004 for the geohazards and Worley Parsons 2012 for incorrect operations).

The disadvantages of using SME opinion are:

- The level of subjectivity in the SME opinion can lead to biased estimates of the failure frequencies.
- The approach is not suitable for new threats where little pipeline-specific expertise exists.

Potential bias can be reduced by requesting opinions from several SMEs and applying a structured communication technique such as the 'Delphi' technique (Ayyub 2014) to reconcile them. The Delphi technique involves several rounds of seeking an independent opinion from an expert panel. Between rounds, an anonymized summary of all the opinions received is presented to the panel in order to allow each SME to update his/her opinion. The updating process ends after a predetermined number of iterative rounds or when expert consensus is reached within a predetermined range of values.

Overall, the subjectivity and potential bias involved in SME-based probability estimation make the results suspect, and therefore these methods should only be used if the use of other more rigorous methods is not possible.

3.3.3 Historical Data

Two approaches have been used to estimate failure frequencies based on historical data. These are:

- A baseline failure rate is estimated from historical data for each threat category and then multiplicative modification factors are applied the baseline failure rate to account for pipeline-specific attributes. This approach was adopted by Wickenhauser and Playdon (2004), Dawson et al. (2010), Sutherby et al. (2000), Cosham et al. (2008), Worley Parsons (2012), Goodfellow et al. (2008) and Goodfellow et al. (2014).
- Historical failure rates are estimated and modified to account for pipeline-specific attributes using mathematical functions based on regression. Martinez and Rodriguez (2000) reported modifying the failure frequency using a relationship between the failure frequency and pipe attributes. The regression relationship was developed using three points representing high, low

and medium failure frequency estimates and the corresponding attribute values. Kariyawasam et al. (2014) estimated the failure rates as a combination of predicted failure rates from historical data and an additive adjustment factor that incorporates the results of integrity assessments. The predicted failure rate was characterized by a regression function that defines the relationship between the historical failure rate for a given threat and the 'mechanistic factors' that influence the threat likelihood. Mechanistic factors were index scores based on SME opinion that account for the parameters effecting the failure. The selected historical failure rates used in this reference are specific to each pipeline sub-system.

The advantages of using historical-based failure frequency estimates are:

- There is a higher confidence in the estimated values than SME opinion due to the use of empirical evidence as a basis.
- It is a rational calculation process that can be repeatable if standardized adjustment factors are used, e.g. Cosham et al. (2008), Goodfellow et al. (2008), and Goodfellow et al. (2014).
- It provides a simple approach to estimate generic failure frequencies (i.e. independent of pipeline-specific factors) or pipeline-specific failure rates once the adjustment factors are defined.

The disadvantages of using historical-based failure frequency estimates are:

- The baseline failure rates are often developed from generic incident databases and do not reflect the condition and environment of a particular pipeline system.
- The adjustment factors developed for the pipeline-specific modifications involve subjective judgement which is subject to the same disadvantages of using SME opinion (see Section 3.3.2).
- The lack of historical failure data for newly-identified threats prevents the application of this approach to new or rare threats.
- Inconsistent incident reporting may lead to inaccuracies in the calculated failure frequencies. For example, Girgin and Krausmann (2016) performed a historical analysis of the liquid pipeline incidents in the U.S. and concluded that incidents caused by natural hazards were under reported.
- Historical data is a reflection of the data collection, design, construction, and operational practices of the past and may not be representative of future trends, which are influenced by both asset aging and a drive for continuous improvement. For example, the analysis of significant incident trends by Sosa and Alvarez-Ramirez (2009) shows a distinct reduction in incident frequencies over a duration of 20 years.

3.3.4 Analytical Models

Analytical models can be broadly categorized into structural reliability methods (e.g. Monte Carlo simulation), probabilistic graphical models (e.g. fault-tree methods, and Bayesian Networks), and fuzzy logic models.

Structural Reliability Methods: Structural reliability methods are used to estimate failure frequencies by considering the uncertainties in the parameters and models that govern pipeline failures. Given a deterministic failure model and the probability distributions of the model input parameters and model error factors, standard reliability methods (e.g. Monte-Carlo simulation) are used to estimate the frequency of failure. Francis et al. (2000) presented a detailed framework of this approach.

In the literature reviewed, this approach was applied in the following areas:

- estimating the failure frequency due to metal loss corrosion (e.g. Mora et al. 2002, McCallum et al. 2004, Chan and Webster 2010, Mihell and Rout 2012, Worley Parsons 2012, and Perez et al. 2014);
- estimating the failure frequency due to third-party damage (e.g. Stephens and Nessim 1996, Nessim and Stephens 1998, Lyons et al. 2008 Cosham et al. 2008, and Goodfellow et al. 2014);
- estimating the failure frequency due to fatigue crack growth (e.g. Francis et al. 2002); and
- developing reliability targets for reliability-based design and assessment and limit states design (e.g. Zimmerman et al. 2002, Nessim et al. 2010, and Nessim and Adianto 2014).

Graphical Models: A graphical model is a probabilistic model that expresses the dependence structure between random events. Fault tree methods are a logical representation of all possible basic event combinations leading to a failure event. Basic events are connected with 'AND' and 'OR' gates, and probability theory is used to compute the frequency of the top event (i.e. failure) as a function of the probabilities of the basic events. A Bayesian network model is a graphical representation of the causal links between basic events that lead to a top event (i.e. failure). Bayesian networks are similar to fault tree models, except that the relationships between the basic events are defined through conditional probabilities rather than a mathematical operator determined by the 'AND' or 'OR' relationships used in constructing fault trees.

Graphical models were applied in the following areas:

- estimating equipment impact frequencies on a buried pipeline using fault-tree methods (e.g. Chen and Nessim 1999, Chen et al. 2006, and Toes and Rogers 2010);
- estimating the failure frequency due to SCC (e.g. Jain et al. (2012); and
- estimating the failure frequency due to internal and external corrosion (e.g. Ayello et al. 2014).

Fuzzy Logic: Recently, fuzzy logic, which is a non-probabilistic method for addressing uncertainty, has been used to estimate the failure rates of onshore pipelines. Fuzzy logic methods are based on fuzzy set theory, in which an element may be in both failure and success categories with different degrees of membership. Accordingly, the theory eliminates the crisp boundaries between the categories in traditional set theory, which is the basis of probability theory. Fuzzy logic methods define a set of rules that can be used to combine the fuzzy sets.

Fuzzy logic allows for modelling linguistic representations of imprecision (e.g. labels such as 'poor', 'fair', 'excellent') and uncertainty (e.g. lack of knowledge about the coating condition being either 'poor' or 'fair'). Using a fuzzy set of rules, linguistic labels for uncertainty and imprecision can be combined and the uncertainty in the estimated frequency of occurrence of a particular outcome can be estimated.

Applications of fuzzy logic to pipeline include the following:

- developing fuzzy fault tree methods that represent basic event probabilities as fuzzy numbers (e.g. Shahriar et al. 2012, Markowski and Mannan 2009); and
- quantifying expert opinion to characterize inputs for fault tree models (e.g. Yuhua and Datao 2005, and Peng et al. 2009).

Fuzzy logic does not have the well-established mathematical and theoretical basis that underpins probabilistic models. Consequently, the application of fuzzy logic methods has not gained wide acceptance because it is unclear whether they have any advantages over probabilistic models.

The advantages of using analytical models are:

- The estimated failure frequencies are pipeline-specific.
- The characterization of input random variables can include all types of available evidence.
- The assumptions required to characterize the inputs can guide future data collection efforts.
- They allow for differentiation between failure modes, which leads to more accurate risk estimates.
- The influence of mitigation actions can be quantified. For example, Bandstra and Gorrill (2014) estimated the expected failure rates due to axial grooving for a natural gas pipeline, assuming inspection with inline metal loss tools with varying sizing errors.
- Rare and interacting threats can be addressed due to the flexibility in incorporating new models. For example, failure due to crack and corrosion interaction can be addressed using finite element models.

- The Bayesian network methodology provides the flexibility to incorporate uncertainties in the relationships between the connecting events, and an intuitive way to harness expert knowledge regarding the relationships between pipeline parameters.

The disadvantages of these methods are:

- Greater resources and expertise are needed to characterize the input parameters and compute the failure frequencies.
- The complexity of probabilistic models and associated analytical methods may lead to skepticism regarding the results, as the model can be seen by some users as a 'black box'.

3.4 Consequence Estimation Models

3.4.1 Overview

Based on the literature reviewed, release consequences are broadly categorized into three groups:

1. life safety;
2. environmental impact; and
3. financial impact.

It is noted that most of the risk models reviewed did not include a characterization of environmental impact (see Section 3.4.3.3). Consequently, QRA models that quantify all aspects of risk (i.e. including environmental impact) were limited to the following two applications:

- Martinez and Rodriguez (2000) used SME opinion to quantify the cost of product loss, repair cost, shutdown costs, environmental damages in terms of property damage, and impact on the population as a combination of fatalities and injuries.
- Perez et al. (2014) considered all consequences due to the release of hazardous liquids according to the "Guidelines for Quantitative Risk Assessment" known as the Purple Book (CPR 1999).

Hazard scenarios emanating from a pipeline failure event are addressed in Section 3.4.2. Models to quantify the consequences associated with each group are addressed in Section 3.4.3.

3.4.2 Hazard Scenarios

A number of hazard scenarios can result from a pipeline release. Event trees are used to identify these hazard scenarios and calculate their probabilities of occurrence. As demonstrated below, event trees are specific to the product type and the failure mode.

Figure 3.2 shows the event tree given in IGEM/TD/2 (IGEM 2013) for a natural gas release. In this event tree, the first branching point divides failures into ruptures and 'punctures' (i.e. indicated on the tree as a non-rupture). Since the most significant hazard due to a natural gas release is a jet fire or a crater fire, the majority of the available consequence models were developed to estimate the impact of these two hazard scenarios.

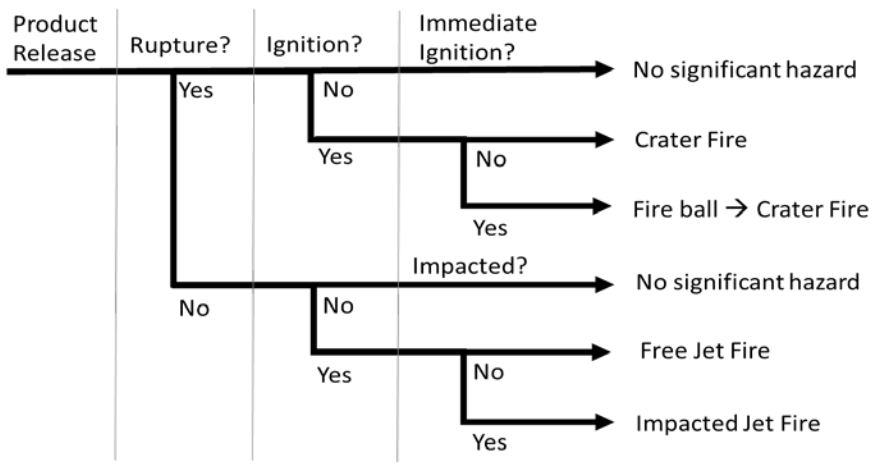

Figure 3.2 Event Tree for a Natural Gas Pipeline Failure Adapted from IGEM/TD/2 (IGEM 2013)

Figure 3.3 shows an event tree adapted from British Standard PD 8010-3 (BSI 2013) for the rupture of a hazardous liquid pipeline. The vapour pressure of the product plays an important role in determining the likelihood of the outcomes listed at the end of the event tree. For non-volatile low vapour pressure (LVP) liquids, such as crude oil, the ignition probability is low and the main release consequences relate to ground and water contamination. For volatile LVP liquids, such as gasoline, a pool fire is also possible in addition to the potential for ground and water contamination. A flash fire or vapour cloud explosion (VCE) can occur if a vapour cloud is formed due to the release of high vapour pressure (HVP) liquids.

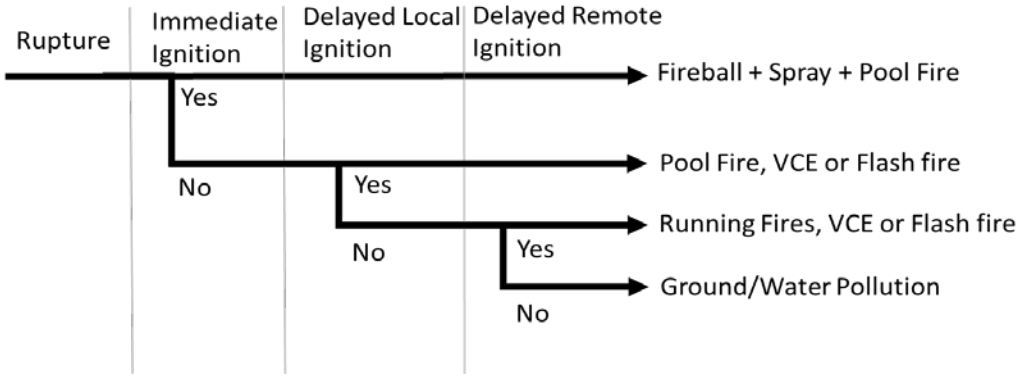

Figure 3.3 Event Tree for a Rupture of a Hazardous Liquid Pipeline Adapted from BS PD 8010-3 (BSI 2013)

3.4.3 Quantification of Consequences

3.4.3.1 Life Safety

3.4.3.1.1 General

There are well-established methods for the estimation of life safety consequences that are typically required to estimate individual and societal risks. For natural gas pipelines, several detailed and simplified safety consequence estimation models that are validated against incident data are available. By contrast, the consequences for hazardous liquid pipelines are not as well established. While specialized software packages are available to estimate the life safety consequences due to pool fires, flash fires and VCEs, information regarding the validation of these models is unavailable in the public domain.

3.4.3.1.2 Natural Gas

Models and software packages used to quantify the life safety consequence resulting from a natural gas release are summarized below:

- *PIPESAFE*: IGEM/TD/2 (IGEM 2013) references the software package PIPESAFE as one of the preferred models for estimating the life safety consequences associated with a natural gas pipeline failure. This model considers the gas outflow and dispersion, the thermal radiation from the initial fireball and the ensuing quasi steady-state fire, and the thermal effects on exposed people. Acton et al. (1998) provides an overview of the development of the mathematical models underlying the software package. Acton et al. (2002) also reports software updates related to the ignition probability, crater source conditions, fire models and thermal radiation effects. A more recent update to the ignition probability model was reported by Acton and Baldwin (2008). Sutherby et al. (2000) used PIPESAFE as a tool for life safety consequence assessments, while Tomic et al. (2014) used it to estimate life safety consequences as part of a system-wide risk assessment.

- *PIR Model*: Stephens et al. (2002) proposed a simplified model to estimate the size of the area within which human safety can be impacted due to a natural gas release. This model estimates the potential impact radius (PIR), which is defined as the distance from the fire source at which the heat dosage results in a 1% chance of mortality. Rothwell and Stephens (2006) benchmarked this model against the predictions of the PIPESAFE software package by comparing outflow rate, thermal radiation, and societal risk estimates. The PIR model was shown to agree with the PIPESAFE predictions for societal risk. Tomic and Kariyawasam (2014) compared the impact radius predictions (based on 1% lethality) from both models to the San Bruno pipeline explosion event. The estimates obtained from both models were shown to be comparable to the actual damage zone.

- *PHAST*: Pettitt et al. (2014) compared the expected number of injuries and fatalities predicted by the consequence modelling program DNV PHAST with the incident data from the Appomattax pipeline rupture and the San Bruno pipeline explosion. The thermal radiation zones estimated by the model were comparable to those observed in both incidents, while the expected number of fatalities estimated from the model were highly conservative due to conservative assumptions regarding building occupancy rate and the duration of exposure to thermal radiation.

Jo and Ahn (2005), Jonkman et al. (2006), Francis et al. (2006), and Kraus (2015) have also proposed simplified analytical approaches to estimate life safety consequences due to the release of natural gas from a single pipeline rupture location.

3.4.3.1.3 Flammable Liquids

Models to quantify life safety consequences due to the release of flammable liquids are typically developed as part of proprietary software packages and are not described in detail in public domain. Applications of some of the available commercial software packages are summarized below:

- To model the consequence of a gasoline release, Dawotala (2012) employed the CANARY software to estimate thermal radiation from pool fires and overpressure due to VCE.
- Sun et al. (2015) and Jujuly et al. (2015) used computational fluid dynamics (CFD) to model pool fires arising from the release of liquefied natural gas (LNG).
- Dziubinski et al. (2006) estimated the life safety consequences associated with the failure of fuel pipelines carrying gasoline and diesel oil. DNV PHAST software was employed to evaluate the thermal radiation due to pool fires and the blast wave hazard zones associated with a potential explosion.

3.4.3.2 Environmental Impact

Environmental impact is determined by the release volume, the sensitivity of the affected habitat to the released product type, the time to habitat recovery and the socio-economic importance of the habitat. Therefore, detailed models to quantify the environmental impact of spills require approaches to estimate release volume, spill trajectories, potential for surface water and ground water contamination, the potential for the spill reaching an environmentally sensitive area, spill clean-up effectiveness, and time to habitat recovery.

The following publications discussed the factors to consider in the context of environmental consequence quantification:

- Perez et al. (2014) included explicit consideration of drinking water resources, ecologically-sensitive areas, commercially navigable waterways, and water crossings.

- Chang et al. (2014) proposed a framework that considers the short-term and long-term ecological and societal impact due to an oil spill.

It is noted that the most detailed environmental models have been developed in the context of regulatory applications submitted in connection with large pipeline projects and not in the context of QRA. The following publications discussed detailed modelling approaches to quantify environmental impact:

- Zuczek et al. (2006) demonstrated the application of a digital elevation model to predict overland oil spill trajectories.
- Worley Parsons (2012) conducted a detailed risk assessment for the Northern Gateway Pipelines project. The assessment used a model called "OILMAP Land" that determines the spill trajectories on land based on the steepest descent path as obtained from a digital elevation model. The velocity of spill flow in water was determined by the speed and direction of surface currents.
- Green et al. (2015) provided a summary of the approach used to assess the ecological and human health risks associated with a hypothetical oil spill from the proposed Northern Gateway Pipeline. In addition to the spill trajectory modelling, the framework considered the behaviour of hydrocarbons in water, and the acute and choric effects of the spill on ecological and human receptors.
- Humber et al. (2012) quantified the potential impact due to an oil spill through detailed fate (i.e. natural degradation of hydrocarbons in the environment) and transport (i.e. pathways for oil movement) modelling for Trans-Northern Pipelines. The modelling included spill volumes; overland spill trajectories including the effects of terrain, barriers and conduits; and risk receptor identification.
- Bonvicini et al. (2015) defined the environmental damage due to an oil spill in terms of the expected clean-up and remediation costs, as well as the contaminated soil and ground water volumes. The "Hydrocarbon Spill Screening Model" (HSSM) developed by the U.S. Environmental Protection Agency (EPA) was used to estimate the extent of contamination. Numerical models based on the finite element method (such as 2D/3DFATMIC, NAPL Simulator) and the finite difference method (such as UTCHEM) were listed as widely applied general-purpose models for simulating the fate and transport of contaminants.
- A supplemental environmental impact study for the proposed Keystone XL Pipeline (DOS 2014, Appendix T) used the HSSM model to estimate the potential for ground water contamination due to an oil spill. The same document (DOS 2014, Appendix P) also included a detailed environmental risk assessment that considers the impact on soil, vegetation, wildlife and water resources, where water resources included ground water, flowing surface waters, aquatic organisms, wetlands/reservoirs and lakes.

Simplified models that quantify the environmental impact include the following:

- Nessim et al. (2014) proposed a simplified model that considers the release volumes and a modifier that adjusts the volume based on the sensitivity of the spill area, which was defined based on the "high consequence area" definition developed by PHMSA (49 CFR Part 195 – Sections 195.450 and 195.6, PHMSA 2011).
- Etkin (2004) described a simplified model to measure the environmental effects of an oil spill in waterbodies, expressed in terms of dollar amounts.

Despite the range of models available to quantify environmental damage, a standardized consequence measure is not available in the literature. In quantitative risk analyses, environmental damage is often characterized by the cost of remediation. Secondary socio-economic effects are often not included. Detailed environmental impact assessments such as those for the Northern Gateway Pipelines project and the Keystone XL project were conducted for the purposes of route selection and regulatory applications. While such detailed environmental impact assessments are not typically carried out as part of quantitative risk analyses intended to support integrity management decisions, they provide useful information that can guide the development of QRA models.

3.4.3.3 Financial Impact

Models to estimate financial impact are not generally available in the public domain. Examples of the failure cost components cited in the literature include:

- product loss, repair cost, and shutdown cost (Martinez and Rodriguez 2000, Mangold et al. 2014);
- costs due to customer impact, public perception and reputation damage, cost of increased regulatory oversight (i.e. other than cost to implement immediate risk reduction measures) and cost to restore operational confidence (Sutherby et al. 2000, Wickenhauser and Playdon 2004, Solis et al. 2014);
- impact on adjacent property, lost revenue and fatality compensation (Wickenhauser and Playdon 2004); and
- clean-up costs (Mangold et al. 2014).

The review indicated that there is no consistency regarding the factors considered in calculating the cost of failure. This is likely due to the fact that the cost components and the methodologies used to estimate them are highly situation-dependent.

3.5 Summary and Conclusions

A review of published literature in the pipeline industry indicates that quantitative risk methods are used extensively. For failure frequency, the review shows that established models exist for key threats including corrosion and mechanical damage. Such models are also incorporated into codes and standards in Europe and Canada (e.g. BSI 2013, CSA 2015, IGEM 2013, and NORSOK 2010). Since engineering and probabilistic models are less established or unavailable for some threats (such as geohazards, incorrect operations, or manufacturing defects) these threats are incorporated into quantitative risk assessments through SME opinion and historical data.

With respect to safety-related consequences, several validated models exist for natural gas releases. For non-volatile LVP liquids, life safety impact is limited due to the low probability of ignition. For volatile LVP liquids, extensive guidelines and specialized software packages are available to quantify life safety consequences due to pool fires. For HVP liquids, specialized software packages are typically adopted from the process industry to quantify life safety consequences. However, there is no industry-wide consensus on the use of consequence models for vapour cloud explosions and pool fires.

Environmental consequences are quantified in terms of the cost of spill clean-up in most of the literature. Most environmental consequence models are proprietary and are not described in detail in the references reviewed. Detailed models for the estimation of environmental impact are typically only used for risk assessments submitted to regulators in connection with large proposed pipeline projects.

Financial consequences are typically characterized by the total cost of failure. Since costs are highly situation-dependent, there are no general models to calculate costs or even a standardized list of the cost components to consider.

In summary, quantitative risk models are available and widely used for natural gas pipelines which constitute 61% of all transmission pipelines in the US. For liquid pipelines, which constitute 38% of pipeline mileage in the US, specialized models and software packages are used to quantify safety and environmental consequences. However, all the specialized software packages are proprietary and validation studies are not available in the public domain. The remaining 1% of the pipelines with other products (e.g. CO2) are beyond the scope of this study.

4. LITERATURE REVIEW - OTHER INDUSTRIES

4.1 Introduction

Industries other than the pipeline industry that were considered in the literature review are:

- nuclear;
- offshore;
- aviation; and
- power transmission.

The literature review of these industries focused on QRA guideline documents describing industry-wide consensus and selected publications from the database searches referred to in Section 3.1. A total of 32 publications were reviewed; eleven in the nuclear industry, eight in the offshore industry, five in the aviation industry and eight in the power transmission industry. The key findings of the literature review are summarized in this section; a summary of each publication reviewed is included in Appendix E.

4.2 Nuclear Industry

4.2.1 Overview of the Risk Assessment Approach

Publications from the U.S. Nuclear Regulatory Commission (NRC) are the key industry guideline documents on QRA methodology. The NRC uses a "probabilistic risk assessment" (PRA) methodology to quantify the frequencies of failures and the associated consequences (NRC 2016a). The PRA methodology includes the following steps:

- Specify the hazards to be prevented or reduced. In the case of nuclear power plants, the hazards include damage to the reactor core and the potential release of radioactive material into the environment.
- Identify the initiating events that could lead to specific hazards. The initiating events are either "internal events", such as power system failure, piping rupture, or "external events", such as earthquakes, floods, and hurricanes.
- Estimate the frequency of occurrence of the initiating events.

The following techniques are used in the PRA process:

- An initiating event is used as a basis for developing an event-tree that models the logical paths from the initiating event to different hazard scenarios, such as damage to the fuel cladding in the reactor core. Event tree branches are defined based on the success or failure of mitigation factors that can prevent the hazards. Mitigation factors are categorized either as hardware and engineering systems or as human factors.
- Fault-tree methods are used to estimate the probability of failure of hardware and engineering systems. For nuclear power plants, fault-trees that model plant-specific sub-system failures are integrated into an event-tree to estimate the overall probability of plant failure.
- Human reliability analysis (HRA) is used to estimate the probability of human errors that can lead to system failure. Swain and Guttmann (1983) describe a detailed approach for HRA in a handbook focused on nuclear power plant applications. Other HRA methods are discussed in Section 4.2.2.
- In addition to fault-tree and HRA methods, PRA may include standard structural reliability methods such as Monte Carlo simulation or Latin hypercube sampling to estimate the probability of basic events in the fault-tree models and the initiating events of the event trees. However, these methods are not part of the basic components of PRA as outlined by the NRC.

Figure 4.1, which is adapted from NRC (NRC 2016b), shows a generic PRA example.

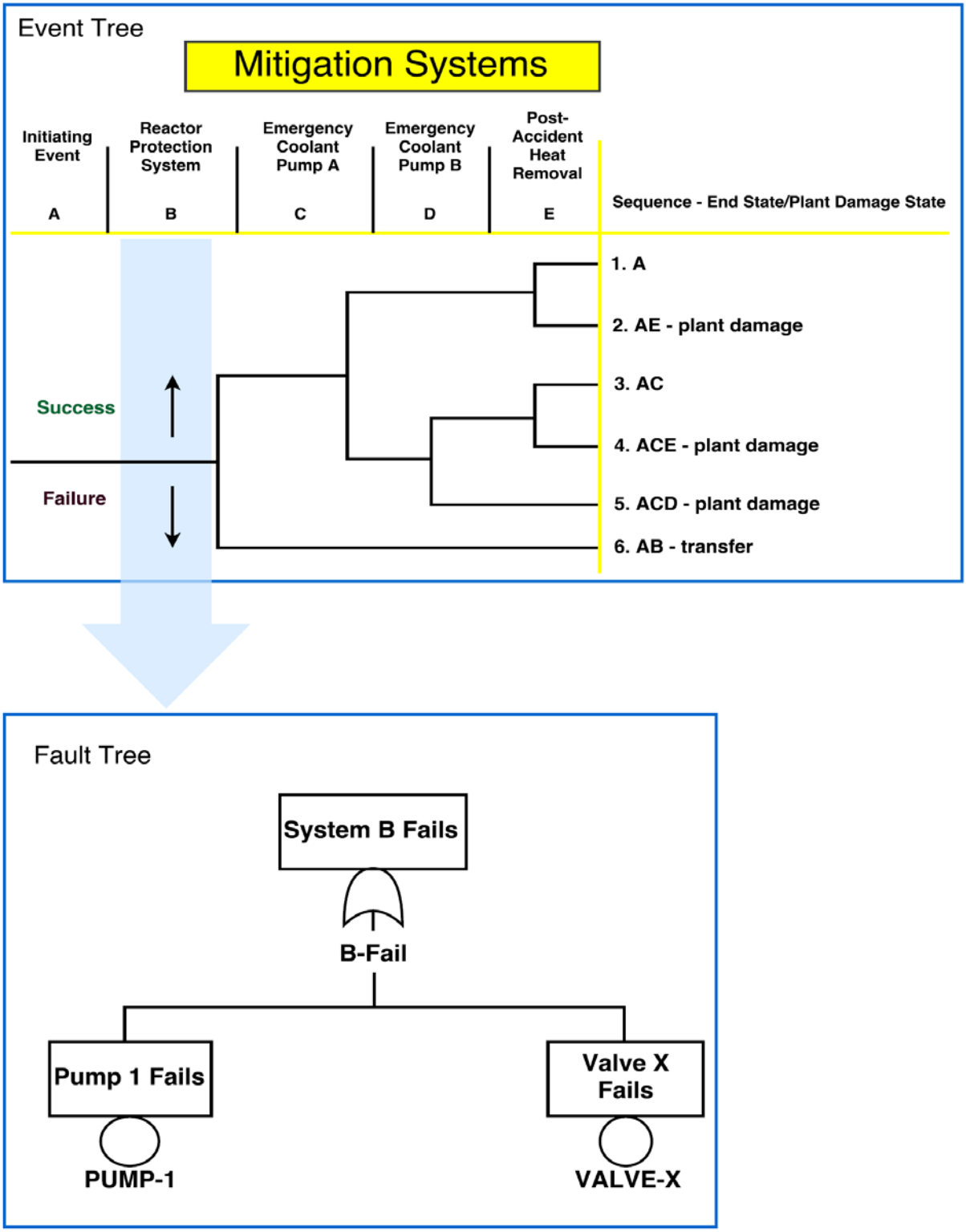

Figure 4.1 Example of a PRA Process

4.2.2 Risk Assessment Guidelines

4.2.2.1 Types of Risk Assessments

The NRC defines three levels of analysis for PRAs. These levels represent intermediate steps required for a full quantitative risk assessment and are different from the levels discussed in Section 5.4.2. These levels are:

- Level 1 PRA: At this level, only the probability of reactor core damage is estimated. All protective and accident mitigation systems are assumed to be active and the conditions leading to the initiating event are well-understood. Level 1 PRAs have relatively small uncertainties because well-established models and methods are used to perform each step of the analysis. Krall et al. (2014) report a detailed methodology to apply Level 1 PRA to nuclear power plants.
- Level 2 PRA: At this level, the core damage is assumed to have occurred and the risk of radioactive material release into the environment is estimated. The quantity of radioactive material released and the speed with which the release occurs are calculated. Uncertainties in the release rate from coolant pipes and the response of the reactor's containment structure contribute to the overall uncertainty in the estimated risk. Therefore, Level 2 PRA results are considered less precise than Level 1 results.
- Level 3 PRA: At this level, the consequences of the release event are addressed. Health effects and economic losses due to the release of radioactive material to the environment are quantified. Level 3 PRAs are considered to be the least precise of the three levels due to the additional uncertainties in the environmental conditions at the time of release.

Each PRA level is evaluated against an acceptance criterion. The hierarchical nature of the risk acceptance criteria and the requirement for different criteria to evaluate system safety and define consequence reduction measures are discussed in Mitra et al. (1981). The NRC report by Mitra et al. (1981) also provides a more detailed discussion of the data requirements and uncertainties associated with the PRA levels.

The NRC assesses only the consequences associated with the health of the population. The consequences resulting from the Fukushima accident in 2011 have highlighted the importance of considering the costs associated with socio-economic and environmental effects. Silva et al. (2014) include these effects and provide a consequence severity index based on the total costs of failure.

4.2.2.2 Selected Components of Risk Assessments

The NRC has used PRAs since the 1970s and several PRA techniques have been updated as described in more recent NRC reports. The following PRA techniques are applicable to QRA processes used in the pipeline industry:

- *SME opinion*: Boring et al. (2005) provided detailed guidelines for the elicitation of expert judgement to estimate equipment failure rates, human error occurrence rates and equipment operability. While the specific worksheets provided in the report are intended for nuclear power plant assessments, the structured approach proposed for eliciting SME opinion is adaptable to the pipeline industry. The steps involved in this approach are:

  1. framing the problem;
  2. identifying SMEs;
  3. soliciting opinion from each SME in written form;
  4. convening the expert panel;
  5. aggregating the responses from all SMEs; and
  6. defining the final result required for the QRA.

- *Uncertainties*: Drouin et al. (2009) provided detailed methodologies to address the uncertainties arising from lack of knowledge. Knowledge uncertainties can be reduced by acquiring new information, whereas uncertainties due to inherent randomness cannot be reduced. Knowledge uncertainties are associated with input parameters, model formats (e.g. determining if a term in the mathematical model is additive or multiplicative), and missing model components (e.g. missing terms of a mathematical function, missing fault-tree models for plant sub-systems). The methods provided by Drouin et al. (2009) are intended to reduce uncertainty, identify the impact of uncertainty on the risk result and propagate the uncertainty within the model (e.g. explicitly represent the uncertainty in basic event probabilities by using a range of values in the probability computations).

- *Probabilistic models*: Khaleel and Simonen (2009) evaluated weld flaw failures and the effectiveness of in-service inspection programs in preventing them. They describe probabilistic approaches to determine flaw depth distributions in the absence of in-service inspections, fatigue crack growth rates, the probability of flaw detection, flaw-sizing errors, and the impact of flaw-acceptance criteria on the distribution of remaining flaws for both weld flaws and stress-corrosion cracking. Elements of the report that are useful for pipeline QRA include the failure mode definitions, the knowledge uncertainties in input parameter probability distributions and the influence of knowledge uncertainty on the estimated failure probabilities.

- *Human reliability methods*: After the Three Mile Island incident, human error was identified as a significant contributor to failures (NRC 2013). Efforts to address the probability of occurrence of human error resulted in the development of the 'Technique for Human Error Rate Prediction' (THERP) documented in the report by Swain and Guttmann (1983). Kirwan (1996, 1997) and Kirwan et al. (1997) used historical data to validate the THERP process, as well as the 'Human Error Assessment and Reduction Technique' (HEART) and the 'Justification of Human Error Data Information' (JHEDI) approaches. The validation has

shown a high correlation between the estimated and historical occurrence probabilities with 72% of all estimated probabilities being within a factor of 10 of the historical rates. These techniques can be used in a pipeline QRA to estimate the role of human error in pipeline failures.

4.2.3 Key Learnings

The key learnings from the review of probabilistic risk assessment methods in the nuclear industry are as follows:

- Uncertainty in the QRA can be addressed by using more conservative acceptance criteria for results that involve a higher degree of uncertainty. For example, less conservative probabilistic acceptance criteria can be used for components with well-defined failure modes and recognized failure probability calculation models, whereas more conservative risk acceptance criteria need to be used if large uncertainties are associated with the consequence models used to estimate risk from the failure probabilities.
- Formal methods, such as those provided by Drouin et al. (2009), can be used to address knowledge uncertainties and incorporate their influence into the decision-making process.
- The standardization of models and analysis approaches is possible for selected threats with well-understood failure modes.
- The development of industry-wide consensus models promotes consistency in risk-based decision-making as the risk estimates will be comparable for different systems. Even though the total model uncertainty may not change, an industry-wide consensus can facilitate the development of acceptable risk benchmarks.
- The QRA process itself offers valuable insights into system behaviour, even if the data is insufficient and large uncertainties are present.

4.3 Offshore Industry

4.3.1 Risk Assessment Guidelines

Offshore oil and gas industry references reviewed included risk assessment guidance notes published by the American Bureau of Shipping (ABS 2000) and marine risk assessment guidelines prepared by DNV for the U.K. Health and Safety Executive (HSE) (DNV 2001). The HSE information on risk assessment for offshore installations (HSE 2006) was also reviewed for its treatment of uncertainty in QRAs. British Standard (BSI 2002) for risk assessment of offshore installations was not included in the detailed review because it is similar to the other guidelines mentioned above.

Marine Risk Assessment Guidelines (DNV 2001)

These guidelines are focused on the selection of an appropriate risk assessment approach (i.e. qualitative, semi-quantitative or quantitative) based on the following:

- Lifecycle stage: The lifecycle stage (e.g. feasibility study, front-end design, detailed design, operation, and abandonment) determines the available information (e.g. design parameters versus historical and operational data) and the decisions that can be made (e.g. design parameters cannot be changed during operations). In addition, the type and quality of information related to design and operational details influences the selection of the risk assessment approach.
- Hazard potential: The potential for high consequence events influences the degree of rigour required in the selected risk assessment process.
- Decision context: A decision context with higher elements of novelty, uncertainty or stakeholder concern requires greater detail. The risk-related decision support framework adopted by UKOOA (1999) is shown in Figure 4.2 . This framework indicates that a typical QRA is most relevant for lifecycle assessments, deviations from standards or best practices, and significant economic implications.

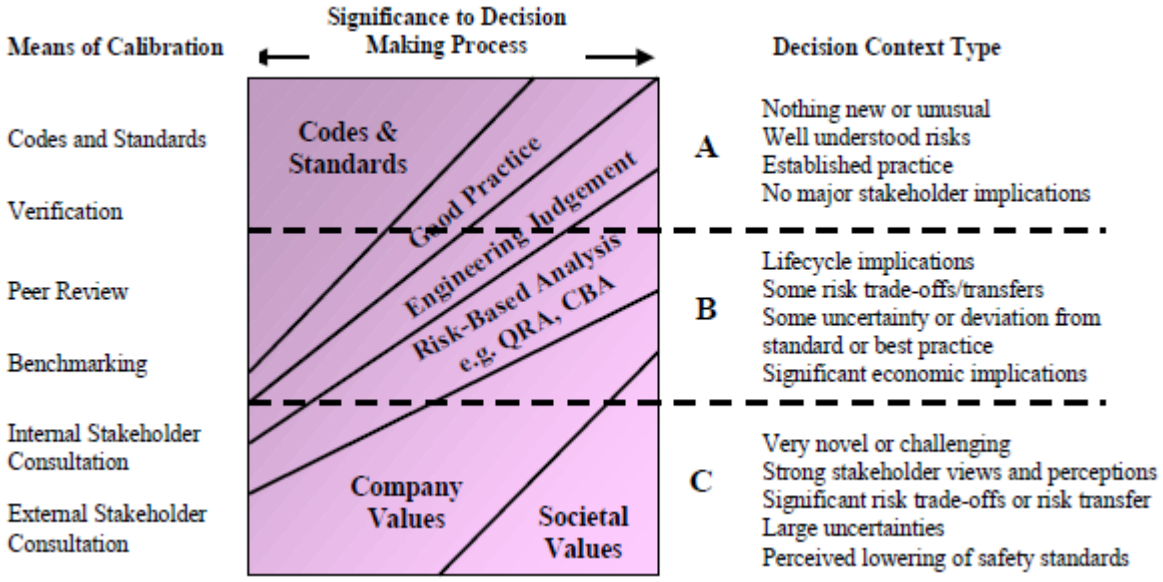

Figure 4.2 Risk-Related Decision Support Framework (UKOOA 1999)

The marine risk assessment guidelines also describe a range of methods covering the following components:

- Hazard identification:

  - the HAZID technique;
  - HAZOP – Hazard and Operability Study;
  - FMEA – Failure Modes and Effects Analysis;
  - SWIFT – Structured What-If Checklist Technique; and
  - influence diagrams;
- Risk estimation approach:
  - qualitative;
  - semi-quantitative; or
  - quantitative;
- Human element:
  - human errors (i.e. type of errors possible while performing a task);
  - human factors assessments (i.e. potential for the occurrence of human errors); and
  - formal human reliability analysis (i.e. estimation of the probability of human error).

Based on the lifecycle stage, hazard potential and decision context, the document provides several worked-out examples for the selection of the hazard identification techniques, risk estimation approaches and decision-making process.

Guidance Notes on Risk Assessment Applications for the Marine and Offshore Oil and Gas Industries (ABS 2000)

The guidance notes cover the following:

- Risk assessment methods: An overview of the risk assessment process adopted in the guidelines is shown in Figure 4.3. The process includes hazard identification, frequency and consequence assessment, and estimation of risk. A list of methods and the details of their application are provided for each element of the risk assessment process. These are discussed in more detail in Section 4.3.2.
- Conducting a risk assessment: the steps required to conduct a risk assessment include defining the study objective and scope, selecting the technical approach and estimating the resources available. Risk assessments are categorized based on the level of detail, certainty and cost. The key factors in selecting the appropriate method are identified as:
  - motivation for analysis;

- types of results needed;
- type of information available;
- complexity and size of analysis;
- type of activity or system; and
- type of loss event targeted.

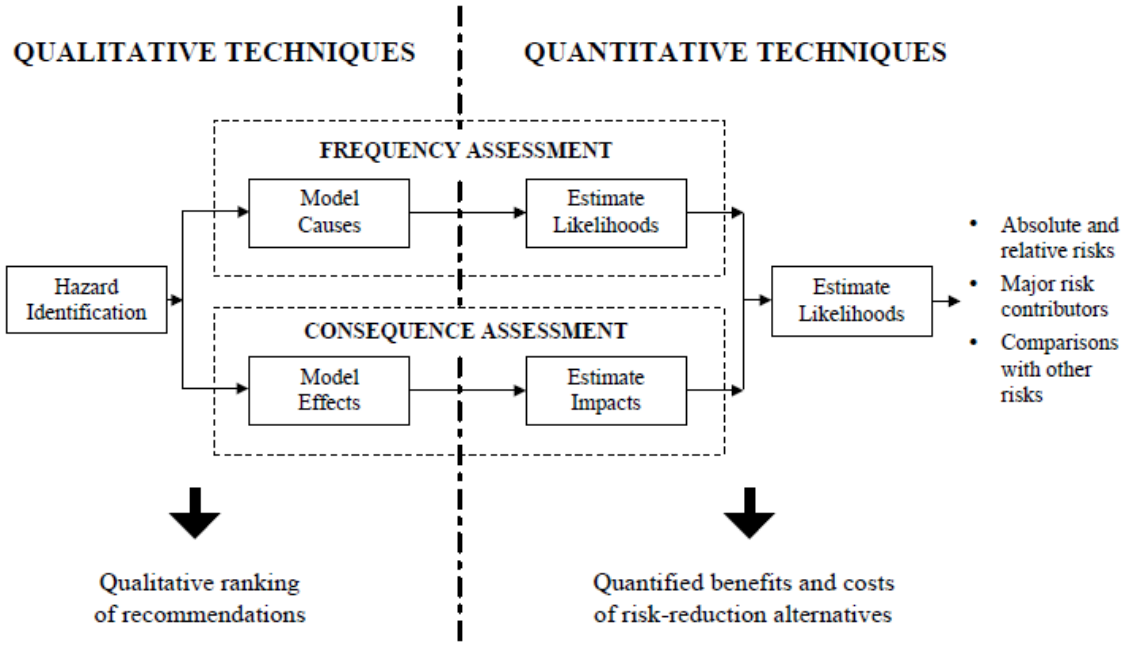

Figure 4.3 Overview of the Risk Assessment Process (ABS 2000)

Guidance on Risk Assessment for Offshore Installations (HSE 2006)

The HSE information sheet provides guidance on the following risk assessment elements:

- legal background;
- approaches to risk assessment;
- the risk assessment process; and
- documentation.

Similar to the DNV (2001) guidelines, the guidance report addresses the types of risk assessment approaches, the factors to consider in the selection of an approach, and the available techniques to estimate the frequency and consequence of failure. In addition, the sources of uncertainty in the

risk assessment process are identified in the blue boxes in Figure 4.4. The yellow boxes in Figure 4.4 illustrate the process, which involves identification of the failure event and quantification of likelihood and consequences. The guideline recommends conducting a sensitivity analysis to quantify the influence of uncertainty on the final risk estimate.

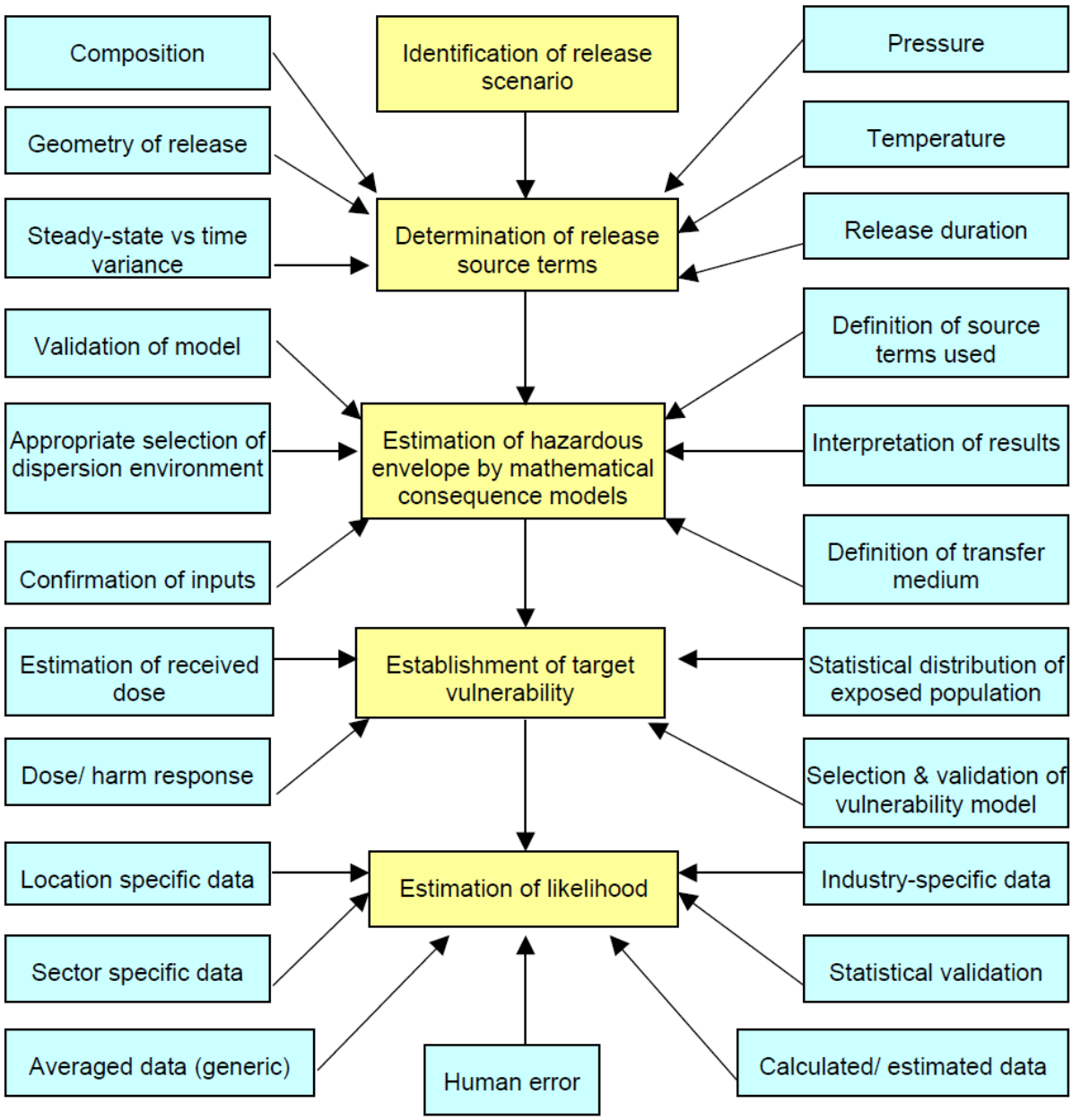

Figure 4.4 Sources of Risk Assessment Uncertainty (HSE 2006)

4.3.2 Risk Assessment Techniques

The guidelines reviewed summarize a wide range of risk assessment approaches, from qualitative to quantitative. Techniques relevant to the pipeline QRA process are summarized below:

- *Analysis of historical data*: ABS (2000) recommends that an analyst using historical data for frequency estimation should consider the source of the data, the statistical quality of the data such as sample size, the reporting accuracy, and the relevance of the data to the event under consideration. Example applications of historical data analysis for offshore marine accidents are provided in DNV (2001).

- *Fault tree analysis*: This is considered to be a powerful and widely used technique (DNV 2001). Its main limitation is the assumption of independence between basic events which can lead to common cause failures being overlooked. ABS (2000) recommends this technique for analyzing system failures caused by a complex combination of events.

- *Event tree analysis*: DNV (2001) and ABS (2000) recommend this approach to analyze failure sequences following an initiating event. Similar to fault tree analysis, the assumption of independence between sequences of events may result in an underestimation of risk.

- *Bow-tie analysis*: A bow-tie analysis is typically a combined fault-tree and event-tree analysis with all the initiating events that lead to a release event on one side and all the potential hazard scenarios resulting from the release on the other side. Elements preventing the release are also called “prevention/control barriers” and those that reduce the consequences are called “mitigating barriers”. The barriers are also referred to as “layers of protection” or “lines of defence”. HSE (2006) recommended this approach to assess the occurrence frequencies of hazardous events.

- *Human reliability analysis*: In this approach, expert opinion regarding human factors is used to estimate the probability of occurrence of human errors during a particular task. ABS (2000) recommends this approach to assess the frequency of human errors. DNV (2001) also uses human reliability analysis, however, it is identified only as a part of the overall methodology for addressing the risk due to the human element, which includes types of human errors and external factors (e.g. machine interfaces) that increase the human error rate.

- *Common cause failure analysis*: ABS (2000) recommends this approach for examining the sequence of events proceeding from multiple incidents arising from the same root cause. SME opinion is employed to develop the probability of failure for each event conditional on the common cause.

In addition to the methods identified in the industry guidelines listed above, the literature includes the following approaches:

- *Structural reliability methods*: For offshore pipeline maintenance, Nessim et al. (2000) used the structural reliability method, in which the probability of failure is estimated based on the probability distributions of the load effect and the resistance of a pipeline. Aljaroudi et al. (2015), applied structural reliability methods to a case study of an offshore pipeline to assess the corrosion threat as part of a QRA.
- *Other approaches*: The recommended practice for 'Risk Assessment of Pipeline Protection' due to accidental external events (DNV 2010) describes a conditional probability approach for the quantification of failure frequency due to dropped objects. The conditional probabilities include the frequency of a dropped object, the hit frequency conditional on an object being dropped, the impact energy conditional on a hit, and pipeline integrity conditional on the impact energy and object shape. Wu et al. (2015) employed a Bayesian Network to assess the risk of project failure due to the inability to lay the pipe in an offshore pipe laying project. Xu et al. (2012) presented a quantitative consequence model for marine oil spills that determines spill behaviour based on ocean hydrodynamics, spill trajectory and oil degradation.

4.3.3 Key Learnings

The key learnings from the offshore industry's guidelines on risk assessment are as follows:

- QRA is effective for decision-making when the uncertainties can be well characterized. When significant knowledge uncertainties influence the QRA, hidden or unknown risks may become a large portion of the total risk. In such circumstances, QRA can be less effective.
- Structured threat identification approaches are required for complex systems. These approaches can be either qualitative based on checklists and walk-throughs, or quantitative based on the analysis of data on incidents, near-misses, and operational parameters.
- The selection of an appropriate level of analysis depends on the assessment objectives. Offshore guidelines emphasize the use of QRA throughout the life cycle of the facility as a basis for cost-benefit analysis and decision-making involving economic trade-offs. For novel and challenging projects, decisions based on stakeholder consultations were recommended instead.

4.4 Aviation Industry

4.4.1 Risk Assessment Guidelines

Risk analysis guidelines in the aviation industry are focused on operational safety and aircraft structural integrity. Guidelines on operational safety, which refers to flight safety against risks

associated with operational errors, address hazard identification, risk assessment, and risk mitigation measures for aircraft carriers, air traffic service providers and aerodrome operators. The guidelines from the 'Global Aviation Information Network' (GAIN 2003), 'Civil Aviation Authority' (CAA) in the UK (CAA 2010), and Martinez-Guridi and Samanta (2002) are the primary sources of information related to the assessment of risk associated with operational factors (see Section 4.4.2).

Guidelines for aircraft structural integrity are focused on estimation of the failure frequency for aircraft components. This source of risk is addressed in Section 4.4.3 based primarily on a review by Tong (2001) of aircraft structural risk and reliability with respect to fatigue crack growth and corrosion.

4.4.2 Operational Safety Risk Assessment

4.4.2.1 Hazard Identification

The guidelines on operational safety emphasize hazard identification because of the complexity of aviation systems and the interdependence between elements, e.g. hardware systems, software, personnel, the operating environment, and human-machine interfaces.

Data collection is a part of the operational process in the aviation industry, and hazard identification is primarily based on the data collected during operations (e.g. flight operations, ground operations, and airport facility operations) and the data obtained from maintenance reports. GAIN (2003) provides guidance on data collection and analysis in four categories:

- flight safety event reporting and analysis systems;
- flight data monitoring, analysis and visualization tools;
- human factor analysis tools; and
- special purpose analytical tools for accident investigation, data mining, and risk analysis.

The use of air-carrier operational data for hazard identification is also emphasized in the report for the Federal Aviation Authority (FAA) by Martinez-Guridi and Samanta (2002). The importance of operational data for hazard identification is well-recognized by FAA (Martinez-Guridi and Samanta 2002) and EASA (Cacciabue et al. 2015) and therefore, standardized data-collection processes and software systems have been developed for industry-wide data collection and sharing.

The 'Civil Aviation Authority' (CAA) in the UK (CAA 2010) recommends maintaining a 'hazard log' to record all potential hazards identified through formal and informal methods such as historical incident reports, brainstorming, failure modes and effects criticality analyses (FMECA), and hazard and operability studies (HAZOP).

4.4.2.2 Risk Assessment Approach

The risk assessment approach described by the CAA (CAA 2010) is based on a qualitative assessment of the likelihood of failure and the failure consequences. The guidelines in GAIN (2003) and the report by Martinez-Guridi and Samanta (2002) recommend risk assessment software packages specific to the aviation industry that interact directly with flight safety data collection systems. The risk assessment techniques include fault-tree analysis, event-tree analysis, bow-tie analysis and common cause analysis methods (see Section 4.3.2 for an explanation of these methods).

Cacciabue et al. (2015) presents a comprehensive risk assessment methodology that uses data collected from the safety management system of the European Aviation Safety Agency (EASA). In this report, 11 different factors that affect the severity of an incident were identified. These include direct effects such as life safety (e.g. number of fatalities, permanent impairments, and serious but non-permanent injuries), damage to property, and loss or damage to critical equipment; indirect effects such as public perception, customer impact due to flight delays or cancellations, operational impact due to grounding of aircraft, service disruption over extended periods, and know-how loss (due to loss of either critical equipment or personnel); and factors that increase the direct and indirect effects such as, process breach during flight operations, and absence of safety awareness among personnel.

All of the guidelines consider the influence of human factors on operational flight safety risk and provide guidance for assessing their influence based on either operational data or expert judgement.

4.4.3 Aircraft Structural Integrity Risk Assessment

Tong (2001) used structural reliability methods to estimate the risks associated with aircraft failure due to fatigue crack growth in the welds and corrosion. The report addresses:

- *Interpretation of the probability of failure*: Within the report, failure frequency and the probability of failure are used interchangeably as the associated failure frequencies are small. As fatigue crack growth is a time-dependent process, the probability of failure was expressed in two ways: 1) as a cumulative probability of failure over a duration of interest, and 2) as an average probability of failure within a specified time period (termed “instantaneous” failure), which is calculated as the rate of change in the cumulative probability of failure. The report recommends estimating the average probability of failure as a ‘failure rate per hour of flight’, and suggests a maximum failure rate in the order of 10^{-7} per flight hour.
- *Modelling uncertainty*: Probability distributions are defined for the following input parameters:
    - material properties;

- initial fatigue susceptibility of the component (i.e. initial crack size distribution and time to fatigue crack growth initiation);
- crack growth rate; and
- reliability of inspection.

The reliability of non-destructive inspection is represented by the probability of detection as a function of crack depth and minimum detectable crack depth. Following the inspection, unacceptable cracks are assumed to be repaired and variability in the quality of repair is accounted for by modelling the distribution of cracks introduced during re-welding.

- *Reliability techniques*: Reliability techniques used to estimate the failure probability due to fatigue crack growth include the strength-load interference method, the conditional probability technique, the Monte-Carlo simulation and the first- and second-order reliability methods (FORM/SORM).

4.4.4 Key Learnings

Key learnings from the aviation industry's guidelines on risk assessment are as follows:

- Hazard identification is the most challenging element of operational risk assessments, whereas quantifying input parameter and model uncertainty is the most challenging element of integrity risk assessments. Standardization of input parameter distribution types and guidelines for characterizing model uncertainties are useful for the application of QRA methods to integrity assessments.
- Industry-wide standardization of data formats allows for data consolidation, sharing and improved data analysis, which can facilitate many aspects of the risk assessment process, including hazard identification. All operational safety risk assessment guidelines reviewed (e.g. GAIN 2003, Martinez-Guridi and Samanta 2002) emphasize this aspect and provide common formats and tools for data collection.
- The airline industry incorporates data collection into operational processes rather than treating it as a separate activity. This approach reduces the effort required for data collection during QRA.

4.5 Power Transmission Industry

4.5.1 Risk Assessment Guidelines

The primary risk associated with power transmission systems is the risk of loss of service. Loss of service can be caused by either structural component failures or operational factors, such as a system failure due to unknown interdependencies between processes and components. For

example, the 2003 blackout in North America occurred due to the failure of an overloaded power transmission line, which triggered a system-wide failure. In that instance, unknown interdependencies between a component failure and system failure led to a system-wide failure. Such a failure could have been avoided if the isolation of failed local components from the system was a part of the operational process.

The risk assessment guidelines developed by the risk assessment working group (RAWG 2005) for the North American Electric Reliability Council were reviewed. These guidelines address qualitative, semi-quantitative, and quantitative risk assessment approaches. The steps involved in the risk assessment process are given as follows:

- identify and characterize the assets;
- identify and characterize the threats;
- identify and characterize the existing protective and mitigation factors;
- identify and characterize the vulnerabilities;
- estimate the probabilities of failure and consequences of failure; and
- estimate and evaluate the risk.

Guidance is provided for the following key elements of the risk assessment framework:

- defining the scope and objectives;
- selecting a risk assessment team;
- gaining the cooperation of stakeholders and information providers;
- defining the assets;
- characterizing the threats, protective and mitigation measures, vulnerabilities, and probabilities and consequences of failure;
- presenting and documenting the risk information; and
- conducting a peer review of the risk results.

4.5.2 Risk Modelling Approaches

Figure 4.5 shows the conceptual risk modeling framework in the North American Electric Reliability Corporation (NERC) white paper (NERC 2010) on risk assessment methods for power systems. The recommended model is dependent on the event severity, e.g.:

- QRA approaches are recommended for high frequency and low consequence events as a means of evaluating the cost-benefit associated with different risk management actions.
- Scenario analysis (i.e. deterministic what-if scenarios) and extreme value theory models are recommended for low frequency and high consequence events.

The white paper also emphasized the importance of developing risk measures that are based on measurable data. A composite measure to estimate the event severity was proposed, which considers the duration of the event, the amount of power demand lost, the number of system components that are out-of-service, and the damage state of transmission facilities.

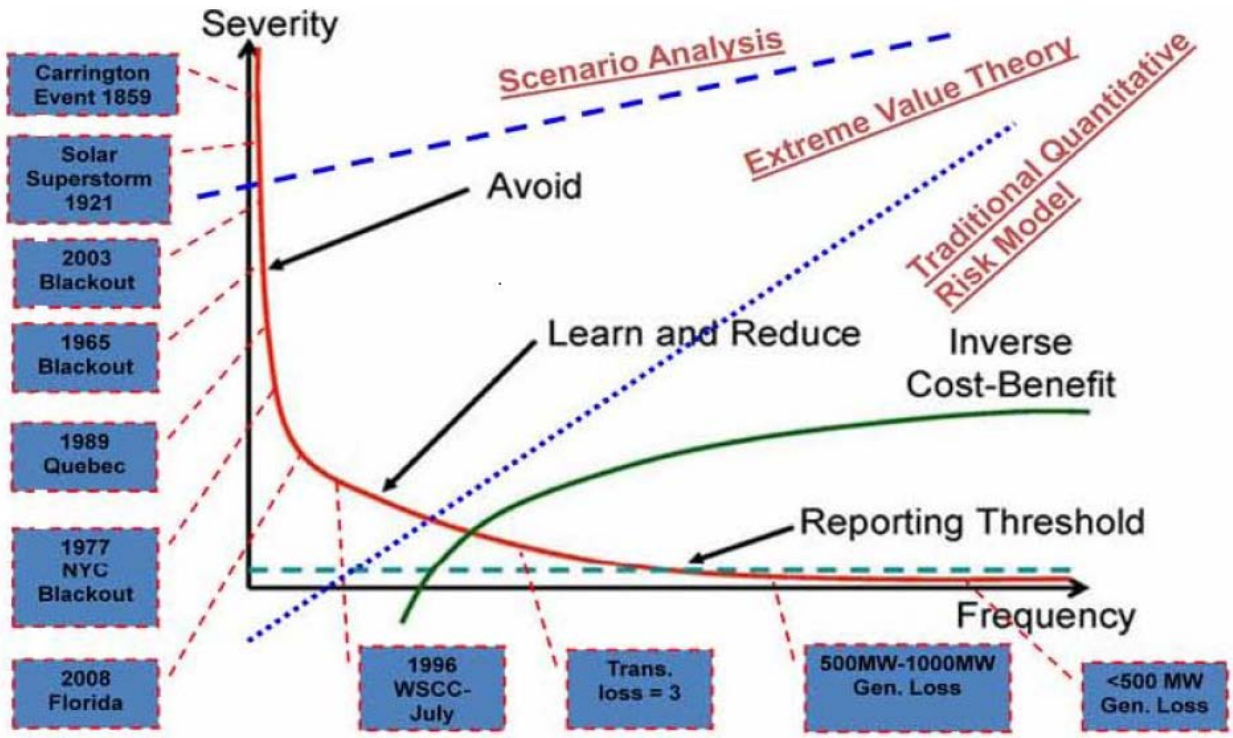

Figure 4.5 Risk Modelling Approaches Based on Event Severity (NERC 2010)

The risk of service loss associated with the loss of system connectivity is addressed using probabilistic and statistical methods, e.g.:

- Hong and Lee (2009) used a fault-tree approach to quantify the reliability of the components and estimated the risk of system failure caused by component outages;
- Dunn et al. (2015) used historical data to develop vulnerability curves to assess the risk of electric supply failure associated with component failures under extreme winds;
- Winkler et al. (2010), Dueñas-Osorio and Rojo (2011), and Ouyang and Dueñas-Osorio (2014) employed a network topology method to assess the risk of loss of system connectivity due to component failures in the hurricane events; and
- Siraj et al. (2015) employed a Bayesian belief network to assess the vulnerability of high-voltage transformers during a seismic event.

4.5.3 Key Learnings

The key learnings from the power transmission industry's use of risk assessments are as follows:

- It is important to select risk measures that can be benchmarked against real data, as the lack of realistic and standardized risk measures can deter the use of QRA. For example, habitat recovery time, which is proposed in some international standards as a measure of environmental impact, is difficult to benchmark against the reality because the habitat baseline is typically not well-defined. In addition, the selection of quantifiable risk measures facilitates the use of historical data in risk estimation.
- While component risk estimation is well-established in the transmission industry, system-wide risk estimation is more challenging because of component interdependencies and potential domino effects. In the context of the pipeline industry, a similar challenge applies to risk assessments that consider the whole pipeline system including the line pipe, attachments, control systems and operators.

4.6 Summary and Conclusions

Risk assessment methods and guidelines in the nuclear, offshore, aviation, and power transmission industries were reviewed. The review findings that are most relevant to transmission pipeline QRA are summarized as follows:

- QRA is used extensively for decision-making regarding integrity management actions. Both offshore and power transmission industry guidelines emphasize that QRA is suitable for characterizing moderate levels of uncertainty during operation and maintenance, as seen in Figure 4.2 and Figure 4.5. Guidelines for all industries suggest that QRA is effective when the uncertainties involved can be well characterized. Offshore and power transmission industry

guidelines suggest that QRA may be unsuitable for problems involving unusually large uncertainties (e.g. very novel and challenging projects, insufficient knowledge to characterize failure modes or unknown dependencies between events). However, nuclear industry guidelines indicate that the QRA process in itself provides valuable insights into system performance, even in the presence of significant uncertainties.

- The influence on the total risk due to different levels of uncertainty regarding individual QRA components can be dealt with by using appropriate conservatism in the risk acceptance criteria for each level of uncertainty. In the nuclear industry, the uncertainties influencing nuclear plant component failures are well understood. Therefore, acceptance criteria for this component of QRAs incorporate less conservatism than does acceptance criteria relating to the highly uncertain event of a release of radioactive material to the environment. A similar approach could be adopted by the pipeline industry where reliability acceptance criteria for well-understood threats and failure modes can be defined less conservatively than risk acceptance criteria that are compared to risk estimates produced using consequence models that involve greater levels of uncertainty.

- Well-established risk measures and risk acceptance criteria facilitate the selection of an appropriate risk modelling approach. As demonstrated in the nuclear industry, the use of PRA methods increased once well-defined risk measures and acceptance criteria became available. Conversely, the absence of established risk acceptance criteria in the power transmission industry has discouraged the use of QRA.

- The separation of risk into operational factors and integrity factors facilitates the selection of appropriate QRA methods. For operational risk, qualitative methods are often used in the offshore and aviation industries. For integrity risk, QRA is utilized in the nuclear, offshore and aviation industries and the results are used in maintenance optimization or risk mitigation. This is a useful distinction for pipelines where pipeline integrity risk can be addressed using QRA, whereas more qualitative approaches can be used for operational factors such as human error.

- The nuclear and aviation industries have developed detailed guidelines for the quantification of the knowledge uncertainties associated with models and input parameter distributions. Similar guidelines would be useful for QRA applications in the pipeline industry.

- As demonstrated in the aviation industry's FAA and EASA guidelines, the aggregation of industry-wide data using well-defined formats facilitates data sharing and improves the process of hazard identification. Data collection in the aviation industry is further facilitated by incorporating it into operational processes. Adopting such an approach in the pipeline industry would support risk estimation and facilitate the identification of rare and interacting threats.

5. GUIDELINES FOR QUANTITATIVE RISK MODEL DEVELOPMENT

5.1 General

These guidelines provide a framework for performing quantitative risk analyses (QRA) for natural gas and hazardous liquids transmission pipelines. The purpose of the guidelines is to assist operators in developing new QRA models, and in identifying and addressing gaps in their existing models. The guidelines are also intended to help regulators evaluate the accuracy, completeness, and effectiveness of the QRA models developed by operators. The intended audience is assumed to be familiar with the concepts of the risk assessment process and its application within the industry.

5.2 Scope of the Guidelines

These guidelines address risk estimation, which involves estimating the failure frequency and failure consequences. The scope of the guidelines is limited to quantitative methods. These methods define the failure frequency in failures *per mile-yr* (or failures *per km-yr*), and the failure consequences in terms of quantifiable physical parameters, such as a dollar value, number of fatalities, spill volume, or area affected. The guidelines address the QRA process for a system-wide risk assessment, as well as more narrowly-focused QRA studies such as those carried out to address individual failure threats (e.g. corrosion) or individual consequence components (e.g. life safety).

Other components of the risk management process, such as formal hazard identification methodologies focused on identifying catastrophic events, risk acceptance criteria, and risk mitigation methods are beyond the scope of these guidelines. The guidelines are intended to provide a general framework and guidance for building and evaluating operator-specific models, and not to recommend or endorse any particular models for estimating failure frequency and consequence. Approaches that can be used to verify and validate risk models are also described.

5.3 Framework

Figure 5.1 illustrates the steps involved in conducting a QRA and demonstrates how these steps relate to the standard risk analysis process. The QRA process describes the steps involved in creating the key components needed to perform a risk analysis. The risk analysis process shows the steps involved in the computation of risk, which is the product of the failure frequency and failure consequence.

The steps involved in conducting a QRA are:

- identify the objectives;
- select quantitative models for:
  - failure frequency estimation; and
  - failure consequence estimation
- collect and manage data related to the pipeline characteristics and potential consequences;
- estimate risk;
- document the process covering the quality of the data and the details of the approaches used for the estimation of failure frequencies and consequences; and
- validate the models and results.

Conducting a QRA can be an iterative process due to the interdependencies between the steps involved. For example, the type of data (e.g. descriptive categories versus quantified measurements) and the specific parameters required (e.g. activity rates on ROW versus equipment hit rates, or number of coating holidays versus ILI detected corrosion features) are driven by the modelling approach, while model selection may be dependent on the available data.

The QRA process (including risk analysis) is described in Section 5.4.

The risk analysis process involves the following steps:

- System definition: Define the system including the physical boundaries of the pipeline being analyzed and the assessment period.
- Threat identification: Identify all applicable and knowable threats.
- Frequency and consequence estimation: Estimate the failure frequencies and failure consequences.
- Risk estimation: Estimate the required risk measures using the failure frequencies and failure consequences.

As shown in Figure 5.1, the ultimate goal of the risk analysis process is to provide the information needed to evaluate the risk and inform decision making. While the risk acceptance criteria, which are used as a basis for risk evaluation, are beyond the scope of these guidelines, typical approaches for utilizing the risk analysis results to evaluate risk and make decisions are described in Section 5.5.

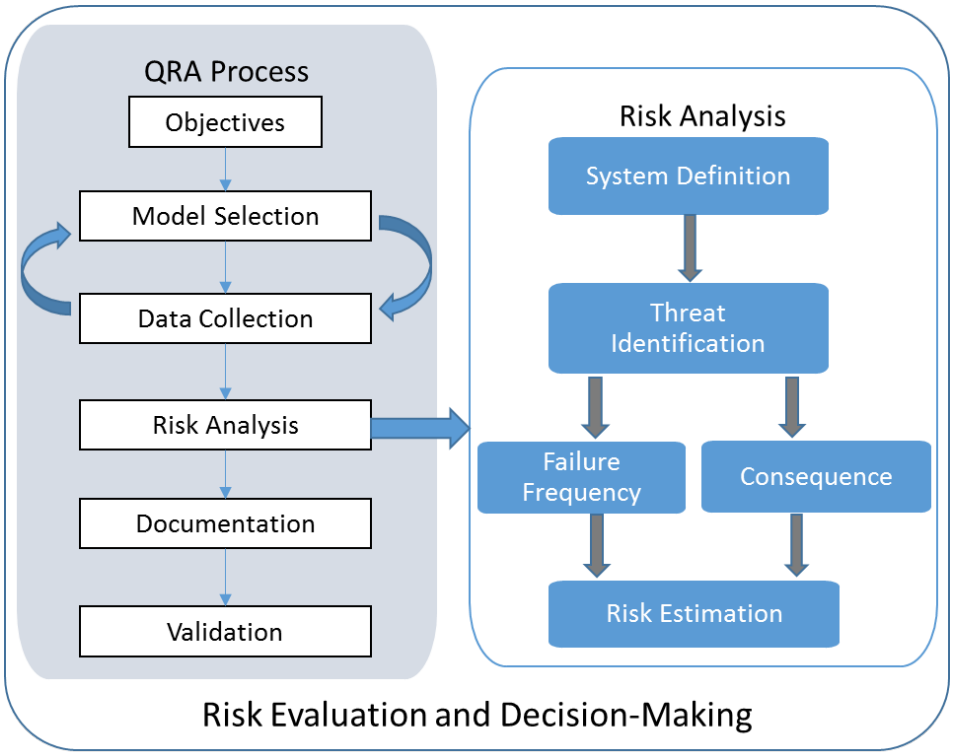

Figure 5.1 Framework for the QRA Process

5.4 The QRA Process

5.4.1 Objectives

The purpose of a QRA may include one or more of the following:

- identify high-risk locations and the main contributing threats;
- evaluate the risk against an acceptance criterion;
- evaluate the changes in risk over time;
- guide integrity management decisions; and
- demonstrate regulatory compliance.

The objectives define the scope and critical aspects of the QRA process including:

- the risk parameters to quantify, which drives the selection of consequence estimation models;
- the physical assets to be included and the boundaries of the system;

- the operational conditions considered;
- the level of rigour required in risk estimation and the resources needed to complete the assessment;
- the threat categories to consider and the failure frequency estimation models; and
- the duration of the assessment for time-dependent threats.

5.4.2 Model Selection

5.4.2.1 Failure Frequency Estimation Models

5.4.2.1.1 Introduction

Failure frequency models are categorized into three levels depending on the degree to which they make use of objective data and engineering models. The levels of analysis in order of increasing objectivity are:

- Level 1: SME Opinion
- Level 2: Historical Data
- Level 3: Probabilistic Models

In a system-wide QRA, all levels of analysis may be employed to address different threat categories or different aspects of the model used for an individual threat (e.g. defining the distributions of the random inputs to an engineering model). The following sections describe different approaches and strategies to increase confidence in the results of each level of analysis, and to ensure that comparing or combining their results leads to reasonable conclusions.

5.4.2.1.2 Level 1 – SME Opinion

Failure frequency estimation through the elicitation of SME opinion is perceived to be easier than other methods and is often employed in system-wide risk ranking and screening. The benefits of this approach are listed as follows:

- requires limited resources and is simple to implement;
- provides failure frequency estimates in the absence of recognized engineering models; and
- compensates for data gaps by leveraging pipeline-specific information through the experience of the SMEs.

Since the approach depends heavily on the judgment of the SMEs involved, the degree of subjectivity reflected in the assessment results is higher than for other levels of analysis. The limitations of this approach are listed as follows:

- verification and validation of the results are difficult without the results of other levels of analysis;
- high uncertainty since all model components are defined subjectively, including:
  - the parameters considered to be influential in determining the results;
  - the relationships between these parameters and the risk estimates; and
  - the estimated value of each parameter;
- the influence of different sources of uncertainty cannot be quantified;
- the level of conservatism reflected in the results is difficult to quantify;
- the influence of different mitigation measures is difficult to estimate; and
- does not provide guidance on the collection of new data to improve the model and reduce the associated uncertainty.

Quantifying failure frequencies based on SME opinion is appropriate when available data and models do not support the use of other levels of analysis. When SME opinion is employed, the following guidelines can be followed to improve the failure frequency estimates:

- Estimate the failure frequency as a product of the rate of occurrence of the initiating event and a series of conditional probabilities of intermediate events. For example, the failure frequency due to geohazards can be calculated as the product of the rate of occurrence of an extreme event such as a flood, multiplied by the probability of a pipeline failure given the occurrence of the flood. This approach allows the geotechnical experts to characterize the geohazard frequency, and the pipeline experts to characterize the pipeline response to the hazard.
- Separate failure frequency estimates by threat category and pipe segment to make the situations for which SME judgment is required as specific as possible.
- Express failure frequencies as a function of three elements representing exposure, mitigation, and resistance (DNV and Muhlbauer 2012) to ensure consideration of all relevant issues and recognize the influence of mitigation.
- Use structured approaches to elicit SME opinion on failure rates. Examples of structured approaches are:
  - the Delphi method as detailed by Ayyub (2014), which is an iterative process used to reach a consensus amongst a panel of experts, resulting in a reduction of bias in the opinion of any single expert opinion; and

- the guidelines for expert elicitation used by the U.S. Nuclear Regulatory Commission (Boring et al. 2005), which are a simplified version of the Delphi method and other standardized expert elicitation techniques, with guidance on developing customized questionnaires for expert opinion elicitation.

The use of the above approaches is intended to ensure that the risk estimate is consistent with the knowledge and opinions of the SMEs, but does not change the subjective nature of the results. Therefore, this option needs to be considered as a last resort when all the other approaches are impractical.

5.4.2.1.3 Level 2 – Historical Data

Historical data is used to estimate generic failure frequencies based on industry-wide data and to estimate pipeline-specific failure frequencies by applying modification factors to the generic failure frequencies.

Generic Failure Frequencies: In this approach, historical data from industry-wide failure databases is used to estimate the generic failure frequency for individual threats. This approach is typically used when the objective of QRA is to quantify risk at a specific location. The benefits of this approach are listed as follows:

- allows for rapid QRA while reducing subjectivity through the use of recorded data;
- uses industry-wide data, which reduces the need for the pipeline-specific data collection that would be required for the application of more detailed models; and
- allows for repeatability of the analysis based on appropriate documentation of the data used.

The main limitations of this approach are listed as follows:

- does not consider pipeline-specific parameters;
- does not identify locations of high risk and significant threats within a specific pipeline system;
- cannot be used to estimate the failure frequencies for rare and newly identified threats;
- does not provide a basis for characterizing the effect of mitigation actions taken;
- makes it difficult to identify important parameters influencing the failure frequencies as historical records do not typically include all the required parameters;
- does not provide guidance for the collection of new types of data;
- reflects past pipeline characteristics and operational environment, which may not be representative of the future condition of aging pipelines and changing operational factors; and

- depends on the accuracy of failure cause classification of past incidents, which can be subjective and may not consider threat interactions as a failure cause.

In this approach, an estimate of failure frequency would ideally be obtained by selecting historical data from pipelines with matching attributes (e.g. diameter, vintage, product type, coating type) to the segment being analyzed. This, however, is not possible as the large majority of available incident data does not include the required information on the attributes of the pipelines on which the incident occurred. While efforts have been made in recent years to include detailed pipeline information in incident databases, the large number of parameters influencing failure frequency would make data subsets that match any given pipelines too small to provide reliable failure frequency estimates.

Failure Frequencies with Modification Factors: To overcome some of the limitations of generic failure frequency estimates, modification factors can be applied to the historical data to obtain pipeline-specific failure frequencies. Modification factors can be developed using engineering models, statistical analysis or SME opinion. The benefits of this approach are listed as follows:

- improves the objectivity of QRA over the SME approach while being easier to implement than a full probabilistic approach; and
- allows for consideration of pipeline-specific factors.

As the basis for the development of modification factors is not standardized, the definition of these factors will typically include significant subjective input. The disadvantages of this approach are listed as follows:

- greater subjectivity compared to an approach based on probabilistic models; and
- significant effort required to develop realistic modification factors.

When this approach is used, the accuracy of failure frequency estimates can be enhanced in the following ways:

- develop modification factors based on engineering models and probabilistic methods where possible; e.g. reduction factors for the failure frequency due to mechanical damage in BS PD 8010-3 (BSI 2013) are developed based on probabilistic methods;
- consider the guidelines set out in Section 5.4.2.1.2 for the use of SME opinion if expert opinion is used in the development of modification factors; and
- consider other levels of analysis for rarely occurring threats as the use of small sample sizes from recorded data can underestimate the true likelihood of failure.

5.4.2.1.4 Level 3 – Probabilistic Models

Probabilistic models use either structural reliability methods (e.g. Monte Carlo simulation), or graphical logic models such as fault-tree methods and Bayesian networks. In this approach, engineering principles and formal probabilistic logic are used to evaluate pipeline-specific failure frequencies. The benefits of this approach are listed as follows:

- reflects all relevant pipeline-specific factors through implicit consideration of the relevant parameters;
- has the potential to provide the most objective estimate of failure frequencies compared to other levels of analysis;
- can be based on recognized and validated engineering models;
- allows pro-active consideration of rare and newly-identified threats based on fundamental engineering and probabilistic principles;
- accounts for specific integrity maintenance actions and mitigation measures either by considering the changes to the input parameters (e.g. in-ditch measurements reduce ILI sizing uncertainty for corrosion features) or through explicit modelling (e.g. removal of corrosion features that are repaired from the model);
- identifies the most influential parameters affecting the failure frequency;
- identifies data gaps, which helps in prioritizing data collection efforts;
- allows for model upgrades to include state-of-the-art engineering models; and
- provides direction for reducing the overall uncertainty either through data collection or engineering model improvements.

As is the case with all engineering models, the results from probabilistic models must be evaluated in the context of the approximations made in defining the inputs, the mathematical relationships used to model failures and the numerical methods used to estimate the failure frequency.

The limitations of this approach are:

- Substantial effort is required to characterize model inputs.
- Considerable computational resources may be required depending on the model implementation.
- Lack of model uncertainty characterization adds uncertainty to the failure frequency estimates.
- The complexity of the models result in them being seen as a ‘black box’ by unfamiliar users, leading to skepticism regarding the results.

Guidelines for the application of reliability-based methods are available in international pipeline standards and codes such as BS PD 8010-3 (BSI 2013) and CSA Z662 Annex O (CSA 2015). Model results can be improved by considering the following list of possible actions:

- include all possible sources of uncertainty, such as model errors and measurement errors;
- consider input parameter bounds in selecting probability distributions (e.g. corrosion growth rates cannot be negative and should therefore not be modelled by a normal distribution);
- ensure goodness-of-fit in the appropriate distribution tails region as the distribution tails have a significant influence on estimates of low failure frequencies;
- consider the guidelines set out for the use of SME opinion in Section 5.4.2.1.2 if subjective judgment is used to characterize model inputs; and
- apply appropriate techniques in the implementation of probabilistic calculations (e.g. use an appropriate sample size in Monte Carlo simulation to obtain accurate failure probabilities and ensure convergence of first- and second-order reliability methods (FORM/SORM) to the correct solution).

Probabilistic models may incorporate subjective judgment in characterizing the inputs and selecting appropriate engineering models and reliability methods. However, the subjective component in using these models is limited in comparison to the other two methods. In addition, subjectivity in this approach can be progressively reduced through data collection, improved engineering models and standardized probabilistic calculation methods.

5.4.2.2 Failure Consequence Estimation Models

5.4.2.2.1 Life Safety

Quantifying life safety is controversial in certain societies, as the process of quantification itself is seen as an acceptance of hazard to human life. However, every decision in a modern industrial society has a risk of life safety associated with it even though the risk is not explicitly quantified and can be minimal. On this basis, several jurisdictions around the world, as well as pipeline standards in Europe (BS PD 8010-2, IGEM/TD/2/1764, CPR 1999), and Canada (CSA Z662) have accepted methods to quantify life safety.

The primary hazards from product release are thermal effects, toxic effects, asphyxiation and blast pressure. Thermal effects occur due to:

- fireballs or jet fires due to the release of natural gas;
- flash fires due to the release of HVP liquids; and
- pool fires due to the release of flammable LVP liquids.

Other life safety hazards, such as toxic effects and blast pressure, occur due to the release of HVP liquids.

Safety impact modelling must consider all possible hazard scenarios for the product type under consideration, coupled with a characterization of the exposed population. Key hazards and examples of widely-used models are listed below for each product type.

- Natural Gas: Jet fires
  - The potential impact radius (PIR) model proposed by Stephens et al. (2002) for estimating the zone influenced by the thermal effects due to jet fires is well suited to simplified evaluations.
  - Detailed models which consider meteorological conditions are available as proprietary software packages, e.g. PIPESAFE, referenced in BS PD 8010-3 (BSI 2013), and DNV PHAST (DNV 2016).
- HVP Liquids: Flash fires, toxic effects and blast pressure
  - Examples of general purpose consequence modelling software, as recommended by the International Association of Oil and Gas Producers (IOGP 2010) include CANARY by Quest consultants, PHAST by DNV GL, EFECTS by TNO, and TRACER by Safer Systems.
  - Guidelines for detailed numerical modelling with CFD are available in IOGP (2010) and the Norwegian Standard NORSOK Z-13 Annex F (NORSOK 2010).
- Flammable LVP Liquids: Pool fires
  - Pool fires are also addressed by the proprietary software packages and CFD models mentioned above for HVP liquids.

5.4.2.2.2 Environmental Impact

Environmental impact is dependent on the following:

- product type;
- exposure of receptors;
- toxicity of the product for each receptor; and
- socio-economic importance of the affected resources.

Guidelines for Quantitative Risk Model Development

General guidelines for ecological risk assessment have been published by several environmental protection agencies, e.g. EPA (EPA 2000), and CSA Z763-96 (CSA 1996). Minimum factors to be considered by all models in the assessment of environmental impacts are:

- the total volume of product released;
- the area affected by the released product; and
- the importance of the spill area.

Large uncertainties are associated with the characterization of the environmental impact of liquids due to variabilities in:

- terrain;
- spill characteristics, e.g. density, viscosity, soil permeability, evaporation, pooling;
- performance of leak detection systems;
- spill response planning;
- potential receptors identified;
- pathways to receptors;
- sensitivity of the receptors to product exposure;
- definition of habitat recovery; and
- duration of the recovery.

The state of the art approaches to modelling the behaviour and impact of crude oil spills in inland waterbodies were reviewed by a Royal Society of Canada expert panel (Lee et al. 2015). The review highlighted a general lack of data required to quantify the effects of onshore oil spills, as well as the lack of baseline assessments of different habitats to differentiate between the effects of oil spills and the ensuing clean-up efforts.

Different environmental impact estimation approaches with varying data requirements and rigour of analysis exist. Modelling approaches are divided into three levels of analysis. These include:

- Level 1: SME Opinion
- Level 2: Simplified Models Using Historical Data
- Level 3: Detailed Models

Level 1 – SME Opinion

SME opinion can be used to quantify environmental consequence in the absence of reliable data to permit the use of more detailed approaches. Similar to the guidelines set out in Section 5.4.2.1.2, structured approaches for the elicitation of SME opinion can be used to ensure consistency of the results. In addition to the minimum factors such as volume released, area affected, and importance of the area, it would be beneficial for a structured SME approach to consider the spill impact separately for the following receptors:

- soil;
- vegetation and ecosystem;
- wildlife; and
- water resources.

Level 2 – Simplified Models using Historical Data

Current incident databases, such as PHMSA's database (PHMSA 2016), can be used to make generic estimates of typical average release volumes as a function of pipeline diameter. However, these estimates do not reflect pipeline-specific attributes, such as the elevation profile, leak detection system, valve placements and time to valve shut-off once a leak is detected, and they do not have sufficient data to represent a wide range of possible release scenarios.

Estimation of environmental costs based on the historical data has typically been limited to the clean-up costs (Bonvicini et al. 2014). Secondary impact, such as socio-economic costs due to the loss of an environmental resource, vary with time and habitat. Socio-economic costs can be estimated, using modifiers to represent environmental sensitivity, and then included in the total environmental costs. An example of a simplified model that estimates pipeline-specific secondary environmental costs is the basic oil spill cost estimation model (BOSCEM) (Etkin 2004).

Level 3 – Detailed Models

The most rigorous approach to estimate environmental impact is to use detailed models for:

- Release volume: Guidelines in Oland et al. (2012) and 49 CFR 194.105 (DOT 2011) provide an overview of an approach that can be used to estimate the worst-case release volume for LVP liquids based on the time to detection and block valve closure and the drain down volume after valve closure. An advanced methodology for HVP liquid release volume modelling is incorporated into the PIPETECH software referenced in BS PD 8010-3 (BSI 2013). More realistic estimates or release volumes can be obtained by considering uncertainty in the performance of leak detection systems.
- Area affected: Spill trajectory models are used to identify the area affected by the product release. These models use digital elevation data of the terrain to identify the distance travelled

and pathways to receptors. Some examples of spill trajectory mapping models are the Hydrocarbon Spill Screening Model (HSSM) developed by the EPA (Weaver et al. 1994) and OILMAP (RPS 2016).

- Habitat assessment: Estimation of habitat recovery times requires a baseline environmental assessment. Such an assessment includes data collection regarding the parameters influencing the habitat sensitivity, including the characteristics of the soil, vegetation, wildlife and water resources. This information is then used to define the damage caused by contact with the spill and the recovery time for each component of the habitat. Examples of this type of assessment are available in the detailed environmental impact assessments conducted for the Northern Gateway Pipeline Project (Worley Parsons 2012), and the Keystone XL Pipeline Project (DOS 2014).

Implementation of these models requires detailed data regarding the terrain, not only along the pipeline ROW, but also for all possible spill pathways that could affect potential receptors.

5.4.2.2.3 Financial Impact

The financial impact due to product release includes direct costs and indirect costs. Direct costs include:

- cost of lost product;
- repair cost;
- costs associated with downtime (e.g. lost revenues, penalties and restart costs);
- third-party property damage costs;
- legal costs; and
- third-party compensation due to litigation.

Indirect costs include:

- loss of customer satisfaction;
- loss of reputation; and
- costs incurred due to increased regulatory oversight.

Most components of the financial impact of failure (particularly the indirect costs) are situation-specific and some components may not be relevant in some cases (e.g. third-party compensation costs are not relevant for pipelines in barren land). Since the financial impact of failure is borne by the operator, the appropriate cost components and models depend on the operator's corporate values and the objectives of the QRA.

5.4.3 Data Collection

5.4.3.1 Data Requirements

The parameters required for QRAs are similar to those listed in 49 CFR 195 Appendix C (PHMSA 2011). Examples of the type of data that QRAs may require include:

- pipe geometry – e.g. wall thickness and diameter;
- pipeline material and construction – e.g. grade, toughness, pipe body quality, and installation temperature;
- attachments and welds – e.g. fittings and attachments, attachment weld quality, seam weld type, and girth weld type;
- pipeline integrity data – e.g. above-ground survey results, in-line inspection results, direct assessment results, defect growth rates, repairs, coating type, coating condition, CP data, ROW surveillance methods and intervals, excavation protocol, and dig notification requirements and response;
- right-of-way-attributes – e.g. terrain, elevation profile, location class, depth of cover, population density, HCA designation, crossings, geo-hazards, groundwater depth, soil corrosiveness, alignment markers, ROW indications, mechanical protection, public awareness, ROW activity, and shared utilities in ROW;
- product type and characteristics;
- operational parameters – e.g. maximum allowable operating pressure, pressure profile, operating temperature, pressure range and pressure history; and
- pipeline history – e.g. vintage, hydrostatic tests, failure history, equipment age, and previous seismic and flooding events.

Specific data requirements vary with the types of dominant threats and the approaches used to estimate failure frequencies and consequences. For example, a simplified model for life safety consequence due to a natural gas release requires data regarding population density, internal pressure and diameter. On the other hand, a detailed model for the same purpose requires additional data regarding meteorological conditions, such as ambient temperature, wind speed, and wind direction; as well as specific building locations and occupancy types.

5.4.3.2 Data Quality

Data quality can be assured through validation rules such as the following:

- Completeness checks to determine if all of the data associated with a pipeline attribute or event is available. For example, if a hydrostatic test is performed, a complete record would contain the date of testing, the location of the test section, pressure-measurement points in the section, the elevation profile of the test section, maximum pressure and its location, test duration, pressure and temperature records, and any failures detected or repairs performed.
- Validity checks to verify that a given value is within the viable range. For example, the nominal wall thickness cannot be less than 3 mm, and physical properties such as material strength cannot have negative values or unrealistically high values relative to specifications.
- Consistency checks to verify that two different values of a data record are compatible. For example, seamless pipe is not available for diameters greater than 26 inches and a pipeline constructed in 1956 would most likely have a DSAW seam.

Data validation methods and tools to configure the data based on consistency rules are part of the data management process (see Section 5.4.3.4). For example, the report by Skow et al. (2015) on crack in-line inspection tool performance includes an appendix detailing a procedure for data validation. Details regarding the collection and maintenance of data are addressed under Data Management in Section 5.4.3.4.

5.4.3.3 Data Gaps

Data gaps can be addressed by:

- Using inferred inputs from industry-wide data, e.g. UK Standard BS PD 8010-3 (BSI 2013) provides the distribution properties for dent-gouge dimensions that could be incorporated into a structural reliability analysis to estimate the failure frequency due to equipment impact.
- Eliciting SME opinion for QRA inputs over a range of values instead of a point estimate. This range can then be used in sensitivity analyses (see below).
- Performing a sensitivity analysis by varying the QRA inputs over a range of values. The range of values should represent an optimistic, a conservative and a best estimate for a missing input. Based on the sensitivity of the risk measure to the input parameter, a cautious best estimate could be determined for the final risk measure.
- Revisiting the model selection to avoid the need for missing data.

5.4.3.4 Data Management

A framework for data quality management is available in ISO 8000:150 (ISO 2011). The ISO framework describes processes for:

- Data Operations: Addresses factors that influence data standards and definitions, data configuration, and data processing activities such as data creation, modification, and transfer.

- Data Quality Monitoring: Defines the objectives of data quality management, methods to assess data quality, and quality assurance measures.
- Data Quality Improvement: Corrects errors in the data, finds the root causes for the errors, and identifies preventive methods.

Knowledge of the QRA process objectives and approach would enhance data management in the following ways:

- identifying the value of new data based on the sensitivity of the risk estimate to the input range;
- prioritizing data collection based on the most important data gaps;
- coordinating data collection activities in conjunction with other risk and integrity management actions;
- organizing data from all available sources in the formats needed for QRA; and
- identifying the data needed to improve the risk model.

5.4.4 Risk Analysis

5.4.4.1 Overview

The risk analysis process in Figure 5.1 illustrates the required steps for risk estimation. The selection of failure frequency and failure consequence estimation methods is addressed in Section 5.4.2. Guidelines for the remaining components are provided in this section. Aspects of risk analysis, such as system definition, threat identification and risk estimation, are addressed in the following sections.

5.4.4.2 System Definition

This step involves defining the following aspects:

- the physical boundaries of the pipeline;
- inclusion (or exclusion) of equipment, attachments and fittings; and
- duration of the assessment period.

5.4.4.3 Threat Identification

ASME B31.8S (ASME 2014) provides a standardized list of nine threat categories for gas transmission pipelines, which are also applicable to other transmission pipelines. These threat categories are:

- 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, and third parties, dents and/or gouges, vandalism;
- incorrect operational procedure; and
- weather-related and outside force: cold weather, lightning, heavy rains or floods, earth movements.

Applicable threat categories may also be identified based on:

- historical incidents within the pipeline system;
- other standards and codes (e.g. BS PD 8010); and
- failure causes identified in PHMSA's incident database reflecting the most likely threat categories applicable to US transmission pipelines.

Additionally, all interacting threats should be considered. One approach for identifying threat interactions is based on the qualitative risk index methodology of INGAA (INGAA 2013), which identifies the following examples of interacting threats:

- coincident threats, e.g. internal and external corrosion at the same location, ground movement at the location of construction-related defects; and
- interaction of time-dependent or time-independent threats with resident threats, e.g. wall loss due to corrosion at the location of manufacturing imperfections or mechanical damage, and flooding with construction defects.

A different approach to identifying threat interactions is described in Kariyawasam et al. (2014). In this approach, threat interactions are grouped in the following categories:

- interacting coincident defects, e.g. crack within a corrosion feature;
- interacting activating threats, e.g. ground movement near circumferential SCC; and
- interacting common mode conditions, e.g. external corrosion and SCC due to coating disbondment.

In addition, formal hazard identification approaches exist that can be used to identify any pipeline system-specific threats. These include:

- Hazard Identification Studies (HAZID);
- checklists;
- What-if analysis or Structured What-if Checklist Technique (SWIFT);
- Hazard and Operability analysis (HAZOP); and
- Failure Mode and Effects Analysis (FMEA).

Detailed descriptions of the formal methods and guidance on their application are available in 'Methods for Marine Risk Assessment' (DNV 2002) and guidance notes from the American Bureau of Shipping (ABS 2000).

5.4.4.4 Risk Estimation

5.4.4.4.1 General

Risk is estimated as the expectation of failure consequences, which generally equals the failure frequency multiplied by the magnitude of the failure consequences. In addition, other common formats of expressing risk have been used in the pipeline industry. These include individual risk, F-N curves and risk matrices. The selection of failure frequency and failure consequence models is addressed in Section 5.4.2.1 and Section 5.4.2.2. This section describes how these models can be used to estimate and display risk.

5.4.4.4.2 Failure Modes

Failures are generally grouped into categories with similar failure consequences (referred to as failure modes in this document). Failure modes include:

- Small leaks: pin-hole leaks due to corrosion features or other defects that are deeper than wall thickness, but allow the pipeline to maintain pressure capacity. These are generally holes less than 10 mm in diameter (CSA 2015).
- Large leaks: leaks resulting from the burst of a pipeline due to the loss of pressure capacity that do not result in axial extension by fracture or plastic collapse. These are generally holes greater than 10 mm in diameter, but less than the diameter of the pipe (CSA 2015).
- Ruptures: unstable extension of an axially-oriented defect failure (e.g. failure of corrosion features, seam-weld cracks) or a girth-weld tensile failure. For these failures, the opening is greater than or equal to the pipe diameter (Bolt 2006).

Since the magnitude of the consequences associated with each of these failure modes is very different, the frequency and risk associated with each failure mode is calculated separately and added up to arrive at an estimate of total risk.

5.4.4.4.3 Risk Measures

As discussed in Section 5.4.2.2, pipeline failure risks can be categorized into safety-related, environmental and financial. The parameters used to quantify risk of each of these categories are as follows:

- Life Safety:
    - Expected number of casualties, which includes the number of injuries and fatalities. This measure provides a basis for converting life safety consequences to monetary units in order to develop an aggregated risk estimate. This conversion can be based on the "value of a statistical life", which is available from the DOT Memo on "Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in the U.S. Department of Transportation Analyses – 2015 Adjustment" (DOT 2015).
    - Individual Risk (IR), which is defined as the probability of fatality for a person at a particular location due to a pipeline failure. It is typically calculated for a given location, such as a residence or business, where individuals can be present for extended periods of time. It is estimated along the pipeline profile and varies with the distance from the pipelines and the likelihood that the person will be present at the location being considered. IR is a widely used risk measure, with explicit guidance on acceptance criteria (e.g. UK Standards BS PD 8010 and IGEM/TD/2).
    - Societal risk (SR), is represented by an F-N curve, which is a plot of the frequency F, of incidents resulting in N or more fatalities. An F-N curve is associated with a specified length of pipeline. It is calculated as the sum of the frequencies of all possible failure scenarios for the pipeline length under consideration that cause each N or more fatalities. Similar to IR, well-recognized risk acceptance criteria are available for SR.
- Environmental Impact:

- Monetary costs that account for environmental sensitivity and include clean-up costs, and second order socio-economic impacts. Guidance on the acceptance criteria for environmental monetary costs is limited.
- Spill volumes adjusted for site sensitivity. Risk acceptance criteria based on the spill volumes and sensitivity of the environment are recommended by Nessim et al. (2014).
- Habitat recovery time is estimated as the time for restoration of an environmental resource. The estimation of habitat recovery is ideally based on a clearly-defined natural resource and a quantified measure of restoration (e.g. population density of a particular aquatic species, and allowable residual spill volume in the soil). Guidelines on acceptance criteria for habitat recovery times are available in NORSOK Z-013 Annex A (NORSOK 2010).

- Financial Impact:
  - Monetary costs including third-party property damage and other business impacts listed in Section 5.4.2.2.3. Acceptance criteria for financial risk depend on the business priorities of the operator.

Selection of a particular risk measure depends on the purpose of the QRA and the associated risk acceptance criteria. Risk measures fall into one of the following categories:

- Aggregated measure: a single aggregated measure for life safety, environmental and financial impacts, which can expressed as a dollar value. This approach facilitates decision-making by comparing segments and assets based on a single risk measure.
- Independent measures: separate measures can be used for life safety, environmental impact, and financial cost (see Section 5.4.2.2.3). These measures can be used for purpose-specific risk assessments that focus on safety or environmental risks. Using separate measures also facilitates a constrained optimization approach, in which cost can be optimized subject to meeting minimum standards of safety or environmental protection.

5.4.4.4.4 Granularity

Sufficient granularity is required to identify locations of high-risk and significant threats at a given location. For this purpose, risk estimates are broken down as follows:

- Distributed Risk: Dynamic segmentation based on changes in the parameters that influence the estimates of either the failure frequency or the failure consequences. A new segment with uniform risk is typically created at any point where a change of any of these parameters occurs. For point-data (such as features identified through inline inspections), the segmentation is based on the density, severity, and growth rate of the features.
- Location-specific Risk: For risk associated with single features, the location-specific risk is estimated based on the failure frequency of the particular feature and the associated consequences.

- Contributions to segment risk: To facilitate risk-based segment ranking and identification of the dominant threats, models should allow risk to be displayed for each user defined segment by threat, by failure mode, and by risk measure.

5.4.4.4.5 Risk Aggregation

The data quality, analysis rigour and model availability may vary by:

- threat category;
- failure mode;
- pipeline segment (e.g. due to differences in the quality of inspection data between piggable and non-piggable segments); and
- time for the same segment (e.g. changes to inspection technologies change the quality of the data available from one inspection to the next).

The level of subjectivity and the uncertainty in the risk estimates may, therefore, vary due to the above variabilities. If the risk estimates for individual segments or threat categories are based on a cautious best-estimate of the inputs that reflect the best state of the knowledge, risk sensitivity to the uncertainties, and consideration of model errors, then the aggregated risk will represent the best estimate of the total risk.

5.4.5 Documentation

Appropriate documentation of the QRA process provides justification for the decisions made; a record of changes made to process, data, or models; and continuity in the case of changes to ownership or personnel. Documentation should contain sufficient information to allow an informed third party to verify the process and models used. Elements to consider for documentation are listed as follows:

- objectives of the QRA including the scope, system definition, operational conditions, and assessment period covered;
- models selected for the QRA and the rationale for their selection;
- assumptions and limitations associated with each model employed;
- data used in the analysis including:
    - sources of the data;
    - process for inferring model inputs from various data sources;
    - approach for addressing data gaps; and

  - comments on data quality from each source;
- basis for the selection of threat categories including any formal hazard identification methods undertaken;
- list of threats considered and rationale for any threat screening used to exclude non-relevant threats from the QRA;
- where SME opinion is used:
  - data submitted for the SME's review;
  - description of the approach used to obtain the opinion of the SMEs;
  - questions submitted to the SMEs and the format in which they were asked;
  - background and qualifications of each SME; and
  - minutes of the meetings if a group workshop was conducted;
- where historical data is used:
  - basis for the selection of data relevant to the pipeline system (e.g. diameter, location class, and regulatory conditions);
  - modification factors applied; and
  - process of developing the modification factors;
- evidence of validation of the software used;
- for probabilistic models:
  - description of each model component;
  - basis for selecting the probability distribution of the input parameters;
  - estimated model error;
  - models used to estimate the probabilities of different failure modes; and
  - models used to define time-dependent factors (e.g. corrosion growth rates);
- intermediate results obtained in the QRA process:
  - failure frequencies for each segment by threat category; and
  - separate consequence estimates of life safety, environmental and financial impact;
- risk measures considered in consequence estimation;

- methods used for consequence estimation;
- results of sensitivity analyses, if performed, and the important parameters identified; and
- format used to present the risk results to the decision-makers.

5.4.6 Risk Model Validation

5.4.6.1 General

The standard approach for validation of deterministic models by comparing their results to empirical data is not applicable to risk models unless large sets of data are available. For rare or moderately rare events, it is difficult to make direct comparisons between the risk output and past performance as the complex set of circumstances resulting in rare events are not ordinarily replicable and the number of events available for verification is generally insufficient to make stable statistical estimates of the associated frequencies. Therefore, strategies other than the usual direct comparison between model results and case-specific observations must be used. Viable validation approaches are described in the following sections.

5.4.6.2 Component Verification

Component verification involves verifying each component of the risk analysis model independently against available data sets. For example, deterministic engineering models used to predict corrosion failures, such as ASME B31G (ASME 2012), can be validated by comparing the model results to experimental data. Probabilistic models such as a fault-tree model for equipment hit rates can be validated by comparing their results to incident data.

5.4.6.3 Hindcasting

In the hindcasting approach, historical data is used in the QRA process to estimate risk for specified time periods in the past. The QRA process is verified by checking if the risk 'hindcasts' are consistent with historical data regarding high-risk locations and significant threats.

This process is suitable for use with probabilistic models and may not be suitable for other levels of analysis. For example, SME opinion is typically based directly on past experience, which constitutes the hindcast information that the model is tested against. Similarly, hindcasting is not suitable if the data sets available for validation are sparse.

5.4.6.4 Error Bounds

Uncertainty in QRA results can be quantified by defining a range of outputs based on optimistic and conservative values of uncertain input parameters. The range of risk estimates represents the

error bounds applicable to the QRA results. The model can be validated by checking if the risk from historical data falls within the error bounds of the risk model predictions. However, the usefulness of this approach decreases as the error bounds become wider.

5.4.6.5 Benchmarking

A suite of benchmark problems based on industry-wide consensus can be developed that represent a range of QRA application scenarios. These cases can be analyzed using a recognized and validated model (or a number of models), providing expected results and associated error bounds. Models can then be evaluated based on matching the test case results within reasonable error bounds. Examples of test case scenarios may include: evaluation of system-wide or threat-specific QRA, use of different levels of analysis for failure frequency and consequence estimation, individual and societal risk calculations at specific locations. The development of detailed test case scenarios can be considered in future work.

5.4.6.6 Sensitivity Analysis

In this method, risk outputs are generated by repeating the QRA for a range of the input parameter values. The sensitivity of the risk outputs to the input parameters can then be evaluated based on comparison with the sensitivities observed in the historical trends. In addition, a certain degree of confidence can be derived from the agreement between the sensitivity analysis trends and the judgment of SMEs.

5.5 Risk Evaluation and Decision Making

QRA results facilitate decision-making in the following ways:

- An aggregated risk measure is suitable for comparing pipeline risk to risks from other facilities, comparing and ranking segments within a pipeline system, identifying dominant failure threats and performing cost-benefit analyses for proposed pipeline integrity preventative and mitigative measures.
- Independent risk measures are applicable to safety or environmental assessments at specific sites, which may be required for construction of new pipelines or changes to operational conditions of existing pipelines (e.g. pressure uprating, flow reversal and class location changes). These results are often used to demonstrate regulatory compliance.
- F-N curves, as shown in Figure 5.2, enable comparisons of life safety risk between different segments or between assessment periods for the same segment. They can also be used to evaluate risk against recognized acceptance criteria.

- IR contours, which are plots of the individual risk as a function of distance from the centerline of the pipe (see Figure 5.3), can be used to assess life safety risk in the same ways mentioned above for F-N curves.
- Risk profiles along the pipeline length, as shown in Figure 5.4, enable identification of high-risk locations and identification of significant threats when separated by threat categories.
- Risk matrices, as shown in Figure 5.5, can be used for the same purposes as aggregated or independent risk measures (see above), with the added benefit of displaying the failure frequencies and failure consequences explicitly. This enables the decision-maker to distinguish between high frequency-low consequence and low frequency-high consequence events or segments.
- A plot of changes in risk as a function of time, as shown in Figure 5.6, enables risk forecasting and decision-making regarding time-dependent threat mitigation including inspection intervals and defect repair planning.

The NRC report by Drouin et al. (2009) provides additional guidelines on risk-informed decision-making under uncertainty.

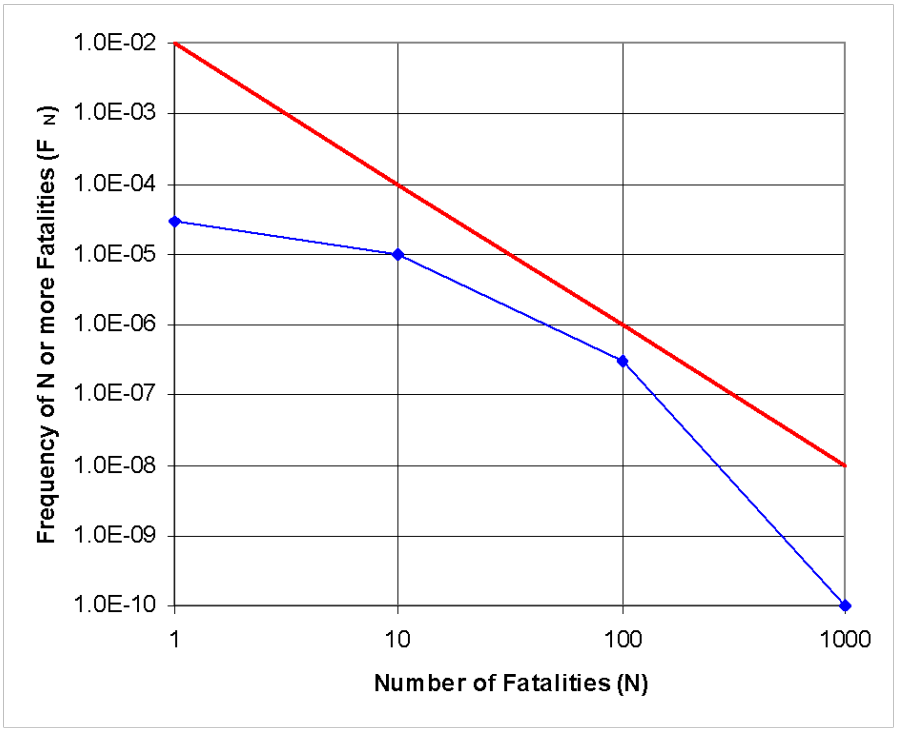

Figure 5.2 Example of F-N Curve for a Pipeline Segment

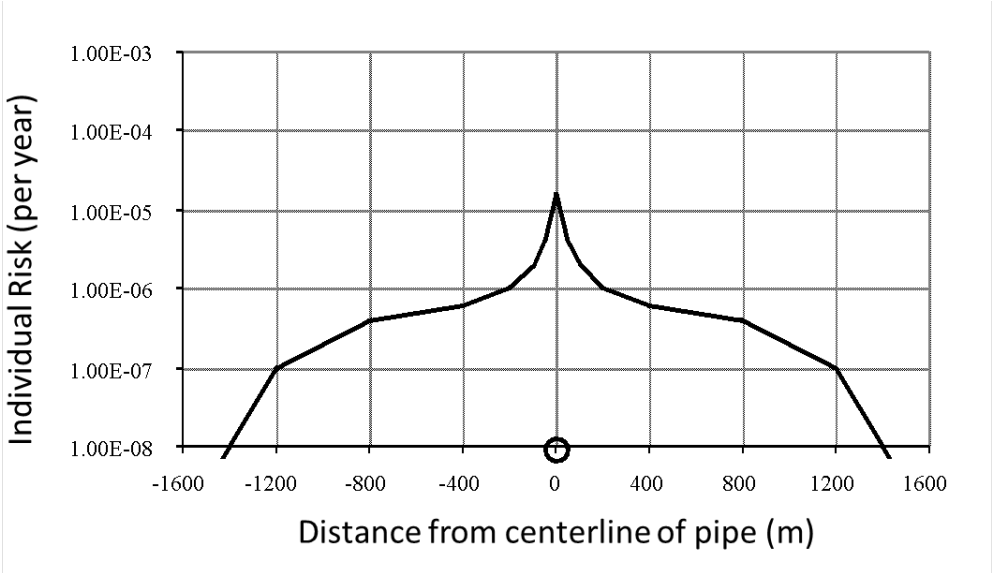

Figure 5.3 Example of an Individual Risk Contour at a Given Location

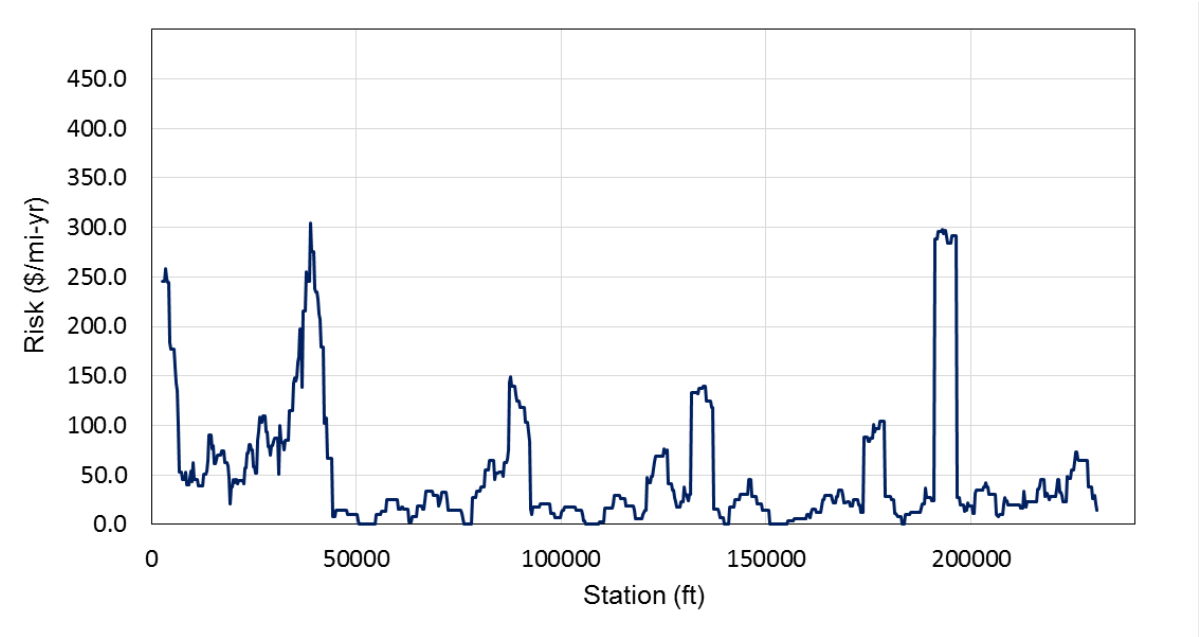

Figure 5.4 Example of a Risk Profile Along a Pipeline Segment

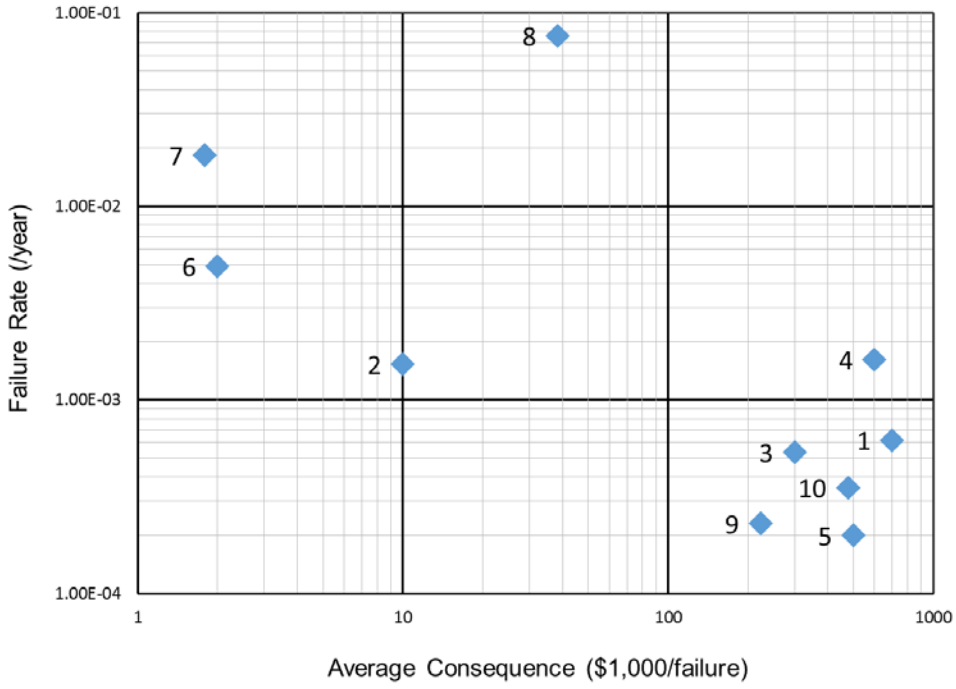

Figure 5.5 Example of a Risk Matrix

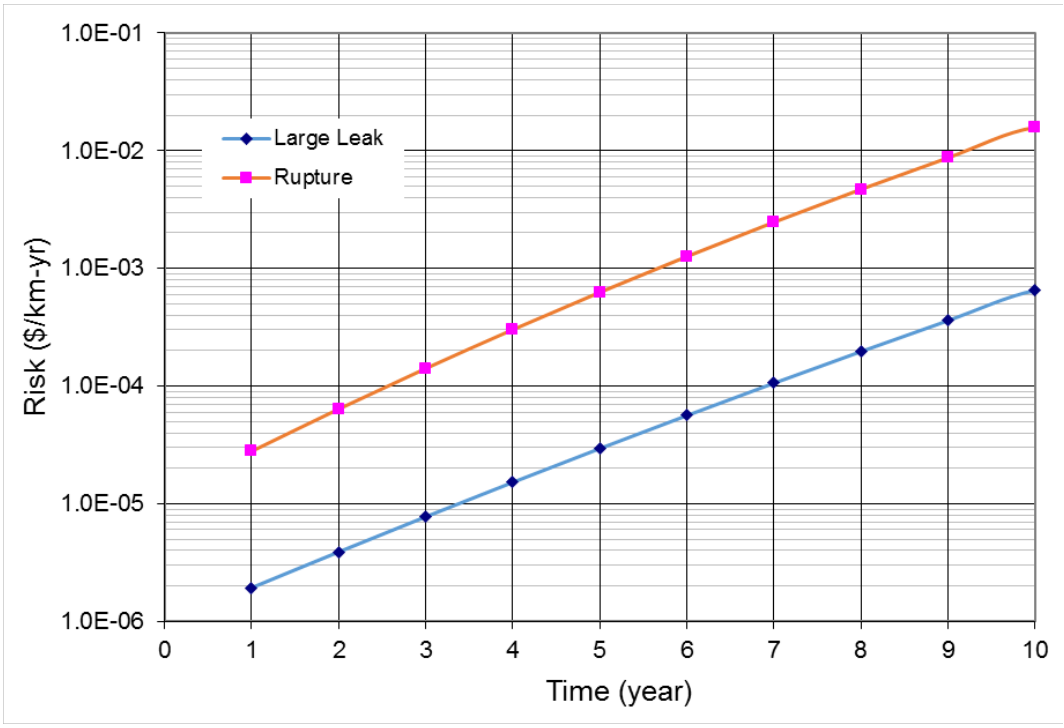

Figure 5.6 Example of Risk Variation with Time

6. COMMENTARY ON OTHER FACILITIES AND LNG PLANTS

6.1 Objective and Scope

Oil and gas transmission pipeline systems typically include stations and facilities, which have one of the following functions:

- processing or refining the product (e.g. gas processing plants or refineries);
- moving the product (e.g. compressor or pump stations); and
- storing the product for future utilization (e.g. tank farms or storage caverns).

Layouts of these facilities for oil and gas pipeline systems are illustrated in the schematics shown in Figure 6.1 and Figure 6.2, which were obtained from (PHMSA 2016a and PHMSA 2016b).

This section provides a literature review of the types of risk models currently in use for facilities and a commentary on the potential use of pipeline QRA components to improve facility risk modelling. The potential for developing integrated asset risk models that address pipelines and facilities is also discussed.

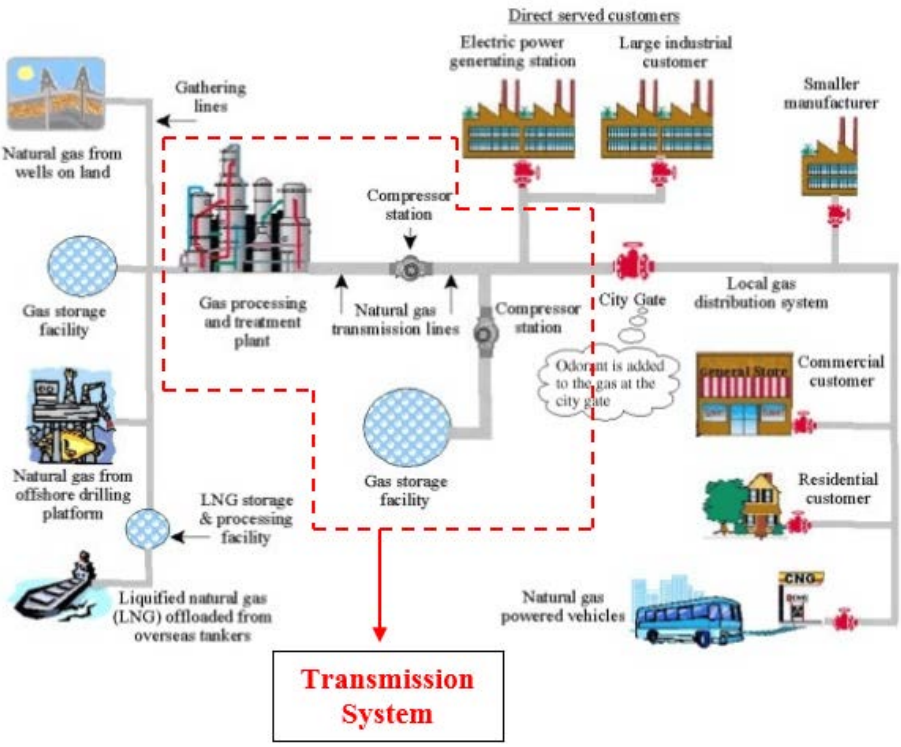

Figure 6.1 Gas Pipeline System Schematic

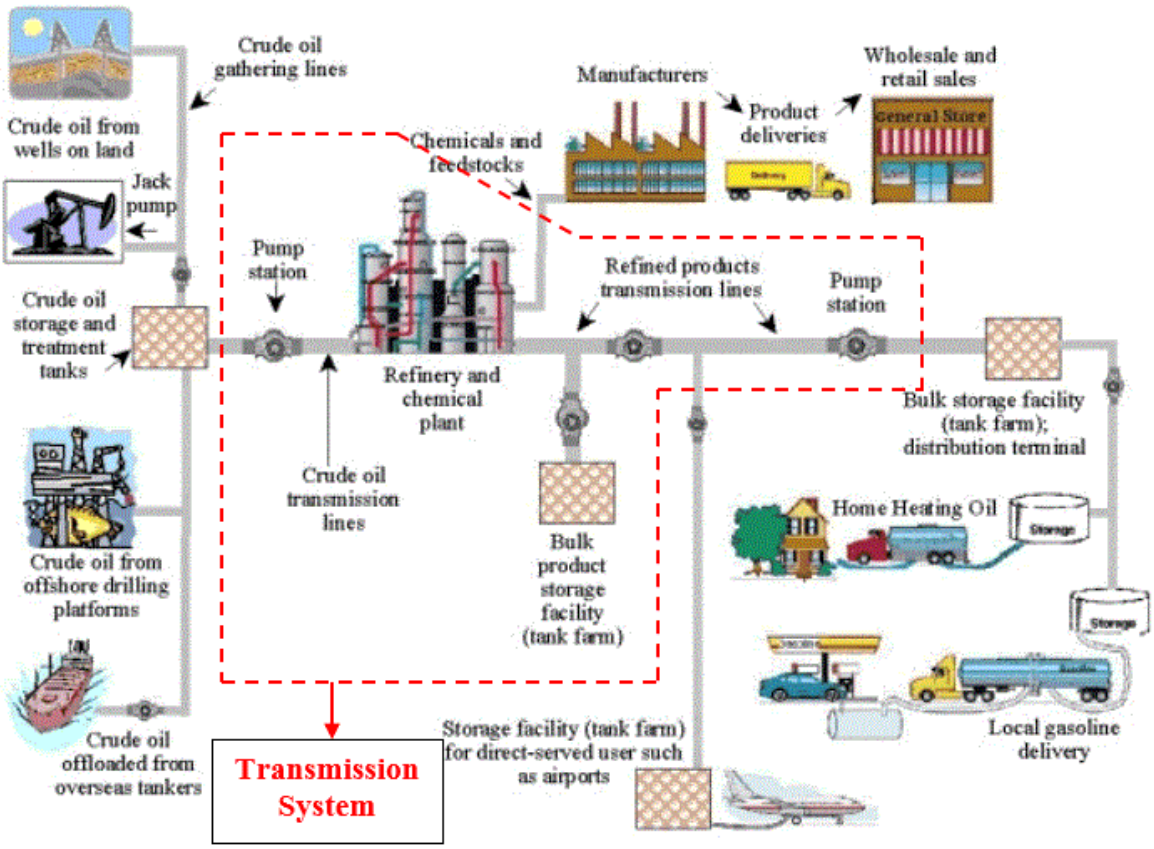

Figure 6.2 Oil Pipeline System Schematic

Based on the schematics shown in Figure 6.1and Figure 6.2, the review focused on six major facility types as summarized in Table 6.1. In addition to the facility types in Table 6.1, liquefied natural gas (LNG) processing terminals are included. LNG terminals process and liquefy natural gas or vaporize LNG for import or export purposes and may be connected to transmission pipeline systems. Throughout this section, the term "component" refers to hydrocarbon-containing equipment or components inside a facility.

Commentary on Other Facilities and LNG Plants

Facility	Typical Components	Source
Gas Compressor Station	compressors; heat exchangers (e.g. gas coolers); piping; valves; vessels (e.g. gas scrubbers)	EIA 2007 TCPL 2014
Gas Processing and Treatment Plant	heat exchangers; piping; storage tanks; valves; vessels (e.g. separators, filters)	EIA 2006
Gas Storage Facility	compressors; piping; heat exchangers; storage caverns/reservoirs; storage wells; valves; vessels	Wickenhauser et al. 2006 APA 2013
Petroleum Pump Station	breakout tanks; piping; pumps; valves	TCPL 2015 Argonne 2007
Petroleum Refinery and Chemical Plant	heat exchangers; piping; pumps; storage tanks; valves; vessels (e.g. distillation columns, reactors)	OSHA 2015 Chevron 2014
Petroleum Storage Facility	pumps; piping; storage tanks; valves	API 2005
LNG Plant	compressors; heat exchangers; piping; pressure relief device; pumps; storage tanks; vessels	DOE 2005

(1) Include pressure, process or reactor vessels.

Table 6.1 Types of Facilities in a Pipeline Transmission System and Their Typical Components

6.2 Review of Risk Models

6.2.1 Models

Two QRA models for oil and gas facilities were found in the public domain. These models focus on risk due to failure (loss of containment) of components in the facility. These models are recommended or prescribed by regulators or industry organizations in the United States and The Netherlands. They are:

1. **American Petroleum Institute Recommended Practice 581 Risk-Based Inspection Methodology, 3rd Edition, 2016**

   The American Petroleum Institute Recommended Practice 581 (API 2016) provides methods to calculate quantitative failure risk estimates for pressurized fixed components in refining, petrochemical, exploration and production facilities. The calculated risks are used to establish a risk ranking of the components of interest and develop an integrity management program for these components. This model will be referred to as API 581 throughout this report.

Commentary on Other Facilities and LNG Plants

2. **Bevi Risk Assessment Version 3.3, 2015**

   Bevi Risk Assessment (RIVM 2009) is a QRA model established in The Netherlands by the National Institute of Public Health and the Environment (RIVM). The primary purpose of this model is to determine the acceptable risk level for land use planning around facilities containing hazardous products. This model was based on the DNV risk software, SAFETI, and was modified to comply with the Dutch regulations. The modified software is called SAFETI-NL (Witlox and Worthington 2007). In 2015, a revised model, Gas Transport Bevi, Version 3.3 (RIVM 2015) was released, which includes QRA procedures specific to oil and gas onshore facilities. This model will be referred to as Bevi v3.3 throughout this report.

Two examples of the application of QRA to facilities were also found in the public domain. These models were developed by consulting firms for pipeline operators. The development of these models predominantly involved collecting and piecing together various models (e.g. the jet fire model and the failure frequency estimation model) into a single QRA model. These models are:

1. **C-FER QRA of TransGas Natural Gas Storage Caverns, 2006**

   C-FER developed a QRA model to analyze the financial and life safety risks associated with TransGas salt cavern natural gas storage facilities (Wickenhauser et al. 2006). The risk estimates calculated by the model were then used in a cost optimization analysis to determine the most cost-effective maintenance plan. This model was further modified in a subsequent C-FER – TransGas Project in 2014 to include reservoir storage facilities. The model only estimates the risks associated with the cavern or reservoir and its components up to the wellhead. This model will be referred to as the C-FER Gas Storage QRA throughout this report.

2. **Bercha Group QRA of Northern Gateway Project Pump Station**

   The Bercha Group developed a QRA model to assess the personnel and public safety risk inside and outside pumps stations of the proposed Northern Gateway Project (Bercha 2012). The Northern Gateway Project consists of an oil pipeline and a condensate pipeline in the same right-of-way. The QRA was carried out for the largest pump station in the system, which will pump both oil and condensate for the two pipelines. This model will be referred to as the Bercha Pump Station QRA throughout this report.

The main focus of API 581 and the C-FER Gas Storage QRA is to facilitate integrity management planning for facilities. Bevi v3.3 is used to demonstrate regulatory compliance with respect to land use planning and development around facilities. Similarly, the Bercha Pump Station QRA is used to demonstrate the acceptability of the individual risk levels for workers and the public in and around the station.

6.2.2 Risk Analysis Process

As with pipelines (Figure 3.1), the risk analysis process for facilities involves the following steps: system definition, threat identification, as well as failure frequency, consequence and risk estimation. These steps are described in various petrochemical and process industry publications (HSE 2002, CSChE 2004, ASME 2008 and Mannon 2012). The utilization of these steps in each risk model reviewed as part of the project is described in detail in the sections below.

6.2.3 System Definition

All of the quantitative risk models reviewed specify the system being analyzed as a collection of components carrying hazardous products within the facility boundary. Examples of these components are listed in Table 6.1. Risk estimation is typically performed for each individual component inside the facility, such as compressor units, pressure vessels or storage tanks.

With the exception of Bevi v3.3, none of the risk models define the boundary between the pipeline and the facility for the purpose of QRA modelling. Nevertheless, it is usually assumed that all components inside the facility site boundary or gate fall under the scope of the facility QRA. Bevi v3.3 covers all components within the boundary of the facility and sections of transport pipelines that branch-off to the facility site. The pipeline sections that fall under the scope of Bevi v3.3 are to be defined from a transition point determined by a competent authority. Bevi v3.3 also provides detailed initial screening procedures for selecting components in the facility that might pose a hazard to public safety outside the facility, which is consistent with its objective of assessing land use planning around the facility.

6.2.4 Threat Identification

API 581 and C-FER Gas Storage QRA explicitly consider multiple threats that can cause component failure, such as corrosion, crack, mechanical fatigue or natural hazard. Conversely, Bevi v3.3 and Bercha Pump Station QRA models only consider generic failure frequencies based on failure statistics, which can be interpreted to represent all failure causes.

6.2.5 Failure Frequency Estimation

6.2.5.1 Overview

Each risk model provides either an estimate of, or methods to estimate, the annual component failure frequency. With the exception of piping, the failure frequency estimates do not consider the size of the component. The failure frequency of piping is estimated per unit length-year, and it is a function of the pipe diameter. The only exception to this is the API 581 model, which does not define the failure frequency of piping on a per unit length basis, but only per unit time.

Commentary on Other Facilities and LNG Plants

All of the facility risk models listed above categorize the failure frequency by failure mode, where failure modes are grouped based on the failure consequence severity. API 581, C-FER Gas Storage QRA and Bercha Pump Station QRA define the failure mode based on the hole size. For Bevi v3.3, the failure mode is defined based on either the hole size or the release rate. Examples of release-rate-based definitions include 'instantaneous release of the entire content' or 'release of the entire content within 10 minutes in a continuous and constant stream'.

None of the risk models discussed here use SME opinion to estimate the failure frequency. Instead, the failure frequency is estimated using historical data or probabilistic and engineering modelling.

6.2.5.2 Historical Data

API 581, Bevi v3.3 and Bercha Pump Station QRA utilize historical data to estimate the failure frequency of various components in the facilities. The methodology used by each model is described below.

- **API 581**

  API 581 provides baseline historical failure frequencies and models to adjust these baseline failure frequencies. Two adjustment factors are used: one based on different threat categories, such as corrosion or brittle fracture, and the other based on the safety management system (SMS) implemented in the facility. The threat-specific adjustment factors are calculated from the component characteristics, the component susceptibility to the active damage mechanisms and inspection history of the component. All of the adjustment factors for multiple threats are then combined into a single adjustment factor using the procedure laid out in API 581 to estimate the component-specific failure frequency. The SMS adjustment factor is calculated from a series of scores that are based on user responses to a questionnaire on the attributes of the management system. The total score is then used to modify the failure frequency. Despite this comprehensive approach, API 581 specifies that the calculated failure frequencies are not intended to reflect the actual failure probabilities of various components and therefore, should not be used as absolute estimates in reliability analyses. Instead, the estimated failure frequency values are intended only for risk-ranking or risk-comparison between components.

- **Bevi v3.3**

  Bevi v3.3 provides generic component failure frequencies without any adjustments for the specific component or threat characteristics. These values were derived from historical failure statistics of the components or analogous components in the case of a lack of historical failure data. The application of these generic failure frequency values assumes that state-of-the-art technology and a good SMS are practiced in the facility. Bevi v3.3 allows for the use of failure frequencies other than the generic ones provided, if such frequencies are justified by a more advanced analysis (such as a fault tree analysis).

- **Bercha Pump Station QRA**

  The failure frequencies used by the Bercha Group were taken from The Netherlands Purple Book (1999), which is the QRA guideline predecessor of Bevi v3.3. Similar to Bevi v3.3, no component or threat-specific adjustment factors are used.

The unadjusted historical failure frequency approach used by Bevi v3.3 and The Netherlands Purple Book produces failure frequencies that represent industry averages. These values may not reflect the realities of a specific facility, and their usage could result in under- or overestimation of the risk results.

In 2012, the Health and Safety Executive (HSE) in the United Kingdom published historical failure frequency data (HSE 2012) for components in facilities with hazardous products, such as pressure vessels, pumps and valves. These failure frequency data are intended to be used for land use planning analysis around the facilities. In the same year, the Federal Energy Regulatory Commission (FERC) (FERC 2012) compiled historical failure frequency data for components in LNG facilities from various sources in the public domain. These sources include HSE, the Purple Book, the Bevi Risk Assessment model and various other studies (such as Gas Research Institute GRI 1981 and Pelto Baker 1984). These data can be used as supplements or substitutes in a QRA if they are found to be more suitable for a given component.

6.2.5.3 Probabilistic and Engineering Models

The C-FER Gas Storage QRA is the only study that utilized probabilistic and engineering models to estimate the failure frequencies of storage caverns and reservoirs. In particular, a probabilistic-based graphical model in the form of a fault tree was used. This fault tree was developed in-house by C-FER. The probabilities of the basic events used to construct the fault tree are based on a combination of historical data and engineering models. One example of the engineering models used to estimate the frequency of the basic events is the C-FER in-house pipeline structural reliability model for corrosion, which was applied to the well casing.

6.2.6 Consequence Estimation

6.2.6.1 Overview

Similar to pipeline failures, the consequences of a component failure and product release inside a facility depend on the product type and the failure mode, which determine the possible hazard scenarios. Also similar to the practice in pipeline industry, event trees are used to define all possible hazard scenarios associated with the released product and their probabilities of occurrence. Analysis of these hazard scenarios is used to estimate the life safety, environmental and financial consequences.

6.2.6.2 Hazard Scenarios

API 581 and Bevi v3.3 consider three types of hazard scenarios: fires, explosions and toxic clouds. Depending on the product type, release rate and time of ignition, fire scenarios can be further categorized as either flash fires, fireballs, pool fires or jet fires. API 581 also considers hazards resulting from non-flammable, non-explosive and non-toxic product releases, such as chemical splashes or steam burns. These models use event trees to identify and calculate the probability of occurrences of these hazard scenarios. An example of an event tree used in API 581 is shown in Figure 6.3. Methodologies used to calculate the hazard area associated with each hazard scenario are also provided in the above-mentioned risk models.

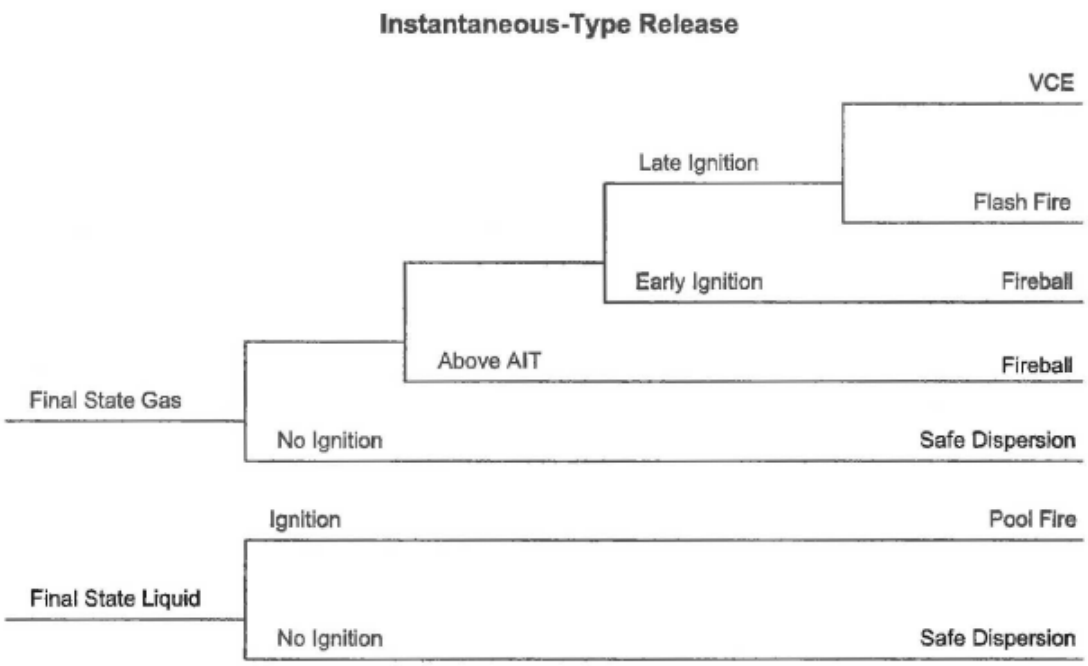

Figure 6.3 API 581 Level 1 Consequence Analysis for Instantaneous-Type Release Event Tree

The C-FER Gas Storage QRA only considers the jet fire scenario. This model assumes that delayed ignition of a gas release will form a non-hazardous buoyant gas cloud due to the lack of ignition sources at the heights (above ground level) that the gas will reach. The jet fire model was adapted from Stephens et al. (2002).

The Bercha Pump Station QRA also uses event trees to define all possible hazard scenarios. Fires and explosions are considered while toxic clouds are ignored due to the non-toxic nature of the product (i.e. crude oil and condensate). The size of the hazard areas resulting from these scenarios and the magnitude of the associated consequences were modelled using the commercial hazard assessment software TRACE (TRACE 1997) developed by Safer Systems.

Commentary on Other Facilities and LNG Plants

Other hazard scenario models are available in the public domain, as listed below. While it is outside the scope of this commentary to provide a detailed review of these models, they can be considered as alternatives to those reviewed in this report if they are deemed to be appropriate for a particular facility. Examples of these models are listed below:

- Bagster and Schubach 1996: prediction of jet fire dimensions;
- Rew et al. 1997: modelling of thermal radiation from hydrocarbon pool fires;
- Planas-Cuchi et al. 2004: modelling of overpressure from boiling liquid expanding vapor explosion (BLEVE) explosions;
- Fay 2006: modelling of large pool fires from an LNG release;
- Alonso et al. 2008a: consequence analysis of building damages due to vapour cloud explosions;
- Alonso et al. 2008b: consequence analysis of damages to humans due to vapour cloud explosions; and
- Sun et al. 2015: CFD modelling of a thermal radiation hazard around an existing LNG station from LNG pool fires.

The hazard scenarios described in this section can result in injuries and fatalities to the exposed population. The fire and explosion scenarios can also damage exposed components and infrastructure. In addition, some releases can have a negative impact on the environment (e.g. liquid spills) or financial consequences that affect the facility operator (e.g. business interruption cost). Details on how each facility risk model reviewed here addresses the life safety, environmental and financial consequences are described in the following three sections.

6.2.6.3 Life Safety

All of the facility risk models reviewed considered life safety consequences. API 581 and Bevi v3.3 consider life safety consequence due to fires, explosions and toxic clouds resulting from failure events. API 581 also considers the life safety consequences associated with the dispersion of non-flammable, non-explosive and non-toxic products. Since C-FER's model was focused on natural gas storage facilities, it considered only jet fires, which are the main hazard scenario associated with a natural gas release. Similarly, the Bercha Pump Station QRA only considered fire and explosion scenarios since the pump station will only carry crude oil and condensate.

API 581 and the C-FER Gas Storage QRA measure life safety consequences by the number of casualties (fatalities and injuries). This was calculated as the sum for all hazard scenarios of the product of the probability of occurrence, the calculated hazard area and the surrounding population density, where the population density included both workers and members of the public in the proximity of the facility. The expected number of casualties can be converted to an equivalent cost using a "cost per casualty" parameter. API 581 does not provide a specific value for this

parameter, leaving it up to the user to determine an appropriate value. The updated C-FER Gas Storage QRA in 2014 used a value of CAD$9 million per casualty, which was derived based on a study conducted by the United States Department of Transportation (DOT) on the value of a statistical life (DOT 2013).

Bevi v3.3 quantifies life safety consequences in terms of individual and societal risk, and it only considers the population outside of the facility boundary. The Bercha Pump Station QRA used only individual risk to both facility staff and members of the public.

6.2.6.4 Environmental Impact

Among the risk models reviewed here, only API 581 provides an approach to evaluate environmental consequences. However, this model is limited to estimating the liquid spill volume. The spill volume is then used to estimate the clean-up cost, which is a product of the spill volume and the clean-up cost per unit spill volume. The unit clean-up costs are dependent on where the spill is released. For example, spills into waterways will incur a higher clean-up cost than spills on dry land.

Environmental impact is not considered by Bevi v3.3 or the Bercha Pump Station QRA since these models are exclusively focused on life safety. The C-FER Gas Storage QRA does not consider environmental impact because the environmental consequences of a natural gas release are considered to be minimal.

6.2.6.5 Financial Impact

Since the focus of Bevi v3.3 and Bercha Pump Station QRA is on life safety, the financial consequences of failures are not accounted for by these models. On the other hand, the financial impact is an important component of the consequence models used in API 581 and the C-FER Gas Storage QRA, which focus on integrity management.

The list of costs accounted for by the financial consequence model in API 581 is as follows:

- the repair or replacement costs of the failed component;
- the repair or replacement costs of surrounding components based on the flammable and explosive damage area; and
- the business interruption costs due to downtime of the facility.

Aside from these costs, API 581 also provides a procedure to convert life safety and environmental consequences into financial costs. The financial consequence model in the C-FER Gas Storage QRA includes all of the elements in API 581 plus the cost of lost gas. The updated C-FER model in 2014 also provides a procedure to convert the life safety consequences into an equivalent financial cost (see Section 6.2.6.3).

6.2.7 Risk Estimation

Risk results from the four facility risk models reviewed are dependent on the main objective of each model. For Bevi v3.3, where the focus is on the life safety of the public outside the facility boundary for the purpose of land use planning, the outcomes of the analysis include individual risk contours and societal risk estimates presented in the form of F-N curves. Similarly, the Bercha Pump Station QRA produces individual risk contours in and around the facility to assess worker and public safety inside and outside the station.

The main objective of API 581 is to rank different components based on the level of risk and develop an inspection plan for each component. Similarly, the C-FER Gas Storage QRA results were used for cost optimization of the maintenance actions for the facility. Accordingly, the final results of these two models are expressed as an equivalent cost per year.

6.2.8 Domino Effect

Depending on the layout of the components in a facility, it is possible for a flammable/explosive event due to a failure of a component to cause a secondary failure of one or more adjacent components, leading to catastrophic damage. Examples of secondary hazard events include BLEVE or rupture/leak from a missile impact caused by the primary failure. The term “domino effect” is used to describe this phenomenon.

The domino effect was observed to be a somewhat frequent occurrence in chemical accidents that occurred either in facilities or during transportation (Kourniotis et al 2000). In particular, it was observed that the proportion of accidents involving liquid fuels or vapor hydrocarbons with at least one domino occurrence is greater than 50% (50 out of 93 sample accidents).

Out of the five risk models reviewed, only Bevi v3.3 explicitly includes a procedure to account for the domino effect in the risk estimation. The domino effect is considered only in estimating the probability of rupture of a high-pressure gas pipelines due to irradiation from an ignited flange leak in a nearby component. This was accomplished by determining the number of neighbouring flanges that can cause pipeline rupture and adding the rupture failure frequency due to the domino effect to the generic failure frequency of the pipeline.

There are numerous published studies on modelling the domino effect in facilities. These studies should be reviewed and considered in future facility risk model developments. Several of these models are summarized below:

- Khan and Abbasi (1998) described modelling of the probabilities of occurrence and consequences of domino effects in chemical process industries.
- Cozzani and Salzano (2004) detailed modelling of the probability of damage of components in process facilities due to overpressure.

- Pula et al. (2007) provided modelling of the probability of missile impact resulting from the burst of horizontal cylindrical vessels.
- Abdolhamidzadeh et al. (2010) used Monte Carlo simulation modelling of the probability of domino effect occurrence in process facilities.
- Jujuly et al. (2015) described CFD modelling of an LNG pool fire for domino effect analysis.

6.3 Comparison with Pipeline Models

6.3.1 Model Comparison

Facility risk models vary in complexity depending on their objective. Models that are used for the development of the integrity management programs (e.g. determining the frequency or method of inspection for high-risk components) are typically more complex and comprehensive than models that are solely focused on the evaluation of life safety risks. This variation is especially associated with the threat identification and failure frequency estimation stages of the risk analysis process.

Facility and pipeline risk models are compared for three key steps in the risk assessment process, namely threat identification, failure frequency estimation and consequence estimation. To highlight the advancements that have been made in both pipeline and facility risk models, the comparison is focused on the more advanced and complex models. Based on this comparison, elements of pipeline risk models that can be used to improve facility risk models are identified.

Threat Identification

Pipeline models consider multiple threats, which are standardized and listed in such publications as the ASME B31.8S Standard for Onshore Gas Pipelines (ASME 2014). The detailed facility risk models, such as API 581 and the C-FER Gas Storage QRA, also consider multiple threats. A comparison of the applicable threats considered in each model is shown in Table 6.2.

ASME B31.8S	API 581	C-FER Gas Storage QRA
Equipment failure	Brittle fracture	Erosion
External corrosion	Component lining damage	Equipment failure
Incorrect operation	Corrosion under insulation	External corrosion
Internal corrosion	External corrosion	Hydrate formation
Manufacturing defect	High-temperature hydrogen attack	Incorrect operation
Mechanical damage	Mechanical fatigue	Internal corrosion
Stress corrosion cracking	Stress corrosion cracking	Manufacturing defect
Weather/outside forces	Wall thinning	Mechanical damage
Welding/fabrication defect		Mechanical fatigue
		Stress corrosion cracking
		Weather/outside forces
		Welding/fabrication defect

Table 6.2 List of Applicable Threats in a Pipeline Code and Two Facility Risk Models

There are many similar threats across these models. The differences in applicable threats are usually related to the location or operating characteristic of the component. For example, API 581 does not consider mechanical damage (possibly because facilities are usually gated and not accessible to the public). On the other hand, a high-temperature hydrogen attack is a significant threat only for refining facilities that use hydrogen in their operations.

As discussed in Section 3.2.4, recent developments in pipeline risk models include the consideration of threat interactions. Interacting threats have not been considered in any of the facility risk models reviewed and could be considered as a possible future improvement of these models.

Failure Frequency Estimation

Pipeline risk models use SME opinion, historical data or probabilistic and engineering models to estimate the failure frequency. Failure frequency estimation in the facility risk models described here also use either historical data or probabilistic and engineering models, but none of these models use SME opinion.

Risk estimation based on modifying generic historical failure frequency data with adjustment factors to account for specific characteristics/threats of the component is used in both pipeline and facility risk models. In the probabilistic and engineering model approach, pipeline risk models utilize either the graphical method (e.g. fault tree) or the structural reliability method. One of the facility models reviewed utilizes a fault tree to estimate failure frequencies, but no facility models

that use the structural reliability method were found. This is likely due to the high degree of structural and geometric complexity of facility components.

There is potential to adapt some of the pipeline structural reliability models for facility components. In the C-FER Gas Storage QRA model, the frequency of casing failure due to corrosion is estimated using a corrosion structural reliability model originally developed for pipelines. This application was possible due to the geometric and material similarities between pipelines and well casing pipe. This demonstrates that some pipeline structural reliability models may be used to estimate the failure frequencies of facility components with similar shape and materials, such as the piping system or horizontal cylindrical pressure vessels. Any such transfer of models should be based on a careful review to ensure model applicability in the facility context.

Consequence Estimation

Both pipeline and facility risk models use comprehensive consequence modelling of hazard scenarios resulting from a product release. These models use event trees to calculate the probability of occurrence of all possible hazard scenarios, which depend on the product type, failure mode, release rate and time of ignition.

Both pipeline and facility models also consider the three consequence components, namely life safety, financial and environmental impact. The methodologies used to determine life safety and financial consequences are well-developed in both industries. Life safety consequences are typically characterized by individual and societal risk estimates. Financial impact calculations consider repair costs, service interruption costs, life safety compensation, and clean-up costs.

The approach used to characterize the environmental impact of a failure event in a petroleum facility is rather simplistic. API 581, the only model that address environmental impact, only provides a procedure to calculate the spill volume. Other factors that are usually covered in environmental impact models for pipelines, such as spill trajectories, potential for surface water and groundwater contamination and time for recovery of the habitat, are not considered. This is probably due to the fact that petroleum facilities in the U.S. are under the Environmental Protection Agency (EPA) Spill Prevention, Control, and Countermeasure (SPCC) regulation (40 CFR Part 112) (EPA 2005) that requires a secondary containment system (e.g. dikes) to prevent oil spill discharges to the environment. Where there is a potential for spills to contaminate areas outside the facility, the more comprehensive pipeline environmental impact models can be adapted for facilities.

6.3.2 Integration of Pipeline and Facility Risks

As described in Section 6.2.7, depending on the main purpose, facility risk models quantify risk in the form of either individual risk contours, societal risk curves or total dollar amounts with the combined life safety, financial and environmental risks. These are similar to the outputs of pipeline

risk models, making it possible to aggregate pipeline and facility risks to develop a risk profile of all assets in a transmission pipeline system.

One issue that poses a problem to the simple integration of pipeline and facility risks is variations in the assumptions, objective and level of detail used by different models. These variations may render the risk estimates incompatible for aggregation even though they are expressed in the same units. This issue was indirectly raised in API 581, which includes a disclaimer that its results should only be used to provide risk ranking of components and assist in the development of an inspection program, not for a rigorous reliability analysis of components. Thus, integration of risk results from pipeline and facility models should be undertaken with caution.

6.4 Summary

A review of the literature in the petrochemical and process industries has shown that QRA models are used extensively to assess the life safety risk around a facility or for the development and optimization of integrity management programs for the facility's components. Some of these QRA models are prescribed in codes or regulations in the United States and the Netherlands. There is a varying level of complexity of the available models depending on the objective of the QRA.

QRA that is used to assess the life safety risk around a facility does not usually evaluate each individual failure threat for different components. These models use generic historical failure frequencies that represent all possible failure causes for the components. For QRA models used for integrity management purpose, each applicable threat is considered individually based on either historical data (with adjustment factors) or probabilistic and engineering models.

Consequence measures for facilities are typically categorized into life safety, environmental and financial impacts. Consistent with their objective, QRAs that are used to assess life safety risk ignore the environmental and financial impacts of failure. On the other hand, QRAs aimed at defining integrity management programs consider all three categories, converted into an equivalent dollar amount.

QRA models for facilities are well developed, and their methodologies are mostly similar to those used for pipelines. Improvements to facility models that can be derived from the pipeline models include consideration of interacting threats, application of structural reliability analysis to estimate the failure frequency and application of more comprehensive liquid spill models for spills that extend beyond the facility boundary. Integration between pipeline and facility risk results appears to be straightforward since risk results are usually characterized by the same metrics (e.g. individual risk, dollar amount). However, caution should be used since the integration of risk results obtained from models with different assumptions, purposes and levels of detail might not be appropriate.

7. SUMMARY AND RECOMMENDATIONS

7.1 Summary

An industry survey and literature review were undertaken to investigate the current industry usage of QRA models in the pipeline industry. The survey showed that QRA models are most commonly used to evaluate risk against defined acceptance criteria, to monitor changes in risk over time, and to identify high-risk locations. Industry operators reported that they used a combination of quantitative and qualitative models for such tasks as excavation program planning, hydrostatic test interval evaluations, class location change evaluation, fitness-for-service assessments, design option comparisons and route selection. The survey also showed that all the reported qualitative models were used only for risk-based ranking of pipeline segments and identifying significant threats at specific locations. These findings suggest that quantitative risk models are being used when qualitative models are inadequate for specific purposes. The industry survey also demonstrated that the most desirable QRA model attributes include the flexibility to consider inputs in all formats as well as the ability to produce results that can be used to analyze risk by location and by threat, and to facilitate decision-making. The primary obstacles to the use of QRA are the effort involved in collecting data, the lack of acceptance criteria and the lack of standardized risk models. The survey participants also expressed the need for a standardized list of threats and interacting threats for consideration in QRA.

The literature review covered QRA model usage in the pipeline industry (including facilities and LNG plants), as well as other industries, including nuclear, aviation, offshore and power transmission. The conclusions of the review related to pipeline integrity management are as follows:

- In general, the models reviewed use the nine threat categories in ASME B31.8S (ASME 2014). Probabilistic models are used to estimate the failure frequencies associated with each threat. For major threats, such as corrosion, cracks and mechanical damage, structural reliability methods are the most common method of estimating the failure frequency. For other threat categories, SME opinion and historical data are more typically used. The publications included in the review did not address interactive threats, with the exception of Kariyawasam et al. (2014), who proposed a methodology to categorize interactive threats.

- Established models are available for quantifying the safety and financial consequences of natural gas releases. These include simplified publically available models as well as detailed commercial software packages.

- For hazardous liquids, safety consequence models are available as proprietary software packages. However, there are no established models to quantify the environmental and socio-economic consequences associated with low vapour pressure liquid releases. There is also no industry consensus regarding modelling approaches and no public domain information on the validation of the available proprietary models. Comprehensive environmental impact models

have been developed in connection with environmental impact assessments for new pipeline projects; however, these models are not typically used in QRA models.

With regard to other industries, the review showed that failure frequency estimation methods are common across all industries, with fault-tree methods and structural reliability methods being the most widely used. As with the pipeline industry, models to quantify consequences are less established and not consistently used. Instead, in the case of the nuclear industry, the NRC recognizes the large uncertainties in consequence models and deals with these uncertainties by defining two levels of analysis: one utilizing frequency-based estimates and acceptance criteria, and the other using risk-based estimates and acceptance criteria. The NRC has also developed standardized implementations of this two-stage approach. Quantitative risk acceptance criteria are absent in industries other than nuclear.

Operational factors are emphasized over structural integrity in the offshore and aviation industry QRA guidelines. As hazard identification is the most challenging element of operational risk assessment, the guidelines focus on data collection formats, and data analysis methods for hazard identification. The potential for human errors is also considered to be a significant source of operational risk in the nuclear, offshore and aviation industries. The characterization of knowledge uncertainties in connection with the estimation of the frequency of structural integrity failures is emphasized in guidelines from the nuclear and aviation industries. In the power transmission industry, QRA methods are recommended for cost-benefit analyses related to high frequency and low consequence events, whereas deterministic methods are recommended for low frequency and high consequence events.

In addition to the pipeline and other industries, risk models used for facilities and LNG plants were also reviewed. The methodologies used for the QRA of facilities are similar to those used for pipelines, and therefore, integration of QRA results for pipelines and facilities is possible. However, caution should be used when integrating risk results obtained from models developed with different assumptions, purposes and levels of detail.

Based on the review results and C-FER's prior experience, guidelines for the development and evaluation of pipelines QRA models were developed. The guidelines can be used by pipeline operators to develop or improve company-specific QRA models, and by regulators to evaluate such models. They are consistent with international risk assessment standards, such as ISO: 31010 (IEC 2009), BS PD 8010 (BSI 2013), NORSOK Z-13 (NORSOK 2010), and CSA Z662 Annex B (CSA 2015). They describe the methodologies required to estimate the failure frequency and failure consequences and to combine these into appropriate risk measures. They are intended to enable the development of repeatable, traceable and verifiable QRA models that treat uncertainties consistently. Different levels of analysis are described in the guidelines to enable the development of simplified subjective risk models and provide the tools to facilitate incremental improvements toward more detailed and objective models.

7.2 Future Work

- The literature review of risk models in the pipeline industry identified several gaps in the models required for QRA. The important gaps that could addressed in future work include the following:
  - A standardized method for identifying and classifying interacting threats does not exist, despite the fact that the industry recognizes the significance of threat interactions in estimating pipeline risk. In the industry survey, the need for a standardized list of interacting threats was highly ranked. Standardizing threat interactions would increase the likelihood of their inclusion in QRA.
  - Standard risk measures and simple models for environmental impact are lacking within the industry. This inhibits the use of quantitative measures, since detailed environmental assessments such as those performed in connection with regulatory submissions for large pipeline projects may be too onerous for the purpose of integrity management. The standardization of risk measures for environmental impact would promote the use of QRA and encourage the development of simplified models that address these risk measures.
  - Most life safety models for hazardous liquids are adapted from the process industry. These models are proprietary and are available through the use of specialized commercial software. For this reason, it is difficult to compare different approaches and evaluate their results. The lack of public-domain models also makes it difficult to assess the influence of consequence model uncertainty on the estimated risk. As demonstrated for natural gas pipelines, the availability of simplified life safety models for hazardous liquids pipelines would promote the use of QRA approaches to evaluate safety risks.
- Guidance on the characterization of input distributions, model uncertainties, and the effect of knowledge uncertainties on the estimated risk would facilitate wider application of QRA in the pipeline industry. As the QRA approach matures within the pipeline industry and data collection methods improve, addressing model uncertainties becomes more important than addressing data uncertainty.
- A pilot study that uses the guidelines to evaluate an existing quantitative risk model would demonstrate their value to operators and regulators. To conduct such a study, one or more QRA models currently in use must be made available, along with the data typically used with those models. Specifically, the guidelines can be used to evaluate the suitability of the model for the stated objectives, the validity of the data used, the risk analysis components included, the validation approaches undertaken, and the quality of model documentation.
- The development of a suite of benchmark problems is recommended to facilitate risk model validations by operators or other parties. Given such a suite, operator-specific QRA models can be validated by testing the model with given inputs and comparing the outcomes with the benchmarked outputs. The benchmark problems can be designed to address a variety of QRA objectives, levels of data quality, and resources.

8. REFERENCES

8.1 References – Pipeline Industry

Acton, M. and Baldwin, P. 2008. Ignition Probability for High-pressure Gas Transmission Pipelines. Proceedings of the 7th International Pipeline Conference, Paper No. IPC2008-64173, Calgary, Alberta, September 29-October 3.

Acton, M., Baldwin, T. and Jager, E. 2002. Recent Developments in the Design and Application of the Pipesafe Risk Assessment Package for Gas Transmission Pipelines. Proceedings of the 4th International Pipeline Conference, Paper No. IPC2002-27196, Calgary, Alberta, September 29-October 3.

Acton, M., Baldwin, P., Baldwin, T. and Jager, E. 1998. The Development of the Pipesafe Risk Assessment Package for Gas Transmission Pipelines. Proceedings of the 4th International Pipeline Conference, Paper No. IPC2002-27196, Calgary, Alberta, June 7-11.

American Society of Mechanical Engineers (ASME). 2014. Managing System Integrity of Gas Pipelines. AMSE B31.8S-2014, ASME Code for Pressure Piping B31, Supplement to ASME B31.8, September 30.

Ayello, F., Jain, S., Sridhar, N. and Koch, G. 2014. Quantitative Assessment of Corrosion Probability – A Bayesian Network Approach. Corrosion, Vol. 70, No. 11, November, pp. 1128-1147.

Ayyub, B. 2014. Risk Analysis in Engineering and Economics, Second Edition. CRC Press, Boca Raton, Florida, March.

Bandstra, D. and Gorrill, C. 2014. The Effects of Corrosion Measurement Error on a Safety Risk Assessment – A TransGas Case Study. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33471, Calgary, Alberta, September 29–October 3.

Bonvicini, S., Antonioni, G., Morra, P. and Cozzani, V. 2015. Quantitative Assessment of Environmental Risk Due to Accidental Spills from Onshore Pipelines. Journal of Process Safety and Environmental Protection, Vol. 93, January, pp. 31-49.

British Standards Institution (BSI). 2013. Pipeline Systems, Part 3: Steel Pipelines on Land – Guide to the Application of Pipeline Risk Assessment to Proposed Developments in the Vicinity of Major Accident Pipelines Containing Flammables. PD 8010-3:2009+A1:2013, July 31.

Canadian Standards Association (CSA). 2015. Oil and Gas Pipeline Systems. Standard Z662-15, Mississauga, Ontario, June.

Chan, P. and Webster, D. 2010. Probabilistic Assessment of ILI Metal Loss Features. Proceedings of the 8th International Pipeline Conference, Paper No. IPC2010-31298, Calgary, Alberta, September 27-October 1.

Chang, S., Stone, J., Demes, K. and Piscitelli, M. 2014. Consequences of Oil Spills: A Review and Framework for Informing Planning. Ecology and Society, Vol. 19, No. 2, Article 26.

References

Chen, Q. and Nessim, M. 1999. Reliability-based Prevention of Mechanical Damage to Pipelines. Prepared for the Offshore/Onshore Design Applications Supervisory Committee – Pipeline Research Committee, of Pipeline Research Council International, Inc. Catalog No. L51816. August.

Chen, Q., Davis, K. and Parker, C. 2006. Modeling Damage Prevention Effectiveness Based on Industry Practices and Regulatory Framework. Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10433, Calgary, Alberta, September 25-29.

Cicansky, K. and Yuen, G. 1998. Risk Management at TransCanada Pipelines. International Pipeline Conference, Calgary, Alberta, June 7-11, Vol. 1, pp. 9-14.

Cosham, A., Haswell, J. and Jackson, N. 2008. Reduction Factors for Estimating the Probability of Failure of Mechanical Damage Due to External Interference. Proceedings of the 7th International Pipeline Conference, Paper No. IPC2008-64345, Calgary, Alberta, September 29-October 3.

Committee for the Prevention of Disasters (CPR). 1999. Guidelines for Quantitative Risk Assessment "Purple Book" CPR 18E. Prepared Under the Supervision of the Committee for the Prevention of Disasters, First Edition, The Hague, The Netherlands.

Dawotola, A. 2012. Quantitative Risk Analysis of Spillage in a Petroleum Pipeline. International Petroleum Exhibition & Conference, SPE Paper No. 161487, Abu Dhabi, UAE, November 11-14.

Dawotola, A., van Gelder, P. and Vrijling, J. 2009. Risk Assessment of Petroleum Pipelines Using a Combined Analytical Hierarchy Process – Fault Tree Analysis (AHP-FTA). Proceedings of the 7th International Probabilistic Workshop, Delft, Netherlands, pp. 491-501.

Dawson, J., Colquhoun, I, Yablonskikh, I, Wenz, R. and Nguyen, T. 2010. Deterministic QRA Model and Implementation Experience via an Integrity Management Software Tool. Proceedings of the 8th International Pipeline Conference, Paper No. IPC2010-31236, Calgary, Alberta, September 27-October 1.

Dziubinski, M., Fratczak, M. and Markowski, A. 2006. Aspects of risk analysis associated with major failures of fuel pipelines. Published in the Journal of Loss Prevention in the Process Industries, Vol. 19, pp. 399-408

Esford, F., Porter, M., Savigny, K., Muhlbauer, K. and Dunlop, C. 2004. A Risk Assessment Model for Pipelines Exposed to Geohazards. Proceedings of the 5th International Pipeline Conference, Paper No. IPC2004-0327, Calgary, Alberta, October 4-8.

Etkin, D. 2004. Modelling Oil Spill Response and Damage Costs. Proceedings of the 5th Biennial Freshwater Spills Symposium, May.

Francis, A., Jandu, C. and McCallum, M. 2006. A Quantified Risk-based Design Assessment of a Localised "Pinch-point" on the Proposed Route of a High-pressure Natural Gas Pipeline. Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10074, Calgary, Alberta, September 25-29.

References

Francis, A., Gardiner, M. and McCallum, M. 2002. Life Extension of a High Pressure Transmission Pipeline Using Structural Reliability Analysis. Proceedings of the 4th International Pipeline Conference, Paper No. IPC2002-27159, Calgary, Alberta, September 29-October 3.

Francis, A., Espiner, R. and Edwards, A. 2000. Guidelines for the Use of Structural Reliability and Risk Based Techniques to Justify the Operation of Onshore Pipelines at Design Factors Greater Than 0.72. Proceedings of International Gas Union - World Gas Conference, Nice, France, June 8.

Girgin, S. and Krausmann, E. 2016. Historical Analysis of U.S. Onshore Hazardous Liquid Pipeline Accidents Triggered by Natural Hazards. Journal of Loss Prevention in the Process Industries, Vol. 40, March, pp. 587-590.

Goodfellow, G., Haswell, J., Jackson, N. and Ellis, R. 2014. Revision to the UK Pipeline Quantitative Risk Assessment Guidelines IGEM/TD/2 and PD8010-3. Proceedings of International Pipeline Conference, Paper No. IPC2014-33218, Calgary, Alberta, September 29-October 3.

Goodfellow, G., Haswell, J., McConnell, R. and Jackson, N. 2008. Development of Risk Assessment Code Supplements for the UK Pipeline Codes IGE/TD/1 and PD 8010. Proceedings of the 7th International Pipeline Conference, Paper No. IPC2008-64493, Calgary, Alberta, September 29-October 3.

Green, J., Postlewaite, L. and Anderson, P. 2015. Context for Assessing Effects on the Biophysical and Human Environment – The Pipeline Ecological and Human Health Risk Assessment for the Northern Gateway Pipeline Project. Proceedings of the Thirty-eighth AMOP Technical Seminar, Environment Canada, Ottawa, ON, pp. 526-535.

Humber, J., Glass, M., Cote, E. and Denby, A. 2012. Fate and Transport Modelling: Quantifying Potential Impacts for Pipeline Integrity and Emergency Response Preparedness. Proceedings of the 9th International Pipeline Conference, Paper No. IPC2012-90743, Calgary, AB, September 24-28.

Institution of Gas Engineers and Managers (IGEM). 2013. Assessing the Risks from High Pressure Natural Gas Pipelines. IGEM/TD/2, Second Edition, Communication 1764.

Jain, S., Ayello, F., Beavers, J. and Sridhar, N. 2012. Development of a Probabilistic Model for Stress Corrosion Cracking of Underground Pipelines Using Bayesian Networks: A Concept. Proceedings of the 9th International Pipeline Conference, Paper No. IPC2012-90340, Calgary, Alberta, September 24-28.

Jo, Y. and Ahn, B. 2005. A Method of Quantitative Risk Assessment for Transmission Pipeline Carrying Natural Gas. Journal of Hazardous Materials, Vol. A123, September, pp. 1-12.

Jonkman, S., Vrijling, J. and Van Gelder, P. 2006. A Generalized Approach for Risk Quantification and the Relationship Between Individual and Societal Risk. Safety and Reliability for Managing Risk, Guedes Soares & Zio (Eds), Taylor & Francis Group, London, pp. 1051-1059.

Jujuly, M., Rahman, A., Ahmed, S. and Khan, F. 2015. LNG Pool Fire Simulation for Domino Effect Analysis. Reliability Engineering and System Safety, Vol. 143, November, pp. 19-29.

References

Kariyawasam, S., Wang, H., Ong, B., Al-Amin, M. and Zhang N. 2014. Quantitative System Specific Likelihood Algorithms for System Wide Risk Assessment. International Pipeline Conference, Calgary, Alberta, September 29 - October 3, IPC 2014-33639.

Kraus, J. 2015. A Critical Evaluation of Risk Assessment Methodology for Natural Gas Pipeline. Safety and Reliability: Methodology and Applications – Nowakowski et al. (Eds), Taylor & Francis Group, London, pp. 43-47.

Lyons, C., Haswell, J., Hopkins, P., Ellis, R. and Jackson, N. 2008. A Methodology for the Prediction of Pipeline Failure Frequency Due to External Interference. Proceedings of the 7th International Pipeline Conference, Paper No. IPC2008-64375, Calgary, Alberta, September 29-October 3.

Mangold, D., Muhlbauer, K., Ponder, J. and Alfano, T. 2014. Implementation of Quantitative Risk Assessment: Case Study. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33641, Calgary, Alberta, September 29-October 3.

Markowski, A. and Mannan, M. 2009. Fuzzy Logic for Piping Risk Assessment (pfLOPA). Journal of Loss Prevention in the Process Industries, Vol. 22, November, pp. 921-927.

Martinez, J. and Rodriguez, E. 2000. Developing Tolerable Risk Criteria for Gas Transmission Pipelines. Proceedings of the 3rd International Pipeline Conference, Calgary, Alberta, October 1-5, Vol. 1, pp. 63-69.

McCallum, M., Francis, A., Illson, T., McQueen, M., Scott, M. and Clarke, S. 2004. A Robust Approach to Pipeline Integrity Management Using Direct Assessment Based on Structural Reliability Analysis. Proceedings of the 5th International Pipeline Conference, Paper No. IPC2004-0541, Calgary, Alberta, October 4-8.

Mihell, J. and Rout, C. 2012. Risk Assessment of Modern Pipelines. Proceedings of the 9th International Pipeline Conference, Paper No. IPC2012-90072, Calgary, Alberta, September 24-28.

Mitchell, J., Jasper, S. and Mihell, J. 2014. A Semi-Quantitative Risk Assessment to Support Oil Pipeline Risk-Based Design. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33659, Calgary, Alberta, September 29-October 3.

Mora, R., Parker, C., Vieth, P. and Delanty, B. 2002. Probability of Exceedance (POE) Methodology for Developing Integrity Programs Based on Pipeline Operator-Specific Technical and Economic Factors. Proceedings of the 4th International Pipeline Conference, Paper No. IPC2002-27224, Calgary, Alberta, September 29-October 3.

Nessim, M., Adianto, R. and Stephens, M. 2014. Limit States Design for Onshore Pipelines – Methodology and Implications. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33434, Calgary, Alberta, September 29-October 3.

Nessim, M. and Adianto, R. 2014. Limit States Design for Onshore Pipelines – Design Rules for Operating Pressure and Equipment Impact Loads. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33436, Calgary, Alberta, September 29-October 3.

References

Nessim, M., Yoosef-Ghodsi, N., Honegger, D., Zhou, J. and Wang, S. 2010. Application of Reliability Based Design and Assessment to Seismic Evaluations. Proceedings of the 8th International Pipeline Conference, Paper No. IPC2010-31557, Calgary, Alberta, September 27-October 1.

Nessim, M. and Stephens, M. 1998. Managing the Operating Risk Posed by Metal Loss Corrosion and Mechanical Interference. Proceedings of the 2nd International Pipeline Conference, Calgary, Alberta, June 7-11.

NORMA Official Mexicana (NOM). 2010. Administration de la integridad de ductos de recoleccion y transporte de hidrocarburos. NOM-027-SESH-2010, Abril 7.

Peng, X., Zhang, P. and Chen, L. 2009. Long-distance Oil/Gas Pipeline Failure Rate Prediction Based on Fuzzy Neural Network Model. Paper for 2009 World Congress on Computer Science and Information Engineering, Los Angeles, California, March 31-April 2, pp. 651-655.

Perez, J., Weir, D., Seguin, C. and Ferdous, R. 2014. Development and Implementation of a Liquid Pipeline Quantitative Risk Assessment Model. Proceedings of the 10th International Pipeline Conference, Paper No. IPC 2014-33705, Calgary, Alberta, September 29-October 3.

Pettitt, G., Ramsden, M. and Shakleton, J. 2014. Benchmarking Consequence Models with Actual Pipeline Events. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33546, Calgary, Alberta, September 29 - October 3.

Pipeline and Hazardous Materials Safety Administration PHMSA [Internet]. 2016. Pipeline Mileage and Facilities [current as of September 27, 2016]. PHMSA, Available from http://www.phmsa.dot.gov/pipeline/library/data-stats/ pipelinemileagefacilities

Pipeline and Hazardous Materials Safety Administration (PHMSA). 2011. Appendix C to Part 195 – Guidance for Implementation of an Integrity Management Program. 49 CFR Ch. 1 (10-1-11 Edition), U.S. Department of Transportation.

Rothwell, B. and Stephens, M. 2006. Risk Analysis of Sweet Natural Gas Pipelines – Benchmarking Simple Consequence Models. Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10059, Calgary, Alberta, September 25-29.

Shahriar, A., Sadiq, R. and Tesfamariam, S. 2012. Risk Analysis for Oil & Gas Pipelines: A Sustainability Assessment Approach Using Fuzzy Based Bow-tie Analysis. Journal of Loss Prevention in the Process Industries, Vol. 25, Issue 3, pp. 505-523.

Solis, R., Simon, A., Gonzalez, J., Muhlbauer, W. and Lugo, A. 2014. Development of a Probabilistic Pipeline Risk Assessment Software for Mexico's Oil State Company. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33108, Calgary, Alberta, September 29-October 3.

Sosa, E. and Alvarez-Ramirez J. 2009. Time-correlations in the Dynamics of Hazardous Material Pipeline Incidents. Journal of Hazardous Materials, Vol. 165, June, pp. 1204-1209.

Standards Norway (NORSOK). 2010. Risk and Emergency Preparedness Assessment. NORSOK Standard Z-013, Edition 3, Lysaker, Norway, October.

References

Stephens, M., Leewis, K. and Moore, D. 2002. A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines. Proceedings of the 4th International Pipeline Conference, Paper No. IPC2002-27073, Calgary, Alberta, September 29 – October 3.

Stephens, M. and Nessim, M. 1996. Pipeline Maintenance Planning Based on Quantitative Risk Analysis. Proceedings of the 1st International Pipeline Conference, Calgary, Alberta, June 9-13.

Sun, B., Guo, K. and Pareek, V. 2015. Dynamic Simulation of Hazard Analysis of Radiations from LNG Pool Fire. Journal of Loss Prevention in the Process Industries, Vol. 25, May, pp. 200-210.

Sutherby, R., Fenyvesi, L., Colquhoun, I. and Rizkalla, M. 2000. System Wide Risk-Based Pipeline Integrity Program at TransCanada. Proceedings of the 3rd International Pipeline Conference, Calgary, Alberta, October 1-5, Vol. 1, pp. 13-21.

Toes, G. and Rogers, M. 2010. A Revised Fault Tree Method for Determining the Effectiveness of Slabbing. GL Noble Denton, Report Number: 9551, Issue: 1.0, May 11.

Tomic, A., Kariyawasam, S. and Kwong, P. 2014. Effective Consequence Evaluation for System Wide Risk Assessment of Natural Gas Pipelines. Proceedings of the 10th International Pipeline Conference, Paper No. IPC 2014-33474, Calgary, Alberta, September 29-October 3.

Tomic, A. and Kariyawasam, S. 2014. Comparison of PIR to Pipesafe-Based 1% Lethality Zones for Natural Gas Pipelines. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33477, Calgary, Alberta, September 29-October 3.

U.S. Department of State (DOS) Keystone XL Pipeline Project. 2014 [Internet]. Final Supplemental Environmental Impact Statement [current as of September 16, 2016]. Available from: https://keystonepipeline-xl.state.gov/finalseis/.

Wickenhauser, P. and Playdon, D. 2004. Quantitative Pipeline Risk Assessment and Maintenance Optimization. Proceedings of the 5th International Pipeline Conference, Paper No. IPC2004-0451, Calgary, Alberta, October 4-8.

WorleyParsons. 2012. Semi-Quantitative Risk Assessment – Submitted in Response to Joint Review Panel Information Request Number 8.1(B). Northern Gateway Pipelines Limited Partnership – Enbridge Northern Gateway Project. Letter to National Energy Board. June.

Yuhua, D. and Datao, Y. 2005. Estimation of Failure Probability of Oil and Gas Transmission Pipelines by Fuzzy Fault Tree Analysis. Journal of Loss Prevention in the Process Industries, Vol. 18, Issue 2, March, pp. 83-88.

Zimmerman, T., Nessim, M., McLamb, M., Rothwell, B., Zhou, J. and Glover, A. 2002. Target Reliability Levels for Onshore Gas Pipelines. Proceedings of the 4th International Pipeline Conference, Paper No. IPC2002-27213, Calgary, Alberta, September 29-October 3.

Zuczek, P., Deng, C., Mihell, J. and Adams, K. 2006. An Overland-Hydrographical Spill Model and its Application to Pipeline Consequence Modeling. Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-64389, Calgary, Alberta, September 25-29.

8.2 References – Nuclear Industry

Boring, R., Gertman, D., Joe, J., Marble, J., Galyean, W., Blackwood, L. and Blackman, H. 2005. Simplified Expert Elicitation Guideline for Risk Assessment of Operating Events. U.S. Nuclear Regulatory Commission, INL/EXT-05-00433, June.

Drouin, M., Parry, G., Lehner, J., Martinez-Guridi, G., LaChance, J. and Wheeler, T. 2009. Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decision Making Main Report. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, NUREG-1855, Vol. 1, March.

Khaleel, M. and Simonen, F. 2009. Evaluations of Structural Failure Probabilities and Candidate Inservice Inspection Programs. United States Department of Energy Office of Science and Technical Information, Report No. NUREG/CR-6986; PNNL-13810, Richland, WA, May 1.

Kirwan, B. 1997. The Validation of Three Human Reliability Quantification Techniques – THERP, HEART and JHEDI: Part III – Practical Aspects of the Usage of the Techniques. Applied Ergonomics, Vol. 28, No. 1, February, pp. 27-39.

Kirwan, B., Kennedy, R., Taylor-Adams, S. and Barry Lambert. 1997. The Validation of Three Human Reliability Quantification Techniques – THERP, HEART and JHEDI: Part II – Results of Validation Exercise. Applied Ergonomics, Vol. 28, No. 1, February, pp. 17-25.

Kirwan, B. 1996. The Validation of Three Human Reliability Quantification Techniques – THERP, HEART and JHEDI: Part 1 – Technique Descriptions and Validation Issues. Applied Ergonomics, Vol. 27, No. 6, December, pp. 359-373.

Krall, A., Sawant, P., Choi, S., Khatib-Rahbar, M. and Helton, D. 2014. Compendium of Analyses to Investigate Select Level 1 Probabilistic Risk Assessment End-State Definition and Success Criteria Modeling Issues. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, NUREG/CR-7177, May.

Mitra, S., Hall, R. and Coppola A. 1981. A Study of the Implications of Applying Quantitative Risk Criteria in the Licensing of Nuclear Power Plants in the United States. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, NUREG/CR-2040, May.

Silva, K., Ishiwatari, Y. and Takahara, S. 2014. Cost Per Severe Accident as an Index for Severe Accident Consequence Assessment and its Applications. Reliability Engineering and System Safety, Vol. 123, March, pp. 110-122.

Swain, A. and Guttmann, H. 1983. Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, NUREG/CR-1278, August.

U.S. Nuclear Regulatory Commission (NRC). 2013. Three Mile Island Accident. Published as Backgrounder, Office of Public Affairs, February.

U.S. Nuclear Regulatory Commission (NRC). 2016a. Probabilistic Risk Assessment. Published in the Backgrounder Fact Sheet, Office of Public Affairs, February.

References

U.S. Nuclear Regulatory Commission (NRC) [Internet]. 2016b. Probabilistic Risk Assessment (PRA) [current as of September 27, 2016]. NRC, Available from http://www.nrc.gov/about-nrc/regulatory/risk-informed/pra.html

8.3 References – Offshore Industry

Aljaroudi, A., Khan, F., Akinturk, A., Haddara, M. and Thodi, P. 2015. Risk Assessment of Offshore Crude Oil Pipeline Failure. Journal of Loss Prevention in the Process Industries, Vol. 37, September, pp. 101-109.

American Bureau of Shipping (ABS). 2000. Guidance Notes on Risk Assessment Applications for the Marine and Offshore Oil and Gas Industries. Houston, Texas, June.

British Standards Institution (BSI). 2002. Petroleum and Natural Gas Industries – Offshore Production Installations – Guidelines on Tools and Techniques for Hazard Identification and Risk Assessment. BS EN ISO 17776:2002, October.

Det Norske Veritas (DNV). 2010. Risk Assessment of Pipeline Protection. Recommended Practice DNV-RP-F107, October.

Det Norske Veritas (DNV). 2001. Marine Risk Assessment. Health and Safety Executive, Offshore Technology Report 2001/063.

Health and Safety Executive (HSE). 2006. Guidance on Risk Assessment for Offshore Installations. Hazardous Installations Directorate, Offshore Division, Offshore Information Sheet No. 3/2006.

Nessim, M., Stephens, M. and Zimmerman, T. 2000. Risk-Based Maintenance Planning for Offshore Pipelines. Offshore Technology Conference, Houston, Texas, May 1-4.

United Kingdom Offshore Operators Association (UKOOA). (1999). A Framework for Risk Related Decision Support. Symposium Series No. 147. Sauf Consulting Ltd., London, United Kingdom.

Wu, W., Yang, C., Chang, J., Chateau, P. and Chang, Y. 2015. Risk Assessment by Integrating Interpretive Structural Modeling and Bayesian Network, Case of Offshore Pipeline Project. Reliability Engineering and System Safety, Vol. 142, October, pp. 515-524.

Xu, H., Chen, J., Wang, S. and Liu, Y. 2012. Oil Spill Forecast Model Based on Uncertainty Analysis: A Case Study of Dalian Oil Spill. Ocean Engineering, Vol. 54, November 1, pp. 206-212.

8.4 References – Aviation Industry

Cacciabue, P., Cassani, M., Licata, V., Oddone, I. and Ottomaniello, A. 2015. A Practical Approach to Assess Risk in Aviation Domains for Safety Management Systems. Cognition, Technology and Work, Vol. 17, No. 2, May, pp. 249-267.

References

Civil Aviation Authority (CAA) Safety Regulation Group. 2010. Guidance on the Conduct of Hazard Identification, Risk Assessment and the Production of Safety Cases For Aerodrome Operators and Air Traffic Service Providers. Civil Aviation Authority, CAP 760, December.

GAIN Working Group B, Analytical Methods and Tools. 2003. Guide to Methods and Tools for Airline Flight Safety Analysis. Second Edition, June.

Martinez-Guridi, G. and Samanta, P. 2002. Literature Search for Methods for Hazard Analyses of Air-Carrier Operations. Aircraft Safety Research & Development Branch, Federal Aviation Administration, BNL-69279, June.

Tong, Y. 2001. Literature Review on Aircraft Structural Risk and Reliability Analysis. Department of Defence, Defence Science & Technology Organisation, DSTO-TR-1110, February.

8.5 References – Power Transmission Industry

Dueñas-Osorio, L. and Rojo, J. 2011. Reliability Assessment of Lifeline Systems with Radial Topology. Computer-Aided Civil and Infrastructure Engineering, Vol. 26, No. 2, February, pp. 111-128.

Dunn, S., Wilkinson, S., Galasso, C., Manning, L. and Alderson, D. 2015. Development of Empirical Vulnerability Curves for Electrical Supply Systems Subjected to Wind Hazard. International Conference on Applications of Statistics and Probability in Civil Engineering ICASP12, Vancouver, British Colombia, July 12-15.

Hong, Y. and Lee, L. 2009. Reliability Assessment of Generation and Transmission Systems Using Fault-tree Analysis. Energy Conversion and Management, Vol. 50, No. 11, November, pp. 2810-2817.

North American Electric Reliability Corporation (NERC). 2010. Integrated Bulk Power System Risk Assessment Concepts. White Paper. Reliability Metrics Working Group.

Ouyang, M., Dueñas-Osorio, L. 2014. Multi-dimensional Hurricane Resilience Assessment of Electric Power Systems. Structural Safety, Vol. 48, May, pp. 15-24.

Risk-Assessment Working Group. 2005. Risk-Assessment Methodologies for Use in the Electric Utility Industry. North American Electric Reliability Council's Critical Infrastructure Protection Committee, September 9.

Siraj, T., Tesfamariam, S. and Dueñas-Osorio, L. 2015. Seismic Risk Assessment of High-voltage Transformers Using Bayesian Belief Networks. Structure and Infrastructure Engineering, Vol. 11, No. 7, June, pp. 929-943.

Winkler, J., Dueñas-Osorio, L., Stein, R. and Subramanian, D. 2010. Performance Assessment of Topologically Diverse Power Systems Subjected to Hurricane Events. Reliability Engineering and System Safety, Vol. 95, No. 4, April, pp. 323-336.

8.6 References – Guidelines

American Bureau of Shipping (ABS). 2000. Guidance Notes on Risk Assessment Applications for the Marine and Offshore Oil and Gas Industries. Houston, Texas, June.

The American Society of Mechanical Engineers (ASME). 2014. Managing System Integrity of Gas Pipelines, ASME Code for Pressure Piping, B31, Supplement to ASME B31.8. ASME B31.8S-2014, New York, New York, September 30.

The American Society of Mechanical Engineers (ASME). 2012. Manual for Determining the Remaining Strength of Corroded Pipelines, Supplement to ASME B31 Code for Pressure Piping. ASME B31G-2012, New York, New York, September 30.

Ayyub, B. 2014. Risk Analysis in Engineering and Economics, Second Edition. CRC Press, Boca Raton, Florida, March.

Bolt, R. 2006. A Guideline "Using or Creating Incident Databases for Natural Gas Transmission Pipelines, Report of Study Group 3.4. 23rd World Gas Conference, Amsterdam, The Netherlands, June 1-5.

Bonvicini, S., Antonioni, G., Morra, P. and Cozzani, V. 2014. Quantitative Assessment of Environmental Risk due to Accidental Spills from Onshore Pipelines. Process Safety and Environmental Protection, Publication of the Institution of Chemical Engineers, Volume 93, pp. 31-49, April.

Boring, R., Gertman, D., Joe, J., Marble, J., Galyean, W., Blackwood, L. and Blackman, H. 2005. Simplified Expert Elicitation Guideline for Risk Assessment of Operating Events. INL/EXT-05-00433, Idaho National Laboratory, Idaho Falls, Idaho, June.

British Standards Institution (BSI). 2013. Pipeline Systems, Part 3: Steel Pipelines on Land – Guide to the Application of Pipeline Risk Assessment to Proposed Developments in the Vicinity of Major Accident Pipelines Containing Flammables. PD 8010-3:2009+A1:2013, July 31.

Canadian Standards Association (CSA). 2015. Oil and Gas Pipeline Systems. Standard Z662-15, Mississauga, Ontario, June.

Canadian Standards Association (CSA). 1996. Introduction to Environmental Risk Assessment Studies. Guideline Z763-96, Mississauga, Ontario, June.

Det Norske Veritas (DNV) [Internet]. 2016. QRA and Risk Analysis Software – Phase and Safeti, Taking Hazard Analysis One Step Further [current as of September 27, 2016]. DNV GL, Available from https://www.dnvgl.com/services/qra-and-risk-analysis-software-phast-and-safeti-1676

Det Norske Veritas (DNV) and Muhlbauer, W. 2012. Pipeline Risk Assessment – The Essential Elements: An Initiative through Collaboration of DNV and W. Kent Muhlbauer. Pipeline & Gas Journal, Vol. 239, No. 5, May.

Det Norske Veritas. 2002. Marine Risk Assessment. Offshore Technology Report 2001/63, Prepared for the Health and Safety Executive, London, United Kingdom.

References

Drouin, M., Parry, G., Lehner, J., Martinex-Guridi, G., LaChance, J. and Wheeler, T. 2009. United States Nuclear Regulatory Commission - Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decision Making. Main Report NUREG-1855 Vol. 1, Albuquerque, New Mexico, March.

Etkin, D. 2004. Modeling Oil Spill Response and Damage Costs. Biennial Freshwater Spills Symposium, New Orleans, Louisiana, April 6-8.

Institution of Gas Engineers & Managers (IGEM). 2013. Assessing the Risks from High Pressure Natural Gas Pipelines. IGEM/TD/2 Edition 2, Communication 1764, Derbyshire, United Kingdom.

International Association of Oil & Gas Producers (IOGP). 2010. Consequence Modelling. Risk Assessment Data Directory, Report No. 434-7, Derbyshire, United Kingdom, March.

International Organization for Standardization (ISO). 2011. Data Quality – Part 150: Master Data: Quality Management Framework. Technical Specification ISO/TS 8000-150:2011(E), Geneva, Switzerland, December.

Interstate Natural Gas Association of America (INGAA). 2013. Interacting Threats to Pipeline Integrity – Defined and Explained. www.ingaa.org. Washington, D.C.

Kariyawasam, S., Wang, H., Ong, B., Al-Amin, M. and Zhang, N. 2014. Quantitative System Specific Likelihood Algorithms for System Wide Risk Assessment. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33639, Calgary, Alberta, Canada, September 29-October 3.

Lee, K., Boufadel, M., Chen, B., Foght, J., Hodson, P., Swanson, S. and Venosa, A. 2015. Expert Panel Report on the Behaviour and Environmental Impacts of Crude Oil Released into Aqueous Environments. Royal Society of Canada, Ottawa, Ontario, Canada, November.

Nessim, M., Adianto, R. and Stephens, M. 2014. Limit States Design for Onshore Pipelines – Methodology and Implications. Proceedings of 10th International Pipeline Conference, Paper No. IPC2014-33434, Calgary, Alberta, Canada, September 29-October 3.

RPS Group Applied Science Associates (RPS) [Internet]. 2016. OILMAP: Oil Spill Model and Response System [current as of September 27, 2016]. RPS ASA, Available from http://www.asascience.com/software/oilmap/

Oland, C., Rose, S., Grant, H., Lower, M., Spann, M., Kirkpatrick, J. and Sulfredge C. 2012. Studies for the Requirements of Automatic and Remotely Controlled Shutoff Valves on Hazardous Liquids and Natural Gas Pipelines with Respect to Public and Environmental Safety. ORNL/TM-2012/411, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 31.

Pipeline and Hazardous Materials Safety Administration (PHMSA) [Internet]. 2016. Incident Statistics - Incident Reports Database [current as of September 16, 2016]. Available from: http://www.phmsa.dot.gov/hazmat/library/data-stats/incidents

References

Pipeline and Hazardous Materials Safety Administration (PHMSA). 2011. Appendix C to Part 195 – Guidance for Implementation of an Integrity Management Program. 49 CFR Ch. 1 (10-1-11 Edition), U.S. Department of Transportation.

Skow, J., Lu, D. and Koduru, S. 2015. In-line Inspection Crack Tool Performance Evaluation. Pipeline Research Council International, Inc. (PRCI) Catalog No. PR-244-133731-R01, July 14.

Standards Norway (NORSOK). 2010. Risk and Emergency Preparedness Assessment. NORSOK Standard Z-013, Edition 3, Lysaker, Norway, October.

Stephens, M., Leewis, K. and Moore, D. 2002. A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines. Proceedings of the 4th International Pipeline Conference, Paper No. IPC2002-27073, Calgary, Alberta, Canada, September 29-October 3.

U.S. Department of State (DOS) Keystone XL Pipeline Project. 2014 [Internet]. Final Supplemental Environmental Impact Statement [current as of September 16, 2016]. Available from: https://keystonepipeline-xl.state.gov/finalseis/.

U.S. Department of Transportation (DOT). 2015. Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses - 2015 Adjustment. Memorandum, Washington, D.C., June 17.

U.S. Environmental Protection Agency (EPA). 2000. Risk Characterization Handbook. Prepared for the U.S. Environmental Protection Agency by Members of the Risk Characterization Implementation Core Team, a group of EPA's Science Policy Council, EPA 100-B-00-002, Washington, D.C., December.

Weaver, J., Charbeneau, R., Tauxe, J., Lien, B. and Provost, J. 1994. The Hydrocarbon Spill Screening Model (HSSM) Volume 1: User's Guide. Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Ada, Oklahoma, April.

WorleyParsons. 2012. Semi-Quantitative Risk Assessment – Submitted in Response to Joint Review Panel Information Request Number 8.1(B). Northern Gateway Pipelines Limited Partnership – Enbridge Northern Gateway Project. Letter to National Energy Board. June.

8.7 References – Other Facilities and LNG Plants

Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D. and Abbasi, S. 2010. A New Method for Assessing Domino Effect in Chemical Process Industry. Published in the Journal of Hazardous Materials, Vol. 182, No. 1, pp. 416-426.

Alonso, F., Ferradas, E., Perez, J., Aznar, A., Gimeno, J. and Minarro, M. 2008. Consequence Analysis to Determine Damage to Buildings From Vapour Cloud Explosions Using Characteristic Curves. Published in the Journal of Hazardous Materials, Volume 159, Issues 2-3, November, pp. 264-270.

References

Alonso, F., Ferradas, E., Sanchez, T., Aznar, A., Gimeno, J. and Alonso, J. 2008. Consequence Analysis to Determine the Damage to Humans From Vapour Cloud Explosions Using Characteristic Curves. Published in the Journal of Hazardous Materials, Volume 150, Issue 1, January, pp. 146-152.

APA Group (APA). 2013. Mondarra Gas Storage Facility Factsheet. August.

American Petroleum Institute (API). 2016. API Recommended Practice 581: Risk-Based Inspection Methodology. Third Edition, April.

American Petroleum Institute (API). 2005. API Standard 2610: Design, Construction, Operation, Maintenance, and Inspection of Terminal & Tank Facilities. Second Edition, May.

The American Society of Mechanical Engineers (ASME). 2014. Managing System Integrity of Gas Pipelines, ASME Code for Pressure Piping, B31, Supplement to ASME B31.8. ASME B31.8S-2014, New York, New York, September 30.

American Society of Mechanical Engineers (ASME). 2008. Inspection Planning Using Risk-Based Methods. Standard ASME PCC-3-2007, New York, New York, June 30.

Argonne National Laboratory. 2007. Overview of the Design, Construction, and Operation of Interstate Liquid Petroleum Pipelines. U.S. Department of Energy, Office of Scientific and Technical Information, Oak Ridge, TN, November.

Bagster, D. and Schubach, S. 1996. The Prediction of Jet-fire Dimensions. Published in the Journal of Loss Prevention in the Process Industries, Volume 9, Issue 3, May, pp. 241-245.

Bercha Group Limited. 2012. Northern Gateway Pipeline Pump Station Quantitative Risk Analysis. Final Report P1107. Calgary, AB, May 2.

British Standards Institution (BSI). 2013. Pipeline Systems, Part 3: Steel Pipelines on Land – Guide to the Application of Pipeline Risk Assessment to Proposed Developments in the Vicinity of Major Accident Pipelines Containing Flammables. PD 8010-3:2009+A1:2013, July 31.

Canadian Society for Chemical Engineering (CSChE). 2004. Risk Assessment – Recommended Practices for Municipalities and Industry. Canadian Society for Chemical Engineering, Ottawa, ON.

Canadian Standards Association (CSA). 2015. Oil and Gas Pipeline Systems. Standard Z662-15, Annex B, Mississauga, Ontario, June.

Chevron. 2014. Appendix 3, Overview of Oil Refining Process. Chevron Refinery Modernization Project EIR. March.

Committee for the Prevention of Disasters (CPR). 1999. Guidelines for Quantitative Risk Assessment "Purple Book" CPR 18E. Prepared Under the Supervision of the Committee for the Prevention of Disasters, First Edition, The Hague, The Netherlands.

References

Cozzani, V. and Salzano, E. 2004. The Quantitative Assessment of Domino Effects Caused by Overpressure. Part 1. Probit Models. Published in the Journal of Hazardous Materials, Vol. A107(3), April, pp. 67-80.

Energy Information Administration (EIA). 2007. Natural Gas Compressor Stations on the Interstate Pipeline Network: Developments Since 1996. Office of Oil and Gas, November.

Energy Information Administration (EIA). 2006. Natural Gas Processing: The Crucial Link Between Natural Gas Production and Its Transportation to Market. Office of Oil and Gas, January.

Fay, J. 2006. Model of Large Pool Fires. Published in the Journal of Hazardous Materials, Volume 136, Issue 2, August 21, pp. 219-232.

Federal Energy Regulatory Commission (FERC). 2012. Meeting Summary: Corpus Christi Project, Docket No. PF12-3-000, LNG Engineering Conference Call, May 7.

Gas Research Institute (GRI). 1981. Development of an Improved LNG Plant Failure Rate Database. Gas Research Institute, GRI-80/0093.

Health and Safety Executive (HSE). 2012. Failure Rate and Event Data (FRED) for Use Within Risk Assessments. PCAG chp_6K Version 12, June 28.

Health and Safety Executive (HSE). 2002. Application of QRA in Operational Safety Issues. Prepared by Det Norske Veritas Ltd. for the Health and Safety Executive, Research Report 025, Colegate, Norwich, United Kingdom.

Jujuly, M., Rahman, A., Ahmed, S. and Khan, F. 2015. LNG Pool Fire Simulation for Domino Effect Analysis. Reliability Engineering and System Safety, Vol. 143, November, pp. 19-29.

Khan, F. and Abbasi, S. 1998. Models for Domino Effect Analysis in Chemical Process Industries. Published in Process Safety Progress, an Official Publication of the American Institute of Chemical Engineers, June.

Kourniotis, S., Kiranoudis, C. and Markatos, N. 2000. Statistical Analysis of Domino Chemical Accidents. Published in the Journal of Hazardous Materials, Volume 71, Issues 1-3, pp. 239–252, January.

Mannon, S. 2012. Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control. Elsevier Publishers, Volume 1, Fourth Edition, Oxford, United Kingdom.

Netherlands. 1999. Guidelines for Quantitative Risk Assessment: "Purple Book". Publication Series on Dangerous Substances (PGS 3) CPR 18E.

Occupational Safety & Health Administration (OSHA). 2015. Petroleum Refining Process. Section IV: Chapter 2, United States Department of Labor, Washington, D.C.

References

Pelto, P. and Baker, E. 1984. Analysis of Liquefied Natural Gas (LNG) Release Prevention Systems. International Synfuels Policies and Technologies Symposium, PNL-SA-12278, Philadelphia, PA, August 19.

PHMSA [Internet]. 2016a. Natural Gas Pipeline Systems [Current as of September 27, 2016]. Available from http://primis.phmsa.dot.gov/comm/NaturalGasPipelineSystems.htm?nocache=5631

PHMSA [Internet]. 2016b. Petroleum Pipeline Systems [Current as of September 27, 2016]. Available from http://primis.phmsa.dot.gov/comm/PetroleumPipelineSystems.htm?nocache=8575

Planas-Cuchi, E., Salla, J. and Casal, J. 2004. Calculating Overpressure from BLEVE Explosions. Published in the Journal of Loss Prevention in the Process Industries, Volume 17, Issue 6, November, pp. 431-436.

Pula, R., Khan, F., Veitch, B. and Amyotte, P. 2007. A Model for Estimating the Probability of Missile Impact: Missiles Originating from Bursting Horizontal Cylindrical Vessels. Published in Process Safety Progress, Volume 26(2), June, pp. 129-139.

Rew, P., Hulbert, W. and Deaves, D. 1997. Modelling of Thermal Radiation from External Hydrocarbon Pool Fires. Published in Process Safety and Environmental Protection, Volume 75(2), May, pp. 81-89.

National Institute for Public Health and the Environment (RIVM). 2009. Gas Transport Establishments as Defined in Section 1b, Paragraph G of the Revi and Mining Installations as Defined in Section 1b, Paragraph H of the Revi.

Rijksinstituut for Volksgezondheid en Milieu (RIVM). 2015. Handleiding Risicoberekeningen Bevi. Ministerie van Volksgezondheid, Welzijn en Sport. Versie 3.3, Juli 1.

Safer Systems. 1997. TRACE Integrated Software for Chemical Risk Management, User's Guide, Version 8. November.

Stephens, M., Leewis, K. and Moore, D. 2002. A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines. Proceedings of the 4th International Pipeline Conference, Paper No. IPC2002-27073, Calgary, Alberta, Canada, September 29-October 3.

Sun, B., Guo, K. and Pareek, V. 2015. Dynamic Simulation of Hazard Analysis of Radiations from LNG Pool Fire. Journal of Loss Prevention in the Process Industries, Vol. 25, May, pp. 200-210.

TransCanada Pipelines Ltd. (TCPL) [Internet]. 2015. Pump Stations Fact Sheet [Current as of September 27, 2106]. EE4721-TCPL-PR-FS-0017-Rev02. Available from http://www.energyeastpipeline.com/wp-content/uploads/2015/10/Energy-East-Pipeline-Pump-Stations.pdf

References

TransCanada Pipelines Ltd. (TCPL) [Internet]. 2014. The Basics of a Compressor Station [Current as of September 27, 2106]. Available from https://www.princerupertgas.com/wp-content/uploads/2014/04/prince-rupert-natural-gas-transmission-compressor-station-basics-factsheet-transcanada.pdf

U.S. Department of Energy (DOE), Argonne National Laboratory. 2007. Overview of the Design, Construction, and Operation of Interstate Liquid Petroleum Pipelines. Environmental Science Division, ANL/EVS/TM/08-1, Chicago, IL, November.

U.S. Department of Transportation (DOT). 2015. Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses - 2015 Adjustment. Memorandum, Washington, D.C., June 17.

U.S. Environmental Protection Agency (EPA). 2005. Part 112 – Oil Pollution Prevention. SPCC Guidance for Regional Inspectors, Appendix B – 40 CFR Part 112, July 1.

Wickenhauser, P., Wagg, B. and Barbuto, F. 2006. Quantitative Risk Assessment: Underground Natural Gas Storage Facilities. Proceedings of the 6th International Pipeline Conference, Paper No. IPC2016-10411, Calgary, AB, September 25-29.

Witlox, H. and Worthington, D. 2007. QRA's for Dutch Installations: II. Overview of Risk Tool SAFETI-NL Selected by the Dutch Government. iChemE Symposium Series No. 153.

8.8 References – Summary and Recommendations

The American Society of Mechanical Engineers (ASME). 2014. Managing System Integrity of Gas Pipelines, ASME Code for Pressure Piping, B31, Supplement to ASME B31.8. ASME B31.8S-2014, New York, New York, September 30.

British Standards Institution (BSI). 2013. Pipeline Systems, Part 3: Steel Pipelines on Land – Guide to the Application of Pipeline Risk Assessment to Proposed Developments in the Vicinity of Major Accident Pipelines Containing Flammables. PD 8010-3:2009+A1:2013, July 31.

Canadian Standards Association (CSA). 2015. Oil and Gas Pipeline Systems. Standard Z662-15, Mississauga, Ontario, June.

The International Electrotechnical Commission (IEC). 2009. Risk Management – Risk Management Techniques. IEC/ISO 31010 Edition 1.0, Geneva, Switzerland, November.

Kariyawasam, S., Wang, H., Ong, B., Al-Amin, M. and Zhang N. 2014. Quantitative System Specific Likelihood Algorithms for System Wide Risk Assessment. International Pipeline Conference, Calgary, Alberta, September 29 - October 3, IPC 2014-33639.

Standards Norway (NORSOK). 2010. Risk and Emergency Preparedness Assessment. NORSOK Standard Z-013, Edition 3, Lysaker, Norway, October.

APPENDIX A – GLOSSARY

Appendix A – Glossary

Consequence: the effect of a pipeline failure on individuals or populations, property, or the environment.

Event Tree Analysis (ETA): an approach to characterize all possible outcomes arising from an undesirable event; represents all possible consequences of a failure event.

Failure Mode: the way in which a component fails.

Failure: a condition in which a pipeline exceeds one or more of its limit states.

Fault Tree Analysis (FTA): a logical and diagrammatic approach to define the combinations of basic events that cause an event of interest (called the top event).

Hazard Identification: the recognition that a hazard exists and the definition of its characteristics.

Hazard: a condition or event that might cause a failure, incident or any other condition that has the potential to cause harm to people, property, or the environment.

Individual Risk: the annual probability of fatality due to a pipeline incident for an individual situated at a particular location.

Limit State: a state beyond which a pipeline no longer satisfies one of its performance objectives.

Mechanistic Model: a physics-based mathematical model that predicts the pipeline response under a given set of conditions.

Model Uncertainty: the residual uncertainty in the predictions of a calculation model for which the exact values of all input parameters are known.

Probability of Failure: the probability that a component or a system will fail during a specified time interval (usually taken as one year). It equals 1.0 minus the reliability. Probability is the degree of belief regarding the likelihood of occurrence of an event.

Quantitative Risk Analysis (QRA): an approach that quantifies risk using probabilities to quantify likelihood and measurable parameters to quantify consequences.

Reliability analysis: an analysis that is carried out to estimate the reliability or probability of failure of a component or system.

Reliability: the probability that a component or system will perform its required function without failure during a specified time interval (usually taken as one year). It equals 1.0 minus the probability of failure.

Appendix A – Glossary

Risk: a compound measure of the frequency and severity of an adverse event. It is typically expressed as a product of the failure frequency of the event and its consequences.

Risk Analysis: the use of available information to identify hazards and estimate the associated risk.

Risk Assessment: the process of performing risk analysis and risk evaluation.

Risk Estimation: the process of combining probability and consequence analysis to produce a measure for risk.

Risk Evaluation: the process of evaluating if the estimated risk meets specified risk criteria or safety targets.

Societal Risk: a measure of risk to the society which is expressed as the frequency of the number of casualties (F-N curves) or the expected number of fatalities occurring due to a pipeline failure.

Threats: events or processes that may cause a release of product from the pipeline.

Time-dependent Limit State: a limit state for which reliability (or the probability of failure) changes as a function of time.

Time-independent Limit State: a limit state for which reliability (or the probability of failure) does not change as a function of time.

APPENDIX B – INDUSTRY SURVEY QUESTIONNAIRE

Appendix B – Industry Survey Questionnaire

(Note: This survey will be provided in an online format to the respondents. The format of the survey in the online form is indicated in the parentheses after each question. It is designed to take less than an hour of respondent's time.)

Recently, the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration ("PHMSA") announced three new research projects related to the evaluation of quantitative risk models and risk criteria, and held a workshop on Sep 9-10, 2015. C-FER Technologies (1999) Inc. ("C-FER") was awarded the project titled, "Critical Review of Candidate Pipeline Risk Models". The objective of the project is to conduct a critical review of the probabilistic quantitative risk analysis approach and use the review results to produce guidelines for developing and assessing the next generation of pipeline risk models. These guidelines will be based on an assessment of the desirable model attributes related to accuracy, verifiability, transparency, practicality and fit within the decision-making processes used by both operators and regulators.

This survey of operators, regulators and other industry partners will be used to identify the desirable attributes of a quantitative pipeline risk model.

The following questions address the risk models currently in use at your company

1. How many risk models does your company currently use? (choice from 0 to 5, more than 5)

Please provide answers for your current models: (if answer to Q1 > 1, the following questions Q2-Q5 will be repeated up to 5 times depending on answer to Q6)

2. Please provide a name for the risk model. (comment box)

3. Please briefly describe the risk model. (comment box)

4. Do you classify the current risk model as a qualitative model or a quantitative model? See the descriptions below and select the most appropriate option: (radio button)

   - *Qualitative*: Model results are represented on a subjective scale either as risk indices or as verbal descriptions, e.g., severe, high, medium, and low.
   - *Quantitative*: Model results are represented in terms of measurable units, e.g., expected dollar values for risk of damage.
   - *Other*: (provide comment below)

5. How is the model currently used? Select all that apply:

   - Demonstrate regulatory compliance
   - Identify significant failure threats at specific locations
   - Identify high risk locations

- Rank pipeline segments by risk
- Compare pipeline risk to the risk associated with other assets within the company
- Evaluate changes in risk over time
    - Evaluate the risk against a defined acceptance criteria
    - Evaluate the impact of class location changes
    - Determine inline inspection intervals
    - Select excavations
    - Evaluate the benefits of a hydrostatic test
    - Evaluate mechanical damage prevention strategies.
    - Evaluate the risk mitigation strategies associated with road crossings or river crossings
    - Inform route-selection for the new pipelines or pipeline re-route
    - Evaluate pipeline design options
    - Evaluate pipeline fitness for service
    - Other: (Please specify).(comment box)

6. Would you like to describe another model you currently use? (radio button)

- Yes
- No

The attributes of an ideal risk model depend on the objective of the risk analysis and the definition of the system scope. However, there are some generic attributes that are applicable to all risk models. Consider an ideal quantitative risk model while scoring the following attributes.

7. Score the following desirable attributes of an ideal quantitative risk model according to their importance. (Most Important (5) to Least Important (1))

- Inputs: Considers all forms of evidence available to operators (e.g., incident/failure data, assessment results, or mechanistic understanding)
- Defaults: Suggests appropriate defaults when information is missing
- Transparency: Has clear documentation on algorithms, models and approach.
- Flexibility: Considers pipeline-specific factors

- Repeatability: Produces consistent results upon repeated analysis by different analysts
- Threats: Quantifies the risk associated with the standard threats
- Rare threats: Quantifies the risk associated with interacting threats and rare threats
- Validation: Has been validated with respect to model framework and model outputs and has an open model structure that facilitates further validation by a third party.
- Output type: Produces results that can be compared against a risk criteria or against other asset risk
- Resolution: Identifies risk by location and by threat
- Decision-making: Produces results that form a basis for decision-making
- Value of new data: Assesses the value of collecting new information
- Other: Please provide comments below. (comment box)
- Uncertainty: Estimates the uncertainty in the results based on the level of uncertainty in the inputs

The purpose of this project is to review available options and produce recommendations for developing practical, verifiable and updatable quantitative risk models. However, there is a wide spectrum of possible approaches to probabilistic quantitative modeling with varying levels of detail and rigor, and the degree to which the benefits of the methodology can be realized depends on the approach used.

8. Given the above, score which of the following are the most important obstacles to the adoption of quantitative risk models? (Most Important (5) to Least Important (1))

- High effort and resources required for data collection and risk-analysis
- Lack of trained personnel to perform risk analysis
- Lack of standardized quantitative risk models
- Lack of regulatory acceptance
- Lack of accepted quantitative risk evaluation criteria
- Reluctance to calculate explicit safety risk estimators (e.g. expected number of fatalities)
- Other: Please provide comments below. (comment box)

Standardization of models would ensure consistent results industry-wide and requires less effort on the part of the users to evaluate and select models for their system. On the other hand, less

model standardization would allow the user to select the best-possible model for their system, but requires more effort to assess and validate the appropriateness of the model.

9. Given the above back ground, score which of the following attributes of risk models are the most desirable to be standardized? (Most desirable (5), Least desirable (1))

- Type of data inputs and data storage platform
- Form of output results (e.g., dollar value, expected number of fatalities)
- Methods for calculating probability
- Methods for calculating consequence
- List of threats to consider including rare threats and interacting threats
- Other: Please provide comments below. (comment box)

Thank you for taking the survey. Please provide the information below for additional follow-up regarding the survey responses

10. Please provide the best way to reach you:

- Name
- Email Address
- Phone Number

APPENDIX C – SUMMARY OF SURVEY RESULTS

Appendix C – Summary of Survey Results

1. How many risk models does your company currently use?

Respondent	Number of Models in Use	Number of Models Described	Model Numbering
1	1	1	11
2	2	1	21
3	2	2	31, 32
4	2	2	41, 42
5	3	3	51, 52, 53
6	3	2	61, 62
7	1	1	71
8	1	1	81

2. Do you classify the current risk model as a qualitative model or a quantitative model?

Model Number	Qualitative	Quantitative
11	Yes	
21		Yes
31	Yes	
32		Yes
41		Yes
42		Yes
51		Yes
52		Yes
53		Yes
61		Yes
62		Yes
71	Yes	
81	Yes	

Appendix C – Summary of Survey Results

3. How is the model currently used?

Options	Model Number					
	11	21	31	32	41	42
Demonstrate regulatory compliance			x	x	x	x
Identify significant failure threats at specific locations	x		x	x	x	x
Identify high risk locations	x	x	x	x	x	x
Rank pipeline segments by risk	x	x	x	x	x	x
Compare pipeline risk to the risk associated with other assets within the company		x				
Evaluate changes in risk over time	x	x		x	x	x
Evaluate the risk against a defined acceptance criteria		x		x	x	x
Evaluate the impact of class location changes					x	x
Determine inline inspection intervals			x	x	x	x
Select excavations				x	x	x
Evaluate the benefits of a hydrostatic test				x		
Evaluate mechanical damage prevention strategies		x		x	x	x
Evaluate the risk mitigation strategies associated with road crossings or river crossings				x	x	x
Inform route-selection for the new pipelines or pipeline re-route					x	x
Evaluate pipeline design options					x	x
Evaluate pipeline fitness for service						

Options	Model Number						
	51	52	53	61	62	71	81
Demonstrate regulatory compliance	x	x	x			x	x
Identify significant failure threats at specific locations	x	x	x		x	x	x
Identify high risk locations	x	x	x		x		
Rank pipeline segments by risk	x			x	x	x	x
Compare pipeline risk to the risk associated with other assets within the company				x	x	x	x
Evaluate changes in risk over time	x		x	x	x		
Evaluate the risk against a defined acceptance criteria	x	x	x	x	x		
Evaluate the impact of class location changes			x				
Determine inline inspection intervals		x		x	x	x	
Select excavations		x					
Evaluate the benefits of a hydrostatic test				x	x		
Evaluate mechanical damage prevention strategies			x			x	x
Evaluate the risk mitigation strategies associated with road crossings or river crossings						x	x
Inform route-selection for the new pipelines or pipeline re-route							
Evaluate pipeline design options							
Evaluate pipeline fitness for service		x	x				

4. Score the following desirable attributes of an ideal quantitative risk model according to their importance.

Options	Respondent			
	1	2	3	4
Inputs: Considers all forms of evidence available to operators (e.g. incident/failure data, assessment results, or mechanistic understanding)		4	5	5
Defaults: Suggests appropriate defaults when information is missing	4	2	4	4
Transparency: Has clear documentation on algorithms, models and approach	5	3	5	3
Flexibility: Considers pipeline-specific factors	5	3	5	4
Repeatability: Produces consistent results upon repeated analysis by different analysts	5	5	5	5

Appendix C – Summary of Survey Results

Options	Respondent			
	1	**2**	**3**	**4**
Threats: Quantifies the risk associated with the standard threats	5	4	5	5
Rare threats: Quantifies the risk associated with interacting threats and rare threats	4	2	5	3
Validation: Has been validated with respect to model framework and model outputs and has an open model structure that facilitates further validation by a third party	5	4	4	4
Output type: Produces results that can be compared against a risk criteria or against other asset risk	5	4	5	4
Resolution: Identifies risk by location and by threat	5	4	5	5
Decision-making: Produces results that form a basis for decision-making	5	4	5	5
Uncertainty: Estimates the uncertainty in the results based on the level of uncertainty in the inputs	4	2	3	4
Value of new data: Assesses the value of collecting new information	4	2	2	5

Options	Respondent			
	5	**6**	**7**	**8**
Inputs: Considers all forms of evidence available to operators (e.g. incident/failure data, assessment results, or mechanistic understanding)	5	5	5	5
Defaults: Suggests appropriate defaults when information is missing	5	3	3	2
Transparency: Has clear documentation on algorithms, models and approach	5	4	1	3
Flexibility: Considers pipeline-specific factors	5	5	4	4
Repeatability: Produces consistent results upon repeated analysis by different analysts	5	5	2	1
Threats: Quantifies the risk associated with the standard threats	4	5	3	5
Rare threats: Quantifies the risk associated with interacting threats and rare threats	5	4	1	2
Validation: Has been validated with respect to model framework and model outputs and has an open model structure that facilitates further validation by a third party	5	4	4	3
Output type: Produces results that can be compared against a risk criteria or against other asset risk	5	5	1	4
Resolution: Identifies risk by location and by threat	5	4	4	5
Decision-making: Produces results that form a basis for decision-making	5	4	5	3
Uncertainty: Estimates the uncertainty in the results based on the level of uncertainty in the inputs	5	4	2	2
Value of new data: Assesses the value of collecting new information	5	4	3	1

5. Score which of the following are the most important obstacles to the adoption of quantitative risk models

Options	Respondents			
	1	**2**	**3**	**4**
Significant effort and resources required for data collection and risk-analysis	2	5	3	4
Lack of trained personnel for performing risk analysis	3	2	1	4
Lack of standardized quantitative risk models	5	2	4	3
Lack of regulatory acceptance	5	3	2	2
Lack of accepted quantitative risk evaluation criteria	5	2	5	2
Reluctance to calculate explicit safety risk estimators (e.g. expected number of fatalities)	3	1	4	2

Options	Respondents			
	5	**6**	**7**	**8**
Significant effort and resources required for data collection and risk-analysis	5	5	2	4
Lack of trained personnel for performing risk analysis	5	4	1	5
Lack of standardized quantitative risk models	3	3	-	-
Lack of regulatory acceptance	5	3	3	3
Lack of accepted quantitative risk evaluation criteria	5	2	5	1
Reluctance to calculate explicit safety risk estimators (e.g. expected number of fatalities)	3	3	4	2

6. Score which of the following attributes of risk models are the most desirable to be standardized

Options	Respondents			
	1	**2**	**3**	**4**
Type of data inputs and data storage platform	3	3	3	5
Form of output results (e.g. dollar value, expected number of fatalities)	4	2	3	3
Methods for calculating probability	5	4	5	3
Methods for calculating consequence	5	4	5	3
List of threats to consider including rare threats and interacting threats	4	4	5	5

Appendix C – Summary of Survey Results

Options	Respondents			
	5	**6**	**7**	**8**
Type of data inputs and data storage platform	2	3	1	5
Form of output results (e.g. dollar value, expected number of fatalities)	1	2	2	4
Methods for calculating probability	4	3	3	3
Methods for calculating consequence	4	2	5	2
List of threats to consider including rare threats and interacting threats	3	4	-	-

APPENDIX D – BIBLIOGRAPHY – PIPELINE INDUSTRY

Appendix D – Bibliography – Pipeline Industry

Acton, M. and Baldwin, P. 2008. Ignition Probability for High-Pressure Gas Transmission Pipelines. Proceedings of the 7th International Pipeline Conference, Paper No. IPC2008-64173, Calgary, Alberta, September 29 - October 3.

This paper provides a revised formulation for the ignition probability of a gas release following a pipe rupture. Ignition probability is dependent on pipe diameter and pressure in the PIPESAFE software package for natural gas pipeline risk assessment. An empirical relationship between these pipeline parameters and the ignition probability is derived based on incident data collected from 1970 to 1996. This paper incorporates new data collected after 1996 to revise the empirical formulation for ignition probability. The data used include original data from 190 ruptures and 43 ignited ruptures, data from UKOPA and the European Pipeline Incident Data group (EGIG) collected between 1970 and 2004, and U.S. OPS data collected between 2002 and 2007. The trends and fit in the revised formulation are similar to the original formulation. The revised formulation provides slightly less conservative estimates of ignition probabilities in comparison to the original formulation.

Acton, M., Baldwin, P., Baldwin, T. and Jager, E. 1998. The Development of the PIPESAFE Risk Assessment Package for Gas Transmission Pipelines. Proceedings of the 2nd International Pipeline Conference, Calgary, Alberta, June 7 - 11.

This paper describes the development of the PIPESAFE software package and the mathematical models employed to estimate risk for natural gas transmission pipelines. PIPESAFE was developed in a collaborative industry effort; this paper focuses on the second phase of model development. It describes updated failure frequency models and failure consequence models, and presents validation results for the consequence model predictions. Detailed mathematical failure frequency models are presented for third party interference, corrosion and fatigue. In the software, failure frequencies due to other causes such as ground movements and manufacturing defects are defined through direct user inputs.

Consequence models include mathematical models for gas outflow, gas dispersion, thermal radiation from the initial fireball and the ensuing quasi steady-state fire, and impact on people. Two different mathematical gas outflow models are presented, which utilize dynamic network simulations in the presence of open or closed valves. A dispersion model is used to predict the bulk trajectory and dilution of the released gas. Two types of models are used to calculate the thermal radiation from the fireball and the quasi steady-state fire: detailed physically-based mathematical models and simplified empirical models. Both models are validated against experimental results. Thermal radiation effects are considered for a moving target, such as a person moving away from the fire, and a fixed target such as a building. Both individual risk and generic societal risk are estimated. A model for estimating site-specific societal risk is also described. Detailed analyses of the sensitivity of the model predictions to the input parameter variations and uncertainties are also performed. The paper concludes with a description of future development plans that are identified based on the results of the sensitivity and uncertainty analyses.

Acton, M., Baldwin, T. and Jager, E. 2002. Recent Developments in the Design and Application of the PIPESAFE Risk Assessment Package for Gas Transmission Pipelines. International Pipeline Conference, Paper No. IPC2002-27196, Calgary, Alberta, September 29 - October 3.

This paper describes the software package PIPESAFE, which estimates the safety risks associated with natural gas pipeline failures and enables an assessment of those risks against recognized risk criteria in the U.K. and the Netherlands. PIPESAFE is a comprehensive risk assessment package that includes pipeline failure frequency models for several failure causes and modes, and a consequence model that estimates gas outflow, dispersion, ignition, thermal radiation and effects on nearby population. The model was developed over several phases, and this paper focuses on developments carried out during Phase 3.

New developments reported in this paper include updates to ignition probabilities, crater source conditions, fire models and thermal radiation effects. The probability of ignition is modelled as a function of pipeline diameter and pressure. A variety of crater geometries and ruptured pipe end alignments are used to analyze the uncertainties associated with a crater release source. A new version of the crater fire model is described. Thermal radiation effects in a two-dimensional field around the crater fire are considered in the update. In addition, the results of two full-scale experimental tests are added to the original validation data which included 18 actual incidents. Although a high variability in the burn radius is observed due to variabilities in the local conditions, PIPESAFE predictions of the thermal effects on people are consistent with the data.

Ayello, F., Jain, S., Sridhar, N. and Koch, G. 2014. Quantitative Assessment of Corrosion Probability – A Bayesian Network Approach. Corrosion, Vol. 70, No. 11, pp. 1128-1147.

This paper presents a Bayesian network approach to estimate the probability of failure associated with internal and external corrosion. The Bayesian network approach is a graphical representation of the events leading to corrosion and corrosion-cased failures. Creating the graphical network with appropriate cause-consequence relationships is the first step in developing a Bayesian network. Once the direction of the links between causes and consequences are established, relationships between them are quantified in terms of conditional probabilities. These probabilities can be derived from physics-based models, expert knowledge and/or historical data. Once a network is complete, it does not require any further inputs other than the status of knowledge regarding the events and their possible outcomes. The status of knowledge is categorized as “known”, “unknown”, and “uncertain” in this paper.

The Bayesian network for internal metal loss considers the factors influencing the occurrence of erosion, microbial corrosion, and uniform and localized corrosion. These factors include the product, flow rate, steel wettability, and presence of inhibitors. The occurrence of various forms of corrosion is linked to wall thickness loss and flaw sizes, which are subsequently combined with other factors influencing the remaining strength of the pipe to model failure. Similarly, the external corrosion network considers the influence of cathodic protection, coating disbondment and soil chemistry. These factors are linked to the magnitude of corrosion rate, density and flaw sizes,

which in turn are linked to failure. The networks developed for internal and external corrosion are validated using data from an existing pipeline. The paper also describes an extension of the corrosion Bayesian network to include an estimation of the probability of failure due to stress corrosion cracking.

Bandstra, D. and Gorrill, C. 2014. The Effects of Corrosion Measurement Error on a Safety Risk Assessment – A TransGas Case Study. Proceedings of the 10th International Pipeline Conference, Paper No. IPC2014-33471, Calgary, Alberta, September 29 - October 3.

This paper describes a case study on the influence of ILI tool depth sizing error on estimated risk results. The case study focuses on TransGas' natural gas transmission system in Saskatchewan, Canada. Life safety risk results are expressed as individual risk. Individual risk is expressed as a ratio of the maximum individual risk to the risk acceptance criteria at each point along the pipeline. Pipeline failure frequency is computed using two approaches. A structural reliability approach is used to estimate the failure frequency associated with internal and external corrosion features measured with ILI. Historical-based approaches with modification factors are used for the remaining pipeline threats.

This case study demonstrates that reducing measurement uncertainty can reduce the risk estimates. Two ILI tools are used to measure axial corrosion features. The first ILI tool is a 'magnetic flux leakage' (MFL) ILI tool with a depth sizing error of 20% of pipe wall thickness. The second ILI tool is a circumferential MFL (CMFL) tool with a depth sizing error of 15% of pipe wall thickness. Using the refined sizing error to reduce the uncertainty in the feature size is shown to reduce the risk estimates from an unacceptable level to an acceptable level.

Bonvicini, S., Antonioni, G., Morra, P. and Cozzani, V. 2015. Quantitative Assessment of Environmental Risk Due to Accidental Spills from Onshore Pipelines. Journal of Process Safety and Environmental Protection, Vol. 93, January, pp. 31-49.

This paper uses quantitative risk assessment techniques to evaluate the potential environmental risk of onshore pipeline spills. The risk is expressed as a risk index and is defined for local damage and environmental societal impacts. This study finds that the effect of spill volume and the cost of groundwater spills is sensitive to soil properties and groundwater depth. It also demonstrates that block valves limit the volume and cost of spills.

In this assessment, the pipeline is divided into segments of uniform soil and groundwater properties. For every segment, a list of possible loss of containment (LOC) events is generated. The local risk indexes are calculated for each LOC event based on three remediation costs: excavation and disposal, soil clean-up, and groundwater clean-up. All costs are calculated as the product of the spill volume and the remediation cost per unit volume spilled. For each pipe segment, the appropriate techniques for remediation are chosen based on the soil and groundwater properties, which include: soil density and porosity, groundwater depth, and aquifer thickness. The remediation cost is calculated based on historical data from pipeline spills and converted to a cost per unit volume. The resulting local damage indexes depend on the probability of the spill

occurring in that specific segment. Environmental societal risk indexes are calculated as the sum of local damage indexes, using a process similar to societal risk curves for safety. The failure rates used in evaluating societal risk are based on methods proposed in other literature.

Chan, P. and Webster, D. 2010. Probabilistic Assessment of ILI Metal Loss Features. Proceedings of the 8th International Pipeline Conference, Paper No. IPC2010-31298, Calgary, Alberta, September 27 - October 1.

This paper uses the "Probability of Exceedance" (POE) methodology to assess pipe segments with corrosion features on a water pipeline. The POE methodology is used to identify potential leak locations associated with ILI-reported features.

Pipelines with dense corrosion features may contain features that interact; the DNV-RP-F101 methodology is adopted to define interacting features by longitudinal and circumferential proximity on the pipe surface. The pressure capacity of pipe segments containing interacting features is evaluated using the modified B31G formulation.

The POE methodology uses two steps. First the 'Point Estimate' method calculates the mean and variance of the pressure capacity. Using this method, pressure capacity is evaluated for eight combinations of length, depth, and width for all the features within the sectioned pipe surface. Based on these values and an assumed probability distribution for pressure capacity, POE is estimated and used as a screening tool to identify locations with high POE. Second, the Monte-Carlo sampling method is used to assess the true magnitude of POE at these locations. The approach identifies potential leak locations on a severely corroded water pipe based on the detected features during an ILI inspection. The methodology is demonstrated as useful for identifying leak locations for detected features, but not for identifying all leak locations because it ignores the uncertainties in feature detection by ILI inspection.

Chang, S., Stone, J., Demes, K. and Piscitelli, M. 2014. Consequences of Oil Spills: A Review and Framework for Informing Planning. Ecology and Society, Vol. 19, No. 2, Article 26.

This paper performs an extensive literature review of papers and reports related to the consequences of oil spills. The review focuses on the potential consequences of an oil tanker spill near Vancouver, Canada. A framework is created to consider the complexity of oil spill disasters. The framework considers the long-term ecological and societal impacts of the oil spill as well as the immediate economic and human safety impacts. To demonstrate the importance of particularities in oil spill consequences, a tanker spill off the coast of Vancouver is examined as a theoretical case study. In this scenario, the proximity to a dense urban area and relatively calm waters are highlighted as special concerns for the area.

Chen, Q. and Nessim, M. 1999. Reliability-based Prevention of Mechanical Damage to Pipelines. Prepared for the Offshore/Onshore Design Applications Supervisory Committee – Pipeline Research Committee, of Pipeline Research Council International, Inc. Catalog No. L51816, August.

This Pipeline Research Council International, Inc., (PRCI) report describes the data collected and the models developed to assess mechanical damage prevention activities. The model uses reliability methodology and consists of two parts. The first part is a fault-tree model that has the occurrence of equipment impact as its top event. Twelve basic events are defined in the fault-tree model to account for pipeline attributes (such as land use) and damage prevention strategies, such as right-of-way patrolling frequency. The second part is a model to estimate the probability of failure due to the puncture. For this purpose, a deterministic model for puncture resistance is developed and used in a structural reliability analysis.

The data collection is accomplished using an industry survey with 21 questions regarding the pipeline right-of-way conditions, the frequency of excavation activity, public awareness and utilization of one-call systems, operator response to one-call notifications and right-of-way surveillance. The probabilities of basic events required for the fault-tree model are derived from 15 responses to the survey. The results of the fault-tree model are validated using the industry-wide impact rate data. Recommendations for mechanical damage prevention are developed based on the analysis of the fault-tree model.

Chen, Q., Davis, K. and Parker, C. 2006. Modeling Damage Prevention Effectiveness Based on Industry Practices and Regulatory Framework. Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10433, Calgary, Alberta, September 25 - 29.

This paper describes a fault-tree model that evaluates the effectiveness of measures to prevent excavation damage. The major damage prevention activities are identified as encroachment management, public awareness, the use of right-of-way indications, the use of permanent alignment markers, right-of-way surveillance, dig notification process, dig notification response, pipeline locating and marking, excavation procedures, and the use of physical protection on the pipeline. Regulatory initiatives for the prevention of mechanical damage are summarized. A sample assessment of the effectiveness of right-of-way surveillance through patrolling is performed, and the results show that the probability of detecting excavation activity is less than 5% for unreported excavations if the patrolling frequency is less than one patrol per month.

Cicansky, K. and Yuen, G. 1998. Risk Management at TransCanada Pipelines. International Pipeline Conference, Calgary, Alberta, June 7 - 11, Vol. 1, pp. 9-14.

This paper describes the “TransCanada Pipelines Risk Assessment Model” (TRPAM) developed as a part of a pipeline maintenance program. The model is used for long term maintenance planning, near term prioritization of maintenance activities, consequence estimates, regulatory compliance and evaluation of design options. The application of this risk based approach is found to increase confidence in maintenance planning and estimate the effects of maintenance actions.

Risk is evaluated using societal risk and individual risk measures. Societal risk is expressed as the number of fatalities per year due to a rupture and is a function of the failure frequency, the ignition probability, the number of people at risk and the probability of fatality. Individual risk is expressed as the total probability of an individual fatality due to rupture of any pipeline within proximity of that individual. Failure frequencies are estimated for geohazards, corrosion, stress corrosion cracking, construction damage, third party damage, and material defects. The failure frequency estimations use field data, inline inspection data, SCADA data, maintenance history and expert opinion.

Cosham, A., Haswell, J. and Jackson, N. 2008. Reduction Factors for Estimating the Probability of Failure of Mechanical Damage Due to External Interference. Proceedings of the 7th International Pipeline Conference, Paper No. IPC2008-64345, Calgary, Alberta, September 29 - October 3.

This paper describes the development of 'reduction factors' as a simplified conservative estimate the probability of failure due to mechanical damage. The threats leading to the loss of containment considered include gouge and dent-gouge damage from external interference. All dents are assumed to contain a gouge. The parametric study considers a range of values for pipe diameter, wall thickness, grade, fracture toughness and design factors. The application of reduction factors shows that these factors are conservative approximations of the probability of failure for most cases.

To derive reduction factors using structural reliability methods three random variables are considered: dent depth, gouge length and gouge depth. The distributions of these random variables are derived from U.K. onshore transmission pipelines incident data. Published fracture resistance models from the literature are employed in the reliability analyses to assess probability of failure due to gouge and dent and gouge. The model uncertainties associated with each model are not considered.

Dawotola, A. 2012. Quantitative Risk Analysis of Spillage in a Petroleum Pipeline. International Petroleum Exhibition & Conference, SPE Paper No. 161487, Abu Dhabi, UAE, November 11 - 14.

This paper presents a quantitative risk assessment methodology for petroleum pipelines. A gasoline and a natural gas pipeline are analyzed with this method and the results are compared. The probability of failure, associated with different hazard events, is determined using an event tree. Historical failure records are used to determine the likelihood of each event branch. The paper concludes that gasoline pipeline failures have a wider impact area than natural gas pipeline failures.

For a gasoline pipeline, the hazard events are pool fire and overpressure. CANARY v4.2 software is used to model both scenarios. The same software is used to model the hazard events of a natural gas pipeline failure, defined as torch fire and vapour cloud dispersion. The individual and societal risks for both scenarios is calculated using SAFETI FX 6.5.1 software. The individual risk is plotted along the pipeline route and an F-N curve is used to evaluate the societal risk.

Dawotola, A., van Gelder, P. and Vrijling, J. 2009. Risk Assessment of Petroleum Pipelines Using a Combined Analytical Hierarchy Process – Fault-tree Analysis (AHP-FTA). Proceedings of the 7th International Probabilistic Workshop, Delft, Netherlands, pp. 491-501.

This paper presents an approach to combine the analytical hierarchy process ("AHP") with fault-tree analysis ("FTA") to perform risk assessment of petroleum pipelines. In this approach, subject matter experts ("SMEs") identify the factors contributing to pipeline failure. As per the AHP, a pairwise comparison of the pipeline segments with each risk factor generates a 'decision matrix', which represents the relative risk ranking of the pipe segments. The relative risk for each segment from a given risk factor can be assessed by comparing across rows, while columns describe the relative risk due to different risk factors for a given pipeline segment. This methodology is applied to a petroleum pipeline system in Nigeria.

Logical consistency within the decision matrix is checked using a 'consistency ratio', which is a function of a random index and a consistency index that is a weighted average of the values in the decision matrix. A consistency ratio of less than 0.1 is considered a suitable threshold in this paper for accepting the SME judgement regarding the important risk factors and the relative risk ranking of the pipeline segments. Once the most important risk factor contributing a segment of pipeline is identified, FTA is proposed for quantifying the probability of failure. As the relative likelihoods between different risk factors have been estimated through expert opinion, knowledge of probability of failure for one factor will provide an estimation for the total probability of failure.

Dawson, J., Colquhoun, I., Yablonskikh, I., Wenz, R. and Nguyen, T. 2010. Deterministic QRA Model and Implementation Experience Via an Integrity Management Software Tool. Proceedings of the 8th International Pipeline Conference, Paper No. IPC2010-31236, Calgary, Alberta, September 27 - October 1.

This paper describes a quantitative risk assessment (QRA) in two steps: a deterministic factor that modifies the baseline historical failure rates and a 'reliability-based step', which employs structural reliability methods to assess probability. This paper considers the threats listed by API 1160, ASME B31.8S, and DNV-RP-F116. Statistical independence between threats is assumed and the annual probability of failure due to any threat is computed assuming a homogeneous Poisson process for underlying pipeline failures.

Three failure modes are considered: small leak, large leak and rupture. Failure consequences corresponding to health and safety, environmental impact and financial impact are considered. The consequences for health, safety and financial impact are expressed in terms of the expected number of injuries and fatalities and as monetary loss. The environmental consequence is quantified by the flammable and toxic area due to a release and the environmental sensitivity and long-term damage. The evaluation of the consequence area is based on an event tree with the following outcomes: safe dispersion, jet fire, vapour cloud explosion, flash fire, fireball, liquid pool fire and boiling liquid expanding vapour explosion (BLEVE). The estimated consequence areas for each outcome are combined into a single estimate based on a probability-weighted empirical equation. The basic products addressed by this consequence modelling approach are natural gas, crude oil,

high-vapour pressure liquids, gasoline, kerosene, diesel and water. The three consequence types are mapped to a consequence severity scale for comparison. The overall risk is expressed in a risk matrix.

Dziubinski, M., Frątczak, M. and Markowski, A. 2006. Aspects of Risk Analysis Associated with Major Failures of Fuel Pipelines. Published in the Journal of Loss Prevention in the Process Industries, Vol. 19, pp. 399-408

This paper presents a risk analysis methodology to assess the life safety impacts associated with a gasoline or diesel transmission pipeline failure and applies the methodology to a pipeline in Poland. A fault tree model is presented to estimate failure frequencies. The fault-tree model considers the following pipeline threats: operational errors, corrosion, construction defects, design errors, third-party damage, and natural hazards. The failure frequencies for basic events in the fault tree are established using industry-wide historical data.

The potential hazards associated with a product release are assessed using an event tree. The probabilities of the events in the event tree are derived from industry-wide failure statistics. Potential hazards include: jet fires, fires on water, ground and water pollution. To quantify the consequences, the following parameters are defined: hole size, duration of release and weather conditions during release. Ground pollution is quantified as the depth of seepage of the product and considers the unignited release volume of the product. Water pollution is quantified as the zone of water surface contaminated, expressed in square kilometers. Life safety is quantified in terms of individual risk and societal risk using PHAST and SAFETI software packages.

Esford, F., Porter, M., Savigny, K., Muhlbauer, K. and Dunlop, C. 2004. A Risk Assessment Model for Pipelines Exposed to Geohazards. International Pipeline Conference, Paper No. IPC04-0327, Calgary, Alberta, October 4 - 8.

This paper describes a quantitative risk assessment on geohazards associated with the OSSA-1 pipeline in Bolivia. The paper identifies the following pipeline threats 1) tectonic threats including fault rupture and liquefaction, 2) geotechnical threats including landslides and debris flows and 3) hydrotechnical threats including river crossing hazards such as scour, bank erosion, encroachment and debris impact. The algorithms for estimating the likelihood of failure are dependent on the categorizations of geotechnical activity levels, the water table conditions, the terrain, the location of pipe and protective measures applied to the pipe. The total probability of failure is estimated as a weighted combination of the above parameters. The model is validated by comparing the results with South American historical pipeline incident data and by re-adjusting the indices as necessary.

Etkin, D. 2004. Modelling Oil Spill Response and Damage Costs. Proceedings of the 5th Biennial Freshwater Spills Symposium, May.

This paper describes a model called the basic oil spill cost estimation model (BOSCEM) to estimate the environmental impact of oil spills in inland waterways. The environmental impact is computed as the summation of the spill response costs, the socio-economic costs, and the environmental damage cost. The oil spill response cost is based on a cost per-gallon spilled and the cost of spill response measures. The cost values are provided for different product types (light fuels, heavy oils, crude oil, and volatile distillates) and for different spill response measures for recovery (mechanical recovery, dispersants, in-situ burn). Cost adjustment factors are based on the pipeline location and the effectiveness of the recovery method.

A similar approach is adopted to estimate the socio-economic and environmental damage costs. The base costs are listed by product type and spilled volume. Socio-economic adjustment factors are based on the cultural value of the spill site and environmental adjustment factors are based on the vulnerability of the freshwater resource and the habitat and wildlife sensitivity.

Francis, A., Espiner, R. and Edwards, A. 2000. Guidelines for the Use of Structural Reliability and Risk Based Techniques to Justify the Operation of Onshore Pipelines at Design Factors Greater Than 0.72. Proceedings of International Gas Union - World Gas Conference, Nice, France, June 8.

This paper presents guidelines for performing structural reliability analysis (SRA) to demonstrate that design factors greater than 0.72 meet the life safety objectives of design codes. The objectives of the ASME B31.8 and BS8010 design codes are identified as reducing the likelihood of failure and limiting the consequence associated with a failure event. In this paper, structural reliability analysis is used to evaluate the design objectives by demonstrating the safety of the pipeline. The paper ends with a discussion regarding the evaluation of the fitness-of-purpose based on the computed failure probability.

The structural reliability analysis methodology is broken into six tasks: establish limit states, identify pipeline threats, formulate limit state functions, perform uncertainty analysis, assess the failure probability and evaluate the results. Ultimate and serviceability limit states are considered for the most credible failure threats: external interference, external corrosion, and crack-like defects. Input parameters representing geometry, material properties, defect sizes and loads are characterized as random variables. Once all the limit state formulations and input random variables are assessed, numerical techniques for the evaluation of the probability of failure are presented.

Francis, A., Gardiner, M. and McCallum, M. 2002. Life Extension of a High Pressure Transmission Pipeline Using Structural Reliability Analysis. International Pipeline Conference, Paper No. IPC2002-27159, Calgary, Alberta, September 29 - October 3.

This paper presents an application of structural reliability analysis (SRA) to demonstrate adequate safety for an extended design life of a hypothetical onshore and offshore pipeline. For the onshore pipeline, the following failure threats are considered: external corrosion, third party interference and fatigue crack growth due to internal pressure cycling. For the offshore pipeline, the following

failure threats are considered: external corrosion, fatigue due to vortex-induced-vibrations, pipe-wall yielding at spans, and fatigue due to internal pressure cycling. Limit state formulas are presented for each of the failure threats considered.

The following random variables are modelled in the reliability analysis: wall thickness, yield strength and fracture toughness. Defect sizing is also characterized with random variables for corrosion, gouges, dents and construction defects. For the example application shown in this paper, external corrosion is found to be the most significant failure threat for the offshore pipeline. This pipeline threat is assumed to be mitigated for the onshore portion through regular inspection and maintenance actions.

Francis, A., Jandu, C. and McCallum, M. 2006. A Quantified Risk-based Design Assessment of a Localised "Pinch-point" on the Proposed Route of a High-pressure Natural Gas Pipeline. Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10074, Calgary, Alberta, September 25 - 29.

This paper describes a quantitative risk assessment of a natural gas pipeline proposed to be built through a highly populated area. The probability of failure is estimated using a structural reliability analysis. The consequence of failure is based on the thermal radiation dose received by a human in the vicinity of the failure.

The peak gas release rate is calculated using the standard choked orifice flow equation. The time-dependent release rate is calculated using widely accepted flow equations and a Colebrook and White formulation of the pipe friction factor. The thermal dose received by an individual is calculated as the time dependent heat flux integrated over the time it takes for the individual to escape from to safe shelter. A causality criteria of 1800 thermal dose units (TDU), or 1000 TDU for sensitive individuals, is used based on U.K. regulator criteria. The time to initial ignition and the distance to shelter are assumed to be uncertain quantities with known distributions.

The individual risk to a person at any specific location is a product of the probability of failure and the probability of an individual receiving a fatal dose of radiation from the failure. This acknowledges that there is a range of locations along the pipeline where a hazardous failure may occur. The societal risk is calculated by combining individual risk with population density. Individual risk is plotted along the pipeline and societal risk is expressed as an F-N curve.

Girgin, S. and Krausmann, E. 2016. Historical Analysis of U.S. Onshore Hazardous Liquid Pipeline Accidents Triggered by Natural Hazards. Journal of Loss Prevention in the Process Industries, Vol. 40, March, pp. 587-590.

This paper presents a review of pipeline failure incidents triggered by natural hazards, "natechs", for U.S. onshore hazardous liquids pipelines. This paper highlights 1) the importance of considering natural hazards a significant threat to onshore hazardous liquids pipelines, and 2) the data limitations associated with identifying and classifying significant incidents triggered by natural hazards.

A relational database was developed to store U.S. natechs failure incident data between 1968 and 2012. The data is sourced from PHMSA pipeline incident reports, U.S. National Response Center (NRC) hazardous substance pipeline spill reports, U.S Federal Emergency Management Agency (FEMA) disaster declarations, and U.S. National Oceanic and Atmospheric Administration (NOAA) storm records. The database implements a keyword-based data mining process to identify natechs that weren't explicitly identified in the PHMSA incident reports. Natechs identified through this process are manually verified and categorized using the available supporting evidence as either significant or insignificant incidents based on the PHMSA incident definitions. The categorization is intended to be consistent for all data over the time period under consideration, despite changes to the reporting requirements within this period.

The analysis shows that natechs account for 5.5% of the total number of incidents between 1986 and 2012. 60% of the natechs are categorized as significant incidents, but no significant yearly trend is observed within the analysis period. Five system component categories are assessed: pipelines, above ground storage, below ground storage, stations and terminals. Pipelines account for 46% of the significant natechs, followed by above ground storage, accounting for 30%. Natural hazards are categorized as geological, meteorological, hydrological, and climatic hazards. Meteorological hazards, which include heavy rainfall, tropical cyclone, storm, winter storm, high wind, tornado and lightning, are identified as the main hazard triggering 36% of natechs from 1986-2012. Geological hazards, which include earthquake, landslide, subsidence, frost heave, and other geological phenomenon, are the second most important hazard category, contributing to 26% of natechs. Four different product types are considered: crude oil, non-HVL refined petroleum products, HVL, and Carbon dioxide. Crude oil releases account for 47% of the natechs. Three categories of release are considered: ground, water, and atmosphere. 48% of natechs result in a release to ground.

Goodfellow, G., Haswell, J., Jackson, N. and Ellis, R. 2014. Revision to the UK Pipeline Quantitative Risk Assessment Guidelines IGEM/TD/2 and PD8010-3. International Pipeline Conference, Paper No. IPC 2014-33218, Calgary, Alberta, September 29 - October 3.

This paper details a revision to the U.K. pipeline quantitative risk assessment (QRA) guidelines. Detailed context is provided for the development and use of quantitative risk assessment methods in the U.K. As well, the paper clarifies the risk management of existing conditions around a pipeline and land use planning for new developments.

The QRA update considers the external interference and landslide threats. The paper describes an update to the damage distributions and the frequency of equipment hits for pipelines in the U.K. for use in the external interference failure frequency assessment. Generic failure frequency curves, which are a function of pipeline diameter, are developed from historical failure data. Modification factors to the generic failure frequency are developed based on the depth of cover and the presence of concrete slab protection. The proportion of failures that result in a pipeline rupture is determined based on the design factors. In order to ensure a reliable mitigation factor, technical specifications for the protective slab covering are also provided.

The frequency of landslide occurrence is based on the landslide incident rate and the survival value of a pipeline. The landslide incident rate is dependent on the U.K. geological conditions and is based on landslide susceptibility factors and categories for landslide potential defined by British Geological Survey. The dimensionless survival value for a pipeline is a function of the pipe wall thickness and the quality of the girth welds.

Goodfellow, G., Haswell, J., McConnell, R. and Jackson, N. 2008. Development of Risk Assessment Code Supplements for the UK Pipeline Codes IGE/TD/1 and PD 8010. International Pipeline Conference, Paper No. IPC2008-64493, Calgary, Alberta, September 29 - October 3.

This paper describes the development of regulatory code supplements for use in risk assessments related to land use planning. Land use planning around pipelines in the U.K. is addressed by a screening process called "Planning Advice for Developments near Hazardous Installations (PADHI). PADHI considers the sensitivity level of the proposed development and its location within the "land use planning" zones resulting in a decision matrix for the development. In addition to PADHI, a more detailed site-specific risk assessment may also be used. This paper describes a site-specific pipeline risk assessments and includes guidance on input data, model assumptions and assessment criteria.

Safety risks are considered in the development of the standardized risk assessment frame work while environmental risks are not considered. Dangerous fluids as defined in PSR 96, including natural gas, ethylene, spiked crude, ethane, propane and LPG and NGL are considered in the assessment. The failure modes considered are leaks and ruptures. Event trees are developed for all product types. Failure rates are based on historical failure frequencies for third party interference, external corrosion, internal corrosion, material and construction defects, ground movement and other damage mechanisms. To address the pipeline parameters such as age, wall thickness and diameter, modification factors for the generic failure frequencies are developed. Risk mitigation measures such as depth of cover, the use of a concrete slab, and design factors are evaluated. The code supplements provide guidance on assessing product release rates, ignition probabilities and thermal radiation effects. Risk measures used are the individual risk criteria, defined in the U.K. Health & Safety Executive (HSE), and the 'FN curve' criteria for societal risk.

Green, J., Postlewaite, L. and Anderson, P. 2015. Context for Assessing Effects on the Biophysical and Human Environment – The Pipeline Ecological and Human Health Risk Assessment for the Northern Gateway Pipeline Project. Proceedings of the Thirty-eighth AMOP Technical Seminar, Environment Canada, Ottawa, Ontario, pp. 526-535.

This paper describes the ecological and human health risk assessment (EHHRA) performed as part of the approval process for the Northern Gateway Pipeline Project. The objective of this assessment is to analyse the potential for spills to reach inland waterways, the spread of hydrocarbons in water, and the acute and chronic effects of the spill on wildlife and human health. The paper describes four locations and three transport fluids (condensate, synthetic oil and diluted bitumen) that were selected for the EHHRA.

The conclusions of the EHHRA indicate significant adverse effects associated with a spill, but the magnitude of the effect is highly variable based on the type of hydrocarbon, the volume of the spill, the location of the spill and whether the release is on land or directly into a watercourse. The effects of a spill into a watercourse are sensitive to the following parameters: the size of the watercourse, the slope and flow volumes, river bed substrate, the suspended particulates in the water, the weather conditions and the types of shoreline. The effects of a land release are considered limited compared to a watercourse release. The chronic effects of a release are estimated to affect local wildlife more than wide-ranging species such as grizzly bears. The acute effects on human health are found to be significant for a condensate release and chronic effects exceed the criteria for exposure when exposure pathways are through soil dermal contact, soil ingestion, and consumption of plant parts, berries and fish.

Humber, J., Glass, M., Cote, E. and Denby, A. 2012. Fate and Transport Modelling: Quantifying Potential Impacts for Pipeline Integrity and Emergency Response Preparedness. Proceedings of the 9th International Pipeline Conference, Paper No. IPC2012-90743, Calgary, Alberta, September 24 - 28.

This paper describes the fate and transport modelling for the Trans-Northern Pipeline Inc. (TNPI) spills in Southern Ontario and Quebec, Canada. The spill scenarios consider gasoline, diesel and jet fuel product types, as well as varying response times for leaks and rupture failure modes. Release volumes prior pipe segment isolation are estimated as the leak flow rate multiplied by the time to valve closure. Drain-down volume following the valve closures is estimated based on the release type and the resulting flow rate to the environment.

The overland flow of the spill is assessed with a digital elevation model that uses the following parameters: terrain type, barriers to flow, conduits for flow, release location, operating conditions, release volume, fluid properties, emergency response times and soil properties. The model results are shown as contours of the extent of the spill over the terrain for 15 minute time increments following the release. Stream tracing analysis is performed to identify if the spill extent intersects with inland streams. Valve placement scenarios are analyzed to identify locations that reduce risk.

Jain, S., Ayello, F., Beavers, J. and Sridhar, N. 2012. Development of a Probabilistic Model for Stress Corrosion Cracking of Underground Pipelines Using Bayesian Networks: A Concept. International Pipeline Conference, Paper No. IPC2012-90340, Calgary, Alberta, September 24 - 28.

This paper presents a probabilistic Bayesian network methodology applied to assessing the probability of failure associated with stress corrosion cracking (SCC) in high-pH environments. The model also evaluates the effect of a known occurrence of SCC on the probabilities of the contributing factors to SCC being in a certain condition. Bayesian network modeling is considered advantageous because it can address the uncertainty in the relationships between the input variables through the use of expert opinion in a more transparent and intuitive manner. In addition, the Bayesian approach allows prior probabilities to be updated as new data is collected.

The Bayesian network presented in the study considers the axial and circumferential stresses on the pipeline, the material properties of the pipeline, the environmental mechanisms for crack initiation and crack growth. Example applications of the development of input probability density functions and the results of the analysis are presented.

Jo, Y.-D. and Ahn, B. 2005. A Method of Quantitative Risk Assessment for Transmission Pipeline Carrying Natural Gas. Journal of Hazardous Materials, Vol. A123, September, pp. 1-12.

This paper focuses on the consequences of a natural gas pipeline failure expressed as individual risk and societal risk. Failure rates of pipelines are calculated using historical data, with external interference from third party activity being the most common form of failure. The consequences of a natural gas leak consider only the thermal effects of a jet fire; the consequences associated with explosions are assumed to be smaller. The peak gas release rate through hole is estimated using choked flow equations. The jet fire is idealized as a point source emitter whose thermal radiation is calculated using thermodynamic heat flux equations. Conservative values are used to estimate the radiation fraction, heat of combustion, and atmospheric transmissivity. Then, the probability of death is estimated using the probability unit formulation, based on other literature, which characterizes the relationship between heat flux, exposure time and fatality. The resulting expression determines the thermal dose required for 99%, 50% and 1% fatality rates. Using the jet fire model to predict thermal doses received at any distance from a pipeline, the radii of fatality is found to be a function of the release rate. Individual and societal risk is calculated by combining these consequences with historical failure rates.

The paper concludes with an example risk assessment of a 1 m diameter pipeline located in a town. The risk profiles are plotted along the length of the pipeline and societal risk is plotted on an F-N curve. The pressure of the pipeline is found to have the highest influence on the estimated risk.

Jonkman, S., Vrijling, J. and Van Gelder, P. 2006. A Generalized Approach for Risk Quantification and the Relationship Between Individual and Societal Risk. Safety and Reliability for Managing Risk, Guedes Soares & Zio (Eds), Taylor & Francis Group, London, pp. 1051-1059.

This paper describes a generalized approach to risk quantification. The tasks for evaluating individual and societal risk are: estimate the probability of a pipeline failure, estimate the intensity of the resulting hazard, analyze the dispersion effects, estimate the number of exposed people and estimate the number of fatalities. The paper concludes with a hypothetical application of the proposed methodology

The probability of a fatality is expressed as a function of the location given a release. Individual risk at a location from a single event is expressed as the probability of fatality multiplied by the frequency of failure. A link between individual and societal risk is illustrated by integrating the individual risk contours from all possible events with the population density. For spatially distributed incidents without a point-source release, integrating risk over the length of risk source

is proposed. Meteorological conditions, such as wind direction and its effect on dispersion of risk are considered.

Jujuly, M., Rahman, A., Ahmed, S. and Khan, F. 2015. LNG Pool Fire Simulation for Domino Effect Analysis. Reliability Engineering and System Safety, Vol. 143, November, pp. 19-29.

This paper describes a CFD simulation of a pool fire at an LNG facility. The simulation uses ANSYS CFX-14 to solve the fundamental fluid dynamics equation and considers turbulence, non-premixed combustion, radiation, and soot formation.

The model is tested on a theoretical LNG-fuelled power plant containing tanks, processing areas, and property lines. The effects of a pool fire on all of these elements is assessed for damage to the assets and the risk to human life. The threat of a 'domino-effect', a pool fire damaging an LNG tank, is assessed. The simulation is repeated with varying wind speeds.

Kariyawasam, S., Wang, H., Ong, B., Al-Amin, M. and Zhang N. 2014. Quantitative System Specific Likelihood Algorithms for System Wide Risk Assessment. International Pipeline Conference, Paper No. IPC 2014-33639, Calgary, Alberta, September 29 - October 3.

This paper presents a framework used by TransCanada for system-wide risk assessments. This is the first part of a two-part paper, and the second part is addressed by Tomic et al. (2014). The rationale for the threats considered and the method to estimate the likelihood of failure are described. The likelihood of failure is modelled as a linear combination of the 'predicted failure rate' associated with specific pipelines, observations from other assessments, and adjustment factors that consider the reliability of the data employed and other non-quantitative factors related to the pipeline. It is calculated with a regression function that defines the relationship between the historical failure rate for a given threat on a subsystem and the physics-based 'mechanistic factors'. Mechanistic factors are numerical indices based on expert opinion that account for the qualitative aspects of the cause and resistance of the system. Failure is defined for the rupture failure mode; leaks are converted to an equivalent rupture rate and added to the estimated rupture rate.

The data included in the assessment are: historical failure incidents, hydrostatic pressure tests, inline inspections, above-ground surveys, pipeline excavations and the mechanistic understanding of pipeline systems. Nine threat categories are considered including three groups of interacting threats: interacting coincident defects, interacting activating threats, and interacting common mode conditions. Validation and benchmarking of the approach is performed by comparing the model predictions with the historical pipeline failure rates and with the predictions from other models used at TransCanada.

Kraus, J. 2015. A Critical Evaluation of Risk Assessment Methodology for Natural Gas Pipeline. Safety and Reliability: Methodology and Applications – Nowakowski. et al. (Eds), Taylor & Francis Group, London, pp. 43-47.

This paper evaluates the uncertainty in a specific risk assessment methodology for use on natural gas pipelines, as it was recently adopted in the Czech Republic. The probability of pipeline failure is estimated based on historical EGIG data collected over a 40 year period. Reduction factors based on expert judgements are applied to the probabilities and are intended to account for the advancements in technology, pipeline construction and operating practices that have changed since the data was collected. The consequences of failure are estimated for each hazard that could result from the failure. Fire balls are modelled using a quantitative method described in a separate report. Jet fires are modelled using a simplified Chamberlain model. Flash fires are modelled using the Pasquill-Gifford model. For each consequence model, the heat flux and exposure time are used to calculate a thermal dose. Individual risk is based on the thermal doses and includes factors to account for the probability that an individual is present at the location of interest and whether shelter from the heat radiation is available to the individual.

The uncertainties associated with the consequence model parameters are evaluated as having a 'minor', 'moderate' or 'major' degree of uncertainty. The evaluation considers the mass flow rate and heat flux, the duration of the hazard and exposure time to individuals, the meteorological conditions at the time of failure, the probability of death, the probability of fire, the effects of personal protection, the influence of terrain and the number of people affected. Most parameters are found to have a 'moderate' degree of uncertainty. Historical data and probability of death are found to have a 'minor' degree of uncertainty. The probability reduction factors used in the fire models, the flash fire heat flux model, the use of personal protection and the influence terrain are found to have a 'high' degree of uncertainty.

Lyons, C., Haswell, J., Hopkins, P., Ellis, R. and Jackson, N. 2008. A Methodology for the Prediction of Pipeline Failure Frequency Due to External Interference. Proceedings of the 7th International Pipeline Conference, Paper No. IPC2008-64375, Calgary, Alberta, September 29 - October 3.

This paper presents the approach used in the U.K. pipeline code supplements to predict the pipeline failure frequency due to external interference. A fracture mechanics model for dent-gouge damage caused by external interference is used to predict pipeline failure. Model inputs are expressed as probability distributions. The failure frequency results were compared with the UKOPA fault and failure database.

The fracture mechanics model used is the semi-empirical 'British Gas' model, which assumes a combination of plastic collapse and brittle failure for defects in pipe wall. The leak and rupture failure modes are defined based on the defect length. The gouge length, gouge depth and dent depth parameters are modelled as Weibull probability distributions based on the UKOPA damage records. The damage incidence rate is also based on the number of incidents from the UKOPA database. Failure frequencies are computed for a number of pipe cases, and are compared to the predictions from the FFREQ software.

Mangold, D., Muhlbauer, K., Ponder, J. and Alfano, T. 2014. Implementation of Quantitative Risk Assessment: Case Study. International Pipeline Conference, Paper No. IPC 2014-33641, Calgary, Alberta, September 29 - October 3.

This paper presents the quantitative risk assessment approach adopted by SemGroup crude oil pipelines as part of an integrity management program. Using subject matter experts (SMEs), relative risk scores of risk indices are incorporated into a quantitative approach. Seven threat categories are considered in the assessment: mechanical damage, incorrect operations, sabotage, geohazards, external corrosion, internal corrosion, and cracking. All data used to evaluate the index scores is grouped into four categories: exposure, mitigation, resistance and consequence. The consequence analysis considers possible consequence scenarios identified as "most probable" and "worst case". Consequence measures include the following costs: spilled product, repair, health and safety, environmental damage, cleanup, lost production and reputation damage.

The results of the risk assessment are presented as risk profiles expressed in monetary units, and as a frequency of failure profile along the pipeline segments. The risk profiles are divided into total risk and consequence-only profiles. The frequency of failure profiles are displayed for each threat separately. Finally, a full network comparison of risk is performed by normalizing the risk over the total asset length.

Markowski, A. and Mannan, M. 2009. Fuzzy Logic for Piping Risk Assessment (pfLOPA). Journal of Loss Prevention in the Process Industries, Vol. 22, November, pp. 921-927.

This paper presents the application of a fuzzy logic system to layer of protection analysis (LOPA), resulting in pipeline fuzzy layer of protection analysis (pfLOPA). The fuzzy logic system is an inference system that depends on if-then-else rules based on linguistic labels and allows for inference from imprecise information. Inputs are converted to fuzzy inputs through a process called "fuzzification". Then, fuzzy set arithmetic and logic operations are performed, followed by "defuzzification" of the output. The defuzzification process converts a fuzzy set output to a single risk index number.

Classical LOPA is uses an event-tree to model the independent protection layers and the hazard frequency. In pfLOPA, each layer of protection is defined to be dependent on the previous layers and fuzzy logic is applied to estimate the probability of failure and the severity of the consequence. The results of the pfLOPA are expressed as a fuzzy risk matrix made up of a mitigated fuzzy frequency and mitigated fuzzy severity. A numerical example demonstrates the application of this approach to a gas pipeline in Poland.

Martinez, J.L. and Rodriguez, E. 2000. Developing Tolerable Risk Criteria for Gas Transmission Pipelines. International Pipeline Conference, Calgary, Alberta, October 1 - 5, Vol. 1, pp. 63-69.

This paper presents a risk assessment approach and tolerable risk criteria developed for pipelines of PEMEX Gas y Petroquimica Basica (PGPB) in Mexico. Total risk is calculated as the product of the expected frequency of pipeline failure and the associated consequence of the failure. The

failure frequency is calculated for the following threats: external corrosion, internal corrosion, third party damage, ground movement, design/materials, and system operations. A methodology to convert rate of failure indices to a quantified event frequency is developed. In this methodology, a regression equation converts the average failure index to a PGPB average incident frequency for each risk factor based on the PGPB incident history between 1990 and 1998.

The consequence of failure is calculated as the unit value of consequence multiplied by the total magnitude of consequence. The magnitude of the consequence index value is converted to a dollar value. The variables influencing the cost are repair and rehabilitation costs, the business impact, environmental damage, the number of fatalities and injuries. Fatalities and injuries are converted to a dollar value based on PGPB willingness to pay to avoid them. The total risk is expressed as an annual cost per mile of pipeline. Risk acceptance criteria are broadly divided into intolerable, controllable, and tolerable categories. Intolerable risk requires immediate risk reduction while controllable risks are planned for risk reduction based on a cost-benefit analysis. PGPG input data is used in a demonstration of the approach.

McCallum, M., Francis, A., Illson, T., McQueen, M., Scott, M. and Clarke, S. 2004. A Robust Approach to Pipeline Integrity Management Using Direct Assessment Based on Structural Reliability Analysis. International Pipeline Conference, Paper No IPC04-0541, Calgary, Alberta, October 4 - 8.

This paper demonstrates the application of the structural reliability analysis on a pipeline belonging to Crosstex Energy Services. Data from direct assessments, above ground surveys and bell-hole excavations, is used to demonstrate equivalence to integrity assessments based on inline inspection (ILI) results. The structural reliability approach is applied to assess the probability of failure due to the external and internal corrosion threats.

The pipeline failure modes are defined as leak or rupture. The limit states are based on the hoop stress and critical defect length. Uncertainties in the occurrence of external corrosion, sizing error and growth rates are characterized using a Bayesian updating approach which uses the direct assessment data and a prior probability based on similar pipeline systems operating in the U.K. Uncertainties in the occurrence of internal corrosion are characterized using a flow simulation model. The resulting failure probability is compared to the reliability analysis performed using the data from ILI. The probabilities of failure based on direct assessment data are lower than those based on ILI data for the external corrosion and both approaches provide similar predictive probabilities for internal corrosion.

Mihell, J. and Rout, C. 2012. Risk Assessment of Modern Pipelines. International Pipeline Conference, Paper No. IPC2012-90072, Calgary, Alberta, September 24 - 28.

This paper presents a risk assessment for proposed and new pipelines where the probability of failure is assessed in the absence of operational and inspection data. Failure rates based on industry-wide statistics are not used because they are not considered to be applicable for new pipelines exposed to improved coating systems and risk-informed mitigation efforts.

The internal and external corrosion feature density and feature size estimation is based on inline inspection (ILI) data from pipelines with similar deterioration mechanisms as the new pipeline. Based on the ILI data, probability distributions for feature length and depth are derived. Feature depth is considered to be time-dependent and has a proposed linear growth rate. A Monte Carlo simulation is used to assess the limit state based on the modified ASME B31G criteria and to estimate the failure probability. The probability of rupture and leak are differentiated based on the NG-18 flaw equation. Total probability of segment failure is based on the estimated probability of a corrosion feature and the density of the corrosion features based on the pipe surface area.

Mitchell, J., Jasper, S. and Mihell, J. 2014. A Semi-Quantitative Risk Assessment to Support Oil Pipeline Risk-Based Design. International Pipeline Conference, Paper No. IPC 2014-33659, Calgary, Alberta, September 29 - October 3.

This paper describes the risk assessment for the proposed Northern Gateway project in northern British Columbia, Canada. Based on the regulatory requirements, the risk assessment is for the full-bore rupture failure mode only. Risk is evaluated as a function of failure frequency and the consequence of failure. While failure frequencies are evaluated using a quantitative approach, for the purposes of the risk assessment, consequences are assessed using a qualitative severity index.

The approach considers three threat categories: internal and external corrosion, manufacturing and construction defects, and external threats including accidental impacts and geohazards. Corrosion threats are evaluated using a qualitative risk screening and quantitative assessments of a similar representative pipe. Manufacturing and construction defects are evaluated using historical data, with modification factors based on pipe-specific parameters. Accident impact is evaluated based on a fault-tree method and reliability models. Geohazards are evaluated using quantitative methods that consider four factors: the occurrence of event, the vulnerability of pipe to the event, and a reduction factor based on mitigation strategies. The quantitative values for each factor are based on expert opinion and the available geotechnical data. Consequences are evaluated based on the estimated spill volume and spill trajectories reaching potential high consequence areas. Since the consequence score represents a relative ranking, it is a qualitative measure. Risk outputs are presented as a risk severity matrix.

Mora, R., Parker, C., Vieth, P. and Delanty, B. 2002. Probability of Exceedance (POE) Methodology for Developing Integrity Programs Based on Pipeline Operator-Specific Technical and Economic Factors. International Pipeline Conference, Paper No. IPC2002-27224, Calgary, Alberta, September 29 - October 3.

This paper presents the use of the probability of exceedance (POE) method to manage pipeline integrity and mitigate risk due to corrosion for the TransGas pipeline system. The probability that the depth of corrosion feature exceeds 80% of the wall thickness is the POE leak criteria, and the probability that rupture pressure ratio exceeds 72% of specified minimum yield strength is the POE rupture criteria.

The ILI-reported feature sizes are adjusted based on the tool specification and verification digs. Critical features sizes are based on the applied growth rate. Feature dimensions are described by

probability distributions. The cumulative POE for leak and rupture is computed over the duration of interest using a linear growth rate model. Various scenarios for feature removal are identified through a deterministic methodology. These scenarios are considered in the evaluation of different sets of cumulative POE for leak and rupture criteria. Re-inspection and remediation intervals are proposed based on the cumulative POE curves and the evaluation of the net present value for each scenario.

Nessim, M. and Adianto, R. 2014. Limit States Design for Onshore Pipelines – Design Rules for Operating Pressure and Equipment Impact Loads. International Pipeline Conference, Paper No. IPC2014-33436, Calgary, Alberta, September 29 - October 3.

This paper presents the reliability-based design rules for onshore pipelines to address operating pressure and equipment impact loads. The design rules use characteristic values for the parameters influencing the demand and capacity of the pipeline related to a particular limit state. The design rules represent the limit state formulations to compute a safety factor for the design such that the reliability targets are met. The paper focuses on calibrating and evaluating the design rules for a range of design cases.

Depending on wall thickness, one of two limit states is found to dominate the results: either a burst of defect free pipe or failure due to equipment impact. By comparing the allowable probability and the transition probability where the dominant limit state changes from one to the other, the appropriate limit state is selected to calibrate the design rule. For failures of defect-free pipe due to internal pressure, all failures are assumed to be ruptures. For failure due to equipment impact, the failure mode is considered to be the burst of a gouged dent. The calibrated design rules are evaluated for 3,000 cases by comparing the target allowable probability with the probabilities evaluated using the reliability analysis.

Nessim, M., Adianto, R. and Stephens, M. 2014. Limit States Design for Onshore Pipelines – Methodology and Implications. International Pipeline Conference, Paper No. IPC2014-33434, Calgary, Alberta, September 29 - October 3.

This paper presents an overview of the limit states design methodology and the implications for onshore pipelines. A deterministic approach that produces consistent pipeline safety without using reliability calculations is developed. Design checks are developed such that a ‘characteristic’ demand value is less than the product of a safety factor and a ‘characteristic’ capacity value. The characteristic demand and capacity values are functions of the characteristic values of the input parameters. This approach implicitly results designs conforming to a selected safety level because it calibrates the safety factors and the selection of the characteristic values to probabilistic results. The deterministic design rules categorize limit states into the following three groups according to the similarity of consequences associated with each: ‘serviceability limit states’, ‘leakage limit states’ and ‘ultimate limit states’

The safety levels for ultimate limit states are defined in five safety classes. Each safety class covers a range of reliability targets and has an allowable probability of failure. The allowable probability of failure is divided between design and in-service ultimate limit states. Gas and LVP liquid

pipelines are assigned safety classes based on the societal-risk based reliability targets and environmental impact of the spill, respectively. The implications of this approach on the pipeline design are evaluated for the limit state design checks developed for two different ultimate and serviceability limit states. Based on the safety class, small diameter pipelines may require an increase in the design wall thickness for protection against equipment impact while the large diameter pipelines may allow for a decrease in the design wall thickness.

Nessim, M., Yoosef-Ghodsi, N., Honegger, D., Zhou, J. and Wang, S. 2010. Application of Reliability Based Design and Assessment to Seismic Evaluations. Proceedings of the 8th International Pipeline Conference, Paper No. IPC2010-31557, Calgary, Alberta, September 27 - October 1.

This paper demonstrates a reliability-based design and assessment methodology applied to pipelines exposed to the lateral spreading of soil during an earthquake event. The demonstration defines a set of design cases, develops a probabilistic characterization for permanent ground displacement (PGD), identifies the critical PGD for each design case, evaluates the strain demands corresponding to the critical PGD and compares the strain demands to the strain capacity of the design case. A total of 24 analysis test cases are defined from two different pipe configurations, varying lengths of lateral spread due to the liquefaction resulting from an earthquake and three different safety targets.

The PGD is characterized by estimating the probability of the occurrence of an earthquake event, the conditional probability of the occurrence of liquefaction given an earthquake event and the conditional probability of PGD given the occurrence of liquefaction. The conditional probability of PGD is assessed with an empirical formula that considers the site soil characteristics, the earthquake event magnitude and distance to source, and the model uncertainty. The average site soil characteristics are assumed to be deterministic, while the model uncertainty and the variability of the earthquake event parameters are modelled probabilistically. A simplified application is demonstrated with the New Madrid Seismic Zone, which is a known seismic source. Strain demands are assessed for the PGD using finite-element analysis. The maximum tensile strains are compared to the strain capacities of the pipe body and a range of expected strain capacities at the girth welds. The comparisons indicate that for the analyzed test cases, strain demands in safety class 1 are low enough to meet the design criteria and for the other safety classes, the tensile capacity of the girth welds influences the design.

Nessim, M. and Stephens, M. 1998. Managing the Operating Risk Posed by Metal Loss Corrosion and Mechanical Interference. International Pipeline Conference, Calgary, Alberta, June 7 - 11.

This paper presents an application of the quantitative approach for managing pipeline risk due to mechanical interference and metal loss corrosion. A framework is presented for risk-based maintenance planning, which prioritizes segments within pipeline systems and optimizes maintenance activities. The paper summarizes the QRA approach and describes the use of decision-influence diagrams to assess the impact of maintenance activities.

The external corrosion probability of failure is estimated using a structural reliability approach. The approach uses a deterministic analytical model to estimate the pipe resistance to internal pressure in the presence of corrosion features. The input parameters of the deterministic model are characterized as random variables and the failure probability is estimated as a function of time. Risk ranking is used to prioritize the segment maintenance; then the impact of inspection and repair on the failure probability is estimated. These probability estimates are used to evaluate total expected cost for a 'no inspection' case and for inspections with various repair criteria. The probability estimation for pipeline failure due to mechanical damage is assessed with a fault-tree model. The effects of maintenance actions, such as increasing the right-of-way patrol frequency, on the failure probability is also estimated. The expected costs of the failure events are compared with the maintenance costs to prioritize maintenance planning.

Peng, X., Zhang, P. and Chen, L. 2009. Long-distance Oil/Gas Pipeline Failure Rate Prediction Based on Fuzzy Neural Network Model. Paper for 2009 World Congress on Computer Science and Information Engineering, Los Angeles, California, March 31 - April 2, pp. 651-655.

This paper presents the use of a fuzzy neural network model to predict pipeline failure frequencies. The artificial neural network (ANN) methodology models the network relationships between the inputs and outputs of a model through layers of functions that use intermediate inputs and outputs. ANN is adapted to include fuzzy numbers as inputs. Fuzzy numbers are mapped to linguistic variables that define the influence of a parameter using 10 positions on a scale between 'very small' and 'very large'.

In this paper, a fault-tree model is developed to predict pipeline failure due to external corrosion. Fuzzy numbers, transformed from linguistic labels, are used as inputs to the fault-tree and fuzzy membership functions are used to estimate the outputs. A set of input and output values are assessed for a 58 km oil pipeline. The data are used to 'train' the fuzzy neural network, which includes assessing the functions and coefficients for the network relationships. The trained neural network is used to predict the pipeline failure rates and the results are compared to historical averages.

Perez, J., Weir, D., Seguin, C. and Ferdous, R. 2014. Development and Implementation of a Liquid Pipeline Quantitative Risk Assessment Model. International Pipeline Conference, Paper No. IPC 2014-33705, Calgary, Alberta, September 29 - October 3.

This paper describes a quantitative risk assessment framework used on mainline pipelines at Enbridge Liquid Pipelines. The following pipeline threats are identified: corrosion, cracking, denting, mechanical damage, geohazards, theft, sabotage, and incorrect operations. Of these, corrosion and cracking are time-dependent and the remainder are time-independent.

The frequency of failure (FoF) is assessed as the product of three elements: exposure, mitigation and resistance. The FoF due to corrosion, is assessed using the inline inspection (ILI) data and the structural reliability methods. The FoF due to cracking and denting are estimated by considering features detected using ILI, uncertainty in the ILI data and historical failure rates. For the

remainder of the threats, exposure, mitigation and resistance are assessed based on subject matter expert judgement and the appropriate historical incident rates.

Consequence is expressed as a dollar value that accounts for the impact of a product release on the health and safety on nearby populations, the environment, the company's reputation, financial losses and the regulatory impact. The consequences are plotted along a pipeline profile with indications for high-population locations, drinking water sources, ecologically-sensitive areas, commercial navigable waterways and water crossings. Risk is the product of the FoF and the consequence and is evaluated for each pipe joint. The risk values are aggregated into segments and are presented as risk profiles and risk matrices. The paper discusses the mitigation measures used for risk control and the lessons learned in developing the quantitative risk assessment model. The challenges identified as part of model development are: managing stakeholder expectations, development dead ends due to lack of a standardized methodology, the lack of consequence models for health, safety and financial losses, the data availability and the quality of available data.

Pettitt, G., Ramsden, M. and Shakleton, J. 2014. Benchmarking Consequence Models with Actual Pipeline Events. International Pipeline Conference, Paper No. IPC 2014-33546, Calgary, Alberta, September 29 - October 3.

This paper describes the key parameters associated with two natural gas pipeline rupture events, which are used to benchmark a consequence model for natural gas pipelines. Key parameters, such as pipe dimensions, rupture length, pipe vintage, internal pressure, rupture cause and the consequences of rupture expressed as injuries and fatalities are described for the Appomattax pipeline rupture and the San Bruno pipeline failure. Using the consequence modelling program DNV PHAST, consequence model components such as modelling the gas discharge rate from the ruptured pipe, the discharge velocity, the crater width, the vertical gas jet and the estimated number of fatalities are compared to the benchmarking events. The comparison shows that the current consequence modelling approaches estimate a thermal radiation zone that is similar to the observed damage in the actual incidents, and provide highly conservative estimates for the expected number of fatalities. The gas discharge rates employed have a significant effect on the estimated number of fatalities. The paper proposes that considering the probability of taking shelter and evacuating the thermal radiation zone may lower the conservatism in the estimated number of fatalities.

Rothwell, B. and Stephens, M. 2006. Risk Analysis of Sweet Natural Gas Pipelines – Benchmarking Simple Consequence Models. International Pipeline Conference, Paper No. IPC2006-10059, Calgary, Alberta, September 25 - 29.

This paper compares the performance of the Potential Impact Radius (PIR) model developed by C-FER against the PIPESAFE model for predicting the life safety consequences due to the rupture and ignition of natural gas pipelines. The C-FER approach is based on simplifying assumptions regarding outflow rate, thermal radiation, and ignition probabilities.

A comparison of the outflow rates produced using the C-FER model and the PBREAK module of PIPESAFE indicates that the effective outflow rate obtained using the C-FER model is consistent with the mean flow rate averaged over a duration of 200s. A comparison of the predicted thermal

radiation produced using the C-FER model and the CRISTAL module of PIPESAFE indicates that the C-FER model over-predicts the thermal radiation in the near-field and under-predicts the thermal radiation in the far-field. This effect remains despite being normalized by a factor combining pipeline pressure and diameter in the C-FER approach. For individual risk comparisons, the C-FER model provides conservative estimates compared to PIPESAFE except for the case of immediate ignition in a long-duration fire with no availability for shelter, due to a lower estimate of ignition probabilities considered in the model development. The comparison of normalized societal risk between the C-FER approach and PIPESAFE shows a large degree of agreement. This indicates that despite discrepancies in the model components between the C-FER approach and PIPESAFE, the overall risk measures produced by both models are similar.

Shahriar, A., Sadiq, R. and Tesfamariam, S. 2012. Risk Analysis for Oil & Gas Pipelines: A Sustainability Assessment Approach Using Fuzzy Based Bow-tie Analysis. Journal of Loss Prevention in the Process Industries, Vol. 25, Issue 3, pp. 505-523.

This paper presents a quantitative risk assessment approach based on a bow-tie analysis and fuzzy set theory. In this approach, the likelihood of occurrence of a critical event leading to product release is represented by a fault-tree and the safety, environmental and economic consequences are represented by an event-tree. The combination of fault-tree and event-tree is termed 'bow-tie analysis'. Fault-tree analysis typically requires 'crisp' probabilities for the basic events that lead to the top event of product release and independence between the occurrences of basic events; instead, this paper describes the use of 'fuzzy' numbers to indicate 1) possible interdependence between basic events and 2) uncertainty in the estimation of event probabilities. The union and intersection events represented by 'AND' and 'OR' gates in the bow-tie analysis are evaluated using the rules of union and intersection from fuzzy set theory.

Consequence is quantified using the 'Fuzzy Synthetic Evaluation' approach. In this approach a linguistic label is assigned to each consequence scenario and 'fuzzy utility values' are developed which relate the linguistic scenario to a fuzzy number. Using fuzzy rule-based algorithms, fuzzy likelihood and consequences are combined to obtain a fuzzy risk index. By applying defuzzification rules, which provide weighting and granularity for the fuzzy sets, the fuzzy risk index is converted to a crisp risk index. The paper demonstrates this methodology with a numerical example.

Solis, R., Simon, A., Gonzalez, J., Muhlbauer, W. and Lugo, A. 2014. Development of a Probabilistic Pipeline Risk Assessment Software for Mexico's Oil State Company. International Pipeline Conference, Paper No. IPC 2014-33108, Calgary, Alberta, September 29 - October 3.

This paper presents the quantitative risk assessment approach adopted by PEMEX, Mexico's state oil company. Seven threat categories are considered: external corrosion, internal corrosion, cracking, weather and external forces, incorrect operations, third party and sabotage/vandalism. For each threat, the probability of failure is based on estimates of three parameters: 'exposure', 'mitigation' and 'resistance'. The total failure probability due to all threats is estimated assuming independence between threats. The consequences of failure are based on damage to receptors and

quantify safety, environmental impacts, impacts on business, and other indirect costs. The collateral damage to the adjacent pipelines is also considered.

The types of available evidence considered include: quantified measures, subject matter expert opinion and historical average values. The level of conservatism in the data is set at either P50, which is considered the most probable value, or P90, which is considered to represent a 10% underestimation. Once the risk estimation is complete, the results are presented as risk profiles and in colour coded segments on the pipeline route in a GIS based platform.

Sosa, E. and Alvarez-Ramirez J. 2009. Time-correlations in the Dynamics of Hazardous Material Pipeline Incidents. Journal of Hazardous Materials, Vol. 165, June, pp. 1204-1209.

This paper shows that pipeline failures cannot be assumed to be uncorrelated and statistically independent events. Using the database of crude oil leaks in the U.S. from 1984 to 2008, this paper attempts to detect clustering of leak events to demonstrate that all pipeline failure events cannot be modelled as a Poisson point-process which assumes no correlation between the occurrences of events. The 'Allan factor' statistic is used to detect the time-dependence between the occurrences of events. This is done by categorizing the failure events over evenly spaced time intervals and normalizing for statistical variance between successive time periods. If the variance remains constant irrespective of the length of the time interval and over all time intervals, it implies a homogeneous Poisson point process. If the occurrence of future events is dependent on the occurrence of past events, then the computed factor varies with the time interval.

The data shows a sudden increase in the number of low-volume spills after 2001, which is due to a change in the reporting requirements. When all the data from 1988 to 2008 is considered, the Allan factor varies with time. However, for failure events with spill volumes greater than 1,000 barrels and property damage greater than USD$100,000, the Allan factor remains constant, indicating a Poisson point-process, The analysis with the data categorized by the cause of failure shows time-dependence for failure due to corrosion and weather or ground movements, but remains time-independent for malfunction and operational errors.

Stephens, M.J. and Nessim, M. 1996. Pipeline Maintenance Planning Based on Quantitative Risk Analysis. International Pipeline Conference, Calgary, Alberta, June 9 - 13.

This paper presents a quantitative risk-based approach for pipeline integrity management and maintenance planning. The components of the framework for maintenance optimization are the system definition, system prioritization, maintenance optimization, refinement of system prioritization and maintenance implementation. This framework is implemented in the PIRAMID software system through a joint industry program, and this paper emphasizes the application of the system prioritization and maintenance optimization components of the framework. The pipeline segments are prioritized by risk ranking based on a quantitative risk analysis, which involves identifying hazards, estimating the probability of failure and evaluating consequences of failure. Historical failure rates and modification factors are used in the probability estimation. Consequences for financial loss, life safety and environmental impact are quantified as the total

loss in dollars, the number of fatalities and the residual spill volume after initial clean-up, respectively.

Maintenance optimization is based on the decision-analysis, which uses an influence diagram to assess the impact of a maintenance action on the probability of failure. The failure probability is estimated using structural reliability methods. The best maintenance strategy is identified based on utility theory which considers the highest expected utility and risk reduction under a cost constraint.

Stephens, M., Leewis, K. and Moore, D. 2002. A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines. International Pipeline Conference, Paper No. IPC2002-27073, Calgary, Alberta, September 29 - October 3.

This paper presents the development of a life safety consequence model for natural gas pipeline failures. The model considers the thermal radiation effects of jet fires and ignores the effects of thermal radiation due to short-lived fireball or flash fires on fatality. An important assumption in the model development is that the ends of the ruptured pipe are aligned longitudinally such that the opposing streams of gas released collide and redirect the jet fires upwards. This assumption results in a conservative estimate of the total area affected at the ground surface. The model does not consider secondary fires due to ignition of nearby components following the jet fire, or meteorological conditions such as wind direction.

The primary components of the consequence model are the fire model and the heat intensity threshold model. The fire model evaluates the radiation intensity based on the heat of combustion, efficiency of combustion, emissivity, distance to heat source, and effective gas release rate from the ruptured pipe. The heat intensity threshold model evaluates the duration of exposure at a given radiation intensity that could lead to a fatality. A hazard equation is developed based on these component models and the assumptions regarding the effective release rates, the location of the heat source. The hazard area is defined by a potential impact radius which is a nonlinear function of pipeline pressure and pipeline diameter. The model is validated with incident data and shows a conservative result in most comparisons.

Sun, B., Guo, K. and Pareek, V. 2015. Dynamic Simulation of Hazard Analysis of Radiations from LNG Pool Fire. Journal of Loss Prevention in the Process Industries, Vol. 25, May, pp. 200-210.

This paper describes the consequences of a hypothetical LNG pool fire occurring at an existing LNG station using a computational fluid dynamics (CFD) model. The pool fire is modelled to occur due to a container leak within an impoundment area at an LNG station located in China. Assuming a constant wind speed and a 10 minute spill duration, the model computes the effect of thermal radiation on the public and the areas surrounding the pool fire. The reduction in consequence due to a water spray curtain is also evaluated.

The Large Eddy Simulation (LES) model is used to describe the mixing process, dissipation rates and turbulence combustion in the simulation. A mixing fraction strategy is used to model the

reaction rates and a Radiative Transfer Equation (RTE) describes the heat radiation from the pool fire. The consequences are quantified using the radiant heat flux incident on surrounding surfaces and the effect of the resulting temperature rise on material properties. The results indicate that the tanks at the facility will survive the proposed fire and that humans located in high activity areas will be able to escape unharmed. The LNG vaporizers are found to be too close to the impoundment area and could suffer catastrophic damage from a pool fire event.

Sutherby, R., Fenyvesi, L., Colquhoun, I. and Rizkalla, M. 2000. System Wide Risk-Based Pipeline Integrity Program at TransCanada. International Pipeline Conference, Calgary, Alberta, October 1 - 5, Vol. 1, pp. 13 - 21.

This paper describes the quantitative risk assessment methodology used in the past by TransCanada Pipelines. The input data includes inline inspections, hydrostatic re-tests, investigative digs, large-scale recoating, pipe replacements, class upgrades and geotechnical monitoring and remediation. Risk is defined as a product of the frequency of occurrence of pipeline failure, consequences of the failure, and the probability of consequences given a failure.

The failure frequencies are based on a combination of physical modeling and historical data. The following threats are considered: external corrosion, stress corrosion cracking, geotechnical and mechanical damage. The consequence model includes parameters for life safety, customer impact, public perception, environmental impacts, regulatory impacts and financial impacts. The total risk is expressed in terms of monetary units. Decision analysis for integrity management is informed by a 'risk value ratio' (RVR), which is the ratio of expected risk reduction due to an integrity activity to the cost of the integrity activity. If the ratio exceeds one, then the cost of the project to perform the integrity activity is considered to be justified to reduce the risk.

Toes, G. and Rogers, M. 2010. A Revised Fault-tree Method for Determining the Effectiveness of Slabbing. GL Noble Denton, Report Number: 9551, Issue: 1.0, May 11.

This report presents a revised fault-tree model for estimating the equipment impact rate due to external interference. The fault-tree model accounts for the presence of physical protective barriers categorized as a concrete slab and a concrete slab with markers. The model considers the type of protective barrier, the type of activity, the type and size of machinery involved, and human factors influencing the machine operator. Thirteen different basic events are identified that lead to the top event, which is defined as the impact to the pipeline. Eight different minimal cut sets, which identify the simultaneous occurrence of the basic events that lead to the top event, are also defined. The cut-set defining the lateral encroachment on the pipeline significantly reduces the benefit of the protective concrete slab. This is identified as one of the reasons for the negligible effect of adding markers to concrete slab to reduce the occurrence of pipeline impacts. The protective slab may also be breached with heavier machinery that does not recognize its presence. Buried markers are ineffective in this case as well.

The report describes the fault-tree model, the data and the methodology to derive the basic event probabilities. A description of the slabbing specifications and human factors associated with

excavation errors are also provided. The report includes a summary of the results of 53 experimental excavations which were part of an experimental program by British Gas to investigate the effects of different protective barriers and excavation equipment types.

Tomic, A. and Kariyawasam, S. 2014. Comparison of PIR to Pipesafe-Based 1% Lethality Zones for Natural Gas Pipelines. International Pipeline Conference, Paper No. IPC 2014-33477, Calgary, Alberta, September 29 - October 3.

This paper compares two different consequence models that assess the life safety risk due to the rupture of natural gas pipelines, the potential impact radius (PIR) model and the PIPESAFE model. The PIR formula provides a simplified formulation to identify a zone of significant impact and does not consider site-specific information. Due to the simplifications involved, the PIR model has built-in assumptions to provide conservative results. The PIPESAFE model is a detailed consequence model that considers site-specific parameters including dominant wind direction at the time of failure. It identifies a hazard zone equivalent to a 1% probability of lethality around the location of a rupture. This paper compares assessments from both the models to the damage zone resulting from the San Bruno pipeline explosion in 2010. Both models identify a damage zone comparable to the observations.

The paper also suggests a modification to the PIR formula intended to reduce conservatism when applied to small diameter pipelines. The outflow rate in the PIR formula is based on a constant value that aligns well with the effective outflow rate of large diameter transmission pipelines. It over-predicts the damage zone radius for pipeline diameters less than 200 mm by 1.5 to 2.5 times when compared to the 1% lethality distance estimated by the PIPESAFE model. This paper developed an empirical formula for outflow rate as a function of pipe diameter and internal pressure. Using the empirical formula for the outflow rate instead of the constant value assumed in the original PIR formulation, the conservatism is reduced by 50%. The modification assumes all other simplifications in the development of the PIR formulation apply to the modified formulation. The original PIR formulation assumed that jets from both ends of the ruptured pipe will align with each other and reduce the momentum of flow; this assumption must hold for the modified formulation when applied to small diameter pipes.

Tomic, A., Kariyawasam, S. and Kwong, P. 2014. Effective Consequence Evaluation for System Wide Risk Assessment of Natural Gas Pipelines. International Pipeline Conference, Paper No. IPC 2014-33474, Calgary, Alberta, September 29 - October 3.

This paper is the second part of a two-part paper (Kariyawasam 2014) that describes the system-wide risk assessment process developed at TransCanada. This paper addresses the life safety consequence assessment for a full-bore guillotine rupture. The consequences due to leaks are accounted for by considering them to be equivalent to a proportion of the rupture consequences. The life safety risk measures used are ‘individual risk’ and ‘societal risk’. Individual risk is defined as “the annual probability of fatality due to a pipeline failure of a hypothetical individual situated on top of the pipeline”. This definition is considered conservative as the potential for the presence of an individual in the vicinity of a pipeline is considered with 100% probability. Societal risk is defined as the function of the expected number of fatalities and their frequency of occurrence over

a length of 1 km. The individual risk and societal risk criteria in the British pipeline standards are adopted for the risk evaluation.

The PIPESAFE software is used to compute outdoor and indoor 1% lethality zones, which identify the distance at which the probability of lethality is less than 1%. The outdoor lethality zone is used to evaluate the individual risk and both the outdoor and the indoor lethality zones are used to evaluate the societal risk. An 'interaction length' along the pipeline length is defined to be twice the 1% lethality distance. For a system-wide application, individual risks are computed over the interaction length and societal risks are computed over a predefined 1 km evaluation length. An example computation for individual and societal risks and comparison against the criteria is included.

U.S. Department of State (DOS) Keystone XL Pipeline Project. 2014 [Internet]. Final Supplemental Environmental Impact Statement [current as of September 16, 2016]. Available from: https://keystonepipeline-xl.state.gov/finalseis/.

This report is an environmental impact statement, which is a part of the requirements for the approval of proposed Keystone XL pipeline. It includes a risk assessment and a model to estimate the environmental impact associated with a pipeline failure. The failure frequency of the pipeline is estimated using historical data with modification factors accounting for pipeline specific mitigation factors. Corrosion, excavation damage, incorrect operations, manufacturing/construction defects, and natural hazards are considered to be viable threats to the pipeline integrity. The discharge volumes due to leak and rupture are estimated as a part of the risk assessment. The consequence estimation considers environmental and human impacts. The environmental consequences model considers the effects on soil, ground water, flowing water, and wildlife. The effect on aquatic wildlife is quantified by the concentrations of dissolved benzene in water and the threshold benzene concentrations for acute and chronic toxicity for different species of aquatic organisms. Similarly, thresholds for benzene concentration in drinking water are compared to the benzene concentration resulting from spill scenarios. The risk in high-consequence areas (as defined by PHMSA) is quantified in terms of the occurrence rates of different sizes of spill volumes.

In the risk assessment, water bodies are grouped into stream categories based on the stream flow and top of stream width. The natural biodegradation of the spilled product is modelled as a generic process instead of being specific to each watercourse. For large aquifers, a specific risk assessment is recommended. The risk screening study for assessing the risk of the oil spill reaching groundwater aquifers uses the U.S. EPA Hydrocarbon Spill Screening Model (HSSM). The model evaluates the benzene concentrations in the ground water for various dilute bitumen release scenarios. The HSSM model is used to estimate the likelihood of the spill reaching the ground water and the distance at which the benzene concentrations attenuate to 0.005 mg/L, which is the maximum contaminant limit for Montana, South Dakota, and Nebraska. For the spill volumes considered, HSSM results show that a spill could affects groundwater at depth 15 m or less.

Wickenhauser, P. and Playdon, D. 2004. Quantitative Pipeline Risk Assessment and Maintenance Optimization. Proceedings of the 5th International Pipeline Conference, Paper No. IPC04-0451, Calgary, Alberta, October 4 - 8.

This paper presents an application of quantitative risk assessment used by TransGas located in Saskatchewan, Canada. The quantitative risk assessment software tool, PIRAMID™, is used to calculate the failure rate, consequences and risk for the gas transmission pipelines. The system is defined based on the physical properties of a pipeline, the probability of failure is estimated for the following threats: equipment impact, external corrosion, geotechnical hazards (heavy rains and floods), internal corrosion, manufacturing cracks (seam weld fatigue), stress corrosion cracking (SCC) and other causes (e.g. overpressure, operator error).

The consequence estimation considers life safety and financial impact. Life safety is estimated as the expected number of fatalities and the financial impact is estimated as a cost in dollars. The consequences for small leaks, large leaks and ruptures are estimated separately. Risk is estimated as the product of the failure probability and the failure consequences. Risk measures are expressed as failure probabilities, the expected cost per kilometer-year, the expected number of fatalities per kilometer-year, and individual risk. Individual risk thresholds are developed based on the land use guidelines in Canada and the U.K. Where risk level is intolerable, the impact of maintenance actions such as increased signage, additional in-line inspections, a hydrostatic pressure test, pipe replacement, feature excavation and repair and mechanical protection is assessed. The integrity maintenance strategy is based on the optimization of cost and safety.

WorleyParsons. 2012. Semi-Quantitative Risk Assessment – Submitted in Response to Joint Review Panel Information Request Number 8.1(B). Northern Gateway Pipelines Limited Partnership – Enbridge Northern Gateway Project. Letter to National Energy Board, June.

This report was submitted to the National Energy Board of Canada to fulfill a requirement for approval of the Northern Gateway Pipeline Project. A semi-quantitative risk assessment is described wherein the failure frequencies are quantitative and the failure consequences are qualitative. The pipeline system threats considered are internal and external corrosion, materials and manufacturing defects, construction defects (welding and installation), third-party damage, incorrect operations and equipment failure. The failure frequency due to stress-corrosion cracking is considered negligible and is not quantified.

Structural reliability methods are used to assess the failure frequencies due to external and internal corrosion. Feature sizes and densities are characterized using data from similar pipelines. The frequency of third-party damage is estimated using a fault-tree model, and the pipeline failure frequency given the damage is estimated using a structural reliability model. Historical data is used to derive failure rates for manufacturing defects, construction defects and equipment failures. Adjustment factors are applied to baseline failure rates to account for pipeline-specific factors. A baseline failure rate for incorrect operations is derived from expert opinion. The effectiveness of management system in preventing incorrect operations is accounted for with an adjustment factor.

Geotechnical hazards include ground movements, stream flow and erosion events, avalanches, and seismically-triggered movements such as lateral spreading. The failure frequency estimates are a product of four factors: the potential for occurrence of a geohazard at a location, the frequency of occurrence, the vulnerability of the pipeline to withstand the effects of the geohazard, and the effect of mitigation measures taken to prevent the failure. Each factor is evaluated separately based on the engineering judgement of an expert panel. The evaluation is estimated with an 'order of magnitude' precision for each factor and threat considered.

Yuhua, D. and Datao, Y. 2005. Estimation of Failure Probability of Oil and Gas Transmission Pipelines by Fuzzy Fault-tree Analysis. Journal of Loss Prevention in the Process Industries, Vol. 18, Issue 2, March, pp. 83-88.

This paper presents a fault-tree method that employs fuzzy numbers derived from expert opinion. A fault-tree comprised of 44 basic events is developed to address the leakage and rupture failure modes of pipelines. The failure threats include corrosion, initial defect characterization, design errors, incorrect operations, third party interference, and geological hazards. The probabilities for the basic events are defined by eliciting expert opinion using the Delphi method. Linguistic labels regarding the likelihood for the basic events are obtained from ten different experts. Each expert opinion is assigned a weighting factor based on their title, education level, and years of experience.

Using a conversion system from linguistic labels to numeric scores and employing the weighting factors, an aggregated fuzzy number is assessed to represent the likelihood of a basic event. The final result is a fuzzy possibility score because the fault-tree analysis is performed with fuzzy numbers for basic events using fuzzy set theory. The conversion of the fuzzy possibility score to a probability value is demonstrated in order to evaluate the total probability from a combination of fuzzy results and available probability values.

Zimmerman, T., Nessim, M., McLamb, M., Rothwell, B., Zhou, J. and Glover, A. 2002. Target Reliability Levels for Onshore Gas Pipelines. Proceedings of the 4th International Pipeline Conference, Paper No. IPC2002-27213, Calgary, Alberta, September 29 - October 3.

This paper presents the methodology used to develop target reliability levels for the onshore natural gas pipelines. The targets are intended to define the upper bound of the acceptable failure rates for significant leaks and ruptures. The target levels are based on the annual acceptable risk and the life safety risk expressed in terms of 'individual risk' and 'societal risk' measures. To derive the target levels, a risk evaluation is performed for a set of design cases with varying design pressures, steel grades, diameters, and class locations. A reliability analysis is performed on the same design cases to estimate the probability of failure due to external corrosion and equipment impact. An estimate of the probability of failure associated with all North American pipelines is evaluated as a weighted average of the individual design cases based on the fraction of pipelines in North America with the same design and operating parameters. The estimated failure frequencies are validated with the historical failure data from the U.S. Department of Transportation from 1985 to 1997, and EGIG data from 1970 to 1998. The life safety consequences are evaluated using the potential impact radius model and an assumed uniform distribution of population density

corresponding with the class location. For the evaluation of individual risk, a single person is assumed to be on the pipeline alignment 100% of the time.

The computed risk is shown to be inconsistent for different class locations over the range of design cases considered. Using the risk acceptance criteria from the U.K. and Canada, reliability targets are proposed as a function of class location, pressure and diameter of the pipeline. This approach results in the design factor variation by class location, operating pressure and diameter. The results lead to a recommended increase in wall thickness for class 3 designs with lower operating pressures and a decrease in wall thickness for large diameter high pressure designs in all class locations.

Zuczek, P., Deng, C., Mihell, J. and Adams, K. 2006. An Overland-Hydrographical Spill Model and its Application to Pipeline Consequence Modeling. Proceedings of the 7th International Pipeline Conference, Paper No. IPC2006-64389, Calgary, Alberta, September 25 - 29.

This paper presents the development of a spill simulation package for a transient three-dimensional spill simulation. The simulation assesses the potential of an oil spill to reach water bodies, the transportation of the spill by the water body and the cost of spill response clean-up. The methodology for estimating the spill spread and trajectory considers the spill volume, pooling, the direction of spreading, infiltration and the evaporation of the product released. The direction of spreading is assessed based on the terrain around a pipeline. A digital elevation model (DEM) is used to model the potential trajectory of a given spill volume and its intersection with pooled or moving water.

The consequence module considers the costs for spill response and clean-up based on the hydrographic terrain, such as river, lake, tundra or marshland. The consequences of an oil spill are quantified in dollars based on the spill response costs and the environmental and socioeconomic damage. The approach is similar to the approaches used in offshore oil spill consequence models.

APPENDIX E – BIBLIOGRAPHY – OTHER INDUSTRIES

APPENDIX E – BIBILOGRAPHY – OTHER INDUSTRIES

Appendix E – Bibilography – Other Industries

1. NUCLEAR

Boring, R., Gertman, D., Joe, J., Marble, J., Galyean, W., Blackwood, L. and Blackman, H. 2005. Simplified Expert Elicitation Guideline for Risk Assessment of Operating Events. U.S. Nuclear Regulatory Commission, INL/EXT-05-00433, June.

This report describes a simplified guideline to elicit expert judgement to estimate failure rates, human error and the operability of equipment. The U.S. Nuclear Regulatory Commission's (NRC) process to estimate the risk and reliability of nuclear power plants relies on probabilistic risk assessment (PRA) and human reliability models (HRA). For cases with insufficient operational data, expert judgement is utilized in the significance determination process (SDP) and accident sequence precursor (ASP) programs. The guidelines describe a formalized process to elicit expert opinion for these cases.

Expert opinion is recommended only when other reliable sources of information are inadequate, and only for risk-significant events. When estimating hardware failure rates, the recommended steps to eliciting expert opinion are: frame the problem, identify experts, conduct the estimation with each expert, hold an expert panel, aggregate the estimates and identify final inputs to the risk analysis. Worksheets are provided to help with the recommended steps. When estimating human error, a similar process is recommended. Worksheets are also provided for the human error estimation.

Drouin, M., Parry, G., Lehner, J., Martinez-Guridi, G., LaChance, J. and Wheeler, T. 2009. Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decision Making Main Report. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, NUREG-1855, Vol. 1, March.

This report presents the methods used to address the uncertainties associated with probabilistic risk assessment (PRA). Epistemic uncertainties (i.e. uncertainties in the formulation of a PRA model) are categorized as parameter, model, and completeness uncertainties. Approaches to address the uncertainties of each category are provided in the report.

A risk-informed decision-making process has the following steps: 1) clearly define the issue and frame the decision required, 2) identify the applicable regulatory requirements, 3) perform risk-informed analysis, which includes deterministic and probabilistic components, 4) implement the decision based on the analysis results and monitor the effects of the decision, and 5) integrate all elements into a final decision. The probabilistic component of risk analysis includes, a) developing a PRA model, b) addressing uncertainties, and c) assessing the impacts of uncertainties on the results of a decision.

Important components of a PRA model include: the definition of the failure modes, the acceptance criteria, the selection of a risk model, comparison of the results with the acceptance criteria, and the documentation of the results. The process to develop risk models includes the model structure, model assumptions, the scope, the level of detail, and aggregation of results for all threats considered.

Fault-tree methods and event-tree methods are considered basic PRA models in this document. Parametric uncertainty in logic models occurs due to the uncertainty in the input parameters such as basic event probabilities, component failure probabilities and human error probabilities. This uncertainty could be characterized by the subjective probability distributions to reflect the uncertainty in the input. Depending on the level of rigour in the analysis, the representation of the parametric uncertainty could be in the form of a point estimate, an interval value or a full probability distribution. The approaches to propagate the uncertainty representation as an interval or as a distribution through the PRA model are discussed in the report.

Model uncertainty can arise from an incomplete understanding of the nature of failure modes. Assumptions made in the model development are a source of model uncertainty. A formal approach to address the model uncertainty of multiple models is to estimate probabilities from each model and use a weighted sum as the final estimate. To reduce model uncertainty, a 'consensus model' approach is suggested wherein a public model that is peer-reviewed and widely adopted by an appropriate stakeholder group is employed in the PRA. Guidelines to address the model uncertainty due to assumptions related to a single basic event, multiple basic events, the logic structure of the PRA model and the logical combinations of events are described.

Completeness uncertainty arises due to the limitations of the model scope leading to unrecognized modes of failure within the PRA process. Although a type of model uncertainty, it is considered to be a separate category since it cannot be quantified in a manner similar to model uncertainty. The options to reduce the influence of completeness uncertainty are: upgrading the PRA model to address the required scope, using a screening analysis so that the limitations are not influential to the decision, using conservative analysis to quantify the risk, and modifying the application so the missing scope does not influence the decision. Guidelines to perform screening and conservative analysis are provided.

Khaleel, M. and Simonen, F. 2009. Evaluations of Structural Failure Probabilities and Candidate Inservice Inspection Programs. United States Department of Energy Office of Science and Technical Information, Report No. NUREG/CR-6986; PNNL-13810, Richland, WA, May 1.

This report presents an application of probabilistic fracture mechanics to estimate failure probabilities for nuclear piping and pressure vessels and to evaluate the effectiveness of in-service inspections to reduce the failure probabilities. The scope of the applications is limited to stainless steel pipe subjected to leaks and ruptures due to fatigue crack growth of existing weld flaws and stress corrosion cracking.

The input distributions for the density and the sizing for different categories of weld-flaws are derived. The factors affecting density and sizing distributions include: the wall thickness, the pipe material, the welding process, the inspection, a welding category (site or shop), pipe inner diameter, weld layers and weld runs. A Monte-Carlo simulation is performed to obtain the flaw sizes and locations within the welds which are fitted to statistical distributions. The distribution parameters are characterized as a function of wall thickness.

The probabilistic fracture mechanics model implemented in the pc-PRAISE (pipeline reliability analysis including seismic events) software is used. The fatigue crack growth model considers the number and intensity of the stress cycles due to pressure cycling in a single factor, termed 'Q-factor'. A sensitivity analysis of the probability estimate considered the variations in the Q-factor affected by through-wall stress-gradients, the amplitude of sustained primary stress, the cyclic stress amplitude, the initial flaw size distribution, and the stress cycles during abnormal/seismic events.

The effect of in-service inspections on the failure probability is evaluated. The probability of detection for different inspection methods is expressed as a function of flaw size and is characterized as 'marginal', 'very good' and 'outstanding' based on a predefined performance test from a previous US NRC report. An inspection frequency of two years with outstanding probability of detection is found to reduce the failure probabilities by two orders of magnitude. A similar methodology is applied to assess the influence of in-service inspection on the failure probabilities due to stress corrosion cracking. An inspection tool with outstanding probability of detection is found to decrease the failure probability by an order of magnitude over a 40-year period even when the inspection frequencies are once every 10 years.

The influence of the uncertainties in the characterization of input parameter distributions such as flaw density and sizing and of the uncertainties in the probabilistic fracture mechanics model on the estimated failure probabilities are assessed based on the sensitivity calculations. In addition to sensitivity studies where a single parameter is varied at a time, an uncertainty analysis is also performed considering all the uncertainties in the inputs and model. Uncertainty analysis indicates that the input distribution characterization uncertainty has the highest effect on the uncertainty of the estimated failure probability. The report concludes by summarizing the effect of initial flaw distributions, and in-service inspection on the failure probabilities of piping components.

Kirwan, B. 1996. The Validation of Three Human Reliability Quantification Techniques – THERP, HEART and JHEDI: Part 1 – Technique Descriptions and Validation Issues. Applied Ergonomics, Vol. 27, No. 6, December, pp. 359-373.

This paper is the first of a three papers addressing the validation of human reliability assessment (HRA) techniques. The objectives of the study are summarized in this paper as: 1) to determine if HRA can produce accurate results that are either precise or pessimistic estimates of failure rates, 2) to determine if HRA techniques can be used by trained assessors consistently or if they require experts for proper application, and 3) to review if the techniques can reliably quantify the reduction in human error due to interventions. The human reliability assessment methods chosen for validation are: the technique for human error rate prediction (THERP), human error assessment and reduction technique (HEART) and justification of human error data information (JHEDI). The basis for the choice of techniques is that they do not require experts in ergonomics.

Kirwan, B., Kennedy, R., Taylor-Adams, S. and Barry Lambert. 1997. The Validation of Three Human Reliability Quantification Techniques – THERP, HEART and JHEDI: Part II – Results of Validation Exercise. Applied Ergonomics, Vol. 28, No. 1, February, pp. 17-25.

This paper is the second of the three papers addressing the validation of human reliability assessment (HRA) techniques. Three objectives are: to determine the validity of the THERP, HEART and JHEDI techniques, to determine which of them is the best; and to determine if the resulting HRA estimates are pessimistic (i.e. predictions of error rates are greater than reality) or optimistic (i.e. lower error rates quantified than true error rates).

The validation method uses representative field data for skill- and rule-based tasks with a broad range of human error probabilities (HEP). A group of 30 assessors were solicited to apply the three HRA techniques and assess a total of 900 HEPs. The validation experiment results show that all three techniques performed with a similar accuracy and an average precision rate of 72%. Although the JHEDI technique is considered to have a slightly better performance than other techniques, there are no means to test the statistical significance of this finding. Although all techniques have performed well in the study, inconsistencies in the usage of techniques are observed.

Kirwan, B. 1997. The Validation of Three Human Reliability Quantification Techniques – THERP, HEART and JHEDI: Part III – Practical Aspects of the Usage of the Techniques. Applied Ergonomics, Vol. 28, No. 1, February, pp. 27-39.

This paper is the third of the three papers addressing the validation of human reliability assessment (HRA) techniques. The objectives are: to identify the source of inconsistencies when applying HRA techniques, to identify methods to improve consistency through training and benchmark examples, and to explore if the human error reduction approaches provided by HRA techniques are valid. The major components of HRA techniques are categorized as: quantifying basic error probability, applying modifiers, analysing dependence between modifiers, and decomposition of the events within a task performance.

A consistency analysis is performed for each component of the HRA techniques. The analysis indicates that the decomposition of events is the primary source of inconsistency for the THERP and JHEDI techniques, while the inconsistency in HEART techniques arises during the selection of modifiers. A list of the strengths and weaknesses of each technique, recommendations for benchmarking certain tasks, and the effects of the subjectivity of assessors are described.

Krall, A., Sawant, P., Choi, S., Khatib-Rahbar, M. and Helton, D. 2014. Compendium of Analyses to Investigate Select Level 1 Probabilistic Risk Assessment End-State Definition and Success Criteria Modeling Issues. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, NUREG/CR-7177, May.

The report presents an application of the PRA process to three selected nuclear power plants using the newly developed MELCOR software. This software was developed to conduct a Level l PRA, which estimates the failure probability associated with the core damage in a nuclear power plant.

MELCOR was developed by Sandia National Laboratories with the Nuclear Regulatory Commission's support. This report forms a part of the development to define options for defining core damage associated with Standard Plant Analysis Risk (SPAR) using MELCOR.

The report presents the Level 1 PRA for two types of reactors, a pressurized-water reactor (PWR) and a boiling-water reactor (BWR). Two nuclear power plants with PWR and one with BWR are selected for the analysis. The initiating events that lead to core damage in PWR plants are selected as partial loss of onsite power and steam generator tube rupture. For the BWR plant, a station blackout is the initiating event. The results from MELCOR are compared to those from the Modular Accident Analysis Program (MAAP). An accident scenario for the PWR plant is reanalyzed with a stratified Monte Carlo approach.

The report demonstrates 1) the effects of modeling assumptions in the PRA, 2) the conservatism associated with different definitions of the core damage state, and 3) the validation of MELCOR, by comparison with MAAP, for the accident scenario studied.

Mitra, S., Hall, R. and Coppola A. 1981. A Study of the Implications of Applying Quantitative Risk Criteria in the Licensing of Nuclear Power Plants in the United States. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, NUREG/CR-2040, May.

This report describes the development of a numerical acceptance criteria based on probabilistic risk assessment (PRA). The U.S. Nuclear Regulatory Commission transitioned from a consequence-oriented approach for the safety evaluation of the plant designs to a PRA approach that includes the frequency and consequences of an accident in the safety assessment. This report addresses the technical implications of setting an acceptance criteria based on the PRA results.

Two categories of numerical criteria, 'acceptable' and 'unacceptable', are identified based on their sufficiency in proving the safety of a system. When a numerical criteria is defined as an acceptable criteria, meeting the criteria will satisfy both the necessary and sufficient conditions to prove safety. An unacceptable numerical criteria on the other hand, will provide only a necessary condition for safety evaluation; other regulatory requirements must be met to provide sufficient safety. Approaches to develop any numerical criteria include: risk comparisons with different human activities, risk comparisons with natural hazards, information from the revealed and expressed preferences and cost-benefit evaluations. To consistently implement any numerical criteria, the report recommends standardizing modelling approaches, methods of quantification of risk, and the data sources to be used in PRA.

The risk criteria considered in the report are: component availability criteria, system availability criteria, accident probability criteria, release criteria, individual risk criteria, and societal risk criteria. These are considered hierarchical. The bottom of the hierarchy is the component availability criteria, which provides constraints on the failure probability of any single component. Failures of the hardware components, human error, and modelling a human-machine interface are considered in the failure probability estimation at this level. The next level is the system availability criteria, which provides constraints on the failure probability of the operational process

and safety system. This failure probability is dependent on the reliability of the components within the system. The fault-tree modelling approach is typically adopted to assess the failure probabilities of either the engineering system or the process. The next level is the accident probability criteria, which provides constraints on the probability of release of radioactive material to the environment. At this level, the tolerance criteria is considered for different kinds of accidents that may lead to a release, such as coolant pipe breaks, containment structure deficiencies, and reactor core melt. Event trees are typically used to model the possible outcomes starting with the accident initiating event up to the release events.

Release criteria, which defines the acceptable level of a radioactive release volume, duration, and frequency release, is the next step in the hierarchical acceptance criteria. At the top of the hierarchy are the individual and societal risk criteria, termed as "risk number criteria". These are independent on the factors affecting a nuclear power plant. Individual risk criteria is defined in terms of the 'individual risk of death' and 'reduction in life expectancy'. Societal risk criteria is defined as the frequencies of early fatalities and delayed fatalities due to radioactive material exposure and limits on exposure dosages.

The report concludes with a discussion of the aspects to consider for the use of risk criteria. These are: uncertainty and variability in the quantified risk, risk measures to use, information requirements, data availability, and limitations of criteria at each hierarchical level. In addition, methods to validate the risk analysis approach, such as, peer-review, risk analyst certification, and risk analysis studies certification are discussed.

Silva, K., Ishiwatari, Y. and Takahara, S. 2014. Cost Per Severe Accident as an Index for Severe Accident Consequence Assessment and its Applications. Reliability Engineering and System Safety, Vol. 123, March, pp. 110-122.

This paper describes a risk measure that considers secondary socio-economic costs and the life safety implications of a nuclear reactor failure. The risk measure is expressed as a cost per severe accident, which is considered to be an index of consequence severity rather than a monetary value. The probabilistic risk assessment (PRA) for nuclear power plants is divided into three levels, where the Level 1 PRA addresses the core damage frequencies, the Level 2 PRA addresses the containment failure frequencies and the Level 3 PRA addresses the consequences of a radioactive particle emission due to a loss of containment. Most studies concentrate on the acute and chronic doses of radioactivity and do not include the secondary social, economic, and environmental impacts. This paper includes all types of consequences as the cost per severe accident index.

The process of computing the cost per severe accident begins with determining the type of nuclear reactor and its location. Severe accident sequences are defined to account for all event outcomes that result in a loss of containment. Determination of the release time, release duration, and the amount of released radionuclides is followed by the Level 3 PRA using the software OSCAAR (off-site consequence analysis of atmospheric releases of radionuclides) developed by Japan Atomic Energy Agency (JAEA). The cost per severe accident is estimated considering health effects, economic impacts, social impacts and environmental impacts. Health effects include

radiation exposure and psychological effects. Economic impacts include costs for sheltering, evacuation, relocation, food intake restrictions and alternative power sources. Social impacts include harmful rumor and environmental impacts include the increase in expenses for decommissioning the plant and land decontamination. A detailed methodology for estimating costs for each component are presented followed by an example application on a virtual 1,100 MWe boiling water reactor (BWR-5) located at the center of JAEA's Research and Development Center in Tokai.

A normalized cost per severe accident for each accident sequence is presented and the accident sequence contributing the most to the total cost is identified. A sensitivity analysis is performed that considers the variation in the inputs, such as radiation effect estimation methods, dose levels associated with sheltering, evacuation, relocation and food intake restrictions. The proposed measure is compared against the source release amounts (computed as a release of Iodine and 40 times the released Cesium) to determine if normalized costs serve as a severity index. The paper concludes with risk management strategies to reduce the accident severity.

Swain, A. and Guttmann, H. 1983. Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final Report. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, NUREG/CR-1278, August.

This handbook presents methods, models and estimated human error probabilities for use in quantitative risk analysis, and was intended, at the time of its publication, for use by the U.S Nuclear Regulatory Commission as a part of the training material in human reliability analysis. In addition to nuclear power plants, the handbook is described as applicable to other large process plants such as chemical plants and oil refineries. The scope of the document is limited to the control room personnel, and does not include maintenance and management personnel. The document describes methods for analysis and quantification of human performance, models for human performance and estimated human error probabilities for certain types of equipment and provides example case studies.

Factors that affect human reliability are described in the document as the 'performance shaping factors'. The qualitative performance shaping factors form the basis for human performance models. Human performance models quantify the probability of different types of human error. The human error categories are; a) error of omission, which includes omitting an entire task, or a step in a task, and b) error of commission, which includes errors in the selection of correct tools and comments, error in the sequence of execution, timing error and qualitative error. Human error probabilities are defined as the ratio of the number of errors to the number of opportunities for error. These are estimated either based on the operations data that provides relative error frequencies for different tasks, or derived from expert judgement and data related to different components affecting human behaviour.

The performance shaping factors affecting the human error probabilities are categorized as, external, internal, and stressors. External factors influencing the performance are situational characteristics, task and equipment characteristics, and job and task instructions. Situational

characteristics include architectural features of the control room, quality of the work environment, work hours and work breaks, availability and adequacy of tools and supplies, job definitions based on task requirements, organizational structure and rewards. Some task and equipment characteristics include perceptual requirements, motor requirements, control-display relationships, anticipatory requirements, interpretation, decision-making, complexity, narrowness of the task, and task criticality. Internal factors influencing the performance are identified as individual training, experience, skill level, personality, motivation, attitudes, physical conditions, group identifications and sex differences. Stressors are identified as psychological stressors, which account for human reaction during abnormal events, physiological stressors such as fatigue, vibration, temperature extremes, pressure extremes, movement constriction, and disruption of a person's circadian rhythm due to shift work.

Methods for analysis and quantification of human performance summarized in the handbook include; a) man-machine system analysis which identifies all possible interactions of people with systems and components, potential situations for errors, likelihood for errors, consequences and solutions to reduce potential impact; b) a technique for human error rate prediction (THERP), which uses event trees called "probability tree diagrams" to perform human reliability analysis with human error probabilities; c) sources to estimate human performance, such as operational data, other industries, field studies, expert opinion; d) distributions for human performance and uncertainty bounds on the estimates; and e) use of expert judgement in the probabilistic risk assessment.

The document concludes with the estimates of human error probabilities related to different components of nuclear power plants and worked-out examples on the application of the methods of analysis described in the handbook.

2. OFFSHORE

Aljaroudi, A., Khan, F., Akinturk, A., Haddara, M. and Thodi, P. 2015. Risk Assessment of Offshore Crude Oil Pipeline Failure. Journal of Loss Prevention in the Process Industries, Vol. 37, September, pp. 101-109.

This paper presents a quantitative risk assessment methodology for offshore pipelines and demonstrates its application through a case study. The pipeline probability of leak and burst due to corrosion is estimated over time. The probability of failure of the leak detection system is also estimated. The consequences of failure are estimated as the sum of the cost of production loss, the inspection cost to locate the failed segment of pipe, segment replacement cost, and the cost of oil spill clean-up. The total cost of failure at any given future year is estimated using compounding interest rates over time and inflation. The total risk is estimated as a function of time considering the probability of failure at one-year increments and the associated total cost of failure.

The quantitative risk assessment methodology is applied to three 200-metre long offshore pipeline segments. Operating pressure, corrosion feature length, depth, growth rate, pipe diameter, pipe wall thickness, and the ultimate tensile strength are characterized as random Normal distributions. The probabilities of leak and burst for each segment are estimated over a 30 years period. The worst segment is identified as having the shortest duration before the expected failure cost exceeds the target risk level.

American Bureau of Shipping (ABS). 2000. Guidance Notes on Risk Assessment Applications for the Marine and Offshore Oil and Gas Industries. Houston, Texas, June.

This document describes a framework to assess the risk associated with marine hazards in the production and shipping of offshore oil and gas. The risk assessment process consists of four basic steps: hazard identification, frequency assessment, consequence assessment and risk evaluation.

Hazard identification techniques include the following: what-if analysis, hazard checklist, and the HAZOP (hazard and operability) analysis technique. A well-defined mechanical or electrical system can be analyzed with a failure modes and effects analysis (FMEA). It is recommended that the interaction between humans and the system being assessed be studied to identify potential human factor issues.

Historical data, event trees, fault trees, common cause failure analysis and human reliability analysis are described as some of the techniques used to estimate frequency of failure. Many of these methods produce quantitative or semi-quantitative estimates of the failure frequency based on qualitative descriptions of the failure scenarios. The consequence estimate includes the following activities: 1) characterizing the source of the hazard, 2) estimating the transport of material or energy released due to the failure of the target of interest, 3) identifying the effects on the target, and; 4) quantifying the effects.

Risk is described by subjective prioritization, risk matrices and risk sensitivity analysis. The steps necessary to perform a risk assessment include: defining the study objective, the scope of the assessment, the technical approaches to use and the resources to commit to the assessment. The levels of analysis are defined as: hazard identification, risk screening, broadly-focused analysis, and narrowly-focused detailed analysis. The key factors suggested for selection of an approach are: motivation, the type of results required, the available data, the complexity and size of analysis, type of system, and type of loss event targeted. A listing of technical approaches and the factors affecting their selection in the risk assessment is provided. The limitations and advantages associated with each type of risk assessment are also detailed. A review of hazards and safety regulations of marine systems around the world is provided.

Det Norske Veritas (DNV). 2001. Marine Risk Assessment. Health and Safety Executive, Offshore Technology Report 2001/063.

This report describes the risk assessment of mobile offshore installation exposed to marine hazards. The report is intended to encourage the use of risk assessment in the offshore industry as a whole. Three sections of the report identify the current state of the marine safety regulatory system, outline risk assessment methodologies, and describe risk assessments used in decision making processes.

The report suggests that risk assessments are required to evaluate the safety risk associated with accidents. According to the report, marine hazards, i.e. hazards associated with the interaction between the marine environment and the installation, are often not considered in risk assessments. These hazards are historically controlled by safety codes and regulations that are developed in reaction to failure events. The frameworks from the United Kingdom (UK) Offshore Oil and Gas industry and the HSE Tolerability of Risk Approach are reviewed to provide a basis for including risk assessment in decision making processes.

The selection of the approach must consider the following key factors: the lifecycle stage of the installation, the major potential hazards, and the risk decision context. This report considers that HAZID techniques are often qualitative and rely heavily on expert judgement, and recommends that they should be creative, drawing from expertise in many areas, but also structured with a clearly defined scope. The techniques that can be performed by an individual are identified as reviews by knowledgeable individuals, hazard checklists, and failure modes, effects, and criticality analysis (FMECA). Group techniques identified include hazard and operability (HAZOP) studies and structured what-if checklists (SWIFT).

The categories of risk assessments discussed in the report are qualitative, semi-quantitative, and quantitative risk analysis (QRA). The qualitative methods are based on simple severity and frequency indexes and are shown on a risk matrix. These methods are limited due to inconsistencies in team member judgements. Semi-quantitative methods use techniques from QRA methods but do not explicitly quantify the results. The techniques used include: fault-tree analysis (FTA) for frequency estimation, and event-tree analysis (ETA) for consequence analysis. Quantitative methods make a clear distinction between the two important elements of risk; frequency and consequences. A challenge for offshore QRA is also identified in the report, which

is the occasional inability to distinguish between frequency and consequences of a single event. The main limitation identified for all QRAs is the uncertainty in the inputs and outputs.

Risk assessments for offshore installations should include human factors since they contribute to 80% of all accidents. The approaches to assess human factors include listing the tasks to be performed, filtering the safety critical tasks, and identifying errors associated with those tasks. Results are used to assign risk control measures or as input to a human reliability analysis for a QRA.

The purpose of risk assessments is to guide the decision making process, on the basis of ALARP, or "as low as reasonably practicable", approach. This approach requires all safety measures be adopted unless the cost is disproportionate to the risk reduction. No acceptable level of risk associated with marine hazards alone is found. Instead, the total risk of all types of hazards must be taken into account when evaluating risk reduction measures. A cost-benefit-analysis is considered to be a useful tool that helps link the results of the QRA to a practical implementation of a safety management system.

Det Norske Veritas (DNV). 2010. Risk Assessment of Pipeline Protection. Recommended Practice DNV-RP-F107, October.

This recommended practice addresses the pipeline risk due to accidental external loads and the consequent damage. A risk-based approach is proposed to account for the risk reduction effect of pipeline protection systems. The document covers offshore installations including risers, pipeline and tie-ins. General considerations recommended in the document include: conservatism in the risk estimation, repeated assessments for optimization of risk mitigation actions, focus on risk reduction following the principle of "as low as reasonably practicable" or ALARP, the economic criteria, and consideration of the total risk. It is recommended that contributions to total risk from threats such as corrosion, erosion and burst be considered, although the scope of the document is limited to addressing the accidental external events.

The process for a pipeline protection assessment includes the following steps: objectives and acceptance criteria, system description, hazard identification, the risk assessment process and acceptable protection identified by risk-reduction to the acceptable criteria. The system description step includes the physical characteristics of the pipeline, all of the activities leading to the accidental event, and the mitigation measures in place. Two methods for estimating the frequency of the end-event (defined as system damage) are presented, either quantitatively based on detailed calculations, or qualitatively based on engineering judgement. Components to consider in the frequency estimate include the activities resulting in the occurrence of an external interference and the protection capacity to prevent damage from external interference events. Qualitative consequence estimation measures are provided for human safety, environmental impact and economic loss. The environmental impact is measured in release volumes and the economic loss is measured in production delay or downtime.

A risk matrix is provided as the decision-making tool for risk reduction. Sensitivity studies are recommended to understand the variations in the data, the drop point of the external load on the pipeline, the capacity of the pipeline and umbilical cables and the consequences.

Health and Safety Executive (HSE). 2005. Guidance on Risk Assessment for Offshore Installations. Hazardous Installations Directorate, Offshore Division, Offshore Information Sheet No. 3/2006.

This report provides a set of qualitative guidelines for offshore installations. The legal risk assessment requirements for UK legislation are outlined. It suggests that risk assessments, especially detailed quantitative risk assessments, should be focused on systems where they can provide the most value. The complexity and rigour of the risk assessment should be proportionate to the complexity of the problem and the estimated risk levels. The three risk assessment methods described, in order of increasing complexity, are qualitative (Q), semi-quantitative (SQ), and quantified risk assessment (QRA). The lower levels of risk assessment (Q and SQ) are recognized as screening tools often used to determine the threats and hazards events that should be assessed with a detailed QRA.

Regardless of the risk assessment technique, identification of all relevant threats is emphasized. For Q and SQ methods, a risk matrix is used to determine the relative risk in terms of severity and frequency. These approaches are designated for use in identifying relative ranking of the threats that need to be addressed further. Emphasis is placed on the identification of risk reduction measures and qualifying the personnel conducting the assessment. The ranking of reduction measures should be based on their effectiveness for eliminating or preventing hazards, rather than the measures that only mitigate or attempt to control consequences.

The guidelines identify the documentation required for a risk assessment. The risk assessment process, assumptions and justifications should be clearly documented.

Nessim, M., Stephens, M. and Zimmerman, T. 2000. Risk-Based Maintenance Planning for Offshore Pipelines. Offshore Technology Conference, Houston, Texas, May 1-4.

This paper presents a methodology for quantitative risk assessment used for the maintenance planning of offshore pipelines. Two different approaches are presented for the failure probability estimation. The historical failure rate method involves considering a baseline failure rate corresponding to a failure mode (small leaks, large leaks and ruptures), based on the statistical analysis of historical failure incidents. The baseline failure rate is modified with line-specific factors based on algorithms developed either from statistical analyses or from analytical models. The probability of failure is estimated as the product of the failure rate and the length of the pipeline segment. The alternative approach is to use structural reliability methods. In this approach, the failure probability is based on the probability distribution of the load effect and the resistance of the structure. The distributions for the load effect and resistance are based on analytical models with input parameters characterized by random variables. The consequences of failure consider three different categories: the economic loss, the number of people at risk as a measure of life

safety, and the residual spill volume (considering the spill decay and clean-up) as a measure of the long-term environmental impact.

Application of the risk-based methodology applied to maintenance planning is demonstrated with two examples addressing existing damage and preventing future damage. Damage due to external metal loss corrosion and equipment impact is assessed and the consequences are expressed in terms of cost. The failure probability is computed using structural reliability methods and the fault-tree approach. For external metal loss corrosion, the optimal time interval for the first inspection, re-inspection intervals, and repair criterion is evaluated by comparing the expected costs of each option. For equipment impact, a cost-benefit comparison of different mechanical protection options is performed.

Wu, W., Yang, C., Chang, J., Chateau, P. and Chang, Y. 2015. Risk Assessment by Integrating Interpretive Structural Modeling and Bayesian Network, Case of Offshore Pipeline Project. Reliability Engineering and System Safety, Vol. 142, October, pp. 515-524.

This paper presents an application of quantitative risk assessment methodology to an offshore pipe laying project. This methodology includes project components such as route planning, side-scan, material selection, equipment testing, anti-corrosion coating, welding, equipment operation, pipeline installation, pipeline connection to shore, and leak testing. In this paper, risk is defined as the effect of uncertainty on the objectives of the project based on the interpretation of the ISO 31000 Standard. The components of the risk assessment methodology are identified as risk identification, analysis, and evaluation. Due to the level of uncertainty and insufficient data at the project planning stage, techniques that handle expert opinions and uncertain relationships between the parameters are selected.

The ‘interpretive structural modeling’ approach is implemented to identify the factors influencing project risk and the inter-dependence of these factors. In this approach, human error factors influencing project risk are identified based on literature and expert opinion, and a self-interaction matrix is developed which shows hierarchical relationships between the selected factors. After establishing the inter-relationships between all of the selected factors through this approach, a ‘Bayesian network’ methodology is applied to assess the probabilities associated with different factors. A Bayesian network methodology is a graphical approach where the cause-consequence relationships are defined through conditional probabilities. In this paper, conditional probabilities are assigned, based on expert opinion, using the ‘Delphi’ technique for the elicitation of probabilities. The final Bayesian network is employed to demonstrate the risks associated with two offshore pipe-laying projects based on the status of their project components.

Xu, H., Chen, J., Wang, S. and Liu, Y. 2012. Oil Spill Forecast Model Based on Uncertainty Analysis: A Case Study of Dalian Oil Spill. Ocean Engineering, Vol. 54, November 1, pp. 206-212.

This paper describes a forecast model for marine oil spills called the “Oil Spill Forecast Model based on Uncertainty Analysis” (OSMUA). The primary purpose is to incorporate the

Hornberger-Spear-Young (HSY) algorithm as an uncertainty analysis tool. The HSY algorithm, widely applied in environmental research, identifies a set of parameters instead of a single optimal value by setting limits on acceptable behaviour and randomly sampling parameters until a range of acceptable parameters is found. The OSMUA is comprised of a hydrodynamic model and a Lagrangian spill trajectory model. The hydrodynamic model used in the OSMUA simulation is the Princeton Ocean Model (POM). This model is well-suited for the coastal simulation needed to determine the magnitude and direction of ocean currents. The Lagrangian discrete particle algorithm is used in the OSMUA to simulate oil slick behaviour. This accounts for spreading, evaporation, dissolution, emulsification and other processes. The paper details the mathematical model and theory behind the OSMUA, especially the application of the HSY algorithm.

As a validation exercise, the paper attempts to recreate the consequences of the 2010 Dalian oil spill that occurred in China. To demonstrate the effectiveness of the HSY algorithm, the volume of the oil spill is assumed to be completely unknown and chosen as a parameter of uncertainty. The amount of oil spilled into the ocean during the Dalian oil spill is largely unknown. A possible range, as estimated by experts, is 10,000 to 50,000 t. This range is used as the sampling space for the applied HSY algorithm. The simulation is run 10,000 times to identify parameters that produce behaviours that had at least a 50% match with the observed positions of spilled oil. There are 280 possible values for the amount of oil spilled. These values are found to be between 16,000 and 37,000 t, with the most likely value being 35,000 t. The OSMUA is validated with an average relative error of 36%; which is reasonable considering the scarcity of observed information.

3. AVIATION

Cacciabue, P., Cassani, M., Licata, V., Oddone, I. and Ottomaniello, A. 2015. A Practical Approach to Assess Risk in Aviation Domains for Safety Management Systems. Cognition, Technology and Work, Vol. 17, No. 2, May, pp. 249-267.

This paper describes an approach to assess risk that is claimed to be more accurate than the methods that are commonly used in the aviation industry. As the industry has moved towards a proactive approach to safety, national and international aviation organizations now require that service providers develop a Safety Management System (SMS). Safety management systems include both retrospective and prospective assessments, regular audits of safety, and systems to manage emergencies and security issues. The European Aviation Safety Agency (EASA) has developed a safety plan that attempts to bring together European standards and best practices related to air transport safety. It identifies three key areas of safety management: incident reporting, performing retrospective analysis, managing flight operations, and management of changes to systems and the implementation of new regulations.

This paper describes a risk assessment methodology called Risk Assessment Methodology for Company Operational Processes (RAMCOP). RAMCOP combines two commonly proposed methods for safety management systems: a bow-tie analysis, and aviation risk management solutions (ARMS). Bow-tie analysis is easy to understand and enables a quick qualitative risk assessment. ARMS is very similar to bow-tie analysis in structure but uses the expert judgement of the group conducting the assessment to determine the probabilities and consequences of events. There are two main limitations of the ARMS method: 1) the overuse of expert judgement could result in the process being used as an exercise in selecting probabilities and consequences such that the risks are in the acceptable range; and 2) the uncertainty in the assessment of probabilities and consequences is not explicitly addressed.

RAMCOP is based on the bow-tie/ARMS methodology but substitutes more accurate methods to evaluate the probabilities of events when expert judgement is considered insufficient. The steps to apply RAMCOP are: define the problem, conduct a qualitative assessment, conduct a quantitative assessment, accept if the risk is acceptable and re-design if the risk is unacceptable. Two methods of assessing the likelihood of failure of a procedure are suggested: *technica empirica stima errori operatori* (TESEO) using expert judgement, and the technique for human error rate prediction (THERP).

A risk acceptability matrix is proposed with seven levels of event probabilities ranging from frequent, one in 140 flights, to events that have never happened before, one in 50 x 10^6 flights. There are six consequence severity categories that consider 11 measures of consequence including: injury, property or aircraft damage cost, reputation and public confidence, customer impact, operational impact, equipment, compliance, process breach, know-how loss, and safety awareness ignorance.

GAIN Working Group B, Analytical Methods and Tools. 2003. Guide to Methods and Tools for Airline Flight Safety Analysis. Second Edition, June.

This guide was written to improve safety in the airline industry by identifying and describing analytical methods to analyze airline data. The guide was compiled by the Global Aviation Information Network (GAIN), an international organization that facilitates the sharing of safety information. A total of 57 methods are grouped into one of four categories: flight safety event reporting and analysis systems, flight data monitoring analysis and visualization tools, human factor analysis tools, or special purpose analytical tools.

Flight safety event reporting and analysis systems include a method for collecting, storing, and analyzing safety event occurrence reports from all personnel involved in flight operations. Safety event reports include maintenance-related issues, operational air safety, cabin safety, ground damage, confidential human factors, hazard reports, and occupational health and safety reports. Reports often include corrective actions taken and the predefined risk category assigned to each event. This enables trend analysis for the rates of higher risk events. There are a number of commercially available software packages for capturing, managing and analyzing safety event reports including the Aeronautical Events Reports Organizer (AERO), Aviation Quality Database (AQD), AVSiS, British Airways Safety Information System (BASIS), First Launch Safety Report System (SRS), and the INDICATE Safety Program. Several text mining programs are also available to search through the open text fields of incident reports to assist in identifying similar incidents and trends. A number of airlines record in-flight data on quick access recorders (QAR) or 'black boxes'. Flight data is typically stored in a database and reviewed for any instances where thresholds are exceeded.

After an airline has established efficient event reporting and flight monitoring systems, it is important to have a systematic approach to investigate human factors. A number of tools are commercially available that guide the user through a systematic data collection process including the aircrew incident reporting system (AIRS), cabin procedural investigation tool (CPIT), human factors analysis and classification system (HFACS), integrated process for investigating human factors, and procedural event analysis tool (PEAT). Two of these tools, HFACS and the integrated process for investigating human factors are based on Reason's latent failure model. The Reason model differentiates between active failures and latent failures. Active failures are considered to be failures caused by direct acts that are unsafe; while latent failures are caused by decisions that may not have an effect for some time, eventually combining with local events to cause a failure. Another technique for analyzing human factors is to record and review flight data, cockpit video, and audio data from flight simulations using tools such as ReVision.

Three risk analysis techniques are summarized: fault hazard analysis (FHA), failure mode and effect analysis (FMEA) / failure modes, effects, and critical analysis (FMECA), and probabilistic risk assessment (PRA). Fault hazard analysis requires an in-depth review of subsystems to determine hazard modes, causes of these hazards, and the resulting consequences. It is a form of FMEA / FMECA analysis that is limited to safety related hazards. FMEA is a step in producing an FMECA; the difference between them is a criticality assignment. The criticality assignment makes FMECA better suited than FMEA for hazard control. Generally, FMECA deals directly with failures and does not include assessing operating procedures or human factors. Probabilistic risk assessment is described as a method to quantify the probabilities and consequences associated

with malfunctions. Modern probabilistic risk assessment includes event/fault-tree analysis, computer models, reliability theory, system analysis, human factor analysis, probability theory, and statistics. Risk analysis tools such as @RISK, Fault Tree+, FaultrEASE, Markov Latent Effects Tool for Organizational and Operational Safety Assessment, Quantitative Risk Assessment System, RISKMAN, and WinNUPRA that simplify event-tree, fault-tree, and probabilistic assessments are available.

Martinez-Guridi, G. and Samanta, P. 2002. Literature Search for Methods for Hazard Analyses of Air-Carrier Operations. Aircraft Safety Research & Development Branch, Federal Aviation Administration, BNL-69279, June.

This paper summarizes a literature search conducted for the Aircraft Research & Development Branch of the Federal Aviation Administration (FAA). The purpose of the literature search is to identify and analyze existing models that could be applied to the hazard analysis, performance measures, and risk indicator design of air-carrier operations. Specifically, this paper considers each models' applicability to the system engineering model of air-carrier operations previously developed by the FAA in conjunction with several air carriers under Title 14 of the Code of Federal Regulations (CFR) Part 121 titled Air Carrier Operations System Model (ACOSM). ACOSM covers the operational processes of air-carrier operations including: managing air-carrier operations, performing air transportation, undertaking aircraft maintenance, inspecting and engineering, training personnel, and providing resources for air-carrier operations. Methodologies that are considered applicable to ACOSM are grouped into six areas: hazard identification, hazard assessment techniques, modeling dependencies and interrelations, risk management tools, data assessment techniques, and risk indicator identification.

A number of the papers stress the importance of capturing hazards caused by human error. One paper suggests that aircraft accidents are typically the result of detrimental management decisions that do not immediately result in an accident, but eventually combine with local errors to result in an incident. Another paper states that 70 to 90 percent of system failures are due to human error. An operations and support hazard analysis (O&SHA) addresses human operation of system components including hardware systems, software, facilities, support equipment, procedures, personnel, operating environment, human-machine interfaces, and maintenance activities. A methodology to identify hazards due to human error as well as estimate human error rates is presented in "The handbook of human reliability analysis with emphasis on nuclear power plant applications".

Papers on hazards in management operations, hazard assessment for hardware- and software-oriented operations, and maintenance hazard identification are summarized. The inspection and maintenance of aircraft are modelled using human reliability analysis (HRA) models. Maintenance Hazard Analysis (MHA) is used to identify hazards resulting from improper maintenance and hazards encountered during maintenance.

Two comprehensive risk management tools are identified. The first is the Flight Operations Risk Assessment System (FORAS) which uses fault-trees to quantify the risks associated with the

environment, the operator, the service provider, the flight path, the aircraft, the cabin, and the air handling. The second tool is the risk assessment tool for the British Airways Group (RATBAG). RATBAG uses a technique called dependency modelling which is very similar to fault-tree analysis.

Safety Regulation Group. 2010. Guidance on the Conduct of Hazard Identification, Risk Assessment and the Production of Safety Cases For Aerodrome Operators and Air Traffic Service Providers. Civil Aviation Authority, CAP 760, December.

This document provides guidance on hazard identification, risk assessment, risk mitigation, and the production of safety cases for air traffic service providers and aerodrome operators. The objective is to provide an acceptable means of compliance to European regulations to improve safety performance. A 'safety case' is a risk assessment and mitigation process that is required by international standards and regulations whenever a change is made to a system that could affect the safety of aerodrome or air traffic operations and services. It includes one or more documents consisting of claims, arguments, and evidence that a system is safe. Higher risk hazards require more detailed evidence. The guidance provides a section-by-section structure for safety cases with definitions for a claim, an argument, and sufficient evidence.

The risk assessment and mitigation process is broken into seven steps: system description, hazard and consequence identification, estimation of the severity of the consequences, estimation of the likelihood of the event, evaluation of the risk, risk mitigation, safety requirements and evidence that the safety requirements have been met and documented. The system description summarizes the purpose, environment, functions, scope, interfaces with other systems, and how the system is being implemented or changed. The process of hazard and consequence identification results in a formal document called a 'Hazard Log' that is used to record all of the potential hazards, consequences and mitigation actions related to a system. Recommended methodologies for hazard identification include: historical incident reports, brainstorming, failure modes and effects criticality analysis (FMECA), and hazard and operational analysis (HAZOP). Additional guidance on brainstorming and the implementation of FMECA and HAZOP is provided in the appendices of the guidance. The determination of hazard consequence severity is based on expert judgement assigned to each one of the five pre-defined consequence categories ranging from 'No Effect Immediately' to 'Accidents'. The likelihood that each hazard consequence will occur is estimated using a similar qualitative category with the associated frequencies ranging from 'extremely improbable' to 'no effect immediately'.

A risk classification matrix is used to determine if the risk for each hazard is acceptable, requires review, or is unacceptable. An acceptable hazard is considered too improbable or not severe enough to warrant concern. Mitigation actions are pursued to achieve a risk level using the "as low as reasonably practicable" (ALARP) principle for hazards that require review. Unacceptable risks require mitigation actions or a redesign of the system to reduce the likelihood or severity of the consequences. The likelihood of hazards that can lead to the same consequence must be added together to determine the probability of the consequence occurring. Mitigation strategies can

include revision of the system design, modifications to operational procedures, changes to staffing, staff training, and emergency and/or contingency plans.

Tong, Y. 2001. Literature Review on Aircraft Structural Risk and Reliability Analysis. Department of Defence, Defence Science & Technology Organisation, DSTO-TR-1110, February.

This report presents a literature review of structural risk and reliability analysis of fatigue failures for aircraft. A deterministic assessment of integrity through the aircraft structural integrity program (ASIP) is considered inadequate to address the stochastic nature of fatigue crack growth. The variability in the crack growth, material properties, fracture toughness, and the distribution of crack sizes are believed to limit the ability of a deterministic assessment to provide a measurement of safety. Therefore, this report presents the advantages of considering a structural reliability approach for aircraft integrity assessments.

Fatigue crack growth leads to a time-dependent variation in aircraft integrity. Two interpretations of risk are presented. One interpretation is the cumulative risk, which employs cumulative probability of failure over the safe life period of an aircraft. This measure is useful for determining the risk of a fleet of aircraft such that the fraction of the total population expected to suffer a fatigue failure is estimated. However, this measure does not indicate the change of the risk rate over the operational life. Another measure of risk is the instantaneous risk, which employs the instantaneous probability of failure event occurring within a population of cracks. In this interpretation, the reliability acceptance criteria is defined in terms of the failure rate per-hour.

The key components required for the structural reliability analysis of aircraft integrity are identified as the variability in the input variables of fracture mechanics analysis. The four groups of input variables are: 1) variability in the material properties, 2) initial fatigue quality of the component, 3) variability in the crack growth rate, and 4) the reliability of the inspection. Material strength and fracture toughness are characterized as random variables. The variability in the initial fatigue quality is represented by an equivalent initial flaw size (EIFS) distribution, and the distribution of time-to-crack initiation (TTCI). EIFS is representative of the initial flaws that are undetectable. The distribution of EIFS is estimated as a derived distribution of TTCI and the sizes of the detected cracks. TTCI is characterized as a three-parameter Weibull distribution. For variability in the crack growth rate, two approaches are identified for use in the structural reliability analysis. The first approach is the representation of fatigue life as a distribution. The second approach is the use of a stochastic crack growth model based on probabilistic fracture mechanics. In this approach, crack growth rate is modelled as a lognormally distributed function of a random parameter. The distribution of time for a crack to reach critical size is derived from the stochastic crack growth rate. The reliability of the inspection is represented through a probability of detection of a crack by non-destructive inspection. Detected cracks are likely to be repaired and the variability in the quality of repair is considered. The equivalent crack size distribution after repair is derived to characterize the representative cracks following the inspection, detection and repair.

The paper presents an overview of the structural reliability methods: the strength-load interference method, the conditional probability technique, Monte-Carlo simulations and first- and second-order reliability methods (FORM/SORM). There is also a review of the application of structural reliability methods for aircraft and helicopter components such as airframe components, engine components and helicopter components. In addition to fatigue crack growth, corrosion and corrosion fatigue are identified as common problems in airframe structures. However, corrosion is considered to be an economic burden and an accelerator for the fatigue crack growth rather than a safety risk. To optimize maintenance costs, structural risk and reliability analyses for corrosion and stress corrosion cracking are recommended. The report concludes with a discussion of the limitations of the structural risk and reliability analysis, such as its dependence on the data quality.

4. POWER TRANSMISSION

Dueñas-Osorio, L. and Rojo, J. 2011. Reliability Assessment of Lifeline Systems with Radial Topology. Computer-Aided Civil and Infrastructure Engineering, Vol. 26, No. 2, February, pp. 111-128.

This paper presents a closed-form solution to assess the system reliability of a lifeline system, such as an electrical distribution system, measured in terms of customer service availability (CSA). The methodology identifies the configurations in which the system can continue to function by partitioning the system into upstream and downstream regions, and recording their reliable states, and the associated number of customers with service. The approach incorporates the effects of network topology, e.g. radial, mesh-grid, and the status of connectivity in the surviving components, to estimate system reliability.

Assuming 100% reliability of the main segment, an efficient method to estimate the system reliability is developed in the paper. An approximate solution methodology is also proposed to reduce the computational costs. The approximate method is developed by adapting and expanding recursive algorithms used in biostatistics. A set of approximate parametric probability models are introduced to quantify the errors in approximating the exact distribution of the CSA. The proposed approach is considered an initial step to assess system-wide customer service reliability based on the knowledge of the component reliabilities with varying levels of accuracy.

Dunn, S., Wilkinson, S., Galasso, C., Manning, L. and Alderson, D. 2015. Development of Empirical Vulnerability Curves for Electrical Supply Systems Subjected to Wind Hazard. International Conference on Applications of Statistics and Probability in Civil Engineering ICASP12, Vancouver, British Colombia, July 12-15.

This paper presents the development of empirical curves for the failure of overhead line components of electrical distribution systems subjected to wind hazards. The empirical curves are developed for the 'faults' (i.e. loss of performance) associated with wind storms in the UK. Fault data includes the duration of the fault, the number of consumers affected, the components damaged and the wind speed. The vulnerability of the distribution systems is represented as the number of faults per-kilometer of overhead line and the percentage of affected consumers. The empirical relationship between the intensity of wind speed and the system vulnerability is assessed.

The maximum wind speed over a six-hour duration, is considered for three different spatial resolutions defined as; 'area space' (2,000 km^2), 'region' (15,000 km^2), and 'district network operator' (60,000 km^2). In order to develop the wind speeds over the required durations and spatial resolution defined as 'area space', a high-resolution atmospheric model is employed. Results show that the vulnerability measures are highly sensitive to the spatial resolution employed to assess the intensity of wind speeds. A significant chance of failure of overhead line components is identified for wind speeds over 30 m/s.

Hong, Y. and Lee, L. 2009. Reliability Assessment of Generation and Transmission Systems Using Fault-tree Analysis. Energy Conversion and Management, Vol. 50, No. 11, November, pp. 2810-2817.

This paper develops a semi-quantitative reliability assessment method for power generation and transmission systems. The process is centered on a fault-tree analysis of the system considering local and system-wide trouble conditions. ”Trouble” is defined as any event leading to the loss of service, e.g. local trouble due to line overload or voltage fluctuation, and system trouble leading to system blackout. The framework of the proposed method consists of four steps: a contingency screening, classification, fault-tree analysis, and risk reduction evaluation. The composite system operated by TaiPower in Taiwan is used as an example of the application of the proposed reliability assessment method.

Contingency screening is a deterministic process used to filter the events to analyze in the fault tree. The screening is based on conditions set by the power transmission system operator. The resulting system conditions from each contingency are classified as causing local trouble, system trouble, or ‘within normal operating parameters’. The local and system trouble contingencies are assessed in the fault tree analysis. The fault tree is a top to bottom visual representation of the Boolean relations between the fault events that cause system reliability issues. The probability of system trouble can then be expressed by combining the probabilities of individual events with parallel and series relations. Risk reduction worth (RRW) is a measure of component importance and the final step in the proposed assessment method. By creating an RRW index for each element of the fault-tree, the value of improvements can be quantified in terms of reduced risk to the overall system.

The 345 kV and 161 kV generation and transmission systems in the Taipower distribution are analyzed with the fault tree methodology. Taipower had proposed two conditions to screen for contingencies; the first is one transmission line or generator is out of service, and the second is two transmission lines are down or the system’s largest generator is out of service. A total of 5,737 contingencies are found to meet these conditions and cause either local or system trouble. The reliability of individual components is performed using historical data. Using the fault-tree method, the probability of system down-time and the frequency and duration of failures are evaluated. These results are found to be consistent with those from the Siemens PTI PSS/E TPLAN software package, while requiring significantly less computing resources.

North American Electric Reliability Corporation (NERC). 2010. Integrated Bulk Power System Risk Assessment Concepts. White Paper. Reliability Metrics Working Group.

This white paper proposes a set of risk management tools to assess the risk and reliability of bulk power systems. It encourages the North American Electric Reliability Corporation (NERC) to embrace risk assessments and risk informed decisions. Three main areas could benefit from a risk-informed approach: standard development, compliance monitoring and lessons learned from events. Currently, power system planners have set thresholds and margins to avoid unacceptable risks. The proposed management of risk differs from the deterministic processes currently used in that it recognizes the probability of risk occurrence and the ability of the system to absorb the impacts of various combinations of events with little or no consequences to power deliverance.

The proposed methodology identifies system weaknesses and significant events that have the potential to directly affect bulk power system performance. Historical event data is used to measure the characteristics of these events including duration, demand lost, damage caused, and the number of components forced out of service. A weighted combination of these metrics is used to determine a severity risk index for the event. The risk associated with each event is calculated as the product of severity and frequency of the event.

The paper suggests that different risk measurement approaches are needed to address events of different severity. The low impact/high frequency events can be assessed using traditional reliability assessments. For low frequency events, predictors such as Extreme Value Theory may be appropriate. High impact/low frequency events are more difficult to quantify. The consequences of these events can be catastrophic and independent of the size and number of redundancies in place. Different measures are often used to express these risks, such as the effect on the population or the geographic area affected. For high impact/low frequency events that have occurred once or not at all, a scenario analysis, although more subjective, is recommended to estimate the resulting diverse consequences.

Ouyang, M., Dueñas-Osorio, L. 2014. Multi-dimensional Hurricane Resilience Assessment of Electric Power Systems. Structural Safety, Vol. 48, May, pp. 15-24.

This paper proposes a probabilistic measure for electrical power system resilience after a disaster. The time-dependent resilience measure is defined as the ratio of the system performance curve over the duration of interest and the target performance curve over the same duration. The expected resilience is defined as a function of the occurrence rate of hazards and the expected impact area for all hazard intensities. The approach for a probabilistic resilience assessment is demonstrated by an application to a power transmission network in Harris County, Texas exposed to hurricane hazards.

To estimate the resilience curve, the following elements are considered: the geographical description of the electric power systems including power plants, virtual generators, transmission substations, transmission lines and critical facilities; the hurricane hazard model considering the occurrence rate of hurricanes and the associated wind speeds at peak gust over the geographical area under consideration; component fragility models to estimate the failure probability of a system component due to a given hurricane hazard intensity; the power system response model considering the effect of component failures on the system performance; and the restoration model to estimate the mobilization of resources. The restoration model is calibrated by comparing the simulated restoration curves with the actual restoration curves observed during hurricane Ike in Galveston, Texas. Finally, a hurricane resilience assessment is performed by estimating the power transmission system resilience over a 100-year period considering various levels of resilience for system components.

Risk-Assessment Working Group. 2005. Risk-Assessment Methodologies for Use in the Electric Utility Industry. North American Electric Reliability Council's Critical Infrastructure Protection Committee, September 9.

Appendix E – Bibilography – Other Industries

This report provides a basic framework for qualitative and quantitative risk assessment methods used in the North American electricity industry. The risk assessment approaches are intended to allow organizations to protect security vulnerabilities, estimate the consequences of adverse events, and characterize risk levels. Special consideration is given to the potential security threats posed by physical and cyber-attacks on critical infrastructure.

The steps of the generic risk assessment process are outlined as follows:

1. identification of assets and loss impacts;
2. identification and characterization of threats;
3. identification of existing protective and mitigative measures;
4. identification and analysis of vulnerabilities;
5. estimation of probabilities and consequences; and
6. estimation of overall risk.

In a qualitative assessment, these steps are presented in an "information reporting form". The semi-quantitative approach uses linguistic labels, such as negligible, low, medium, high or very high, to develop a relative risk ranking. However, this approach is not recommended. For quantitative risk assessments, guidelines are provided to address each step of the risk assessment process.

Additional guidance provided on performing a risk assessment covers: the selection of an appropriate risk assessment approach based on the scope and objectives of the risk assessment, the selection of personnel on the risk-assessment team, methods to gain cooperation from different stake-holders for data collection, procedures to identify assets, steps for conducting the risk assessment, presentation and documentation of the risk information, and peer review of the assessment team's results.

The report concludes with a discussion of selected risk assessment approaches, which are the Edison Electric Institute (EEI) security vulnerability risk assessment; risk analysis and management for critical asset protection (RAMCAP); Australia/New Zealand Standard risk management; vulnerability risk analysis program (VRAP); risk assessment methodology for dams (RAM-D) and risk assessment methodology for transmission (RAM-T); communication, assessment and prioritization program (CAPP); American electric power (AEP) attack tree methodology, and electric power research industry (EPRI) security vulnerability self-assessment guidelines for the electric power industry.

Siraj, T., Tesfamariam, S. and Dueñas-Osorio, L. 2015. Seismic Risk Assessment of High-voltage Transformers Using Bayesian Belief Networks. Structure and Infrastructure Engineering, Vol. 11, No. 7, June, pp. 929-943.

This paper presents a Bayesian belief network (BBN) approach to assess the seismic vulnerability of high-voltage transformers. The BBN is based on the influence of ground motion intensity on failure modes such as the interaction between the conductors, soil instability due to liquefaction, and the rocking behaviour of the transformer. These failure modes lead to the vulnerability of the high-voltage transformer, expressed as a damage state of the transformer. Failure due to the interaction between the conductors is evaluated in terms of the existing conductor length from the configuration and the required conductor length to resist the displacement during a seismic event, which is a function of the operating voltage. Failure due to liquefaction is evaluated in terms of the foundation failure, which is influenced by the ground motion intensity and soil parameters. Failure due to the rocking behaviour of the transformer is evaluated in terms of anchorage of the foundation with damage states defined as 'anchored' and 'unanchored'.

After the BBN is developed, a sensitivity analysis is performed to evaluate the normalized percent contribution from each node in the Bayesian network to the damage state of the transformer. The proposed BBN is then validated against the transformer damage data available from the literature. The application of the model is demonstrated through a case study on BC Hydro substations in British Columbia. The vulnerability of each substation and the influence of two different seismic retro-fitting options on the reduction of vulnerability are also discussed.

Winkler, J., Dueñas-Osorio, L., Stein, R. and Subramanian, D. 2010. Performance Assessment of Topologically Diverse Power Systems Subjected to Hurricane Events. Reliability Engineering and System Safety, Vol. 95, No. 4, April, pp. 323-336.

This paper addresses the influence of the network topology of a power transmission system on its reliability after hurricane events. A joint transmission and distribution component fragility damage model is applied to study the influence of network topology. Spatial configurations for six Texan power transmission networks are employed in the study. The electrical distribution systems are based on their geographical location and include the components such as generators, substations and transmission lines. In the power system damage model, generators are assumed to be impervious to the structural damage due to hurricanes and the effects of back-up generation capacity is not included. Damage to a network element is assumed to lead to a total failure, so partial damage states are not included in the analysis. The coupled transmission-distribution damage model includes explicit modelling of damage to substations, distribution load points (defined as utility poles), power system flow, power lines including transmission and distribution lines, and impacts due to flying debris. The damage model is validated by comparing transmission grid damage during Hurricane Ike.

The influence of network topology on the network functionality is assessed considering the effect of network properties, such as the number of redundant paths (termed "meshedness"), the length of redundant paths (termed "cycle length"), and the distribution of connecting edges between substation nodes expressed as "clustering coefficient", "centrality", and "degree distribution". The

application of this methodology to three different types of topology networks results in the following conclusions: 1) network connectivity is maintained for up to 65% of substation failures, and 2) ring-mesh topology, which has low resistance to randomly located attacks, shows the best performance among the networks considered in maintaining connectivity during hurricane events.