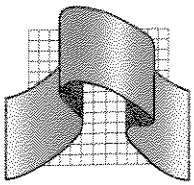

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Draft Final Report

A Pipeline Failure Consequence Assessment Model Based on Influence Diagrams

Confidential to
C-FER's Pipeline Program Participants

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Notice

NOTICE

Restriction on Disclosure

The following companies participated in the Pipeline JIP:

NOVA Corporation of Alberta

Foothills Pipe Lines Ltd.

Interprovincial Pipe Line Company

National Energy Board

Minerals Management Services

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1.0 INTRODUCTION

1.1 Background

This report constitutes one of the deliverables associated with the second phase of C-FER's ongoing joint industry program on risk-based optimization of pipeline integrity maintenance activities. The goal of this phase of the program is to develop specific models and software tools that can assist pipeline operators in making optimal decisions regarding integrity maintenance activities for a given pipeline or pipeline segment. A risk-based approach is used which measures the benefits associated with a given integrity maintenance action in terms of its impact on the risk associated with operation of the pipeline.

Implementation of a risk-based approach, as envisioned in this program, requires quantitative estimates of both the probability of line failure and the adverse consequences associated with line failure should it occur. There is considerably uncertainty associated with the assessment of both the probability and consequences of line failure. To find the optimal set of integrity maintenance actions, in the presence of this uncertainty, a probabilistic optimization methodology based on the use of decision influence diagrams has been proposed. An introduction to this analysis approach and the reasons for its selection are given in a previous report prepared under the first phase of this program (Stephens et al. 1994).

Failure probability estimation, and assessment of the effect of various integrity maintenance action on the failure probability will require the development of separate influence diagrams each tailored to address the parameters and uncertainties associated with a specific failure cause or mechanism (e.g. corrosion, ground movement). However, central to the proposed decision analysis approach is a probabilistic failure consequence assessment module that will estimate the impact of pipeline failure, regardless of cause, on public safety, the environment, and financial cost to the operator. Therefore, as a logical first step in the implementation of the proposed methodology, a pipeline failure consequence assessment model has been developed within the context of a decision analysis influence diagram. In the context of this consequence oriented influence diagram the probability of pipeline failure is treated as an uncertain, but directly quantifiable, parameter.

Based on the assumption that, failure probability estimates can be obtained from elsewhere, (e.g. from historical failure rate data) the consequence oriented influence diagram can be used to perform comprehensive risk assessments and/or for decision making provided that the failure probabilities associated with candidate integrity maintenance strategies are known form previous experience.

1.2 Objective and Scope

This report describes the consequence assessment model that has been developed to quantify, assess and combine the life safety, environmental, and economic consequences of pipeline failure. The consequence model is developed within the context of a decision influence diagram that incorporates integrity maintenance decisions and associated failure probabilities as well as a formal method of determining the optimal choice associated with the required decision. The basic structure of the consequence oriented decision influence diagram described herein is based largely on the findings of a report prepared under a previous phase of this program (Stephens et al. 1994). This document provides a detailed technical description of the influence diagram parameters and the basis for their calculation. The steps involved in solving a decision influence diagram are described in detail in a separate report prepared under this phase of the research program (Nessim and Hong 1995).

2.0 THE DECISION ANALYSIS INFLUENCE DIAGRAM

2.1 Review of Diagram Representation and Terminology

A decision influence diagram is a graphical representation of a decision problem that shows the interdependence between the uncertain quantities that influence the required decision(s). A diagram consists of a network of *chance nodes* (circles) that represent uncertain parameters and *decision nodes* (squares) that represent choices that are to be made. A decision influence diagram will also contain a *value node* (rounded square) that represents the objective or value function that is to be maximized to reveal the optimal set of choice(s) associated with the required decision(s).

All of these nodes are interconnected by directed arcs or arrows that represent dependence relationships between node parameters. Chance nodes which receive solid line arrows are *conditional nodes* meaning that the node parameter is conditionally dependent upon the values of the nodes from which the arrows emanate (i.e. direct predecessor nodes). Chance nodes which receive shaded and/or dashed line arrows are *functional nodes* meaning that the node parameter is defined as a deterministic function of the values of its direct predecessor nodes. This means that conditional node parameters must be defined explicitly for all possible combinations of the values associated with its direct conditional predecessor nodes whereas functional node parameters are calculated directly from the values of preceding nodes. The symbolic notion adopted in the drawing of the influence diagrams presented in this report, and a summary of diagram terminology are given in Figure 2.1.

It is noted that the number and type (i.e. conditional vs. functional) of chance nodes within a diagram has a significant impact on the amount of information that must be specified to solve the diagram and way in which the diagram is solved. A more detailed discussion of the steps involved in defining and solving decision influence diagrams, and a more thorough and rigorous set of node parameter and dependence relationship definitions is presented in a separate report prepared under this phase of the research program (Nessim and Hong 1995). Subsequent discussions assume the reader is familiar with the concepts described in that report.

2.2 The Influence Diagram

The *basic node influence diagram* for consequence evaluation, as developed in this project and implemented within a general decision analysis influence diagram framework, is shown in Figure 2.2. Each node in the basic node diagram is associated with a single uncertain parameter. All nodes with the exception of the Choice node (node 1), the Pipe Performance node (node 3) and the Maintenance Cost node (node 8.1), are directly associated with the pipeline failure consequence assessment model. The Pipe Performance node, which characterizes the pipeline failure probability, is includes to facilitate the calculation of risk (i.e. probability times consequences) and the Choices node, together with the associated Maintenance Cost node, are included to form a true decision analysis influence diagram in which the value associated with each choice can be calculated at the Value node to determine the optimal decision.

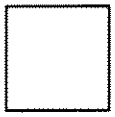
Each node in the basic node influence diagram shown in Figure 2.2 represents a single uncertain parameter (or random quantity) that is characterized by a either a discrete or continuous probability distribution. This report defines each node parameter and explains the calculations that are required at the nodal level to determine the value of each basic node parameter in terms of the values associated with all immediate predecessor nodes. It is noted that to *solve* the decision analysis influence diagram to arrive at the optimal decision, the node parameters must be defined for all possible combinations of direct conditional predecessor node parameters. The probability distribution of each node parameter will be calculated using appropriate probability integration methods as the diagram is solved. The probability integration approach is common to all nodes and a complete discussion of the diagram calculation methodology is given in a separate report prepared under this program (Nessim and Hong 1995).

The basic node diagram shows all of the uncertain parameters that have been identified as having a potentially significant impact on the decision analysis problem. The diagram consists of 28 nodes and a larger number of functional and conditional dependence arrows. At first glance the flow of information and the relationships between parameters illustrated by the basic node diagram are rather difficult to follow and understand. If, however, the various basic nodes are collected into groups of similar-type parameters, the resulting *compound node*

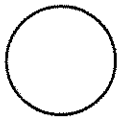
influence diagram shown in Figure 2.3, is by comparison much easier to follow and provides a clearer understanding of the interdependencies between the various node parameters (or in this case parameter groups). The compound node influence diagram and the reduced set of 11 node groups identified within will form the basis for the outline of the remainder of the report with a separate section of the document being allocated to a discussion of the parameters associated with each node group as follows:

Report Section	Node Group
3.0	Choices (node group 1)
4.0	Conditions at Failure (node group 2)
5.0	Pipe Performance (node group 3)
6.0	Release Characteristics (node group 4)
7.0	Hazard Type (node group 5)
8.0	Number of Fatalities (node group 6)
9.0	Spill Characteristics (node group 7)
10.0	Repair and Interruption Costs (node group 8)
11.0	Release and Damage Costs (node group 9)
12.0	Total Cost (node group 10)
13.0	Value (node group 11)

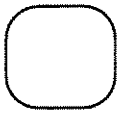
Node Notation



Decision node: Indicates a choice to be made



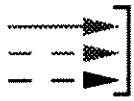
Chance node: Indicates uncertain parameter or event (discrete or continuous)



Value node: Indicates the criterion used to evaluate consequences

Arrow Notation

Solid Line arrow: Indicates probabilistic dependence

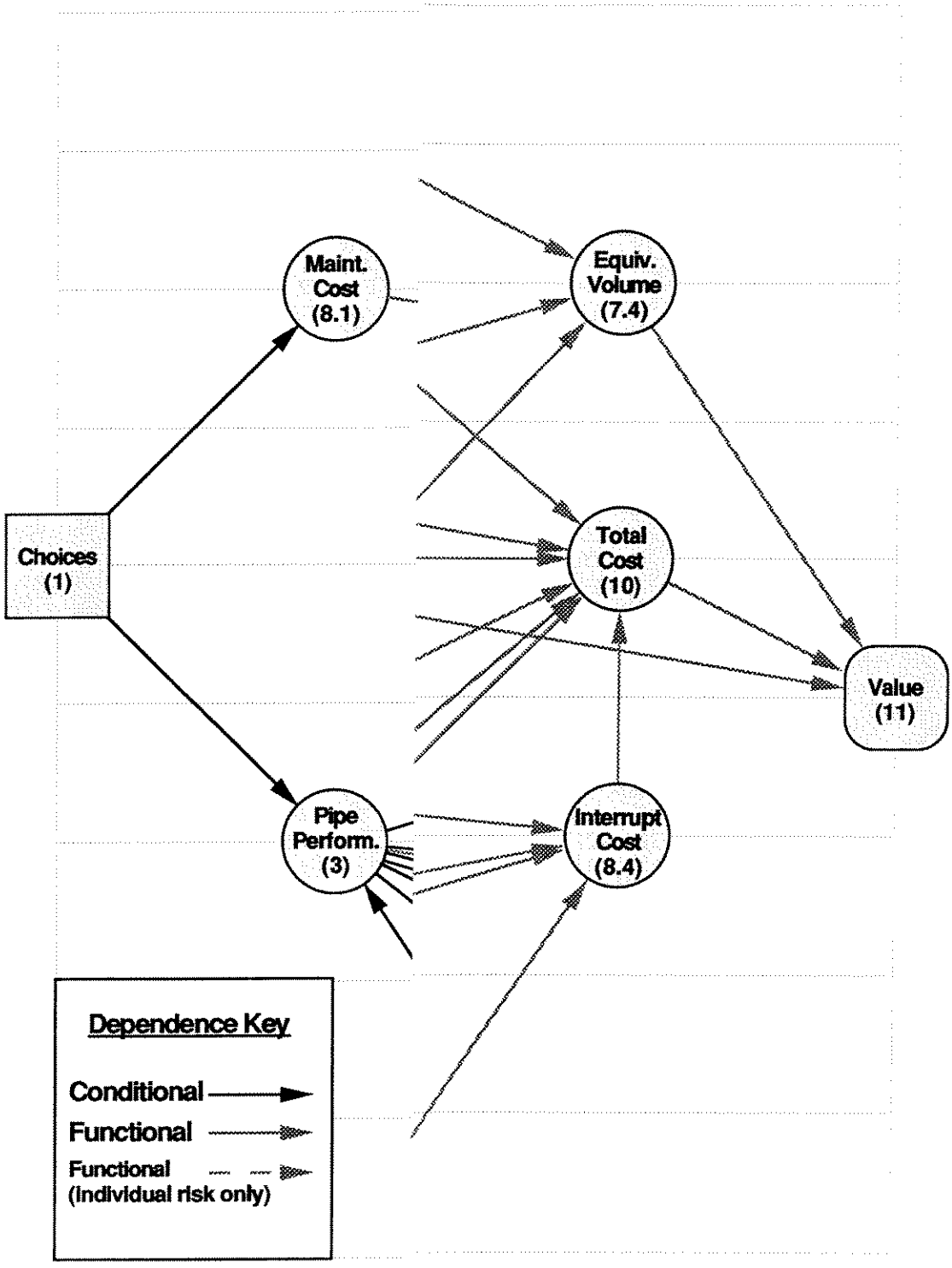


Shaded and/or Dashed Line Arrow: Indicates functional dependence

Other Terminology

Predecessor to node A :	Node from which a path leading to A begins
Successor to node A:	Node to which a path leading to A begins
Functional predecessor:	Predecessor node from which a functional arrow emanates
Conditional predecessor:	Predecessor node from which a conditional arrow emanates
Direct predecessor to A:	Predecessor node that immediately precedes A (i.e. the path from it to A does not contain any other nodes)
Direct successor to A:	Successor node that immediately succeeds A (i.e. the path from A to it does not contain any other nodes)
Direct conditional predecessor to A: (A must be a functional node)	A predecessor node from which the path to node A contains only one conditional arrow (may contain functional arrows)
Functional node:	A chance node that receives only functional arrows
Conditional node:	A chance node that receives only conditional arrows
Orphan node:	A node that does not have any predecessors

Figure 2.1 Influence Diagram Notation and Terminology


Maint.
Cost
(8.1)
Equiv.
Volume
(7.4)
Choices
(1)
Total
Cost
(10)
Value
(11)
Pipe
Perform.
(3)
Interrupt
Cost
(8.4)
Dependence Key
Conditional
Functional
Functional
(individual risk only)

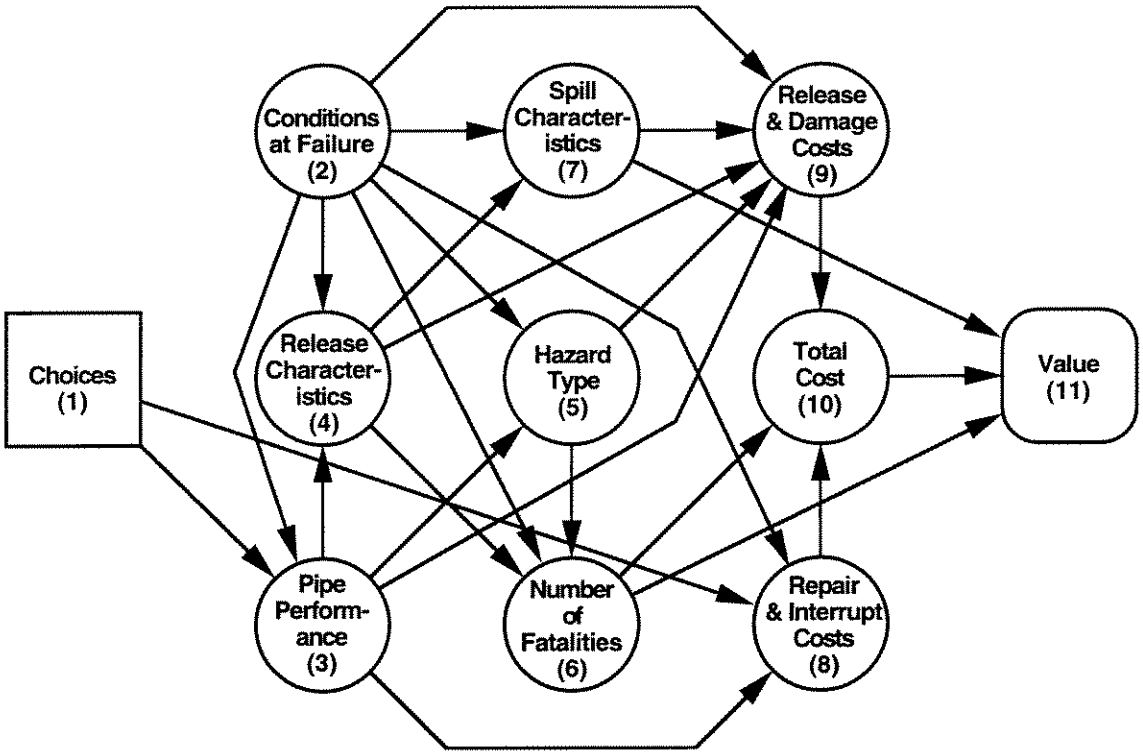


Figure 2.3 Compound node decision influence diagram for integrity maintenance optimization of pipeline systems

Choices

3.0 CHOICES

The first node in the decision influence diagram is the Choices node, which constitutes the one decision node in the diagram developed for this project. It is shown in highlighted versions of the compound node influence diagram in Figures 3.1 and the basic node influence diagram in Figure 3.2.. The specific Choices node parameter is the discrete set of integrity maintenance options or choices, selected by the decision maker and identified by name or number, that are to be evaluated by the influence diagram. Being the first node in the diagram, the Choices node has no predecessors (i.e. it is an orphan node) which implies that the set of choices specified for consideration do not depend on any other parameters or conditions.

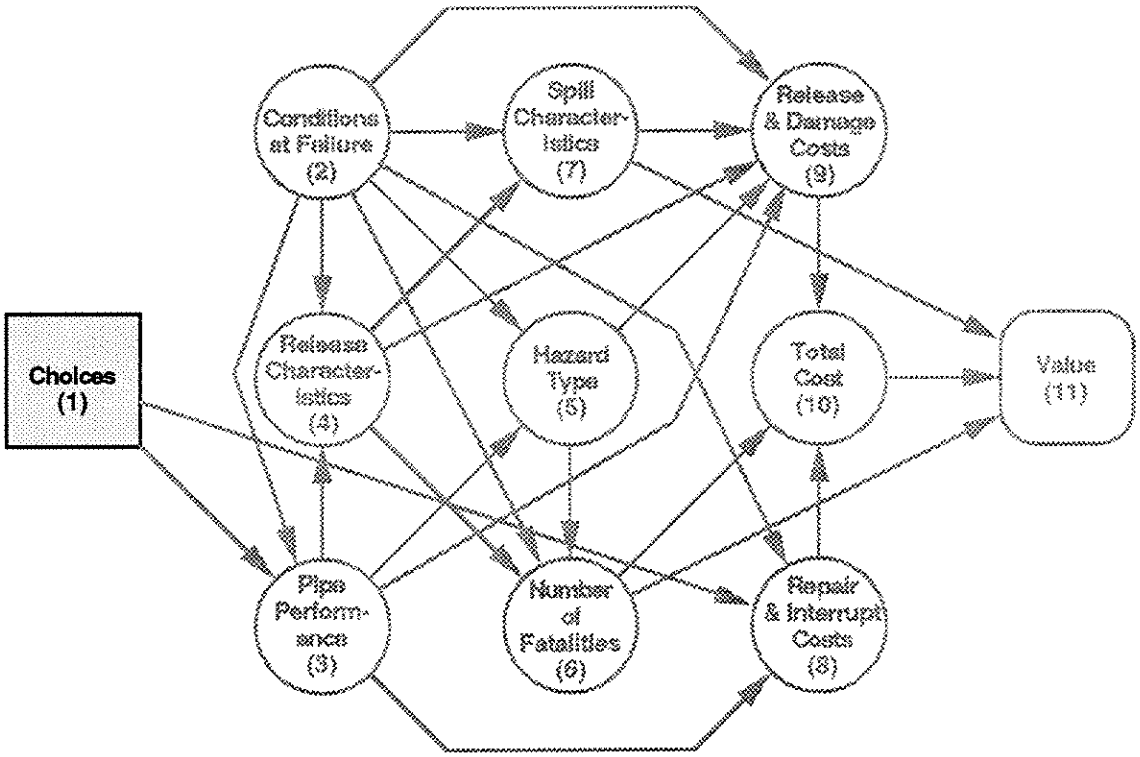


Figure 3.1 Compound node influence diagram highlighting Choices node group

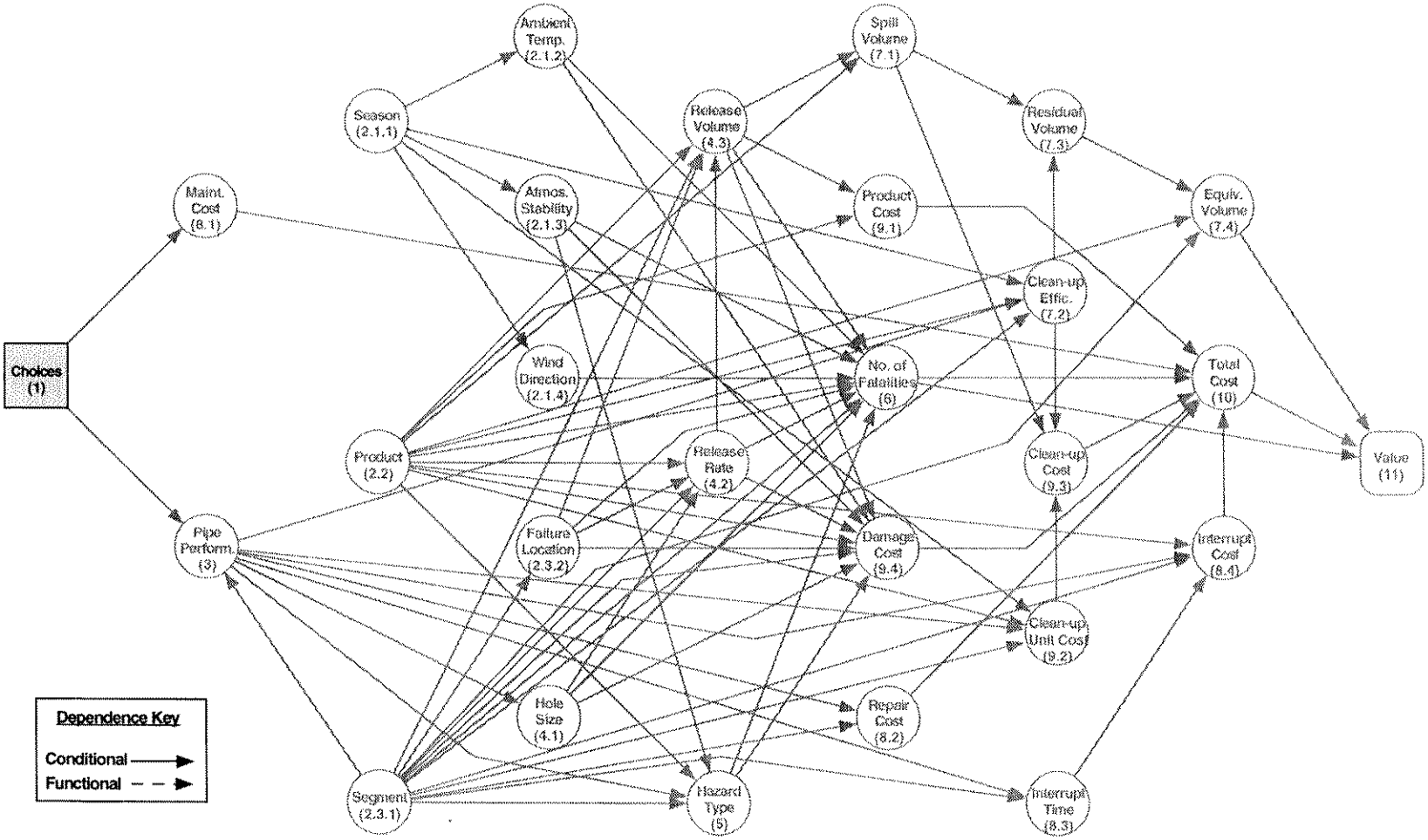


Figure 3.2 Basic node influence diagram highlighting Choices node

4.0 CONDITIONS AT FAILURE

4.1 Overview

The Conditions at Failure node group (group 2) is shown in a highlighted version of the compound node influence diagram in Figure 4.1. This node group involves parameters that are associated with conditions on or around the pipeline that exist at the time and location of failure. The relevant conditions include parameters that reflect the weather conditions at the time of line failure (i.e. season, ambient temperature, atmospheric stability and wind direction), the product type carried in the line at the time of failure, and the specific pipeline segment and the location along the segment where failure occurs. The individual parameters associated with the Conditions at Failure node group, as identified by the shaded nodes in a highlighted version of the basic node influence diagram shown in Figure 4.2, are discussed in the following sections.

4.2 Season

The Season node (node 2.1) is shown in a highlighted version of the basic node influence diagram in Figure 4.2. The specific Season node parameter is the season at time of failure (*Season*). In the context of this project, the parameter is defined by a discrete probability distribution that can take one of two possible values: 'summer' or 'winter'. The basic node influence diagram shows that Season has no predecessor nodes and is therefore not dependent on any other parameters or conditions.

Definition of the node parameter requires specification of the percentage of time during the year when summer and winter conditions apply. The discrete probability distribution for Season is calculated directly from this information by assuming that failure is equally likely to occur at any time in the year. The probability of a given season at failure is therefore set equal to the percentage of time that the time the season is specified to apply.

It is noted that in the context of this project winter is defined as the period during which the ground and/or water surface are assumed to be frozen. This approach to season definition was

adopted primarily to accommodate the subsequent calculation of dependent node parameters relating to liquid spill clean-up efficiency and clean-up cost, both of which are assumed to be dependent on whether or not the ground surface is frozen.

The information required to define the node parameter is location specific. Summer (unfrozen ground) and winter (frozen ground) percentages must therefore be established on a site by site basis using historical information on freezing degree-days for the pipeline location in question. This information can be obtained from historical weather data summaries (e.g. Environment Canada 1984) or directly from local offices of the Atmospheric Environmental Services department of Environment Canada. An example of the form and content of the information that must be specified to define the node parameter is shown in Table 4.1.

4.3 Ambient Temperature

The Ambient Temperature node (basic node 2.2) and its direct predecessor node are shown in a highlighted version of the basic node influence diagram in Figure 4.2. The specific node parameter is the average hourly air temperature at the time of failure (T_a). The predecessor node arrow indicates that Ambient Temperature is a conditional node meaning that the value of the node parameter is conditionally dependent upon the value of its direct predecessor node which is Season. The Ambient Temperature node parameter must therefore be defined explicitly for all possible values associated with the Season node parameter. In the contest of this project the node parameter is defined, for each Season (i.e. summer and winter), by specifying a continuous probability distribution for the average hourly air temperature.

It is noted that average hourly temperature was chosen as the most appropriate ambient temperature measure because product release hazards associated with pipeline failure (e.g. vapour cloud formation and dispersion, jet fires, etc.) are typically associated with a duration measured in terms of minutes or hours.

The information required to define the node parameter is highly location specific. The probability distribution of average hourly temperature should therefore be established on a site by site basis using historical temperature data for the pipeline location in question. This information can be obtained from historical weather data summaries (e.g. Environment Canada

1984) or directly from local offices of the Atmospheric Environmental Services department of Environment Canada. An example of the form and content of the information that must be specified to define the node parameter is shown in Table 4.2.

4.4 Atmospheric Stability

The Atmospheric Stability node (basic node 2.3) and its direct predecessor node are shown in a highlighted version of the basic node influence diagram in Figure ?.?. The specific node parameter is the atmospheric stability class and associated mean hourly wind speed at time of failure (S_{CLASS}, u_a). The predecessor node arrow indicates that Atmospheric Stability is a conditional node. The value of the node parameter set is therefore conditionally dependent upon the values of its direct predecessor node, Season. The node parameter set must therefore be defined explicitly for all possible values associated with the Season node parameter. In the context of this project the Atmospheric Stability node parameter set is defined, for each Season (i.e. summer and winter), by specifying a discrete probability distribution for stability class and wind speed that can take any of six specific values.

The admissible set of parameter values is based on an atmospheric stability classification system developed by meteorologists that can be used to characterized the dilution capacity of the atmosphere; dilution capacity being important because it has a significant effect on the downwind and cross-wind extent of a gas or vapour plume resulting from product release. The system involves six stability classes ('A' through 'F') that reflect the time of day, strength of sunlight, extent of cloud cover, and wind speed.

- Classes A, B, and C are normally associated with daytime ground level heating that produces increased turbulence (unstable conditions).
- Class D is associated with high wind speed conditions that result in mechanical turbulence (neutral conditions).
- Classes E and F are associated with night-time cooling conditions that result in suppressed turbulence levels (stable conditions).

The information required to define the node parameter is highly location specific. The probability distribution of atmospheric stability classes and associated hourly wind speeds should therefore be established on a site by case site using historical weather data for the

pipeline location in question. This information can be obtained from local offices of the Atmospheric Environmental Services department of Environment Canada. An example of the form and content of the information that must be specified to define the node parameter is shown in Table 4.3.

4.5 Wind Direction

The Wind Direction node and its direct predecessor node are shown in a highlighted version of the basic node influence diagram in Figure 4.2. The specific node parameter is the wind direction at time of failure (θ_w). The predecessor node arrow indicates that Wind Direction is a conditional node meaning that the parameter value is conditionally dependent upon the value of its direct predecessor node, Season. The Wind Direction node parameter must therefore be defined explicitly for all possible values associated with the Season node parameter. In the context of this project the node parameter is defined, for each Season (i.e. summer and winter), by specifying a discrete probability distribution for wind direction that can take any of eight specific values, each corresponding to a 45 degree quadrant of compass direction (i.e. N, NW, W, SW, S, SE, E, NE).

The information required to define the node parameter is highly location specific. The probability distribution of wind direction should therefore be established on a site by site basis using historical weather data for the pipeline location in question. This information can be obtained from historical weather data summaries (e.g. Environment Canada 1984) or directly from local offices of the Atmospheric Environmental Services department of Environment Canada. An example of the form and content of the information that must be specified to define the node parameter is shown in Table 4.4.

4.6 Product

4.6.1 Node Parameter

The Product node (node 2.5) is shown in a highlighted version of the basic node influence diagram in Figure 4.2. The diagram indicates that Product has no predecessor nodes and is therefore not dependent on any other parameters or conditions. The specific Product node

parameter is the product type at time of failure (*Product*) which is defined by a discrete probability distribution that can take one of a number of values depending on the number of products carried in the pipeline.

Definition of the node parameter requires specification of the different products carried in the pipeline and the percentage of time during the year that the line is used to transport each product. The discrete probability distribution for Product at failure is calculated directly from this information by assuming that failure is equally likely to occur at any time in the year. The probability of a given product type is therefore set equal to the percentage of the time that the pipeline is specified to carry that product.

The information that must be specified to define the node parameter will obviously be pipeline specific. An example of the form and content of the required information is shown in Table 4.5.

It is noted that the adopted approach to product definition enables the decision analysis model to handle single-product as well as multiple-product pipelines. In addition, the influence diagram developed for consequence assessment has been designed to handle a broad range of petroleum hydrocarbon products. However, the emphasis in the development of product release, release hazard models, and hazard impact assessment models has been on single-phase gas and liquid products typically transported by natural gas transmission lines, crude oil trunk lines and refined product pipelines (excluding petrochemicals).

4.6.2 Deterministic Data Associated with the Product Node Parameter

Parameters associated with nodes that are dependent on the Product node will depend not just on product type but also on the specific values of the physical properties associated with each specified product type. The physical properties relevant to the consequence assessment model (in particular the release rate and release volume models) are listed in Table 4.6. This supplementary product data does not constitute an additional set of influence diagram parameters but rather it represents a set of deterministic data that must be available to all nodes in the influence diagram that require specific product property information to facilitate evaluation of a node parameter. The particular set of physical properties made available to the

diagram for subsequent calculation will depend on the product type identified at the Product node.

As part of this project a list was developed of petroleum gas and liquid products (or product groups) that are typically transported by transmission-type pipelines and for each group a representative hydrocarbon compound (or set of compounds) was identified. This information is summarized in Table 4.7. According to U. S. Federal Regulatory Commission data (Rusin and Savvides-Gellerson 1987) the identified product groups represent greater than 95% of all liquid products transported by pipeline in the United States; similar figures are assumed to apply in Canada. With regard to natural gas it is noted that sour gas (i.e. natural gas containing hydrogen sulphide) has been excluded on the basis that is not usually carried in transmission-type pipelines.

For the representative hydrocarbon compound(s) associated with each of the product groups identified in Table 4.7 a product database was developed that includes relevant physical properties. The database of physical properties associated with each product group is given in Table 4.8. A discussion of the reference sources used to develop the physical property database and the approach used to select representative hydrocarbons for each product group is given in Appendix A.

4.7 Segment

4.7.1 Node Parameter

The Segment node is shown in a highlighted version of the basic node influence diagram in Figure 4.2. The diagram indicates that Segment has no predecessor nodes and is therefore not dependent on any other parameters or conditions. The specific Segment node parameter is the designation of the segment of pipeline which contains the failure location (*Segment*). It is defined by a discrete probability distribution that can take any number of values depending on the number of distinct segments that are defined along the length of the pipeline.

Note that in the context of this project, a segment is defined as a length of pipeline, over which the system attributes that are relevant to failure consequence assessment are taken to be

constant. Definition of the node parameter therefore requires the specification of all relevant pipeline system attributes along the entire length of the pipeline. From this information the pipeline is sub-divided into distinct segments, each segment being defined by a common set of attribute values. The length associated with each segment is then calculated and from this information and the discrete probability distribution for Segment at failure is calculated by assuming that failure is equally likely to occur at any point along the length of the pipeline. The probability of failure associated with a given segment is therefore set equal to the segment length divided by the total length of the pipeline.

As stated, the Segment node parameter is the designation of the segment involved in the failure event, however, the segment identification simply serves to identify which set of deterministic system attribute values are to be associated with the failure location.

4.7.2 Deterministic System Attributes Associated with the Segment Node Parameter

In the context of this project and the influence diagram developed herein, the attributes chosen to collectively define a pipeline segment include parameters that characterize the following:

- the geometric, mechanical and operational properties of the pipeline;
- the land use, population density, and development density adjacent to the pipeline;
- the topographical and geotechnical character of the right-of-way and surrounding area as it affects the potential impact of liquid product spills on the environment; and
- the character of ecosystems in proximity to the pipeline and the sensitivity of these systems to damage caused by liquid product spills.

The specific set of attributes that must be specified to define a segment are listed in Tables 2.9a and 2.9b. The Table 2.9a indicates how each attribute is defined and identifies which attribute sub-sets are required for the assessment of each of the three basic consequence components addressed by the influence diagram (i.e. life safety, environmental damage and financial cost). More specifically, Table 2.9b identifies the sub-set of attributes that are required to define the parameters associated with each node in the influence diagram that are dependent upon the segment node.

It is noted that a significant number of the pipeline system attributes identified in Table 2.9 are defined by a discrete set of predefined choices. The basis for the list of choices developed for each attribute will be explained in the context of describing the calculation procedure for node parameters that depend on these particular attributes in later sections of the report.

It is emphasized that, as is the case for the physical properties associated with each Product, the pipeline system attribute data described above does not constitute a set of additional influence diagram parameters but rather it represents as additional set of deterministic data that is available to all nodes in the influence diagram that require specific system attribute information to facilitate calculation of a node parameter. The particular set of pipeline system attribute values made available to the diagram for subsequent calculation will depend on the segment identified at the Segment node.

4.8 Failure Location

4.8.1 Node Parameter

The Failure Location node and its direct predecessor node are shown in a highlighted version of the basic node influence diagram in Figure 4.2. The specific node parameter is the location of the point of line failure along a given segment (L_S). The predecessor node arrow indicates that Failure Location is a conditional node with the parameter being dependent upon the value of its predecessor node, Segment. In the context of this project the Failure Location node parameter is defined, for each Segment, by a continuous probability distribution of the distance along the length of the segment to the point of failure that can take any value between zero and the length of the segment. It is assumed that failure is equally likely to occur anywhere along the length of any given segment. The continuous probability distribution of failure location along a given segment is therefore taken to be uniform.

As stated, the Failure Location node parameter is the designation of the location of the point of line failure on a given segment, however, the identification of the failure location simply serves to identify the value of certain deterministic pipeline system attributes that vary continuously along the length of the pipeline and which by their continually varying nature do not lend themselves to characterization on a segment by segment basis.

Conditions at Failure

4.8.2 Deterministic System Attributes Associated with the Failure Location Node Parameter

In the context of this project and the influence diagram developed herein, the continuously varying pipeline system attributes that are required to complete the definition of the deterministic parameters associated with the pipeline system are:

- the elevation profile, and
- the operating pressure profile.

These continuously varying system attributes are shown in Tables 2.9a and 2.9b together with the other system attributes that are taken to be constant along the length of each segment.

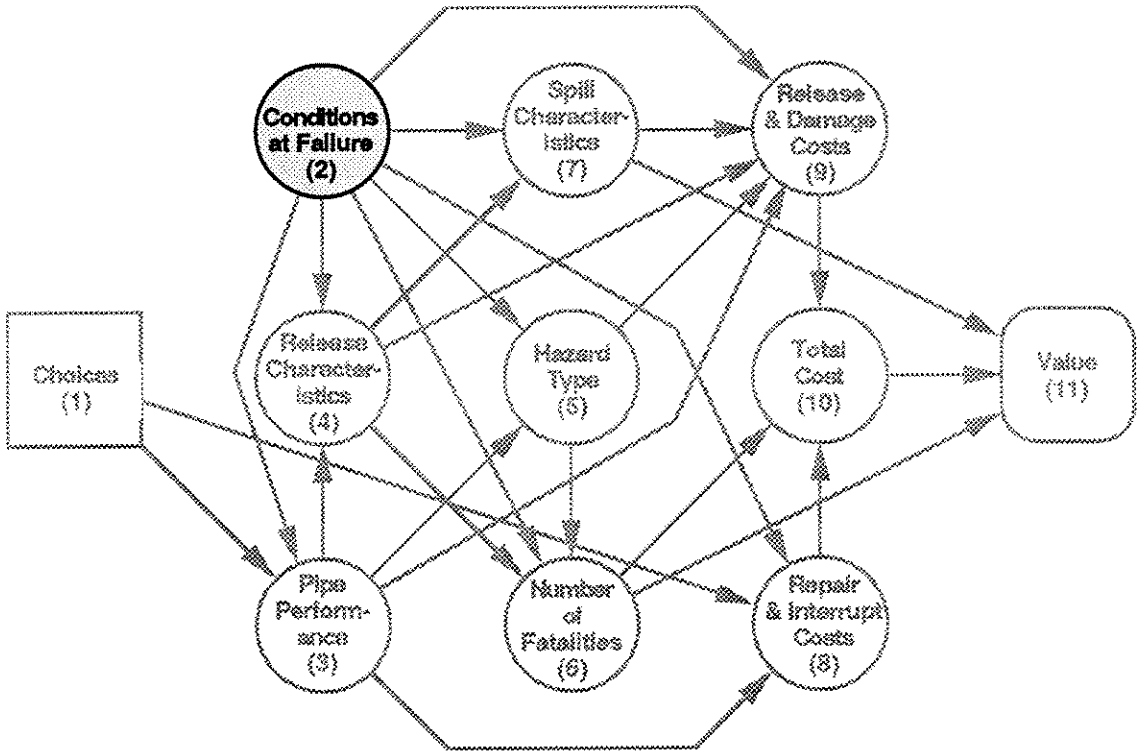


Figure 4.1 Compound node influence diagram highlighting Conditions at Failure node group

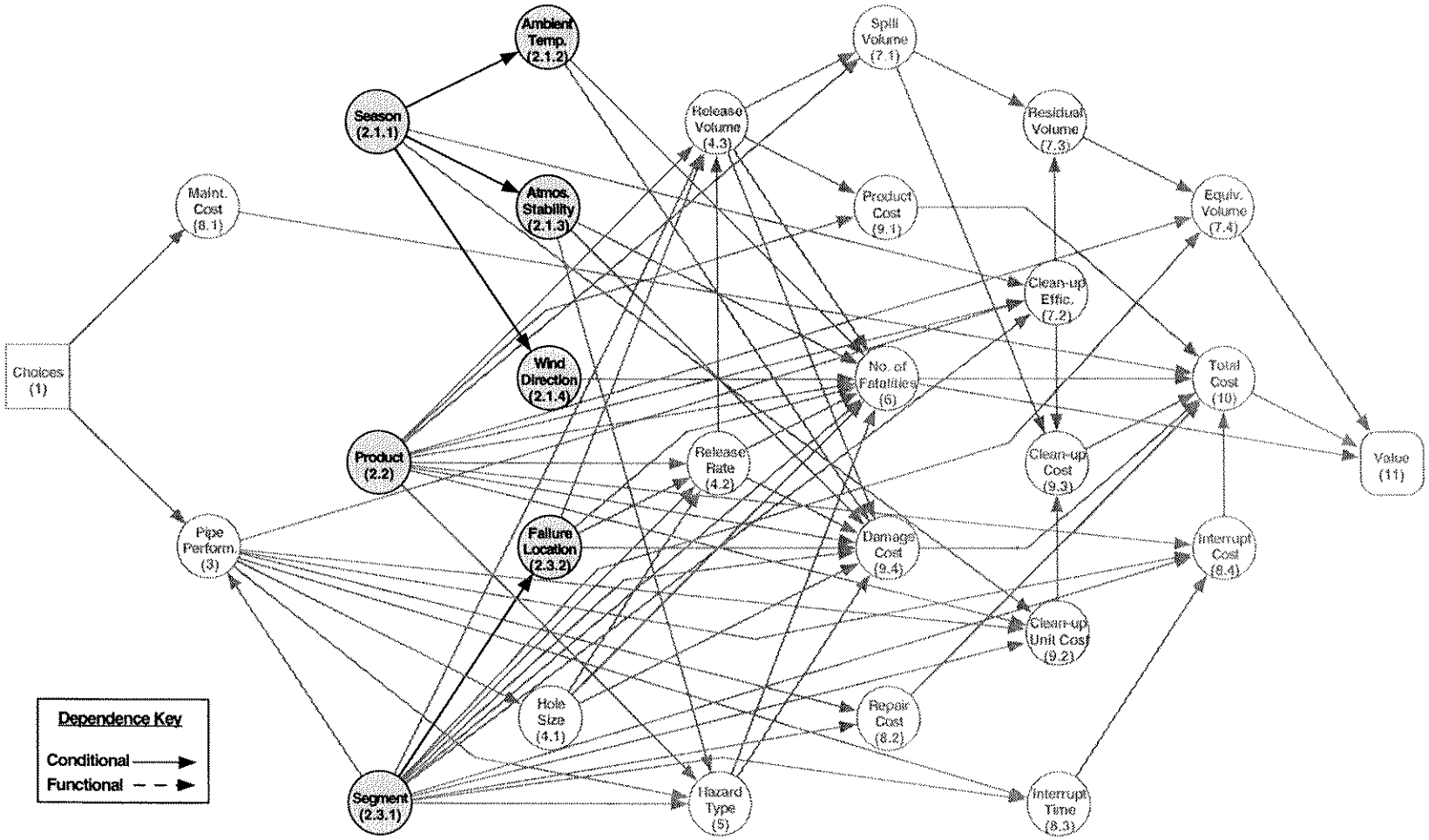


Figure 4.2 Basic node influence diagram highlighting Conditions at Failure nodes and associated immediate predecessor nodes

Season	Percentage of Time
Summer (unfrozen)	58%
Winter (frozen)	42%

Table 4.1 Example of Summer and Winter Season Duration (Edmonton, Alberta)

Season	Ambient Temperature (°C)
Summer	normal distribution (mean =12, standard deviation= 9)
Winter	normal distribution (mean =-9, standard deviation= 9)

Table 4.2 Example of probability distributions for ambient air temperature (Edmonton, Alberta)

Stability Class	Mean Wind speed (m/s)	Fequency of Occurence
Class A	0.1	0.01
Class B	1.7	0.07
Class C	2.7	0.12
Class D	4.9	0.44
Class E	3.1	0.14
Class F	1.4	0.22

Table 4.3 Example of frequency of occurance of atmospheric stability classes and associated mean wind speeds (Edmonton, Alberta)

Wind Direction	Frequency of Occurence
North	0.09
North East	0.04
East	0.07
South East	0.15
South	0.22
South West	0.10
West	0.19
North West	0.14

Table 4.4 Example of frequency of occurance of wind direction (Edmonton, Alberta)

Product	Percentage of Time
Propane	25
Butane	25
Condensate (*i.e.* pentanes)	50

Table 4.5 Example of product breakdown for HVP liquids pipeline

No.	Physical Property	Symbol	Units
1	Lower Flammability Limit	Clfl	(vol.)
2	Heat of Combustion	Hc	J/kg
3	Heat of Vaporization	Hvap	J/kg
4	Molecular Weight	molwt	g/mol
5	Critical Pressure	Pc	Pa
6	Specific Gravity Ratio	SGR	
7	Specific Heat of Liquid	SHL	J/kg•°K
8	Specific Heat Ratio of Vapour	SHR	
9	Normal Boiling Point	Tb	°K
10	Critical Temperature	Tc	°K
11a	Vapour Pressure Constants	VPa	
11b		VPb	
11c		VPc	
11d		VPd	
112	Explosive Yield Factor	Yf	
13	Kinematic Viscosity	Vs	cs

Table 4.6 Physical properties of products required for consequence model evaluation

Fraction	Product Group	Carbon Range	Representative Hydrocarbon
Natural Gas	methane	C_1	CH4 (methane)
Natural Gas Liquids	ethanes propanes butanes pentanes (condensate)	C_2 C_3 C_4 C_5 (C_3 - C_5^+)	C_2H_6 (ethane) C_3H_8 (n-propane) C_4H_{10} (n-butane) C_5H_{12} (n-pentane)
Gasolines	automotive gasoline aviation gas	C_5 - C_{10}	C_6H_{14} (n-hexane)
Kerosenes	jet fuel (JP-1) range oil (Fuel Oil - 1)	C_6 - C_{16}	$C_{12}H_{26}$ (n-dodecane)
Gas Oils	heating oil (Fuel Oil - 2) diesel oil (Fuel Oil -2D)	C_9 - C_{16}	$C_{16}H_{34}$ (n-hexadecane)
Crude Oils	_____	C_5^+	$C_{16}H_{34}$ (n-hexadecane)

Table 4.7 Representative petroleum product groups transported by pipeline

Physical Property	Units	Methane	Ethanes (ethane)	Propanes (n-propane)	Butanes (n-butane)	Condensate (n-pentane)	Gasolines (n-hexane)	Kerosenes (n-dodecane)	Gas Oils (n-hexadecane)	Crude Oil (n-hexadecane)
Clfl	(vol.)	0.05	0.029	0.021	0.018	0.014	0.013	0.007	0.013	0.013
Hc	J/kg	50020000	47200000	46013000	45390000	45010000	43540000	43120000	42900000	42450000
Hvap	J/kg	510000	490000	426200	390000	357500	320000	250000	340000	340000
molwt	g/mol	16.04	30.07	44.09	58.12	72.15	86	170	226	226
Pc	Pa	4600000	4880000	4250000	3650000	3289000	3010000	182000	141000	141000
SGR		0.3	0.374	0.508	0.563	0.625	0.73	0.8	0.84	0.9
SHL	J/kg K		2450	2360	2310	2280	2260	2220	2200	2200
SHR		1.306	1.191	1.13	1.097	1.076	1.054			
Tb	K	111.7	184.6	231.1	261.4	270.9	343	470	560	560
Tc	K	190.4	305.4	369.8	408.2	460.8	507.5	658.2	722	722
VPa		-6.00435	-6.34307	-6.72219	-6.95579	-7.28936	-7.46765	77.628	89.06	89.06
VPb		1.1885	1.0163	1.33236	1.5009	1.53679	1.44211	10012.5	12411.3	12411.3
VPc		-0.83408	-1.19116	-2.13868	-2.52717	-3.08367	-3.28222	-9.236	-10.58	-10.58
VPd		-1.22833	-2.03539	-1.38551	-1.49776	-1.02456	-2.50941	10030	15200	15200
Yf		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Vs	cs						7	1.5	15	500

Note: physical properties given are based on the properties of the representative hydrocarbon compound shown in parenthesis

Table 4.8 Representative physical properties for selected petroleum hydrocarbon products and product groups

No.	Pipeline System Attribute	t Required for Consequence Assessment			
		q.	Economic Conseq.	Environmental Conseq.	
		e 6)	Cost components (node 8&9)	Spill Character. (node 7)	
		uid	Gas	Liquid	Gas	Liquid
1	Pipeline Diameter		X	X		X
2	Pipe Wall Thickness		X	X		X
3	Pipeline Orientation (azimuth angle from Nor		X	X		X
4	Pipeline Elevation Profile			X		X
5	Operating Pressure Profile		X	X		X
6	Product Flow Rate between Throughput Bre		X	X		X
7	Product Temperature		X	X		X
8	Block Valve Spacing		X	X		X
9	Time to Block Valve Closure		X	X		X
10	Detectable Release Volume		X	X		X
11	Time to Leak Detection		X	X		X
12	Time to Leak Stoppage (from time of detectic		X	X		X
13	Adjacent Land Use		X	X		X
14	Pipeline Accessibility		X	X		X
15	Pipeline Crossings		X	X		X
16	Near Field Terrain Character			X		X
17	Significant Far Field Terrain Characteristic			X		X
18	Natural Surface Containment					X
19	Perennial Surface Water within 300m (distar					X
20	Surface Topography (slope towards surface					X
21	Annual Rainfall					X
22	Flood Potential (return period)					X
23	Thickness of Confining Layer Over Aquifer					X
24	Hydraulic Conductivity of Confining Layer					X
25	Hydraulic Conductivity of Aquifer					X
26	Drinking Water Resources within 5km (distance and availability of alt. supply)					X
27	Other Water Resources within 5km (usage and distance)					X
28	Direct Exposure due to Land Use within 5km (usage and distance)					X
29	Sensitive Environments within 10km (distan					X
30	Sensitive Groundwater within 10km (distanc					X

Parameter Type

Segment type - defined at Segment node (2.3.1)

S1 all consecutive segments defined by numeri

S2 all consecutive segments defined by text str

S3 selected segments defined by text string (wi

Coordinate type - defined at Failure Location no

C1 coordinate reference for selected numeric v

No.	Pipeline System Attribute	Clean-up Efficiency (node 7.2)	Clean-up Unit Cost (node 9.2)	Equivalent Volume (node 7.4)
1	Pipeline Diameter			
2	Pipe Wall Thickness			
3	Pipeline Orientation (azimuth angle fro			
4	Pipeline Elevation Profile			
5	Operating Pressure Profile			
6	Product Flow Rate between Throughp			
7	Product Temperature			
8	Block Valve Spacing			
9	Time to Block Valve Closure			
10	Detectable Release Volume			
11	Time to Leak Detection			
12	Time to Leak Stoppage (from time of d			
13	Adjacent Land Use			X
14	Pipeline Accessibility			
15	Pipeline Crossings			
16	Near Field Terrain Character	X	X	X
17	Significant Far Field Terrain Character	X	X	
18	Natural Surface Containment			X
19	Perennial Surface Water within 300m (			X
20	Surface Topography (slope towards su			X
21	Annual Rainfall			X
22	Flood Potential (return period)			X
23	Thickness of Confining Layer Over Aq			X
24	Hydraulic Conductivity of Confining La			X
25	Hydraulic Conductivity of Aquifer			X
26	Drinking Water Resources within 5km (distance and availability of alt. supply			X
27	Other Water Resources within 5km (usage and distance)			X
28	Direct Exposure due to Land Use with (usage and distance)			X
29	Sensitive Environments within 10km ((			X
30	Sensitive Groundwater within 10km (d			X

Parameter Type

Segment type - defined at Segment node (2

S1 all consecutive segments defined by n

S2 all consecutive segments defined by t

S3 selected segments defined by text stri

Coordinate type - defined at Failure Locati

C1 coordinate reference for selected num

5.0 PIPE PERFORMANCE

5.1 Node Parameter

The Pipe Performance node group (group 3) is shown in a highlighted version of the compound node influence diagram in Figure 5.1. The node group consists of a single node called Pipe Performance (node 3) which is shown together with its direct predecessor nodes in a highlighted version of the basic node influence diagram in Figure 5.2. The predecessor node arrows indicate that Pipe Performance is a conditional node meaning that the value of the node parameter is conditionally dependent upon the values of its direct predecessor nodes which include Choices and Segment. The Pipe Performance node parameter must therefore be defined explicitly for all possible combinations of the values associated with the Choice and Segment nodes. In the context of this project the Pipe Performance node parameter is defined by a discrete probability distribution for pipe performance that can take any of four possible states defined as:

- safe (*safe*);
- small leak (*smleak*);
- large leak (*lgleak*); and
- rupture (*rupture*).

Note that a small leak is assumed to involve a small hole and a corresponding low product release rate which does not generally result in particularly damaging release hazards or significant failure related costs. A large leak, involving a significant hole size, and a rupture, involving unconstrained product release from one or both ends of a pipeline, are typically associated with high release rates, particularly damaging release hazards, and significant failure costs. The distinction between large leaks and ruptures is considered necessary mainly to acknowledge the order of magnitude differences in release characteristics and their associated effects on the relative probability of occurrence of various release hazards.

Definition of the Pipe Performance node parameter requires the specification of annual failure rates (i.e. annual rates of failure per unit length of pipeline for failure by small leak, large leak, and rupture) for each integrity maintenance action choice. The discrete probability distribution

of pipe performance is calculated directly from this information for each segment by multiplying the specified failure rates by the segment length to arrive at an annual probability of occurrence of small leaks, large leaks, and ruptures. The probability of safe performance (i.e. no leaks or ruptures) is set equal to 1 minus the sum of the leak and rupture failure probabilities.

The information required to define the node parameter is obviously pipeline specific. In fact, the basis for future projects in the current Joint Industry Program will be to develop models that will facilitate the estimation of pipe performance (i.e. failure rates) as a function of pipeline segment attribute sets and choices regarding integrity maintenance actions. Within the context of the current project, however, failure rates are assumed to be constant along the entire length of the pipeline under investigation (i.e. constant for all segments generated by the Segment node), and the effect of integrity maintenance actions on failure rates are assumed to be addressed by defining appropriate failure rate estimates for each integrity maintenance option identified at the choice node.

Note that the assumption that probability of failure is equal to failure rate times segment length is a valid approximation of the pipeline failure process, which is typically assumed to be random in time and space and therefore characterized by a Poisson process (see for example, Ang and Tang, 1975), as long as the product of failure rate and segment length remains small (i.e. significantly less than 1). If the product of failure rate and segment length exceeds about 0.2 the error in the annual failure probability estimation will start to become significant (i.e. will exceed 10%).

Note also that historical pipeline failure incident data, for selected failure causes such as external metal loss corrosion and outside force (third party damage), suggests that line failure is more likely to occur in the spring or summer season when the ground is unfrozen and activity levels in the vicinity of the pipeline are generally higher. This seasonal variation in failure probability is not reflected in the structure of the current influence diagram (i.e. there is no conditional dependence arrow from season to pipe performance) to reduce diagram complexity and computational effort and because quantitative information on the seasonal variation in failure probability is not readily available.

5.2 Failure Rate Estimates

As part of this project a review of pipeline incident data and statistical summary reports was carried out to facilitate the development of a set of reference failure rates that could be taken to be representative of natural gas, crude oil and petroleum product pipelines as a whole. It is intended that this set of reference failure rates can serve to provide an indication of the relative likelihood of leaks and ruptures, and also serve as a reasonable first approximation of failure rates for average pipeline systems.

The set of reference failure rates developed from the literature review are given in Table 3.1. The rates are based primarily on a statistical summary of natural gas and crude oil pipeline performance in Alberta prepared by the ERCB for the ten year period from 1983 to 1992 (Cassley et al. 1994), supplemented by historical information compiled by British Gas on the relative frequency of small leaks, large leaks, and ruptures (Fearnehough 1985). A detailed discussion of the basis for the failure rates given in Table 3.1 is provided in Appendix B together with a comparison of reference rates with historical failure rate data reported by other pipeline regulatory agencies and industry associations.

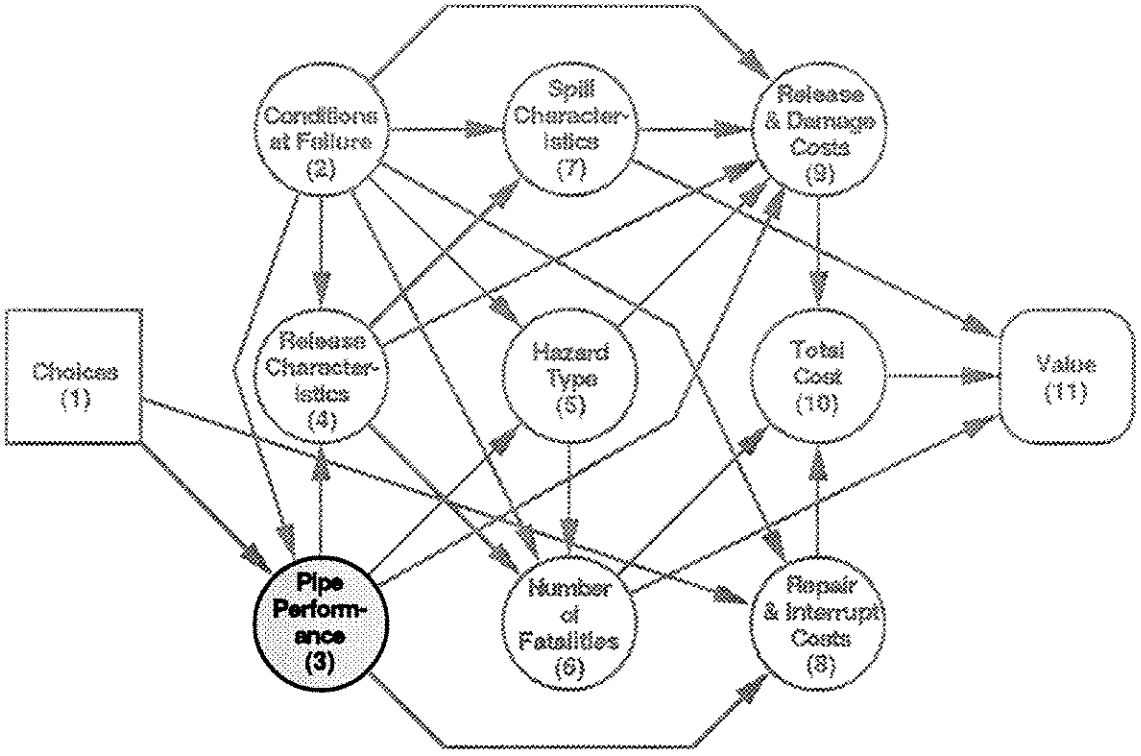


Figure 5.1 Compound node influence diagram highlighting Pipe Performance node group

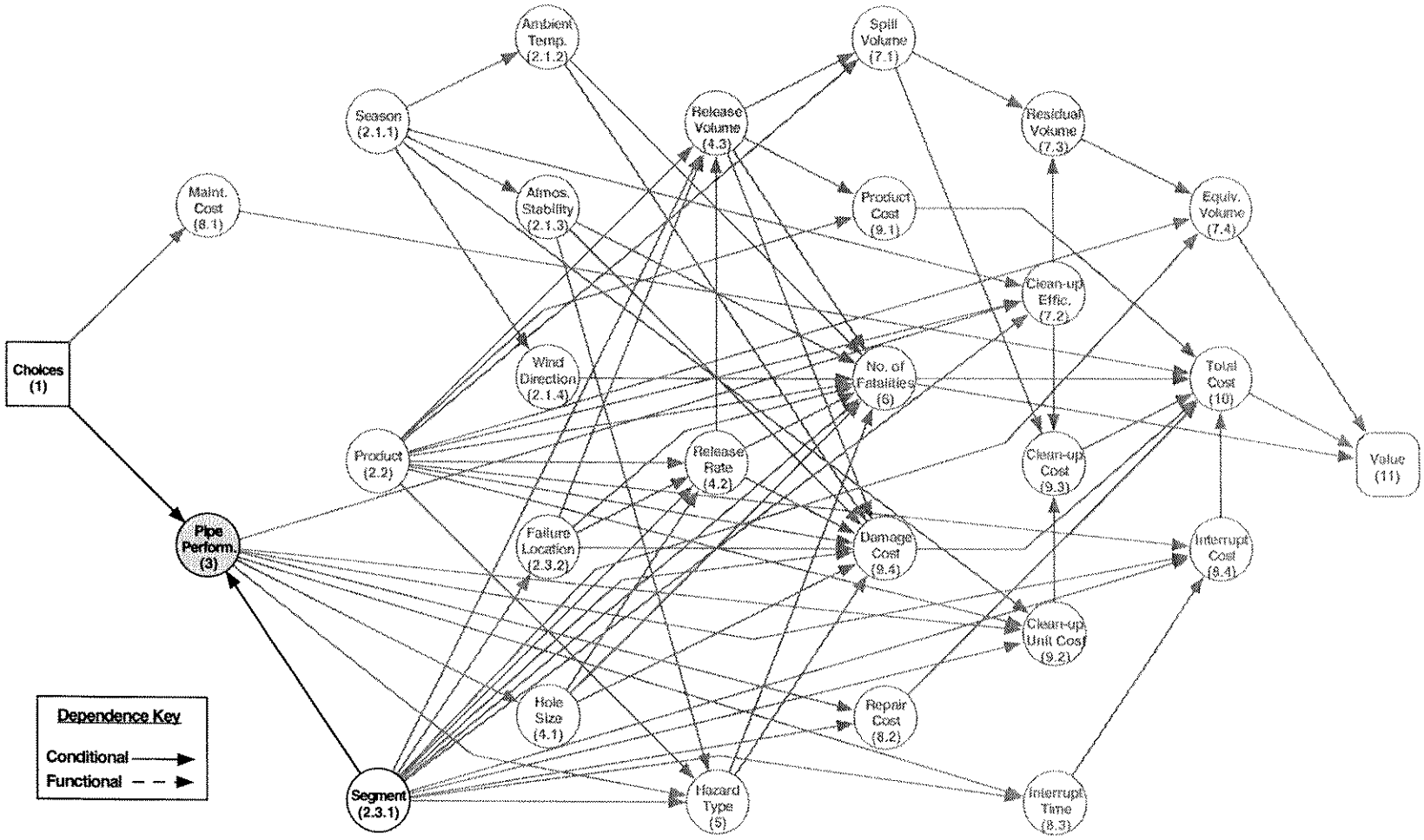


Figure 5.2 Basic node influence diagram highlighting Pipe Performance node and associated immediate predecessor nodes

Failure Mode	**Failure Rate** (per km•year)	**Relative Frequency** (%)
Small Leak	8.7×10^{-4}	87
Large Leak	1.0×10^{-4}	10
Rupture	0.3×10^{-4}	3
Combined Leak & Rupture	1.0×10^{-3}	100

Table 5.1 Reference failure rates for petroleum gas and liquid pipelines

6.0 RELEASE CHARACTERISTICS

6.1 Overview

The Release Characteristics node group (group 4) is shown in a highlighted version of the compound node influence diagram in Figure 6.1. This node group involves parameters that are associated with the rate and volume of product that is released from a pipeline at the time of failure. The individual parameters associated with the Release Characteristics node group, as identified by the shaded nodes in a highlighted version of the basic node influence diagram shown in Figure 6.2, are discussed in the following sections.

6.2 Hole size

6.2.1 Node parameter

The Hole Size node and its direct predecessor node are shown in a highlighted version of the basic node influence diagram in Figure 6.2. The specific node parameter is the effective hole diameter associated with line failure (d_h). The predecessor node arrow indicates that Hole Size is a conditional node meaning that the parameter value is conditionally dependent upon the value of its direct predecessor node, Pipe Performance. The Hole Size node parameter must therefore be defined explicitly for all possible values associated with the Pipe Performance node parameter. In the context of this project the node parameter is defined, for each Pipe Performance state (i.e. safe, small leak, large leak, and rupture), by specifying a continuous probability distribution for the effective hole diameter.

The information required to define the node parameter is to an extent pipeline specific. It is noted that the basis for future projects in the current Joint Industry Program will be to develop models that will facilitate the estimation of the hole size distribution as a function of active pipeline failure mechanisms and choices regarding integrity maintenance actions. However, within the context of the current project, hole size will be defined in a general sense based on historical pipeline incident data.

6.2.2 Hole Size Estimates

As part of this project a review of pipeline incident data and statistical summary reports was carried out to facilitate the development of a set of reference hole diameter distributions that could be taken to be representative of natural gas, crude oil and petroleum product pipelines in general. It is intended that this set of reference hole diameters will result in release rates that are consistent with the assumptions implicit in the definitions adopted for the various pipe performance states upon which hole diameter is dependent (i.e. safe, small leak, large leak and rupture).

Based on the hole diameter ranges reported by British Gas (Fearnehough 1985) and the correlations between hole diameter and pipe performance implicit in the reference failure rates developed herein (see Appendix B) it is assumed that a representative hole diameter range is: 0 to 20 mm for small leaks, 20 mm to 80 mm for large leaks, and one or two pipe diameters for ruptures (depending on whether single- or double-ended release is involved). For lack of sufficient historical data on the relative frequency of hole diameters within the indicated ranges it is assumed that hole diameter is uniformly distributed for both small and large leaks, and conservatively equal to two pipe diameters for ruptures. These assumption, summarized in Table 6.1, effectively define the Hole Size node parameter.

It is noted that the reference hole diameter distributions given in Table 6.1 are based largely on incident data for gas pipelines. Given the nature of failures involving gas pipelines and the potential for effective hole diameter increase due to dynamic fracture propagation during the decompression phase of product release, it is assumed that the reference hole diameter distributions will represent a conservative approximation to the hole size distribution associated with liquid product pipelines.

6.3 Release Rate

The Release Rate node and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 6.2. The predecessor node arrows indicate that Release Rate is a functional node meaning that the specific node parameter, the mass release rate at time of failure ($\dot{m}$), is calculated directly from the value of the parameters associated

with its direct predecessor nodes which include: Product, Segment, Failure Location and Hole Size.

For gas pipelines the mass release rate $\dot{m}_{RG}$ can be calculated using an equation of the form

$$\dot{m}_{RG} = f(d_h, P_0, T_0, product\ \ properties) \qquad [6.1]$$

where d_h is the effective hole diameter and P_0 and T_0 are, respectively, the operating pressure and temperature at the failure location. For liquid pipelines the equation for the mass release rate $\dot{m}_R$ takes the form

$$\dot{m}_R = f(d_h, P_0, T_0, H, product\ \ properties) \qquad [6.2]$$

where H is the hydrostatic pressure head at the failure location which depends on the elevation profile of the pipeline. The specific equations associated with the product release rate models adopted in this project, and the simplifying assumptions associated with their use, are described in detail in Appendix C (see Section 2.0 for gas release, and Section 3.0 for liquid release).

6.4 Release Volume

The Release Volume node and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 6.2. The predecessor node arrows indicate that Release Volume is a functional node meaning that the specific node parameter, the total release volume at failure (V_R), is calculated directly from the value of the parameters associated with its direct predecessor nodes which include: Product, Segment, Failure Location and Release Rate.

For gas pipelines the total release volume V_{RG} can be calculated using the equation

$$V_{RG} = \frac{\dot{m}_{RG} t_{RG}}{\rho_s} \qquad [6.3a]$$

where ρ_S is the product density under standard conditions and t_{RG} is the effective duration of the release event which in turn is given by

$$t_{RG} = f\left(\dot{m}_{RG}, \dot{m}_0, S_V, t_{dtect}, t_{close}, t_{stop}\right) \quad [6.3b]$$

where $\dot{m}_0$ is the mass flow rate in the pipeline, S_V is the block valve spacing, t_{dtect} is the time required to detect line failure, t_{close} is the additional time required to close the block valves, and t_{stop} is the time required to reach the failure site and stop the release (which only applies to failure events involving small leaks).

For liquid pipelines the equation for the total release volume V_R takes the form

$$V_R = \frac{\dot{m}_R t_R}{\rho_s} \quad [6.4a]$$

where t_R is the effective duration of the release event which is given by

$$t_R = f\left(\dot{m}_R, \dot{m}_0, S_V, M_1, t_{dtect}, t_{close}, t_{stop}\right) \quad [6.4b]$$

where M_1 is the total amount of product in the line between the failure location and the surrounding crests in the pipeline elevation profile.

The specific equations associated with the product release volume models adopted in this project, and the simplifying assumptions associated with their use, are described in detail in Appendix C (see Section 2.0 for gas release, and Section 3.0 for liquid release).

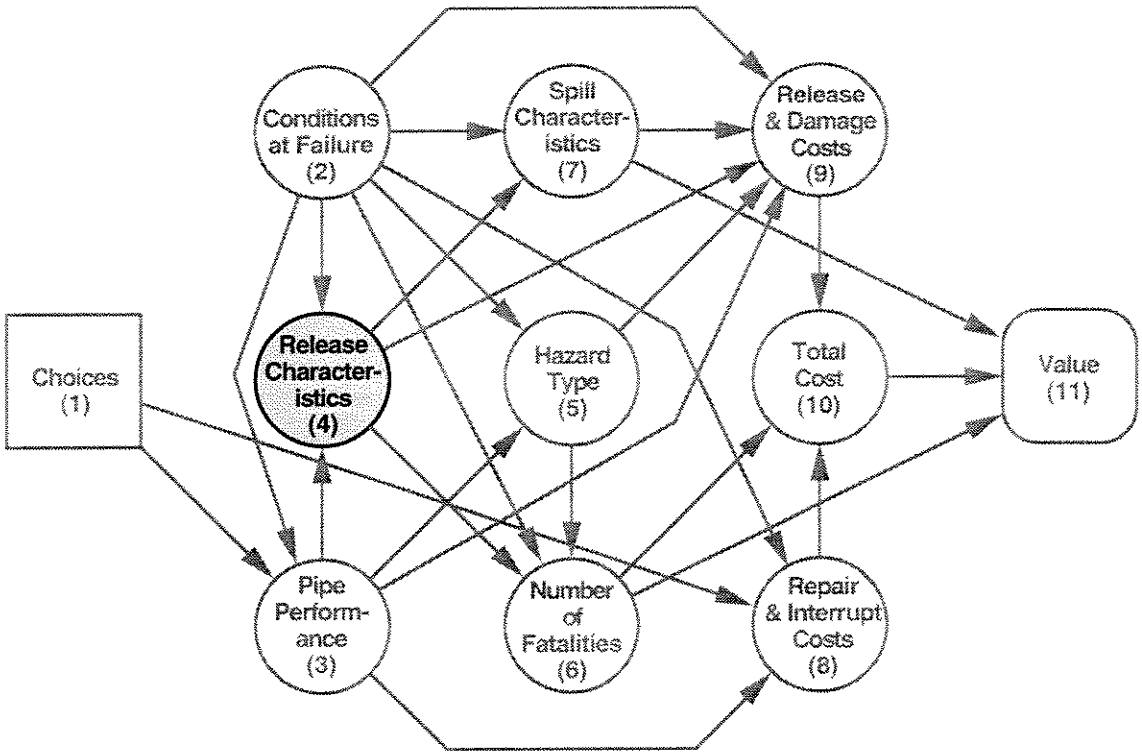


Figure 6.1 Compound node influence diagram highlighting Release Characteristics node group

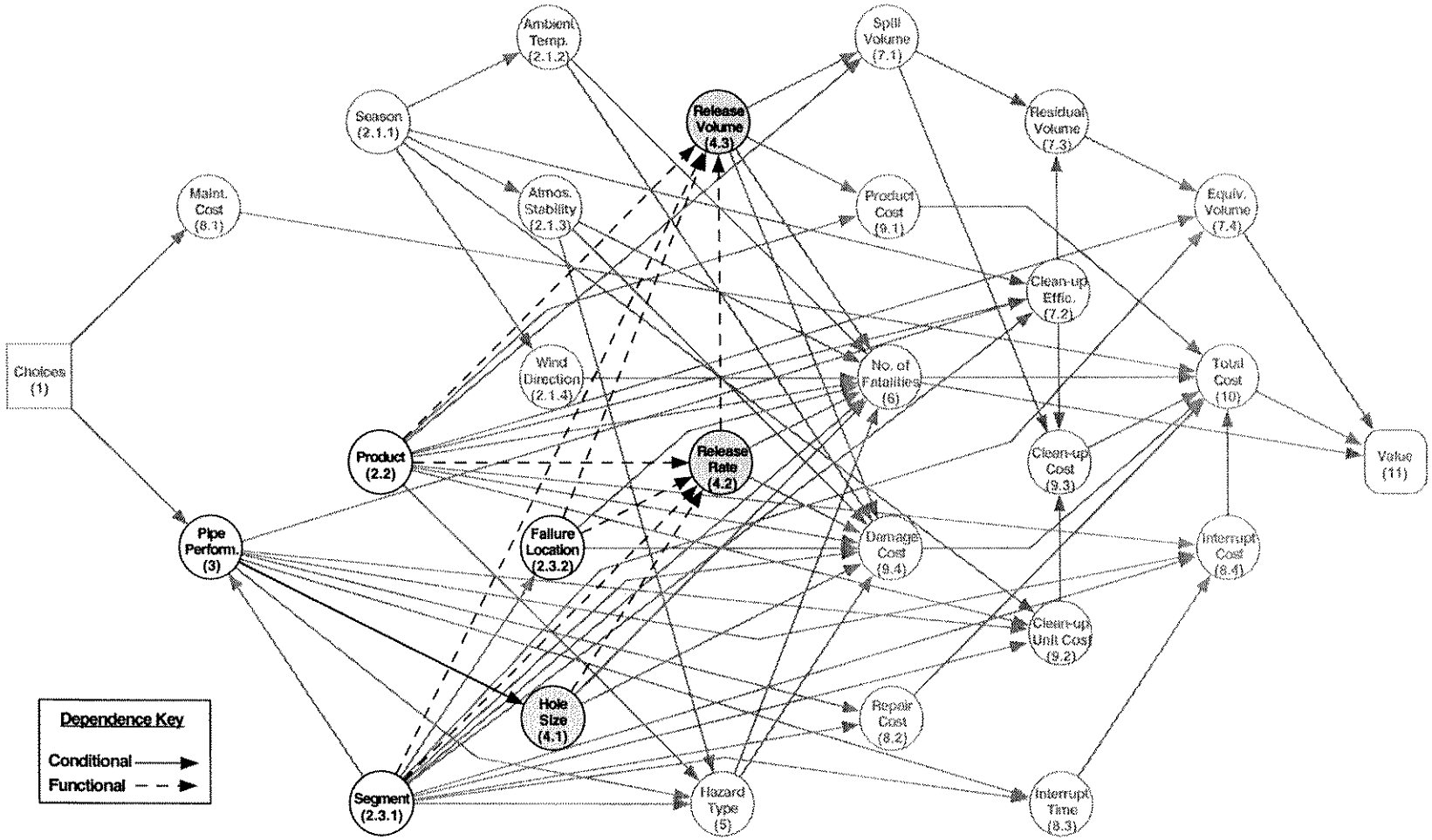


Figure 6.2 Basic node influence diagram highlighting Release Characteristics nodes and associated immediate predecessor nodes

Pipe Performance	Hole Diameter
Safe	discrete value = 0
Small Leak	uniform distribution (mean = 10 mm, std. dev. = ? mm)
Large Leak	uniform distribution (mean = 50 mm, std. dev. = ? mm)
Rupture	discrete value = 2 pipe diameters

Table 6.1 Reference Hole Size Distributions

Hazard Type

7.0 HAZARD TYPE

7.1 Node Parameter

The Hazard Type node group (group 5) is shown in a highlighted version of the compound node influence diagram in Figure 7.1. The node group consists of a single node called Hazard Type (node 5) which is shown together with its direct predecessor nodes in a highlighted version of the basic node influence diagram in Figure 7.2. The specific node parameter is the hazard type associated with product release (*Hazard*). The predecessor node arrows shown in Figure 7.1 indicate that Hazard Type is a conditional node meaning that the value of the node parameter is conditionally dependent upon the values of its direct predecessor nodes which include: Product, Atmospheric Stability, Segment and Pipe Performance. The Hazard Type node parameter must therefore be defined explicitly for all possible combinations of the values associated with these direct conditional predecessor nodes.

In the context of this project the node parameter is defined by a discrete probability distribution for hazard type that can take any of five possible values. The five types of hazard considered are:

- jet fire (*JF*);
- pool fire (*PF*);
- vapour cloud fire (*VCF*);
- vapour cloud explosion (*VCE*); and
- toxic or asphyxiating vapour cloud (*TVC*).

Definition of the Hazard Type node parameter requires the determination of the relative probabilities of the hazard types listed above. This is achieved by first constructing hazard event trees which identify all possible immediate outcomes associated with a pipeline failure event. For use in this project, two simple event trees were developed; one for gas release (Figure 7.3a) and one for liquid product release (Figure 7.3). These event trees were used to develop relationships which define for the relative probabilities of the different possible hazard outcomes in terms of the conditional probabilities associated with the branches of the event

Hazard Type

trees . Based on the event trees shown in Figure 7.3, the relative hazard probabilities are given by the following equations.

The probability of a jet fire or pool fire ($P_{JF/PF}$) is given by

$$P_{JF/PF} = P_i \qquad [7.1]$$

where P_i is the probability of immediate ignition given product release.

The probability of a vapour cloud fire (P_{VCF}) is given by

$$P_{VCF} = (1-P_i)\, P_d\, (1-P_e) \qquad [7.2]$$

where P_d is the probability of delayed ignition given no immediate ignition, and P_e is the probability of explosion given delayed ignition.

The probability of a vapour cloud explosion (P_{VCE}) is given by

$$P_{VCE} = (1-P_i)\, P_d\, P_e \qquad [7.3]$$

and the probability of a toxic or asphyxiating vapour cloud (P_{TVC}) is given by

$$P_{TVC} = (1-P_i)\, (1-P_d). \qquad [7.4]$$

It is noted that implicit in the subsequent application of the relative hazard probability obtained from Equation [7.1] are the following assumptions:

- that products which are transported as a gas will only produce a jet fire;
- that products which are transported as a liquid, and exist as a liquid under ambient conditions will only produce a pool fire; and
- that products which are transported as a liquid, but which exist as a gas under ambient conditions have the potential to produce both a jet fire and a pool fire.

In addition, the structure of the event trees shown in Figure 7.3 and the relative hazard probability equations developed from them also implies the following:

Hazard Type

- that hazard associated with a jet fire scenario takes precedence over a pool fire scenario;
  that hazard associated with scenarios involving ignition take precedence over scenarios that do not involve ignition; and
- that vapour cloud fires and explosions will not occur if pool or jet fires are ignited.

Given the above equations for relative hazard probabilities, the definition of the Hazard Type node parameter requires only the specification of the conditional event probabilities associated with the three event tree branches (i.e. P_a, P_d and P_e) for all combinations of direct predecessor node values.

The information required to estimate the conditional event probabilities associated with acute release hazards can be obtained from historical data compiled on release incidents associated with chemical process plants, product storage facilities, and pipelines. As part of this project a literature review was carried out to identify the specific conditions that have been shown to have a potentially significant effect on the event probabilities. The relevant conditions identified include:

- product type (i.e. gas, liquid);
- failure mode (i.e. small leak, large leak, rupture);
- atmospheric stability class (i.e. stable, unstable); and
- land use type (i.e. industrial, urban, rural).

Based on the literature review, in particular Fearnehough (1985), Crossthwaite et al. (1988), and EGIG (1993), representative conditional event probabilities have been established and from these event probabilities and a matrix of relative hazard probabilities was developed using Equations [7.1, 7.2, 7.3 and 7.4]. The conditional event probabilities are summarized in Table 7.1 and the relative hazard probabilities corresponding to each possible case, which effectively defines the Hazard Type node parameter, are given in Table 7.2. A discussion of the basis for the conditional event probabilities given in Table 7.1 is provided in Appendix D.

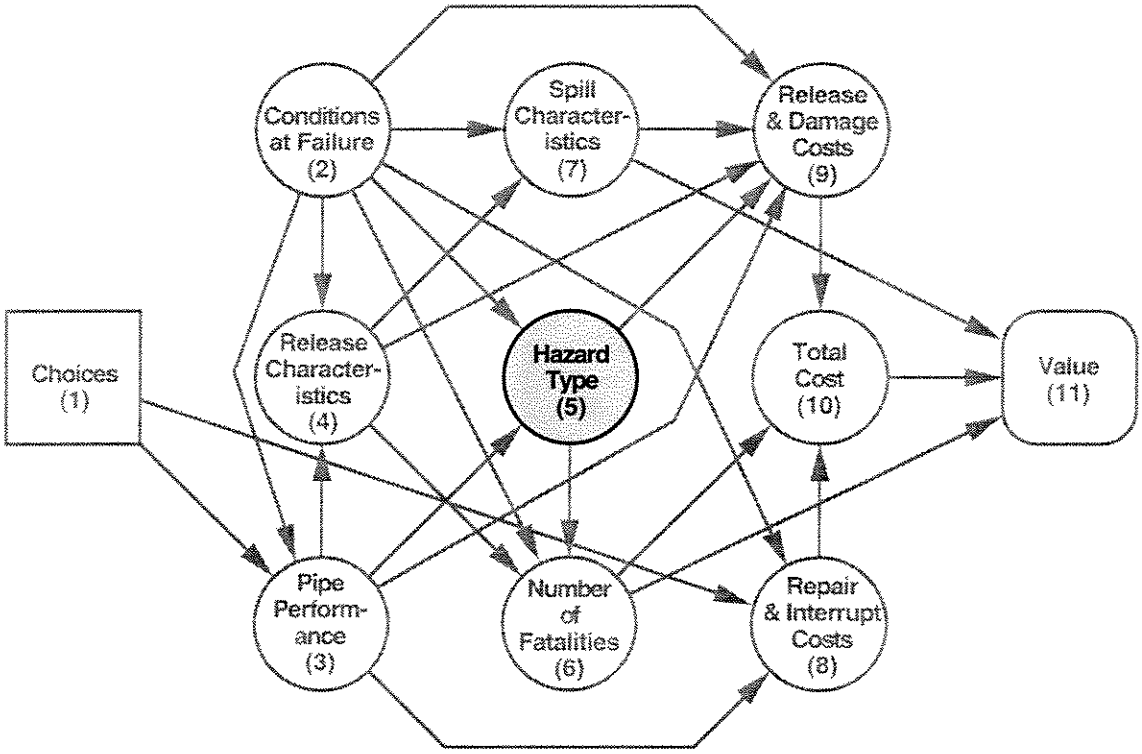


Figure 7.1 Compound node influence diagram highlighting Hazard Type node group

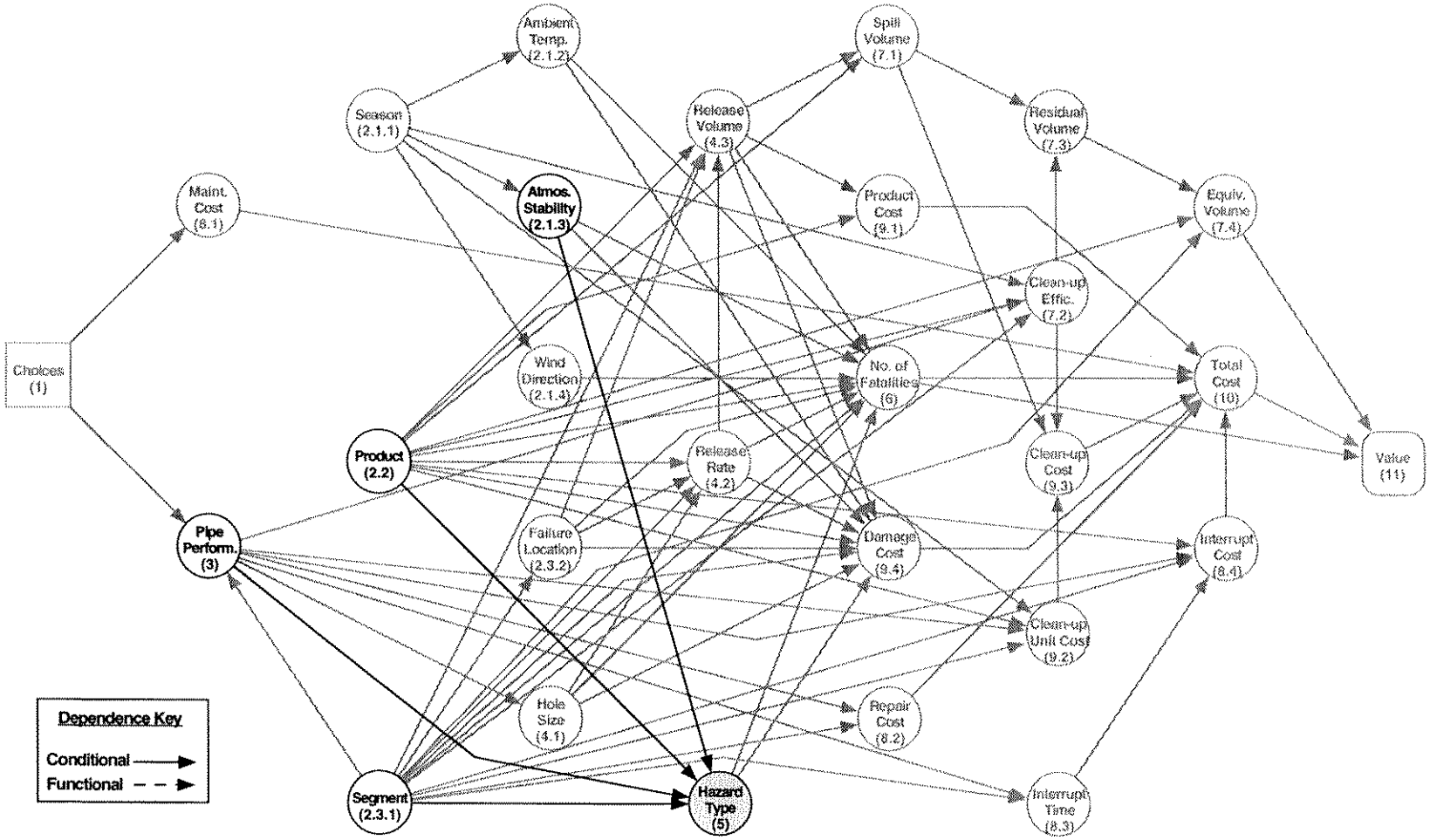
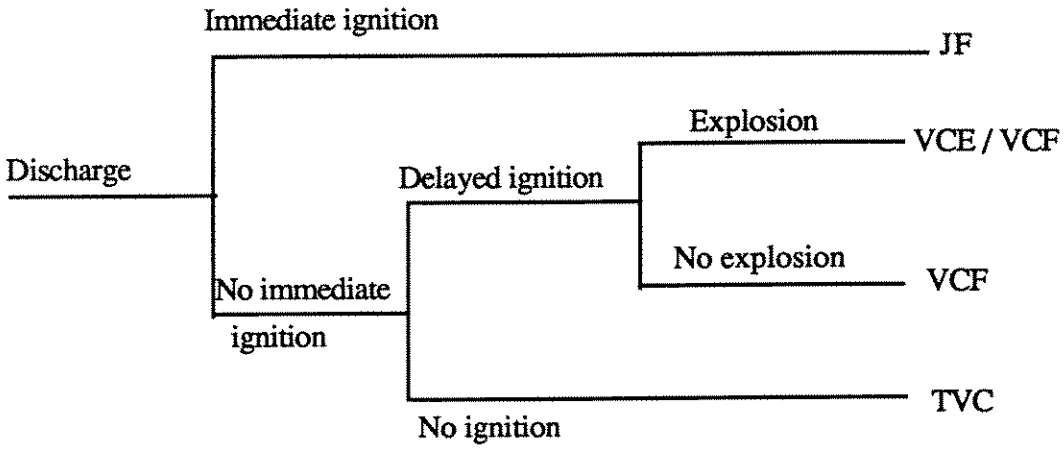
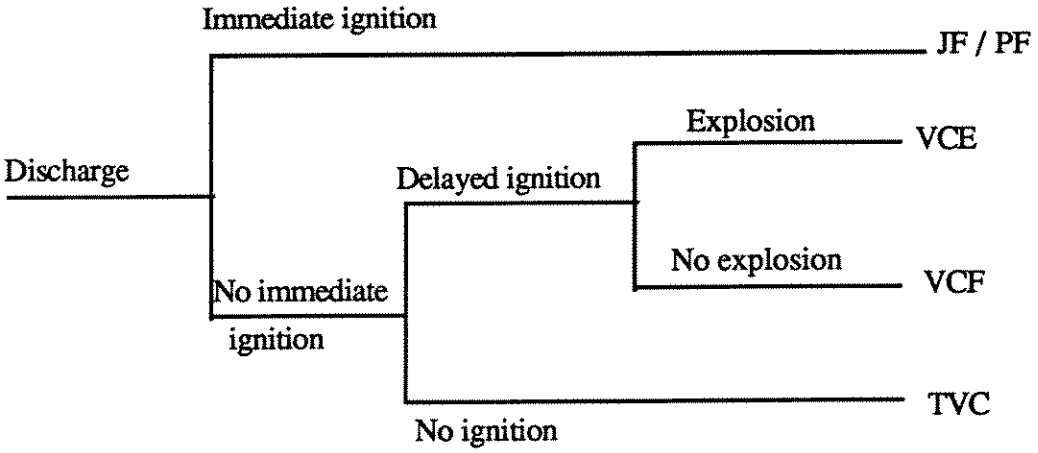


Figure 7.2 Basic node influence diagram highlighting Hazard Type node and associated immediate predecessor nodes



(a) natural gas release



(b) liquid release

Figure 7.3 Acute hazard event trees for product release from pipelines

Case	Product (type)	Pipe Performance (failure mode)	Atmospheric Stability (class)	Segment (land use)	Delayed Ignition Probability	Explosion Probability	Immediate Ignition Probability
1	liquid	small leak	A, B, C, D (unstable)	industrial	0.3	0.33	0.05
2				urban	0.24		
3				rural	0.012		
4			E, F (stable)	industrial	0.27	0.1	
5				urban	0.22		
6				rural	0.011		
7		large leak	A, B, C, D (unstable)	industrial	0.56	0.33	0.05
8				urban	0.45		
9				rural	0.023		
10			E, F (stable)	industrial	0.51	0.1	
11				urban	0.41		
12				rural	0.02		
13		rupture	A, B, C, D (unstable)	industrial	1	0.33	0.05
14				urban	0.8		
15				rural	0.04		
16			E, F (stable)	industrial	0.9	0.1	
17				urban	0.72		
18				rural	0.036		
19	gas	small leak	A, B, C, D (unstable)	industrial	0.15	0.33	0.03
20				urban	0.12		
21				rural	0.006		
22			E, F (stable)	industrial	0.14	0.1	
23				urban	0.11		
24				rural	0.0054		
25		large leak	A, B, C, D (unstable)	industrial	0.28	0.33	0.1
26				urban	0.23		
27				rural	0.011		
28			E, F (stable)	industrial	0.25	0.1	
29				urban	0.2		
30				rural	0.01		
31		rupture	A, B, C, D (unstable)	industrial	0.5	0.33	0.25
32				urban	0.4		
33				rural	0.02		
34			E, F (stable)	industrial	0.45	0.1	
35				urban	0.36		
36				rural	0.018		

Table 7.1 Matrix of conditional probabilities associated with acute hazard event tree branches

Case	Hazard Type			
	Jet Fire or Pool Fire	Vapour Cloud Fire	Vapour Cloud Explosion	Toxic Vapour Cloud
1	0.05	0.1910	0.0941	0.6650
2	0.05	0.1528	0.0752	0.7220
3	0.05	0.0076	0.0038	0.9386
4	0.05	0.2309	0.0257	0.6935
5	0.05	0.1881	0.0209	0.7410
6	0.05	0.0094	0.0010	0.9396
7	0.05	0.3564	0.1756	0.4180
8	0.05	0.2864	0.1411	0.5225
9	0.05	0.0146	0.0072	0.9282
10	0.05	0.4361	0.0485	0.4655
11	0.05	0.3506	0.0390	0.5605
12	0.05	0.0171	0.0019	0.9310
13	0.05	0.6365	0.3135	0.0000
14	0.05	0.5092	0.2508	0.1900
15	0.05	0.0255	0.0125	0.9120
16	0.05	0.7695	0.0855	0.0950
17	0.05	0.6156	0.0684	0.2660
18	0.05	0.0308	0.0034	0.9158
19	0.03	0.0975	0.0480	0.8245
20	0.03	0.0780	0.0384	0.8536
21	0.03	0.0039	0.0019	0.9642
22	0.03	0.1222	0.0136	0.8342
23	0.03	0.0960	0.0107	0.8633
24	0.03	0.0047	0.0005	0.9648
25	0.10	0.1688	0.0832	0.6480
26	0.10	0.1387	0.0683	0.6930
27	0.10	0.0066	0.0033	0.8901
28	0.10	0.2025	0.0225	0.6750
29	0.10	0.1620	0.0180	0.7200
30	0.10	0.0081	0.0009	0.8910
31	0.25	0.2513	0.1238	0.3750
32	0.25	0.2010	0.0990	0.4500
33	0.25	0.0101	0.0050	0.7350
34	0.25	0.3038	0.0338	0.4125
35	0.25	0.2430	0.0270	0.4800
36	0.25	0.0122	0.0014	0.7365

Table 7.2 Relative hazard event probabilities

Number of Fatalities

8.0 NUMBER OF FATALITIES

8.1 Introduction

The Number of Fatalities node group (group 6) is shown in a highlighted version of the compound node influence diagram in Figure 8.1. The node group consists of a single Number of Fatalities node (node 6) which is shown together with its direct predecessor nodes in a highlighted version of the basic node influence diagram in Figure 8.2. The specific node parameter is the number of human fatalities resulting from the acute hazards associated with pipeline failure. Number of Fatalities is a functional node meaning that the value of the node parameter is calculated directly from the values of its direct predecessor node parameters which include: the product (and its characteristics), the failure location, the ambient temperature and wind conditions, and the release rate and release volume.

The node calculations model the emission of gas or liquid vapour into the atmosphere and determine the intensity of different acute hazard types (i.e. heat intensity due to fires or concentration of asphyxiant gas) at different points around the failure location. Based on this, and using estimates of the population density, the number of people exposed to fatal doses of these hazards can be calculated.

In addition to the number of fatalities in a given incident, this node calculates the individual risk curve at any location along the pipeline. The individual risk at a given location is defined as the annual probability of death due to a pipeline incident for an individual living or working at that location. This information is often used as a basis for assessment of the risks associated with life safety. This section describes the data and models used to calculate the number of fatalities and individual risk.

8.2 Basic Calculation of the Number of Fatalities

The number of fatalities due to chemical releases is a function of the hazard intensity and the tolerance threshold of humans to that hazard. Figure 8.3a gives a schematic representation of hazard intensity contours around the release source, while Figure 8.3b shows a schematic of

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the probability of death as a function of the hazard intensity. At the point with coordinates (x,y), the hazard intensity is $I(x,y)$ and the probability of death as a function of the hazard level is denoted $p[I(x,y)]$. Given an incident, the number of fatalities in a small area around (x,y) with dimensions Δx and Δy can be calculated by multiplying the number of people in the area by the probability of death for each person. The number of people is equal to the product of the population density $\rho(x,y)$, the ratio of time (t) spent by a member of the population in the area on average, and the area. This can be written as:

$$n(x,y) = p[I(x,y)] \times [\rho(x,y)\ t\ \Delta x \Delta y] \qquad [8.1]$$

Note that the population density is defined as the number of people who live or work in the area. This is why it is multiplied by the ratio of time spent on average at home or at the workplace to calculate the number of people in the area when the failure occurs. The total number of fatalities for the whole area can be calculated by summing Equation [8.1] over the total area affected by the hazard. This gives:

$$n = t \sum_{Area} p[I(x,y)] \times \rho(x,y) \Delta x \Delta y \qquad [8.2]$$

In Equation [8.2] $\rho(x,y)$ is usually available from survey information. $I(x,y)$ can be calculated as a function of the product type, release rate and weather conditions using a hazard model as will be discussed further in Section 8.3. The probability of death at a given hazard intensity level $p[I(x,y)]$ can be calculated from a probit analysis (e.g. Lees 1980), which is essentially a method of calculating the probability that the tolerance threshold of a randomly selected individual is below the hazard dosage received. For some types of hazard (e.g. thermal radiation), the dosage depends on exposure time and this is usually factored into the probit analysis, based on assumptions regarding the potential for escape within a certain period of time.

In order to simplify Equation [8.2] the following assumptions were made:

1. The population density is constant for the area being considered.
2. Two hazard intensity thresholds can be defined, the first (denoted I_1) is the upper bound of human tolerance defined as the maximum intensity that has a chance of being tolerated (i.e. $p(I) = 1$ for $I > I_1$), and the second (denoted I_0) defines the lower bound of human tolerance defined as the minimum intensity that has a chance of causing death (i.e. $p(I) = 0$

for $I < I_0$). These thresholds take into account all aspects related to hazard dose and potential for escape.

3. The probability of death decreases linearly between the I_1 and I_0 contours.

Based on these assumptions, the number of fatalities n_1 within the upper bound tolerance threshold contour can be calculated from Equation [8.2] by using a fixed value of ρ and a value of $p[I(x,y)] = 1$. For a hazard intensity that decreases monotonically as the distance from the pipeline increases, this leads to (See Figure 8.4):

$$n_1 = t\rho \sum_{A_1} \Delta x \Delta y = t\rho A_1 \qquad [8.3]$$

where A_1 is the area within the I_1 contour. Similarly, the number of fatalities n_0 between the I_1 and I_0 contours is given by:

$$n_0 = 0.5t\rho(A_0 - A_1) \qquad [8.4]$$

where A_0 is the total area within the I_0 contour. The total number of fatalities can be calculated as the sum of Equations [8.3] and [8.4], leading to

$$n = 0.5t\rho(A_0 + A_1) \qquad [8.5]$$

This approach is further illustrated in Figure 8.5, which shows a plot of the thermal radiation hazard intensity against the probability of death for a jet or pool fire. The probability of death resulting from a probit analysis that assumes a constant exposure time of 60 seconds is plotted, and compared to the assumption used in this report. In addition, a simpler assumption used in the public domain software program ARCHIE (FEMA/DOT/EPA 1989), based on a single threshold value that separates certain death from certain safety, is also shown on the plot for comparison.

Finally, distinction between outdoor and indoor exposure is necessary because the hazard tolerance thresholds, and consequently the hazard areas used in Equation [8.5], are different for indoor and outdoor locations. For example, buildings provide protection from thermal radiation hazard, as long as the hazard intensity is lower than the threshold causing ignition of the building. Taking this into account amounts to adding the number of fatalities occurring

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indoors and those occurring outdoors based on the number of people at indoor and outdoor locations at the time of the incident. This leads to:

$$n = 0.5\rho[t_i(A_0 + A_1)_i + t_o(A_0 + A_1)_o] \qquad [8.6]$$

where the subscripts i and o represent indoor and outdoor respectively. In this Equation t_i and t_o represent the ratio of time spent by a resident or worker indoors or outdoors at the location where he or she lives or works.

8.3 Information Required to Evaluate the Node Parameter

8.3.1 General

To implement the model described in section 8.2 the following information is required:

- Properly calibrated upper and lower bound tolerance thresholds for different types of hazards. This information is required for both indoor and outdoor exposure conditions.
- Models to calculate the area within the above-mentioned hazard threshold contours. These are derived from hazard models that calculate the hazard intensity as a function of the distance from the pipeline.
- Population density and exposure times for indoor and outdoor exposure.

These items are discussed in Sections 8.3.1, 8.3.2 and 8.3.3.

8.3.2 Hazard Tolerance Thresholds

A review of the literature was undertaken to define appropriate values of the upper and lower hazard tolerance thresholds. Table 8.1 gives a summary of the results for all acute hazard types relevant to product releases from pipelines. The main sources for this information are publications by the U.K. Health and Safety Executive (HSE) and by British Gas (see Appendix E).

A discussion of the rationale behind the values given in Table 8.1 is provided in Appendix E. The adopted thresholds are generally based on conservative assumptions. They also assume appropriate behaviour by those exposed to the hazard. For example, it is assumed that people

in outdoor locations will move away from the hazard source or seek shelter. Also, in cases where being indoors provides protection from the hazard (such as for sustained jet or pool fires), it is assumed that people will remain indoors.

It is noted that exposure times are taken into account in defining the thresholds for thermal radiation and asphyxiation hazards. Time is relevant to these two types of hazards because the probability of death is a function of the total dose received, which in turn depends on the exposure time. For example, a high heat flux may be tolerated for a small period of time, whereas a lower heat flux may result in death if sustained for a long period of time. The time factor is taken into account by selecting the threshold value corresponding to a reasonable exposure time. The latter is selected on the basis of the hazard duration and the potential for escape. Details are given in Appendix E.

It is noted that fatality thresholds are not applicable to vapour cloud fires for indoor exposure. This is because vapour cloud fires burn for very short periods of time and secondary ignition of objects within the fire zone is very unlikely. It is therefore assumed that vapour cloud fires do not represent a hazard for indoor exposure.

8.3.3 Hazard Models

The area bound by the hazard threshold contours defined in Section 8.3.4 can be defined for each hazard type based on appropriate hazard intensity characterization models. The specific equations associated with the models adopted in this project, and the simplifying assumptions associated with their use, are described in detail in Appendix C. The following serves as a brief overview of the models used.

8.3.3.1 Jet Fire

The hazard intensity associated with a jet fire, I_{JF}, is the heat flux associated with the radiant heat source which is assumed to be located at the effective centre of the flame. The jet fire heat intensity at a given location (x,y) is given by

$$I_{JF}(x,y) = f\left(\dot{m}_{RG}, r_{xy}, x_0, y_0, product\ \ data\right) \qquad [8.7]$$

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where $\dot{m}_{RG}$ is the mass flow rate associated with the gas (or vapour) fraction of released product, r_{xy} is the radius from the effective flame centre to the point of interest and x_0, y_0, are the coordinates of the horizontal projection of the flame centre relative to the point of release. The location of the horizontal projection of the flame centre is given by

$$x_o, y_o = f(\dot{m}_{RG}, d_h, u_a, \theta_r, product\ \ properties) \qquad [8.8]$$

where d_h is the effective hole diameter, u_a is the wind speed, and θ_r is the wind direction relative to the bearing angle of the pipeline. (See also Appendix C, Section 5.0.)

8.3.3.2 Pool Fire

The hazard intensity associated with a pool fire, I_{PF}, is the heat flux associated with the radiant heat source which is assumed to be distribute over the area of the burning pool, the shape of which is approximated by a circle. The pool fire heat intensity at a given location is given by

$$I_{PF}(x,y) = f(\dot{m}_{RL}, r_{xy}, product\ \ data) \qquad [8.9]$$

where $\dot{m}_{RL}$ is the mass flow rate associated with the liquid fraction of released product and r_{xy} is the radius from the centre of the burning pool, which is assumed to be centred on the point of release, to the point of interest. (See also Appendix C, Section 4.0 and 6.0.)

8.3.3.3 Vapour Cloud Explosion

The hazard intensity associated with a vapour cloud explosion, I_{VCE}, is the overpressure associated with the propagating blast wave. The explosion induced overpressure at a given location is given by

$$I_{VCE}(x,y) = f(M_c, r_{xy}, x_1, y_1, product\ \ data) \qquad [8.10]$$

where M_c is the total mass of the flammable portion of the gas or vapour cloud bound by the vapour concentration associated with the lower flammability limit, r_{xy} is the radius from the effective centre of the blast to the point of interest and x_1, y_1 are the coordinates of the

horizontal projection of the blast centre relative to the point of release. The location of the horizontal projection of the blast centre is given by

$$x_1, y_1 = f(\dot{m}_{RG}, \dot{m}_V, S_{class}, u_a, \theta_r, C_{LFL}, product\ \ data) \qquad [8.11]$$

where $\dot{m}_{RG}$ is the mass release rate of the gas fraction, $\dot{m}_V$ is the evaporation rate from the liquid pool, C_{LFL} is the lower flammability limit, S_{class} is the atmospheric stability class and u_a is the mean wind speed. (See also Appendix C, Sections 7, 8, and 10.)

8.3.3.4 Vapour Cloud Fire

The hazard associated with a vapour cloud explosion is direct exposure to the burning cloud of gas or vapour. The extent of the burning area is bound by the vapour concentration contour associated with the lower flammability limit of the product involved. The vapour concentration contour associated with C_{LFL} is given by

$$C_{C_{LFL}}(x,y) = f(\dot{m}_{RG}, \dot{m}_V, S_{class}, u_a, x_1, y_1, C_{LFL}, product\ \ data) \qquad [8.12]$$

where x_1, y_1 are the co-ordinates of the horizontal projection of the centre of the flammable vapour cloud relative to the release point which is given by Equation [8.11]. (See also Appendix C, Sections 7, 8, and 9.)

8.3.3.5 Asphyxiating Cloud

The hazard associated with a toxic or asphyxiating cloud is associated with oxygen deprivation. The extent of the hazard area is bound by the vapour concentration contour associated with the vapour concentration threshold (C_{TVC}) of the product involved. The vapour concentration contour associated with C_{TVC} is given by

$$C_{C_{TVC}}(x,y) = f(\dot{m}_{RG}, \dot{m}_V, S_{class}, u_a, x_2, y_2, C_{TVC}, product\ \ data) \qquad [8.13]$$

where x_2, y_2 are the co-ordinates of the horizontal projection of the centre of the asphyxiating vapour cloud relative to the release point which is given by

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$$x_2, y_2 = f(\dot{m}_{RG}, \dot{m}_V, S_{class}, u_a, \theta_r, C_{TVC}, product\ \ data) \qquad [8.14]$$

(see also Appendix C, Sections 7, and 8.)

8.3.4 Population Density and Exposure Time

Population density is highly dependent on the type of land usage associated with the area adjacent to the pipeline right-of-way. Land use is typically divided into three major categories: industrial, urban and rural. In the context of this project, to allow for further refinement of the estimates of the number of fatalities, the property damage costs (see Section 11), and the environmental impact of liquid product spills (see Section 9), the urban and rural land use categories were further sub-divided into the following categories: commercial, urban residential, rural residential, agricultural, parkland, and remote.

A literature survey was then conducted to identify reference population densities for the various land use categories from which population density range estimates were developed. Based on the ranges developed from the reference densities, representative population densities were established for each land use category. The population density ranges and chosen reference densities are given in Table 8.2 for each of the land use categories identified in the project. The basis for the sited density ranges and reference values is given in Appendix F.

Daily exposure time is defined as the length of time per day spent by an average person at the location in question. For residential areas, this is the time spent by residents at their homes. For industrial areas, it represents the time spent by workers at the workplace. The exposure time is divided into outdoor and indoor portions. This information is summarized in Table 8.3. Exposure time estimates for urban and rural areas are based on values developed by the U.K. Health and Safety Executive and quoted by Fearnehough (1985). For industrial areas, the time is based on 1750 working hours per year. The outdoor time in industrial areas is an estimate made by C-FER to account for time spent in parking lots, working outdoor and being outdoors on breaks. Note that he exposure time ratio t in Equation [8.5] is calculated by dividing the exposure times given in Table 8.3 by 24 hours.

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8.4 Individual Risk Calculation

8.4.1 Introduction

In this work, the attribute representing life safety was selected as the number of fatalities in a given incident, and this parameter is used to calculate the overall utility associated with the pipeline (see Section 13.0). Another parameter that is related to life safety is the *individual risk*. This is defined as the annual probability of death due to possible failure of the pipeline for any individual living or working near the pipeline. This parameter is commonly used to set criteria defining acceptable risk levels because it expresses risk in a manner similar to the way other common risks are defined (e.g. annual risk of dying in a car accident per person). In addition, individual risk is required at the value node to implement the constrained cost optimization criterion.

Individual risk is essentially a separate node hidden under the number of fatalities node. Figure 8.6 shows how this node relates to other nodes in the detailed influence diagram. It is noted that there are some differences regarding the predecessor nodes for individual risk and for the number of fatalities. The first difference is that wind direction is a predecessor of individual risk, but not of the number of fatalities. The number of fatalities is independent of the wind direction because, as shown in Section 8.2, it depends only on the total area within a certain hazard contour and the population density. Since the population density is assumed to be constant in the whole area of interest, and since wind direction affects only the location of the hazard area but not its size, the number of fatalities is independent of wind direction. Individual risk on the other hand, depends on the wind direction because it is calculated at a given location, and the probability of the hazard reaching that location is dependent on the wind direction. For example, if West winds are more frequent than East winds at a given location, the risk East of the hazard source will be higher the risk West of the source.

Another difference is that failure segment and failure location are not predecessors to the individual risk node. This is because influence diagram nodes represent random parameters. Individual risk is calculated at a specific location and therefore the location is not random. Location and segment are, in this case, treated as deterministic parameters defined at the

individual risk node. Therefore, the random parameters representing failure location and segment are not required as predecessors.

8.4.2 Calculation of Individual Risk

Individual risk at a given location is calculated as the product of the annual probability of an incident for which the hazard zone extends to the location of interest, multiplied by the probability that the individual living at that location is present. Calculation of the probability of an incident affecting the location of interest in illustrated in Figure 8.7, which shows the hazard zone for a given release characterized by a specific set of parameters such as the release rate, weather conditions and pipeline characteristics. The figure is based on a circular hazard zone, but the same concept is applicable to elliptical hazard zones as well. Note also that the hazard zone is not centred around the failure location because of the effects of wind. Figure 8.7 shows that for the hazard zone to include the location of interest (point x), the failure must occur within a certain length along the pipeline. This length is called the interaction length for point x, and is denoted l_x. Figure 8.7 illustrates that the interaction length is equal to the secant of the hazard zone passing through point x and parallel to the pipeline.

The annual probability of an incident affecting point x, is therefore equal to the probability of a failure occurring on the interaction length l_x. This is given by λl_x, where λ is the failure rate per km per year. The individual risk, R, is then calculated by multiplying this probability by the ratio (t) of time spent by the person at location x.

$$R = t \lambda l_x \qquad [8.15]$$

Equation [8.15] gives the individual risk for one hazard contour within which the probability of death is 100%. As mentioned in Section, 8.2, the hazard zone in this project is defined by two hazard contours: an upper limit and a lower limit tolerance threshold, with a chance of death of 100% within the upper limit contour and 50% between the two contours. Also, distinction between outdoor and indoor exposure is needed here for the same reasons mentioned in connection with calculating the number of fatalities in Section 8.2. Considering these factors, a similar procedure to that explained in Section 8.2 shows that, Equation [8.15] becomes:

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$$R = 0.5\lambda[t_i(l_{x0} + l_{x1})_i + t_o(l_{x0} + l_{x1})_o] \quad [8.16]$$

where all the parameters are as defined before, with the subscripts *i* and *o* denoting indoor and outdoor exposure.

Equation [8.15] gives the individual risk at a given location for a specific set of input parameters represented by all predecessor nodes shown in Figure 8.6 (e.g., release volume, ambient temperature, atmospheric stability, wind direction, product, release rate, hole size and hazard type), all of which are potentially random parameters. The final individual risk can be calculated as the sum of the individual risks associated with specific combinations of these parameters, each weighted by the probability of the combination occurring. This process is a probability integral which is essentially identical to solving the influence diagram with individual risk as the final node (see Nessim and Hong 1995). Therefore, individual risk can be calculated directly from the diagram.

It is often desirable to define an individual risk curve, which plots the individual risk as a function of distance from the pipeline. This can be achieved by repeating the calculation at different distances from the pipeline and plotting the results. An illustration of an individual risk curve is shown in Figure 8.8.

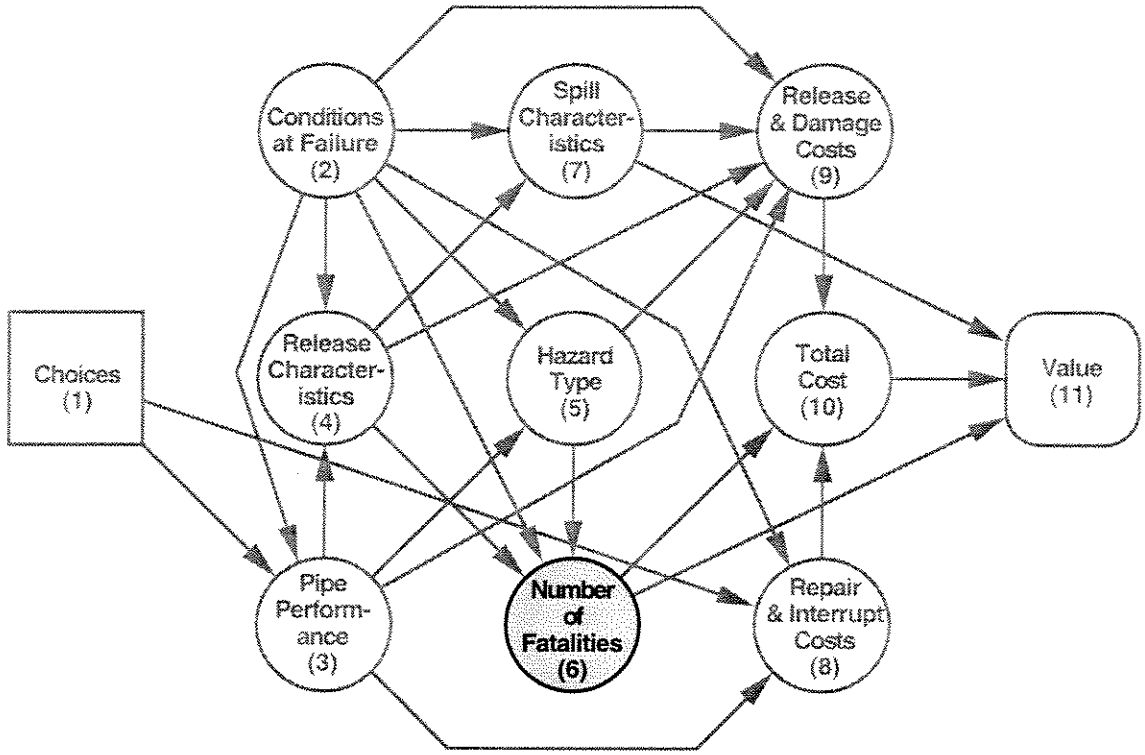


Figure 8.1 Compound node influence diagram highlighting Number of Fatalities node group

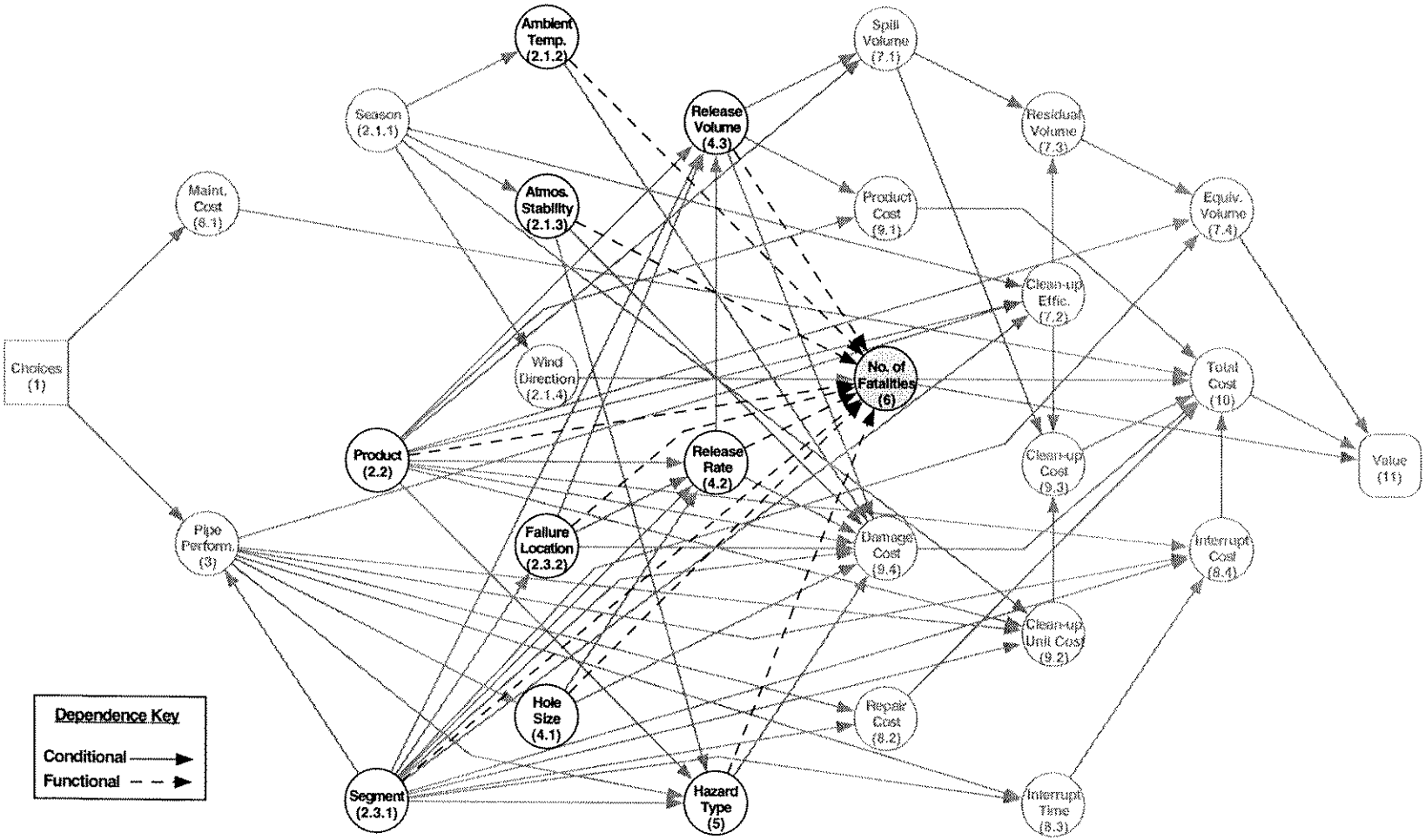
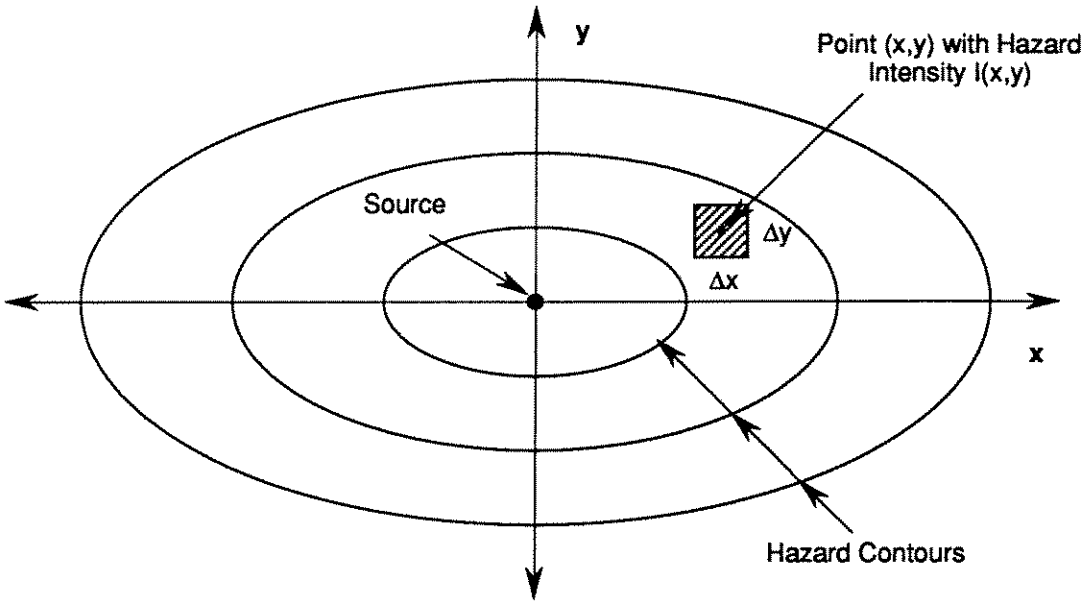
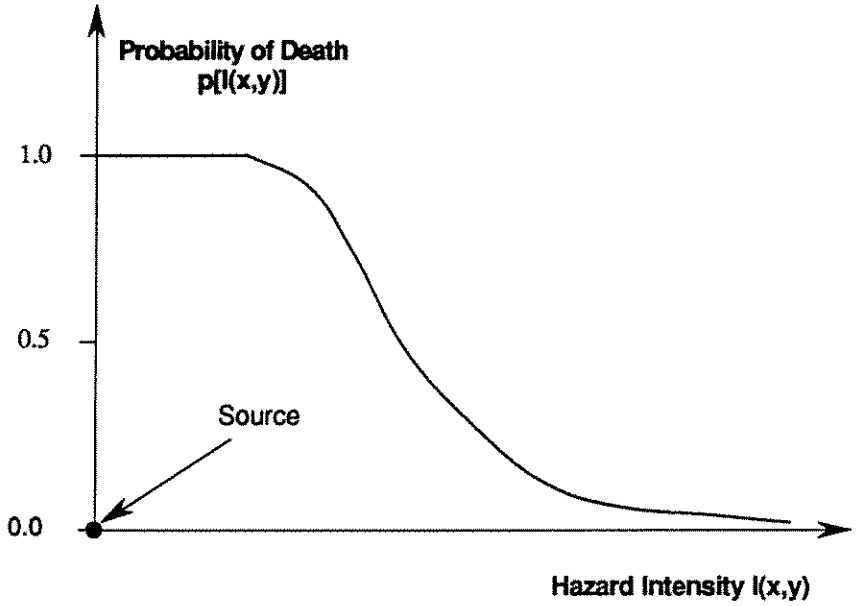


Figure 8.2 Basic node influence diagram highlighting Number of Fatalities node and associated immediate predecessor nodes



a) Hazard Contours



b) Probability of Death as a Function of Hazard Intensity

Figure 8.3 Illustration of the Calculation of the Number of Fatalities

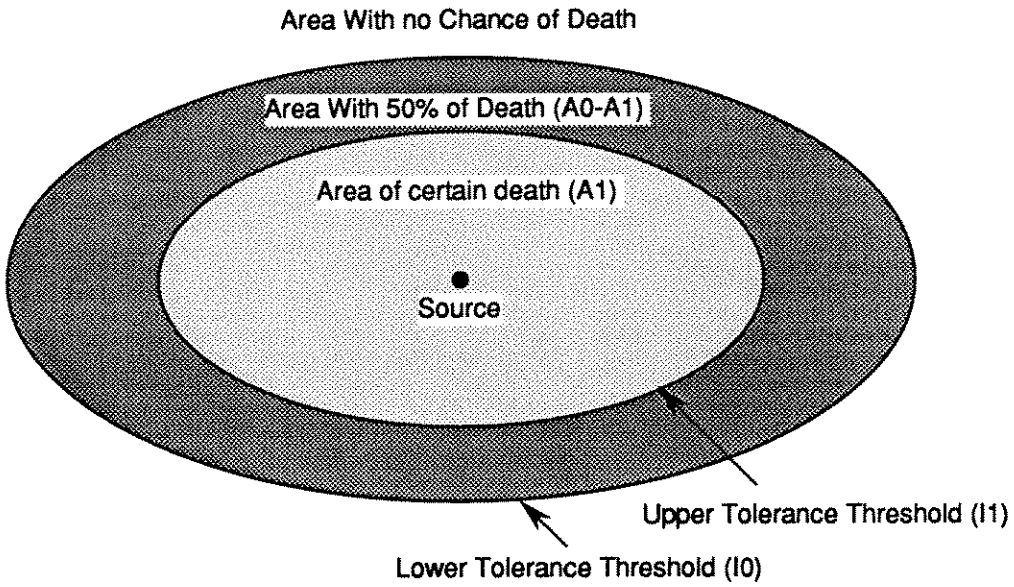


Figure 8.4 Area Model Used in Calculating the Number of Fatalities

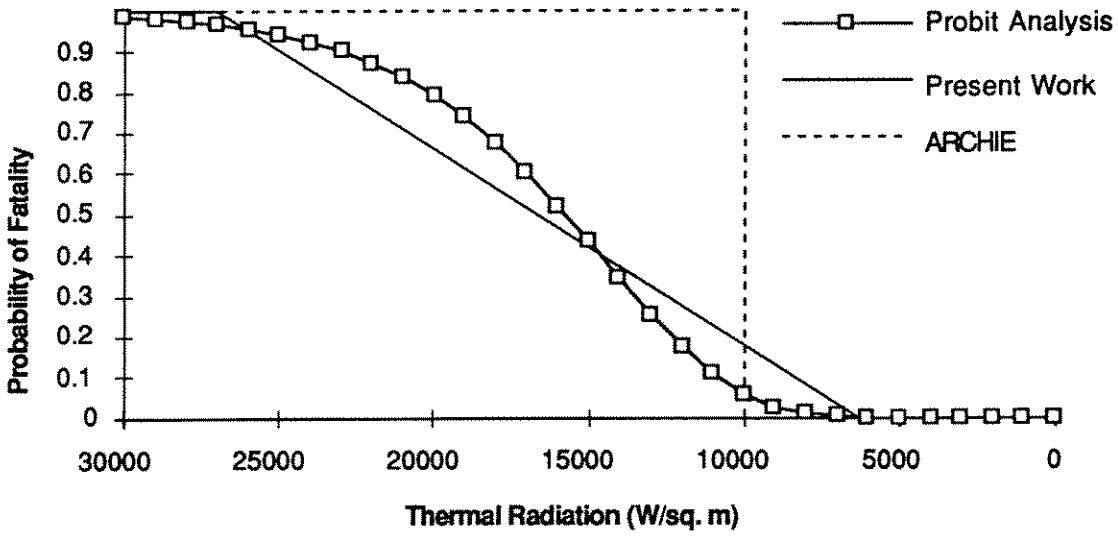


Figure 8.5 Illustration of Different Methods for Calculating the Probability of Death as a Function of the Hazard Intensity

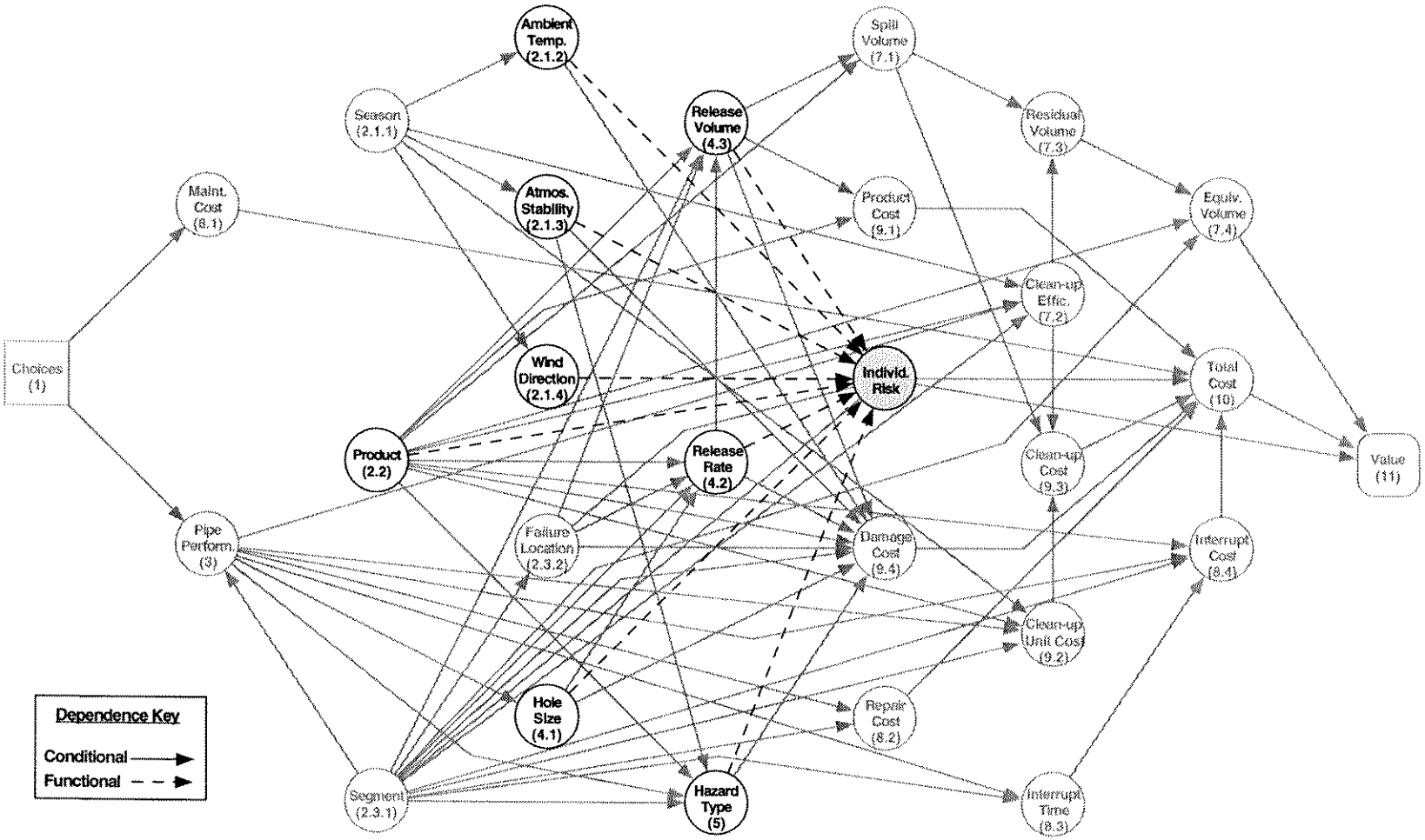


Figure 8.6 Basic node influence diagram highlighting Individual Risk node parameter (within Fatalities node) and associated immediate predecessor nodes

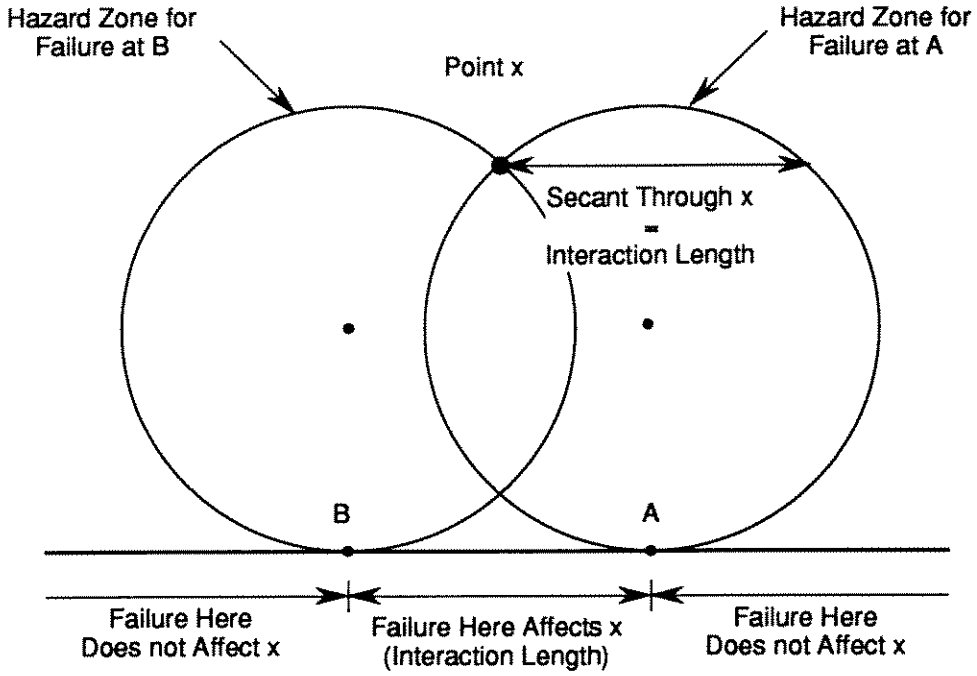


Figure 8.7 Illustration of the Calculation of Interaction Length

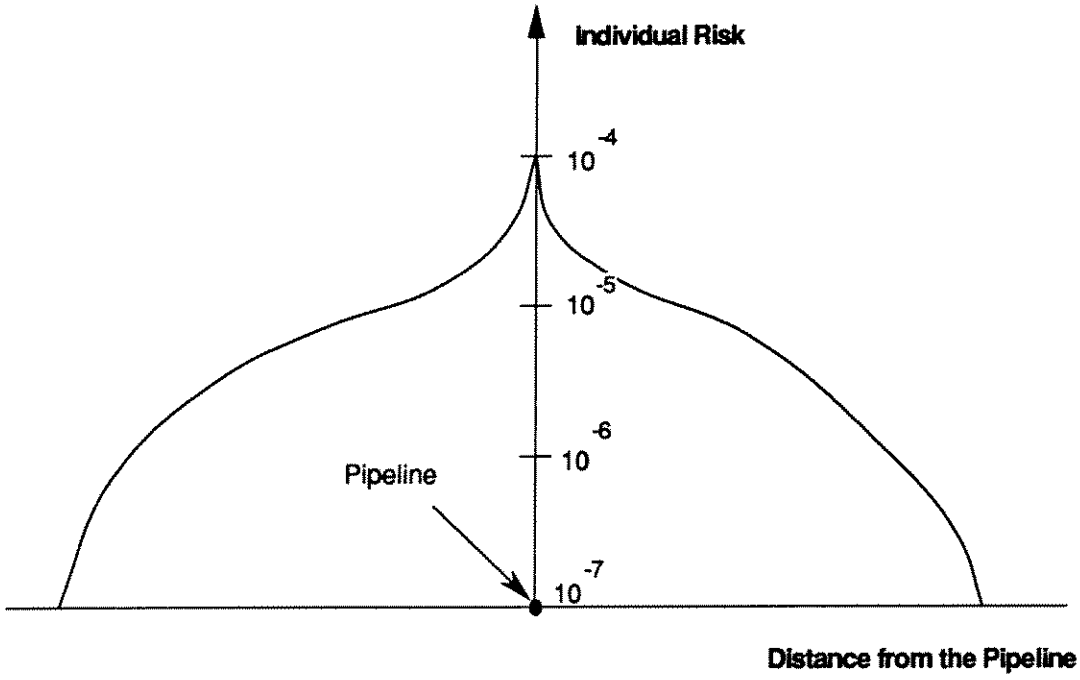


Figure 8.8 Individual Risk Curve

Acute Hazard	Exposure	Parameter	Units	Lower Bound Tolerance Threshold	Upper Bound Tolerance Threshold
Thermal radiation	Outdoor	Heat Intensity	kW/m^2	6.3	27
Thermal radiation	Indoor	Heat Intensity	kW/m^2	15.7	27
Asphyxiation	Outdoor or Indoor	volume concentration	ratio	0.306	0.713
Vapour cloud fire	Outdoor	volume concentration	ratio	0.5 x $C_{LFL}^{(1)}$	$C_{LFL}^{(1)}$
Vapour cloud fire	Indoor	volume concentration	ratio	N/A	N/A
Vapour cloud explosion	Outdoor or Indoor	Pressure	kPa	10.35	68.95

(1) Lower flammability limit of product

Table 8.1 Lower and upper bound fatality thresholds for acute release hazards

Land Use Category		Population Density (people per hectare*)	
Major Use Category	**Sub-Categories**	**Typical Range**	**Representative Value**
Industrial	Industrial	2 to 50	10
Urban	Commercial	10 to 50	50
	Urban Residential	10 to 50	50
Rural	Rural Residential	0.1 to 5	0.5
	Agricultural	0.01	0.01
	Parkland	0.01 to 50	none (highly variable)
	Parkland - forested	0.01 to 50	none (highly variable)
	Remote	0	0
	Remote - forested	0	0

* 1 hectare = 100 m x 100 m = 10,000 m^2

Table 8.2 Population densities associated with land use categories

Average daily hours of exposure	Area type	
	Urban or rural area	Industrial area
Indoor hours	12.2	4.8
Outdoor hours	3.6	0.5

Table 8.3 Number of hours of Exposure by land use classification

9.0 SPILL CHARACTERISTICS

9.1 Overview

The Spill Characteristics node group (group 7) is shown in a highlighted version of the compound node influence diagram in Figure 9.1. This node group involves parameters that are associated with released product volumes that constitute a liquid spill and the potential long-term impact on human health and the environment of that portion of the liquid spill volume that is not removed from the spill site during initial clean-up operations. The individual parameters associated with the Spill Characteristics node group, as identified by the shaded nodes in a highlighted version of the basic node influence diagram shown in Figure 9.2, are discussed in the following sections.

9.2 Spill Volume

The Spill Volume node (basic node 7.1) and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 9.2. The Spill Volume node parameter, V_S, is the total volume of Low Vapour Pressure (LVP) liquid product released at the time of line failure. The predecessor node arrows indicate that Spill Volume is a functional node. The node parameter is therefore calculated directly from the value of the parameters associated with its direct predecessor nodes which include Product and Release Volume.

The total spill volume is given by the equation

$$V_S = \beta_S V_R \qquad [9.1]$$

where V_R is the total release volume and β_S is a product state factor which is equal to zero, if the product is a gas or a High Vapour Pressure (HVP) volatile liquid product that will rapidly boil off upon release (e.g. methane, ethanes, propanes, and butanes) , or 1 if it is an LVP non-volatile liquid product that by definition will remain in the environment as liquid for a significant period of time following release (e.g. condensate or pentanes, gasolines, kerosenes, gas oils, and crude oils). The parameter V_R is calculated at the Release Volume node and the

product state factor (β_S) is calculated directly from the physical properties associated with the product in question.

9.3 Clean-up Efficiency

9.3.1 Node Parameter

The Clean-up Efficiency node (basic node 7.2) and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 9.2. The specific node parameter is κ_c, the efficiency of initial clean-up and basic site reclamation activities. The predecessor node arrows indicate that Clean-up Efficiency is a conditional node meaning that the value of the node parameter is conditionally dependent upon the values of its direct predecessor nodes which include Pipe Performance, Product, Season and Segment.

The Clean-Up Efficiency node parameter must therefore be defined explicitly for all combinations of pipe performance states involving failure (i.e. leak and rupture), for both summer and winter (i.e. frozen and unfrozen) seasons, and for selected combinations of product and pipeline attributes which are considered to have a significant impact on the degree to which spilled product can be removed from the spill site. In the context of this project the node parameter is defined for each combination by specifying a continuous probability distribution for the expected clean-up efficiency (κ_c) that can take any value between zero and 1 with values near zero suggesting that very little of the spilled product is recovered during initial clean-up, and values near 1.0 suggesting that almost all of the spilled product is recovered from the spill site.

It is emphasized that the Clean-up Efficiency values defined at this node are intended to reflect the product recovery and/or removal potential associated with the various techniques currently available for spill containment and clean-up and for basic site reclamation operations that can be carried out in the near term. The type of operations considered in the development of the efficiency estimates include, for example: the use of absorbent pads and booms; skimming and vacuuming operations, possibly in conjunction with the use of recovery trenches or wells; and the excavation and disposal of contaminated soil and/or snow.

The clean-up efficiency estimates are not intended to reflect the product recovery and removal potential associated with long-term site remediation measures. It is assumed that the extent to which site remediation techniques are employed to further reduce the residual volume of spilled product will depend on spill site attributes that reflect the potential impact of hazardous liquid spills on human health and the surrounding environment. These issues are implicitly addressed in the calculation of the parameters associated with the Equivalent Volume node (basic node 7.4) and the Value node (basic node 11).

With the scope limited to initial clean-up and basic site reclamation activities, a literature review was carried out to identify specific product and pipeline right-of-way attributes that are considered to have a potentially significant impact on the efficiency of spill product recovery and removal. Relevant attributes identified in the review process include:

- product viscosity;
- ground surface permeability for spills on land; and
- water flow characteristics for spills into water.

In the context of this project product viscosity is used to distinguish between light and heavy liquid products. Light products are assumed to include the lighter refined products such as gasoline and the middle distillates (e.g. kerosene based products and gas oils) which spread quickly and easily penetrate permeable soils, whereas the heavy products are assumed to include the heavier refined products and crude oils which tend to spread more slowly and in the short term generally do not penetrate as far as the lighter products.

Ground surface permeability (as it affects ground based spills) and water flow characteristics (as they affect water based spills) are combined into a single composite attribute that is defined by eight discrete choices:

- ground of low permeability (i.e. clayey soil or shale);
- ground of moderate permeability (i.e. silt or glacial till);
- ground of high permeability (i.e. clean sand or gravel);
- waterlogged ground masses (i.e. bog or muskeg);
- water covered vegetation (i.e. marsh or swamp);
- static water (i.e. pond or lake);
- slow flowing water (i.e. laminar river flow); and

- fast flowing water (i.e. turbulent stream flow).

It is assumed that the effect of these ground and water characteristics on clean-up efficiency will be directly influenced by the season with frozen winter conditions reducing the effective permeability of the ground surface and providing a physical barrier that will affect the spreading and recovery of spills that occur either onto the surface or under the surface of frozen water.

In addition, it is assumed that pipeline failure modes can be divided into two separate categories: small leaks and large leaks or ruptures. The distinction is being made on the basis that a small leak will typically involve subsurface release and spreading of liquid product whereas a large leak or a rupture will produce a crater providing for surface spreading of released product.

The above product and ground/water attributes, when combined with the two distinct season and failure modes, define a matrix of 64 possible attribute combinations, each of which is potentially associated with a different set of viable clean-up methods and associated clean-up efficiencies. The resulting clean-up efficiency matrix is shown in Table 9.1.

9.3.2 Clean-up Efficiency Estimates

It is assumed that clean-up efficiency estimates can be developed for generic spill scenarios involving each of the product and spill site attributes identified in the efficiency matrix shown in Table 9.1 to a degree of accuracy that depends on the level of effort involved. As a first stage in the development of a realistic set of clean-up efficiency estimates, a subjective approach was adopted based on the judgement of experts in the environmental field. To this end representatives from the Calgary offices of the consulting engineering firms of O'Connor Associates Environmental Inc. and AGRA Earth & Environmental Limited were asked to provide subjective estimates of the likely range of clean-up efficiencies (i.e. the 90% confidence interval on clean-up efficiency) associated with each spill scenario based on previous experience. The responses obtained from each consultant are summarized in Appendix J.

The efficiency range estimates provided by the environmental consultants were then averaged (see Appendix J) and the resulting average lower bound and average upper bound values for each case were taken to represent the 5 percentile and 95 percentile values of a Beta probability distribution. The Beta probability distribution type was chosen because it is a continuous distribution that can be constrained to values between 0 and 1 (representing efficiencies between 0 and 100%). The resulting Beta distribution parameters associated with each case are included in Table 9.1.

9.4 Residual Volume

The Residual Volume node (basic node 7.3) and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 9.2. The specific node parameter, V_{res}, is the volume of non-volatile, LVP liquid product remaining after spill clean-up and basic site reclamation operations have been undertaken The predecessor node arrows indicate that Residual Volume is a functional node meaning that the node parameter is calculated directly from the value of the parameters associated with its direct predecessor nodes; Spill Volume and Clean-up Efficiency.

The residual spill volume is given by the equation

$$V_{res} = V_S(1 - \kappa_c) \qquad [9.2]$$

where V_S is the total spill volume and κ_c is a measure of the efficiency of spill clean-up operations. Both V_S and κ_c are available from previous node parameter calculations.

As noted previously, the efficiency factor represents the effectiveness of techniques that are currently available for spill containment, clean-up and basic site reclamation. It does not reflect the further reduction in residual spill volume that is associated with possible long-term site remediation measures. The Residual Volume node parameter, as calculated, therefore represents an upper bound estimate (with uncertainty) of that portion of the total spill volume which will have the potential to adversely impact long-term human health and the surrounding environment.

9.5 Equivalent Volume

9.5.1 Node Parameter

The Equivalent Volume node and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 9.2. The Equivalent Volume node parameter, V, is defined as the volume of *reference product*, spilled at a *reference site*, which has an environmental damage potential equivalent to that of a given residual volume of a given product spilled at a given site. The predecessor node arrows indicate that Equivalent Volume is a functional node meaning that the specific node parameter is calculated directly from the value of the parameters associated with its direct predecessor nodes which include: Product, Segment, and Residual Volume.

The node parameter calculation model takes the residual spill volume, V_{res}, that is calculated at the Residual Volume node and converts it into an equivalent volume of a reference product spilled at a reference site by taking into account: 1) the toxicity of the spilled product, relative to that of the reference product, and 2) the potential long-term human health impact and environmental damage potential associated with the spill site, relative to that of the reference site. The model assumes that a reference product and reference spill site are defined by the decision-maker.

The concept of an equivalent spill volume is introduced as a means of normalizing the estimate of the environmental damage potential reflected by the residual spill volume node parameter, V_{res}, with respect to a common reference spill scenario. This approach provides the decision-maker with a consistent basis for the evaluation of environmental damage related consequences associated with pipeline failures that could occur at different locations and could involve different products.

Since implementation of the risk-based approach envisioned in this program, requires quantitative estimates of all of the consequences associated with pipeline failure, a quantitative approach to the assessment of potential environmental damage is necessary. However, the level of complexity associated with the current state of the art in quantitative environmental risk assessment as it applies to petroleum product spills, and the level of site specific information

required to conduct such an analysis, suggests that a rigorous quantitative approach to the assessment of environmental damage potential is not feasible within the context of the current program. As an alternative, an approach has been developed to characterise the environmental damage potential of possible spill sites along the length of the pipeline based largely on a qualitative index scoring approach developed for the Canadian Council of Ministers of the Environment (CCME) for the ranking of contaminated sites. The site specific index scores are then subjectively re-scaled based on expert judgement to yield quantitative estimates of environmental damage potential.

9.5.2 Basis for an Equivalent Spill Volume

The residual spill volume normalizing approach that has been developed to estimate an equivalent spill volume is based on the following conceptual framework.

It is first assumed that, for a given spill scenario, a measure of the potential long-term impact on human health and the environment, E, is given by

$$E = f\left(V_{res}, T_x, P_{\exp}, R_{env}\right) \qquad [9.3]$$

where V_{res} is the residual spill volume, T_x is a measure of the toxicity of the spilled product, and P_{exp} and R_{env} are parameters that characterize the environmental exposure pathways and environmental damage receptors within proximity of the spill site, respectively. Product toxicity is defined as a measure of the level of acute or chronic (i.e. short-term or long-term) hazard presented to human health and the environment by the contaminants present in the spilled product (excluding the acute hazards associated with fires, explosions and suffocation which are addressed elsewhere in the decision analysis model). The exposure pathways are defined as the routes that product contaminants can follow to reach environmental receptors and the receptors are the living organisms and/or resources that may be adversely affected by long-term exposure to the various product contaminants.

It is then assumed that for a given residual spill volume of a given product

$$E \propto f\left(P_{\exp}, R_{env}\right) = g(I) \qquad [9.4]$$

where I is a site specific exposure pathway and environmental damage receptor index and $g(\ )$ is a function that transforms the pathway and receptor index, I, into a quantitative measure of the relative environmental damage potential associated with a unit volume of product spilled at the site.

It is also assumed that for a given spill location the overall environmental damage potential is directly proportional to the residual spill volume and the toxicity of the spilled product. This implies that

$$E \propto V_{res} T_x. \qquad [9.5]$$

Based on the stated assumptions it follows that at a given spill site the potential human health impact and environmental damage is given by

$$E \propto V_{res} T_x g(I). \qquad [9.6]$$

If now an equivalent spill volume, V, is defined as the volume of a reference product, with toxicity index T_x^*, spilled at a reference site, with a pathway and receptor index I^*, having the same environmental damage potential as that associated with a spill characterized by V_{res}, T_x and I, then in accordance with Eqn. [9.6]

$$V T_x^* g\left(I^*\right) = V_{res} T_x g(I) \qquad [9.7]$$

By rearranging Eqn. [9.7] the equivalent spill volume is given by

$$V = V_{res} \frac{g(I)}{g(I^*)} \frac{T_x}{T_x^*} \qquad [9.8]$$

Because the above equation for equivalent volume involves product toxicity and damage severity ratios, the toxicity index and damage severity estimate need only be defined in relative terms.

The following sections develop the basis for the evaluation of a relative spill site exposure pathway and receptor index I, a pathway/receptor index transformation function $g(\ )$, and a relative product toxicity indexT_x.

9.5.3 Spill Site Exposure Pathway and Receptor Index

As part of this project a system has been developed to characterise the environmental damage potential associated with points along the length of a pipeline based on an index scoring approach developed under the National Contaminated Sites Remediation Program (NCSRP) at the request of the Canadian Council of Ministers of the Environment. This National Classification System for Contaminated Sites (CCME 1992) is intended for use as "a screening tool to aid in the evaluation of contaminated sites according to their current or potential adverse impacts on human health and the environment". The premise behind the use of the CCME classification system in the present context is that following initial spill clean-up and basic site reclamation, but prior to long-term site remediation, the spill site can be treated as a site contaminated by the residual spill volume and the associated exposure pathways and environmental damage receptors can be ranked using the applicable portions of the index scoring system.

The CCME National Classification System uses an additive index scoring approach to assess the level of hazard presented by a contaminated site. Three categories of site characteristics are considered in this approach with each category being assigned equal importance. The basic categories and associated maximum possible index scores are

Characteristic	Maximum Score
• Contaminants	33
• Exposure Pathways	33
• Receptors	34
Maximum Total Score	100

The exposure pathway scoring approach developed for the National Classification System considers pathways involving groundwater, surface water and direct contact with each pathway being assigned an equal weighting (i.e. an equal maximum index score of 11). The damage receptor scoring approach considers the potential impact on humans, animals, plants and other

environmental resources with human/animal and environmental receptor groups being assigned an essentially equal weighting (i.e. a maximum index score of 18 for human and animal receptors and 16 for environmental receptors).

The contaminant scoring approach developed for the National Classification System was not adopted in this project because it is intended to apply to a very broad range of contaminants and the system assigns an equal weighting (i.e. an equal index score) to all types of petroleum hydrocarbon liquid products. Instead a contaminant assessment approach based on a measure of product toxicity is adopted so that potentially significant differences in the level of hazard presented by different hydrocarbon products can be taken into account (see Section 9.5.5).

The guide to the National Classification System for Contaminated Sites containing the Site Classification Users Guide lists the specific factors that are used to characterize the contaminants, pathways and receptors (CCME 1992). An extract from the users guide, which describes the evaluation factors and the scoring approach for pathway and receptor characteristics, is reproduced in Table 9.2. The parameters necessary to define each of these evaluation factors are incorporated into the set of deterministic pipeline system attributes associated with the Segment node (see Section 4.7.2 and Table 4.9).

The specific subset of pipeline system attributes that must be defined to facilitate calculation of the relative exposure pathway and damage receptor index, I, are identified in a highlighted list of pipeline system attributes in Table 9.3. The specific choices available to define each parameter (see Table 4.9a) and the weighting factors associated with each possible choice are consistent with the index scoring rationale described in the CCME site classification users guide with the following modifications.

Because all ground-based spill sites are assumed to undergo basic clean-up and reclamation activities aimed at minimizing the level of residual soil contamination, it is assumed that residual contaminants will be covered (i.e. below the surface) and that the level of long-term direct exposure to harmful airborne emissions will be negligible for the type of petroleum products considered herein. The direct exposure factors associated with airborne emissions and soil gas migration are therefore set equal to zero and the maximum index score for

exposure pathways associated with direct contact is therefore reduced from 11 to 3 (see users guide scoring approach summarized in Table 9.2).

In addition, because the CCME classification system was developed for ground-based spill sites, special consideration must be given to spills that occur directly into water (e.g. for pipeline failures that occur at river and stream crossings). The approach adopted herein assumes that for product spills in water, the water-based exposure pathways will be scored at their maximum values (i.e. surface water pathway score = groundwater pathway score = 11).

The above implies a maximum possible exposure pathway score of 25 (i.e. 11 for groundwater, 11 for surface water, and 3 for direct contact) which when combined with the maximum possible damage receptor score of 34 results in a maximum total pathway/receptor index score of 59.

9.5.4 Spill Site Environmental Damage Potential Estimate

To integrate the CCME index scoring approach to exposure pathway and damage receptor characterisation into a quantitative environmental consequence assessment model, a transformation function, $g(\ )$, is required to convert the relative pathway/receptor index, I, into a quantitative measure of environmental damage potential. To achieve this goal a subjective approach was adopted based on the opinion of experts in the environmental field.

Using this approach subjective estimates were obtained of the relative severity of environmental damage associated with a representative set of spill scenarios; each scenario being characterized by different combinations of land, surface water and groundwater contamination and different potential land and water uses. Each spill scenario was then evaluated using the CCME index scoring system for exposure pathways and damage receptors and a regression analysis was carried out to develop a function that would convert the pathway/receptor indices into the corresponding environmental damage severity estimates.

The set of environmental damage scenarios considered in this study are outlined in Table 9.4 together with the CCME pathway, receptor and combined pathway/receptor index scores (which assume definite contamination of the indicated exposure pathways). From this set of

scenarios a representative subset (shown in bold face in Table 9.4) was chosen for quantitative evaluation of the relative environmental damage severity associated with the spill of a reference volume of reference product. The representative subset, ranked in descending order of potential damage severity according to the associated CCME pathway/receptor index scores, is shown in Table 9.5 together with the damage severity ratings obtained for each scenario from the environmental risk assessment experts that participated in the study.

Regression analysis carried out on the data presented in Table 9.5 produced an index transformation function of the form

$$g(I) = 0.0346 + 0.03019I - 0.0002324I^2 \qquad [9.9]$$

The data used to develop the index transformation function is shown together with the associated curve in Figure 9.3. The relative damage severity ratings, calculated from the pathway/receptor indices using this transformation function, are given for each scenario in Table 9.5.

The vertical scatter exhibited by the data points plotted in Figure 9.3 indicates that there is considerable disagreement among the participating experts as to the level of damage severity implied by the attributes that have been used to define each reference scenario. This highlights the fact that a true quantitative approach to environmental risk assessment would require a much more detailed characterization of exposure pathways and damage receptors. As indicated, a higher level of system attribute characterization is considered to be beyond the scope of the current project and potentially impractical for use in the current decision-analysis context. It is noted, however, that the basic trend in the data is clearly captured by the index transformation curve and that it generally supports the scenario ranking associated with the CCME pathway/receptor index scoring approach adopted herein.

9.5.5 Product Toxicity

In the context of a quantitative environmental risk assessment, the toxicity of a product is determined using a formal analysis approach in which the level of hazard associated with the product is determined using appropriate dose-response relationships that have been established

from studies of the effects of the product on humans, animal and plants. Because hazardous chemical products can have diverse short-term and long-term effects, both non carcinogenic acute and chronic toxicity as well as carcinogenic chronic effects should be considered in the assessment.

Unfortunately both raw and refined petroleum products are extremely complex hydrocarbon compound mixtures that are highly variable in chemical content, even in their initial state, and once exposed to the environment their chemical content can change significantly over time due to weathering action that occurs as a result of various chemical, physical, and biological processes (Stelljes and Watkin 1993). In addition, the potential human health and environmental impact of many of the chemical compounds contained in typical petroleum products has yet to be studied to the point where reliable dose-response relationships are available for all relevant receptors. For these reasons, standardized methods for quantifying the level of hazard associated with broad classes of petroleum hydrocarbon mixtures (such as gasoline, fuel oil, diesel oil, and crude oil) are not currently available.

Alternatively, a *surrogate* chemical approach can be adopted wherein a petroleum mixture is characterized by the concentration of selected chemical constituents which are known to have a significant potential impact on human and/or environmental receptors (Stelljes and Watkin 1993). The most commonly sited indicator chemicals include the volatile aromatic compounds, in particular benzene and to a lessor extent: toluene, ethylbenzene and xylenes (together known as the BTEX compounds) and some polycyclic aromatic hydrocarbons (PAHs) such as benzo(a)pyrene (Custance et al. 1993). The BTEX compounds are typically used as indicator chemicals because they represent the most volatile, soluble and mobile components in crude oils and constitute a significant portion of lighter refined products such as gasoline. In sufficiently high concentrations they are acutely toxic and benzene is a confirmed human carcinogen. The PAHs are often chosen because they are prevalent in crude oil and middle range distillates (e.g. diesel oil), they are persistent in the environment and many are known animal carcinogens.

Generic studies characterizing the range of BTEX, PAH and other relevant compound groups in typical product mixtures were not found in the literature. This is attributed to the highly variable nature of the chemical composition of petroleum product mixtures noted previously

and the expense associated with the development of a toxicological profile for a given mixture. In the absence of the necessary quantitative data on the concentrations of toxic compounds in typical petroleum product mixtures, it is suggested that the relative product toxicity index, T_x, be set equal for all petroleum products (including the reference product). This is consistent with the approach adopted by the CCME in the Contaminants portion of the site classification scoring system. A specific operator, however, may wish to develop toxicological profiles for different product mixtures transported and use them to obtain more refined estimates of the relative toxicity associated with these products. These relative toxicity esitmates can then be used in Eqn. [9.8], leading to a more accurate assessment of the environmental impact of spills.

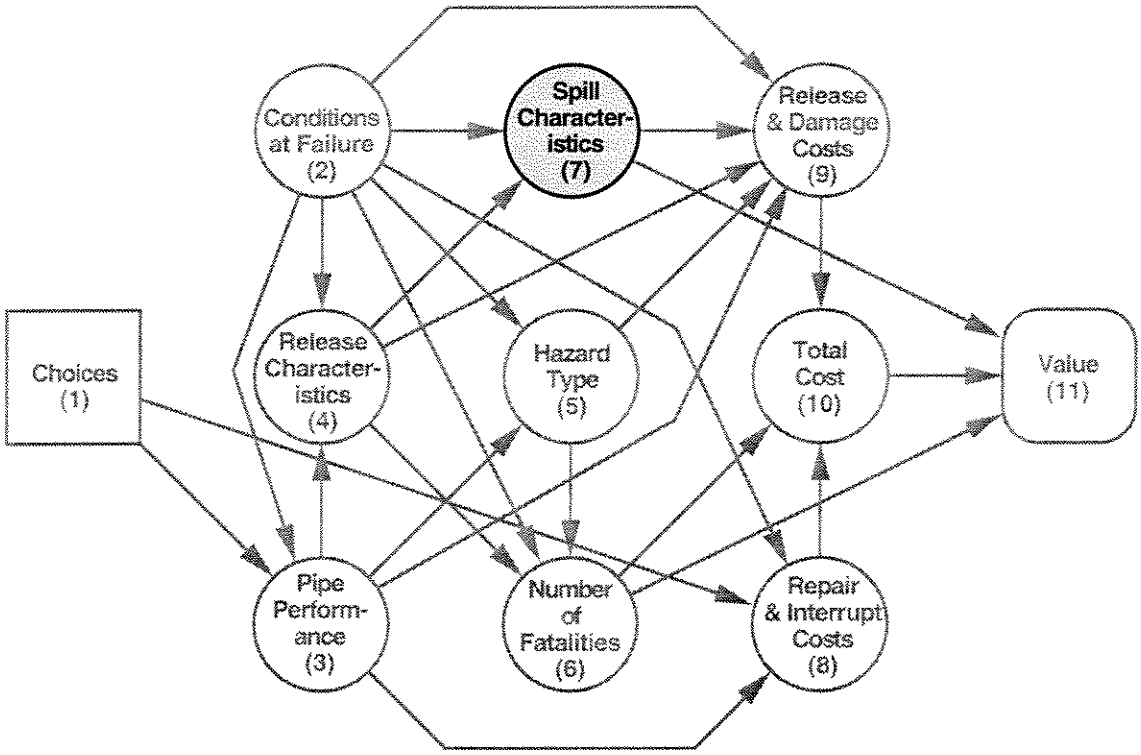


Figure 9.1 Compound node influence diagram highlighting Spill Characteristics node group

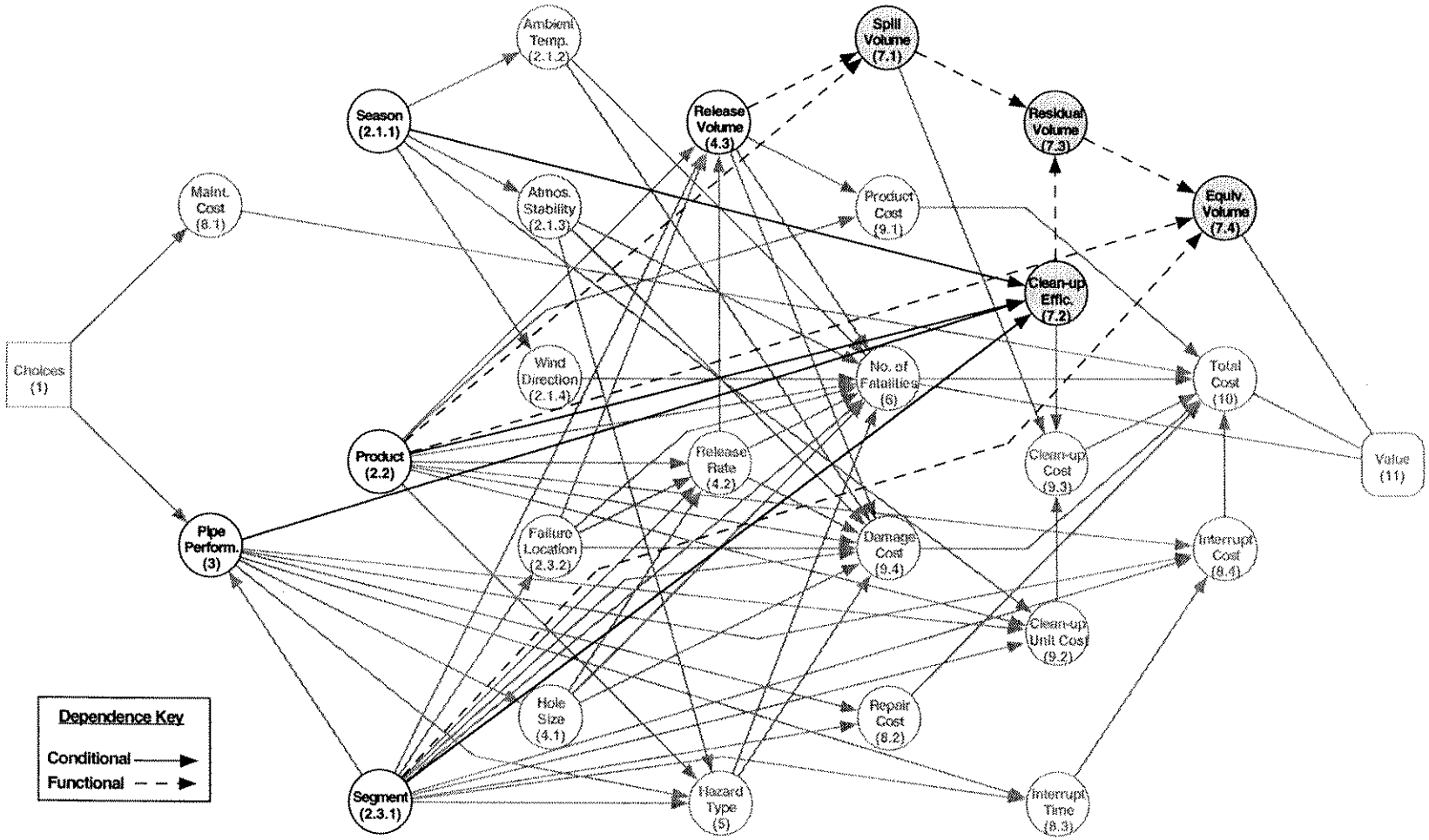


Figure 9.2 Basic node influence diagram highlighting Spill Characteristics nodes and associated immediate predecessor nodes

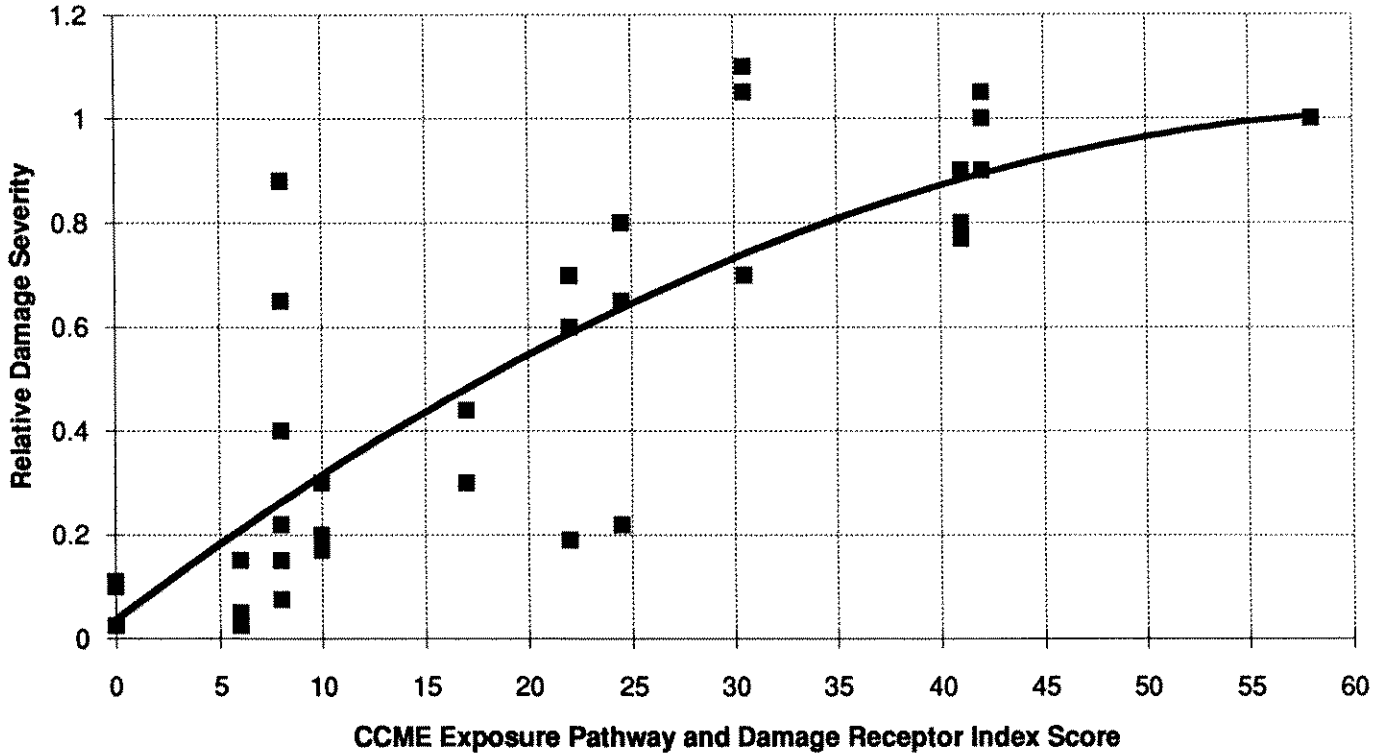


Figure 9.3 Exposure pathway and damage receptor index transformation function

Terrain Character	Season	Clean-Up Efficiency* (fraction of spilled product recovered)			
		Light Refined Product		Heavy Unrefined Product	
		Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)	Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)
Ground	summer	0.638, 0.023	0.398, 0.061	0.779, 0.046	0.667, 0.068
Low Permeability	winter (i.e. frozen)	0.767, 0.053	0.449, 0.061	0.831, 0.046	0.692, 0.068
Ground	summer	0.424, 0.046	0.347, 0.061	0.690, 0.053	0.602, 0.061
Moderate Perm.	winter (i.e. frozen)	0.679, 0.061	0.385, 0.068	0.820, 0.053	0.641, 0.068
Ground	summer	0.184, 0.038	0.175, 0.069	0.551, 0.061	0.434, 0.099
High Permeability	winter (i.e. frozen)	0.513, 0.068	0.229, 0.069	0.771, 0.069	0.448, 0.091
Waterlogged	summer	0.310, 0.053	0.282, 0.068	0.500, 0.061	0.385, 0.068
Groundmass	winter (i.e. frozen)	0.449, 0.076	0.333, 0.068	0.655, 0.076	0.500, 0.061
Water Covered	summer	0.250, 0.058	not applicable (see note)	0.409, 0.083	not applicable (see note)
Vegetation	winter (i.e. frozen)	0.359, 0.068	0.260, 0.038	0.579, 0.106	0.310, 0.053
Static	summer	0.394, 0.033	not applicable (see note)	0.538, 0.038	not applicable (see note)
Water	winter (i.e. frozen)	0.513,0.038	0.180, 0.053	0.679, 0.061	0.207, 0.053
Slow Flowing	summer	0.296, 0.061	not applicable (see note)	0.629, 0.076	not applicable (see note)
Water	winter (i.e. frozen)	0.563, 0.053	0.105, 0.038	0.728, 0.061	0.221, 0.046
Fast Flowing	summer	0.126, 0.054	not applicable (see note)	0.244, 0.061	not applicable (see note)
Water	winter (i.e. frozen)	0.387, 0.038	0.087, 0.047	0.487, 0.053	0.132, 0.038

Note: for spills in water, subsurface release and spread refers to liquid spreading beneath the ice surface and applies in winter only
* Parameter defined by a Beta probability distribution type with the tabulated means and standard deviations (i.e., Beta [mean, standard deviation])

Table 9.1 Characterization of clean-up efficiency for liquid petroleum product spills

CATEGORY	EVALUATION FACTOR	SCORING GUIDELINE	RATIONALE	METHOD OF EVALUATION	SOURCES OF INFORMATION
II. Exposure Pathways	A. Groundwater 1. Known contamination at or beyond property boundary • Groundwater significantly exceeds Canadian Drinking Water Guidelines (CDWG) by >2x or known contact of contaminants with groundwater • Between 1 and 2x CDWG or probable contact with groundwater • Meets Canadian Drinking Water Guidelines	11 6 0	The legislative basis for most jurisdictions is to prevent off-site migration of contamination.	Review chemical data and evaluate groundwater quality. If contamination at or beyond the property boundary exceeds Canadian Drinking Water Guidelines (CDWG) or applicable provincial/territorial guidelines or policies, or if contaminants are known to be in contact with groundwater, then evaluate the site as high.	Canadian Water Quality Guidelines; Provincial/ Territorial Water Quality Guidelines or policies; Guidelines for Canadian Drinking Water Quality.
	2. Potential for groundwater contamination (a) Engineered subsurface containment • No containment • Partial containment • Full containment	 4 2 0	Well contained sites have minimal potential for pollution. Potential for pollution decreases with increasing containment.	Review the existing engineered systems and relate these structures to hydrogeology of the site and determine if full containment is achieved. Full containment is defined as an engineered system, monitored as being effective, which provides for the capture and treatment of contaminants. If there is no system, this factor is evaluated high. If there is less than full containment or if uncertain then evaluate as medium. Typical engineered systems include leachate collection systems and low permeability liners.	
	(b) Thickness of confining layer over aquifer(s) of concern • 3 m or less • 3 to 10 m • >10 m	 1.5 1 0	The thickness of a confining layer (e.g., clay, shale, etc.) between contaminants and any aquifers of concern will affect the attenuation of contaminants and hence the quantity and quality of contaminants reaching the aquifers.	Measure or estimate thickness of any confining layer (e.g., clay, shale, etc.) over all aquifers of concern from existing well records or from a general knowledge of local conditions. If possible, an estimate of the continuity of the confining layer should be made from borehole well record information. Note: an aquifer is defined as a geologic material that will yield groundwater in usable quantities.	Historical geologic maps, well records, government hydrogeologist or local consultants.
	(c) Hydraulic conductivity of the confining layer • $>10^{-4}$ cm/sec • 10^{-4} to 10^{-6} cm/sec • $<10^{-6}$ cm/sec	 1.5 1 0.5	The rate at which contaminants migrate through the confining layer will affect attenuation and the contaminant loading to the aquifers.	Determine the nature of geologic materials and estimate hydraulic conductivity from published material (or use "Range of Values of Hydraulic Conductivity and Permeability" figure at end of Apppendix D). Clays, granite, shales should be scored low. Silts etc. should be scored medium. Sand, gravel, and limestone should be scored high.	Freeze and Cherry, 1979, and other groundwater texts.

Table 9.2a Extract from Site Classification User's Guide
(reprinted with the permission of the CCME)

CATEGORY	EVALUATION FACTOR	SCORING GUIDELINE	RATIONALE	METHOD OF EVALUATION	SOURCES OF INFORMATION
II. Exposure Pathways (cont'd)	A.2. (d) Annual Rainfall • >1000 mm • 600 mm • 400 mm • 200 mm	 1 0.6 0.4 0.2	The quantity of rainfall affects the quantity of leachate produced. Higher leachate quantities have a higher impact on the environment.	Refer to Environment Canada rainfall records for relevant areas. Use 30-year average rainfall for evaluation purposes. Divide rainfall by 1000 and round to nearest tenth (e.g., 667 mm = 0.7 score)	Hydrological Atlas of Canada (Fisheries and Environment Canada, 1978).
	(e) Hydraulic conductivity of aquifer(s) of concern • $>10^{-2}$ cm/sec • 10^{-2}-10^{-4} cm/sec • $<10^{-4}$ cm/sec	 3 1.5 0.5	Aquifers with high hydraulic conductivity can transport contaminants at high velocity over great distances, e.g., solution limestones, highly fractured rocks or gravel deposits.	Determine the nature of geologic materials and estimate hydraulic conductivity of all aquifers of concern from published material (refer to "Range of Values of Hydraulic Conductivity and Permeability" figure at end of Appendix D).	Freeze and Cherry, 1979.
	3. Special Considerations	-4 to +4	(See 3.7.3 in text)	Technical judgment.	

Table 9.2b Extract from Site Classification User's Guide
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CATEGORY	EVALUATION FACTOR	SCORING GUIDELINE	RATIONALE	METHOD OF EVALUATION	SOURCES OF INFORMATION
II. Exposure Pathways (cont'd)	B. Surface Water 1. Observed or measured contamination of water/effluent discharged from site • Known or strongly suspected to exceed Canadian Water Quality Guidelines (CWQG) by >2x • Known or strongly suspected to be between 1 - 2x CWQG • Meets Canadian Water Quality Guidelines	 11 6 0	The legislative basis in all jurisdictions is not to contaminate surface water beyond established limits.	Collect all available information on quality of surface water near to site. Evaluate available data against Canadian Water Quality Guidelines (select appropriate guidelines based on local water use, e.g., recreational, irrigation, freshwater aquatic life, etc.) and relevant provincial/territorial water quality objectives.	CCME Canadian Water Quality Guidelines; Relevant provincial /territorial and federal legislation and regulations.
	2. Potential for surface water contamination a) Surface Containment • No containment • Partial containment • Full containment	 5 3 0.5	The level and type of engineered containment will affect the potential for contaminants to be released to surface water.	Review the existing engineered systems and relate these structures to site conditions and proximity to surface water and determine if full containment is achieved; e.g., evaluate low if there is full containment such as capping, berms, dikes; evaluate medium if there is partial containment such as natural barriers, trees, ditches, sedimentation ponds; evaluate high if there are no intervening barriers between the site and nearby surface water.	Site inspection reports, air photos, etc.
	b) Distance to perennial surface water • 0 to <100 m • 100 to 300 m • >300 m	 3 2 0.5	The distance to surface water will affect the probability of contaminants reaching the watercourse. The Ontario Ministry of the Environment has established a classification for immediate impact zone at 50 m. For conservatism, this zone has been broadened to 100 m.	Review available mapping and survey data to determine distance to nearest surface water bodies.	
	c) Topography • Contaminants above ground level and slope is steep • Contaminants at or below ground level and slope is steep • Contaminants above ground level and slope is flat • Contaminants at or below ground level and slope is flat	 1.5 1.2 0.8 0	Water can run off (and therefore potentially contaminate surface water) with greater ease from elevated sites on slopes.	Review engineering documents on the topography of the site and the slope of surrounding terrain. • steep slope = >50% • flat slope = <5% Note: Type of fill placement (e.g., trench, above ground, etc.)	

Table 9.2c Extract from Site Classification User's Guide
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CATEGORY	EVALUATION FACTOR	SCORING GUIDELINE	RATIONALE	METHOD OF EVALUATION	SOURCES OF INFORMATION
II. Exposure Pathways (cont'd)	B. 2. d) Run-off potential (see nomograph, end of Appendix D) • >1000 mm rainfall and low permeability surface material • 500 to 1000 mm rainfall and moderately permeable surface material • <500 mm rainfall and highly permeable surface material	 1 0.6 0.2	Run-off transports contaminants into water bodies. Water run-off is a function of precipitation and the rate of infiltration (less permeable soils will allow greater run-off).	Refer to Environment Canada precipitation records for relevant areas. Use 30-year average precipitation for evaluation purposes. Determine factor score using "Run-Off Potential Nomograph" figure at end of Appendix D.	Hydrological Atlas of Canada (Fisheries and Environment Canada, 1978).
	e) Flood potential • 1 in 2 years • 1 in 10 years • 1 in 50 years	 0.5 0.3 0.1	The potential for large quantities and concentrations of contaminants to be released to surface water courses over a short period of time will be affected by the flood potential of a water course near the site.	Review published data such as flood plain mapping or flood potential (e.g., spring or mountain run-off) and Conservation Authority records to evaluate flood potential of nearby water courses both up and down gradient. Rate zero if site not in flood plain.	Established flood plain guidelines/ maps; provincial/ territorial soil survey maps.
	3. Special Considerations	-4 to +4	(See 3.7.3 in text)	Technical judgment.	

Table 9.2d Extract from Site Classification User's Guide
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CATEGORY	EVALUATION FACTOR	SCORING GUIDELINE	RATIONALE	METHOD OF EVALUATION	SOURCES OF INFORMATION
II. Exposure Pathways (cont'd)	C. Direct Contact 1. Known contamination of media off-site • Known contamination of soil, sediment or air off-site due to contact with contaminated soil, dust, air, etc. (vector transported should also be considered). • Strongly suspected contamination of media off-site • No contamination of media off-site	11 6 0	Known or measured contamination off-site is an important consideration for determining impact of contaminants.	Record known or measured contamination of soil, sediment or air on or off-site. Note any presence of soil gas, such as methane, associated with site.	
	2. Potential for direct human and/or animal contact a) Airborne Emissions (gases, vapours, dust, etc.) • Known or suspected airborne emissions impacting on neighbouring properties • Airborne emissions generally restricted to site • No airborne emissions	5 3 0	If air emissions are evident off-site, there is a great hazard for direct contamination of neighbouring biota and/or resources.	Review available site information to determine if there have been complaints off-site (due to vapours, gas, dust, etc). Reports for these problems are not likely available for most abandoned sites. Review regulatory site inspection reports. If airborne emissions are known to be impacting neighbouring properties and possibly endangering the public, some immediate action (including characterization of emissions) should be initiated to curtail hazardous emissions or otherwise reduce or eliminate exposure.	Site inspection reports, etc.
	b) Accessibility of Site (ability to contact materials) • Limited or no barriers to prevent site access; contaminants not covered • Moderate accessibility or intervening barriers; contaminants are covered • Controlled access or remote location and contaminants are covered	4 3 0	The greater the accessibility to a site and to contaminants, the greater the chance for contamination of human and animal life by direct contact.	Review location and engineering of the site and determine if there are intervening barriers between the site and humans or animals. A low rating should be assigned to a (covered) site surrounded by a locked chain link fence or in a remote location, whereas a high score should be assigned to a site that has no cover, fence, natural barriers or buffer.	
	c) Hazardous soil gas migration • Contaminants are putrescible and soil permeability is high • Soil contaminants are putrescible but soil permeability is low and/or groundwater is <2 m from surface • No putrescible contaminants at the site.	2 1 0	Methane gas migration has been known to cause explosions adjacent to abandoned landfills.	Consider presence of organic material on site, the depth to water table, soil hydraulic conductivity, vegetative stress, odours, etc.	
	3. Special Considerations	-4 to +4	(See 3.7.3 in text)	Technical judgment.	

Table 9.2e Extract from Site Classification User's Guide
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CATEGORY	EVALUATION FACTOR	SCORING GUIDELINE	RATIONALE	METHOD OF EVALUATION	SOURCES OF INFORMATION
III. Receptors	A. Human and Animal Uses 1. Known adverse impact on humans or domestic animals as a result of the contaminated site • Known adverse effect on humans or domestic animals • Strongly suspected adverse effect on humans or domestic animals	 18 15	Contamination from a site that causes a measurable impact on humans is a great concern.	Review and evaluate reports of impact(s) of site contamination (e.g., increased heavy metal levels measured in blood of nearby residents as a result of site contamination). Any site assigned 15 or more points for this factor should automatically be classified as Class 1. An adverse effect is considered to be any one or more of the following: i) impairment of the quality of the natural environment for any use that can be made of it, ii) injury or damage to property or to plant or animal life, iii) harm or material discomfort to any person, iv) impairment of the safety of any person, v) rendering any property or plant or animal life unfit for use by humans, vi) loss of enjoyment of normal use of property, and vii) interference with the normal conduct of business (from Ontario Environmental Protection Act, 1980)	
	2. Potential for impact on humans or animals a) Drinking water supply i) Known impact on drinking water supply Drinking water supply is known to be adversely affected as a result of site contamination • Known contamination of drinking water supply to levels above CDWG • Strongly suspected contamination of drinking water supply • Drinking water supply is known not to be contaminated	 9 7 0	Water used for drinking should be protected against contamination from any site.	Review available site data (inspection reports, assessment documentation) to determine if drinking water (groundwater, surface water, private, commercial or municipal supply) is known or suspected to be contaminated above Guidelines for Canadian Drinking Water Quality or applicable provincial/territorial guidelines or policies. If drinking water supply is known to be contaminated above these guidelines, some immediate action (e.g., provision of alternate drinking water supply) should be initiated to reduce or eliminate exposure.	Guidelines for Canadian Drinking Water Quality; other drinking water guidelines developed by recognized agencies (e.g., other Health and Welfare Canada guidelines, U.S. EPA, etc.).
	ii) Potential for impact on drinking water supply ° Proximity to drinking water supply • 0 to <100 m • 100 to <300 m • 300 m to <1 km • 1 to 5 km	 6 5 4 3	The nearer a drinking water well is to a contaminant source, the greater the potential for contamination. Well water used for irrigation/agricultural purposes should also be included as it may be used for human consumption.	Review provincial/territorial base mapping or air photos and measure the distance to the nearest resident or drinking water supply. Judge whether the water is being used as a drinking water source. Commonly rural areas use groundwater for drinking purposes. For urban sites, contact the local Public Utilities Commission to determine water source and location.	
	° "Availability" of alternate drinking water supply • Alternate drinking water supply is not available • Alternate drinking water supply would be difficult to obtain • Alternate drinking water supply available	 3 2 0.5	This factor takes into account the availability of replacement water supplies, and is used in the technical sense as a factor to indicate the degree of urgency, not as a sociopolitical consideration.	Determine availability of alternate drinking water supply or distance to alternate source.	

Table 9.2f Extract from Site Classification User's Guide
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CATEGORY	EVALUATION FACTOR	SCORING GUIDELINE	RATIONALE	METHOD OF EVALUATION	SOURCES OF INFORMATION
III. Receptors (cont'd)	A.2. b) Other Water Resources i) Known impact on used water resource Water resource (used for recreational purposes, commercial food preparation, livestock watering, irrigation or other food chain uses) is known to be adversely affected as a result of site contamination • Water resource is known to be contaminated above CWQG • Water resource is strongly suspected to be contaminated above CWQG • Water resource is known not to be contaminated	 4 3 0	The water used for these purposes (groundwater or surface water) should be protected against contamination.	Review documentation for reported or suspected contamination of water used for recreation or food chain uses, and refer to Canadian Water Quality Guidelines or other relevant guidelines (select appropriate guidelines based on local water use) to determine if supply is considered contaminated.	CCME Canadian Water Quality Guidelines; provincial/ territorial water quality guidelines and objectives; etc.
	ii) Potential for impact on water resources ° Proximity to water resources used for activities listed above • 0 to <100 m • 100 to <300 m • 300 m to <1 km • 1 to 5 km	 2 1.5 1 0.5	The nearer a water resource is to a site, the greater the risk of contamination.	Determine distance from the site to the nearest recreational or food chain used water resource.	
	° Use of water resources - if multiple uses, give highest score (use following table)	0.2 - 2	Potential for impact due to use of water resource is related to the type and frequency of use. Human uses are of the highest concern.	Assess water users adjacent to the site from maps and directories.	

Water Use	Frequency of Use: Frequent	Occasional
Recreational (swimming, fishing)	2	1
Commercial food preparation	1.5	0.8
Livestock watering	1	0.5
Irrigation	1	0.5
Other domestic or food chain uses	0.5	0.3
Not currently used but likely future use	0.5	0.2

Table 9.2g Extract from Site Classification User's Guide
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CATEGORY	EVALUATION FACTOR	SCORING GUIDELINE	RATIONALE	METHOD OF EVALUATION	SOURCES OF INFORMATION
III. Receptors (cont'd)	A. 2. c) Direct human exposure i) Known contamination of land used by humans • Known contamination of land used for agricultural or residential/parkland/school purposes above AG or R/P EQC values • Known contamination of land used for commercial or industrial purposes above C/I EQC values • Land is known not to be contaminated	5 3.5 0	Hazards associated with soil contamination are directly related to land use.	Review zoning and land use maps for lands adjacent the site. Evaluate levels of soil contamination against Canadian Environmental Quality Criteria (EQC) for Contaminated Sites (AG = agricultural level; R/P = residential/parkland level; C/I = commercial/industrial level). If soil is known to be contaminated above these levels and possibly endangering public health, some immediate action (e.g., fencing the area, limiting public access, etc.) should be initiated to reduce or eliminate the exposure.	CCME Canadian Environmental Quality Criteria for Contaminated Sites.
	ii) Potential human exposure through land use • Use of land at and surrounding site (use following table; give highest score to worst case scenario) Distance from Site Land Use (current or future) 0 - 300m 300m - 1km 1 - 5km Residential 5 4.5 3 Agricultural 5 4 2.5 Parkland/School 4 3 1.5 Commercial/Industrial 3 1 0.5	0.5 - 5	Hazards associated with soil contamination are directly related to land use and distance of the used land from the site. Residential and agricultural land uses are of highest concern because humans are situated at these locations for longer periods.	Review zoning and land use maps over the distances indicated. If the proposed future land use is more "sensitive" than the current land use, evaluate this factor assuming the proposed future use is in place (indicate in the worksheet that future land use is the consideration). Agricultural land use is defined as uses of land where the activities are related to the productive capability of the land or facility (e.g., greenhouse) and are agricultural in nature, or activities related to the feeding and housing of animals as livestock. Residential/Parkland land uses are defined as uses of land on which dwelling on a permanent, temporary, or seasonal basis is the activity (residential), as well as uses on which the activities are recreational in nature and require the natural or human designed capability of the land to sustain that activity (parkland). Commercial/Industrial land uses are defined as land on which the activities are related to the buying, selling, or trading of merchandise or services (commercial), as well as land uses which are related to the production, manufacture, or storage of materials (industrial).	
	3. Special Considerations	-5 to +5	(See 3.7.3 in text)	Technical judgment.	

Table 9.2h Extract from Site Classification User's Guide
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CATEGORY	EVALUATION FACTOR	SCORING GUIDELINE	RATIONALE	METHOD OF EVALUATION	SOURCES OF INFORMATION
III. Receptors (cont'd)	B. Environment 1. Known adverse impact on a sensitive environment as a result of the contaminated site • Known adverse impact on sensitive environment • Evidence of stress on aquatic species or vegetative stress on trees, crops or plant life located on properties neighbouring the site • Strongly suspected adverse impact on sensitive environment	 16 14 12	The environment should be protected against site contamination. Evidence of impact(s) shows that protection is lacking.	Review records for evidence of vegetative stress or impairment of any nearby sensitive environments. A sensitive environment is defined as a sensitive aquatic environment, nature preserve, habitat for endangered species, sensitive forest reserves, national parks or forests, etc. An adverse effect is considered to be any one or more of the following: i) impairment of the quality of the natural environment for any use that can be made of it, ii) injury or damage to property or to plant or animal life, iii) harm or material discomfort to any person, iv) impairment of the safety of any person, v) rendering any property or plant or animal life unfit for use by humans, vi) loss of enjoyment of normal use of property, and vii) interference with the normal conduct of business (from Ontario Environmental Protection Act, 1980).	
	2. Potential for impact on sensitive environments a) Distance from site to nearest sensitive environment (e.g., sensitive aquatic environment, nature preserve, habitat for endangered species, sensitive forest reserves, national parks or forests, etc.) • 0 to <500 m • 500 m to <2 km • 2 to <5 km • 5 to 10 km	 10 6 2 0.5	It is considered that within approximately 1 km of the site there is immediate concern for contamination. Therefore, an environmentally sensitive area located within this area of the site will be subject to concern. It is also generally considered that any sensitive area located greater than 10 km from the site will not be impacted.	Review Conservation Authority mapping and literature. Also review Ministry of Natural Resources records and Federal Land Capability maps. Identify provincial/territorial and federal designated environmentally sensitive areas.	Relevant provincial /territorial and federal maps of sensitive environments.
	b) Groundwater - distance to important or susceptible groundwater resource(s) • 0 to <500 m • 500 m to <2 km • 2 to <5 km • 5 to 10 km	 6 4 2 1	The closer a site is to a discharge or recharge area, the greater the potential for contamination of a groundwater or surface water resource.	Review groundwater contour maps, if available, and other available reports. Otherwise use established hydrogeologic principles.	Local groundwater maps, etc.
	3. Special Considerations	-5 to +5	(See 3.7.3 in text)	Technical judgment.	

Table 9.2i Extract from Site Classification User's Guide
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No.	System Attribute	Definition	Comment	Needed for CCME Index
1	Pipeline Diameter	numeric value		
2	Pipe Wall Thickness	numeric value		
3	Pipeline Orientation	numeric value		
4	Pipeline Elevation Profile	numeric value	cont. varying	
5	Operating Pressure Profile	numeric value	cont. varying	
6	Flow Rate (betw. breakpoints)	numeric value		
7	Product temperature	numeric value		
8	Block Valve spacing	numeric value		
9	Time to Block Valve Closure	numeric value		
10	Detectable Release Volume	numeric value		
11	Time to Leak Detection	numeric value		
12	Time to Leak Stoppage	numeric value		
13	**Adjacent Land Use**	text string	9 choices	X
14	Pipeline Accessibility	text string	2 choices	
15	Pipeline Crossings	text string	8 choices	
16	**Near Field Terrain**	text string	8 choices	X
17	Far Field Terrain	text string	8 choices	
18	**Natural Surface Containment**	text string	3 choices	X
19	**Distance to Surface Water**	text string	3 choices	X
20	**Surface Topography**	text string	3 choices	X
21	**Annual Rainfall**	text string	4 choices	X
22	**Flood Potential**	text string	4 choices	X
23	**Confining Layer Thickness**	text string	3 choices	X
24	**Confining Layer Conductivity**	text string	3 choices	X
25	**Aquifer Conductivity**	text string	3 choices	X
26	**Drinking Water within 5km**	text string	12 choices	X
27	**Other Water within 5km**	text string	12 choices	X
28	**Land Use within 5km**	text string	12 choices	X
29	**Sens. Environment within 10km**	text string	4 choices	X
30	**Sens. Groundwater within 10km**	text string	4 choices	X

Table 9.3 Pipeline system attributes required to define pathway and receptor index

Scenario		Spill Location	Type of Contamination	Water Usage	CCME Index		
					Path.	Rec.	Total
1	**a**	**Commercial / Industrial**	**soil only**		**3.0**	**3.0**	**6.0**
1	b	Commercial / Industrial	soil + surface water	no current use	14.0	5.5	19.5
1	c	Commercial / Industrial	soil + ground water	food chain	14.0	5.5	19.5
1	d	Commercial / Industrial	soil + surface&ground water	see individual	25.0	5.5	30.5
2	**a**	**Residential - urban**	**soil only**		**3.0**	**5.0**	**8.0**
2	b	Residential - urban	soil + surface water	occasional food chain	14.0	7.5	21.5
2	c	Residential - urban	soil + ground water	food chain	14.0	7.5	21.5
2	d	Residential - urban	soil + surface&ground water	see individual	25.0	7.5	32.5
3	a	Residential - rural	soil only		3.0	5.0	8.0
3	b	Residential - rural	soil + surface water	food chain	14.0	7.5	21.5
3	**c**	**Residential - rural**	**soil + ground water**	**drinking + food chain**	**14.0**	**16.5**	**30.5**
3	d	Residential - rural	soil + surface&ground water	see individual	25.0	16.5	41.5
4	**a**	**Agricultural**	**soil only**		**3.0**	**5.0**	**8.0**
4	b	Agricultural	soil + surface water	livestock watering	14.0	8.0	22.0
4	c	Agricultural	soil + ground water	drinking + irrigation	14.0	17.0	31.0
4	**d**	**Agricultural**	**soil + surface&ground water**	**see individual**	**25.0**	**17.0**	**42.0**
5	a	Recreational	soil only		3.0	4.0	7.0
5	**b**	**Recreational**	**soil + surface water**	**recreation**	**14.0**	**8.0**	**22.0**
5	c	Recreational	soil + ground water	drinking + food chain	14.0	15.5	29.5
5	d	Recreational	soil + surface&ground water	see individual	25.0	17.0	42.0
6	**a**	**Sensitive Recreational**	**soil only**		**3.0**	**14.0**	**17.0**
6	b	Sensitive Recreational	soil + surface water	recreation + food chain	14.0	18.0	32.0
6	c	Sensitive Recreational*	soil + ground water	drinking + food chain	14.0	31.5	45.5
6	**d**	**Sensitive Recreational***	**soil + surface&ground water**	**see individual**	**25.0**	**33.0**	**58.0**
7	**a**	**Remote**	**soil only**		**0.0**	**0.0**	**0.0**
7	b	Remote	soil + surface water	food chain	11.0	2.5	13.5
7	c	Remote	soil + ground water	food chain	11.0	2.5	13.5
7	**d**	**Remote**	**soil + surface&ground water**	**see individual**	**22.0**	**2.5**	**24.5**
8	**a**	**Sensitive Remote**	**soil only**		**0.0**	**10.0**	**10.0**
8	b	Sensitive Remote	soil + surface water	food chain	11.0	12.5	23.5
8	c	Sensitive Remote*	soil + ground water	food chain	11.0	18.5	29.5
8	**d**	**Sensitive Remote***	**soil + surface&ground water**	**see individual**	**22.0**	**18.5**	**40.5**

***Note: 'sensitive' environment assumed to include important groundwater resource**

Table 9.4 Spill scenarios considered in the development of environmental damage severity estimates

Representative Environmental Damage Scenarios For Liquid Product Spills (Ranking in Accordance with CCME National Classification System for Contaminated Sites)						Environmental Damage Severity (reference volume = 100 cubic metres)			
Rank	Scenario		Spill Location	Type of Contamination	Water Usage	Expert 1	Expert 2	Expert 3	Regression
1	6	d	Sensitive* Recreational	soil + surface & ground water	drinking / recreation / food chain	1.00	1.00	1.00	**1.00**
2	4	d	Agricultural	soil + surface & ground water	drinking / irrigation / livestock	0.90	1.05	1.00	**0.89**
3	8	d	Sensitive* Remote	soil + surface & ground water	food chain	0.80	0.77	0.90	**0.88**
4	3	c	Residential - rural	soil + ground water	drinking / food chain	0.70	1.10	1.05	**0.74**
5	5	b	Recreational	soil + surface water	recreation	0.65	0.22	0.80	**0.63**
6	6	a	Sensitive* Recreational	soil only		0.60	0.19	0.70	**0.59**
7	7	d	Remote	soil + surface & ground water	food chain	0.30	0.44	0.30	**0.48**
8	8	a	Sensitive* Remote	soil only		0.20	0.17	0.30	**0.31**
9	2	a	Residential - urban	soil only		0.15	0.88	0.40	**0.26**
10	4	a	Agricultural	soil only		0.08	0.22	0.65	**0.26**
11	1	a	Commercial / Industrial	soil only		0.03	0.05	0.15	**0.21**
12	7	a	Remote	soil only		0.03	0.11	0.10	**0.03**

Note: * the term "Sensitive" denotes sensitive environments defined by the CCME guidelines as sensitive aquatic environments, habitat for endangered species, nature preserve, sensitive forest reserves, national parks and forests, etc.

Damage severity rankings obtained from environmental assessment experts in the following organizations:

Interprovincial Pipe Line Inc. - Safety and Environment Department, Edmonton, Alberta.
O'Conner Associates Environmental Inc., Calgary, Alberta.
AGRA Earth & Environmental Limited, Calgary, Alberta.

Table 9.5 Environmental damage severity ratings

10.0 REPAIR AND INTERRUPTION COSTS

10.1 Overview

The Repair and Interruption Cost node group (group 8) is shown in a highlighted version of the compound node influence diagram in Figure 10.1. This node group involves parameters that represent the annual maintenance and inspection costs associated with integrity maintenance programs, the direct costs associated with pipeline repair following leak or rupture type failure, and the direct costs associated with the pipeline being out of service following failure. Because the service interruption cost is highly dependent upon the duration of the interruption period, the node group also includes a parameter that reflects service interruption time. The individual parameters associated with the Repair and Maintenance Cost node group, as identified by the shaded nodes in a highlighted version of the basic node influence diagram shown in Figure 10.2, are discussed in the following sections.

10.2 Maintenance Cost

The Maintenance Cost node (basic node 8.1) and its direct predecessor node are shown in a highlighted version of the basic node influence diagram in Figure 10.2. The specific node parameter is the annual cost of inspection and maintenance programs directed at maintaining pipeline integrity, c_{main}. The predecessor node arrow indicates that Maintenance Cost is a conditional node meaning that the value of the node parameter is conditionally dependent upon the values of its direct predecessor node which is Choices. The Maintenance Cost node parameter must therefore be defined explicitly for all inspection and maintenance options identified at the Choices node. In the contest of this project the node parameter is defined, for each choice, by specifying a continuous probability distribution for the annual maintenance cost.

The information required to define the node parameter is highly pipeline specific. The probability distribution of annual inspection and maintenance costs for each candidate integrity maintenance program identified at the Choices node should therefore be established for a given

pipeline based on operating company experience and/or budget price estimates provided by contractors that provide pipeline inspection and maintenance services.

10.3 Repair Cost

The Repair Cost node (basic node 8.2) and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 10.2. The specific node parameter is the cost of repair associated with pipeline failure, c_{rpr}. The predecessor node arrows indicate that Repair Cost is a conditional node meaning that the value of the node parameter is conditionally dependent upon the values of its direct predecessor nodes which include Pipe Performance and Segment. The Repair Cost node parameter must therefore be defined explicitly for all possible combinations of the performance states involving failure (i.e. small leak, large leak, and rupture) and for selected combinations of the pipeline system attributes associated with each segment which are known to have a significant effect on repair cost. In the context of this project the node parameter is defined for each combination by specifying a continuos probability distribution for the expected repair cost that can take any value within a defined range.

A literature review was carried out to identify specific pipeline system and right-of-way attributes that can have a potentially significant effect on the costs associated with pipeline repair. The relevant system attributes identified include:

- pipeline diameter
- pipeline accessibility;
- terrain conditions; and
- crossings.

In the context of this project pipeline accessibility is defined by two discrete choices:

- easy access, and
- difficult access,

where sites with easy access are assumed to involve proximity to a service centre and/or ease of equipment access, and sites with difficult access are assumed to involve remoteness from a service centre and/or difficulty with equipment access.

Terrain conditions and crossings are combined into a single composite attribute that is defined by nine discrete choices:

- typical cross-country conditions;
- bog or muskeg;
- marsh or swamp;
- lake;
- uncased roadway or railway crossings;
- cased roadway or railway crossings;
- unprotected river or stream crossings;
- protected river or stream crossings; and
- aerial crossings.

In addition, it is assumed that pipeline failure modes can be divided into two separate categories: small leaks and large leaks or ruptures. The distinction being made on the basis that a small leak can typically be repaired using a full encirclement sleeve whereas a large leak or a rupture will require a cut-out replacement.

If it is further assumed that for a given pipeline system the diameter of the line pipe will remain essentially constant, then diameter can be eliminated from the attribute set and the remaining attributes define a matrix of 36 possible attribute combinations, each of which is potentially associated with a different repair cost. The repair cost matrix is shown in Table 10.1.

Because the repair costs that define the cost attribute matrix are dependent upon the pipeline diameter range and other factors that are considered operator specific, it is assumed that the repair cost information necessary to define the matrix will best be defined by the operating company on a line by line basis or possibly on the basis of distinct line diameter ranges.

10.4 Interruption Time

The Interruption Time node (basic node 8.3) and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 10.2. The specific node parameter is the length of time during which service is interrupted in the event of pipeline failure, t_{int}. The predecessor node arrows indicate that Interruption Time is a conditional node

meaning that the value of the node parameter is conditionally dependent upon the values of its direct predecessor nodes which include Pipe Performance and Segment. The Interruption Time node parameter must therefore be defined explicitly for all possible combinations of the pipe performance states involving failure (i.e. small leak, large leak, and rupture) and for selected combinations of the pipeline system attributes associated with each segment which are known to have a significant effect on service interruption time. In the context of this project the node parameter is defined for each combination by specifying a continuos probability distribution for the service interruption time that can take any value within a defined range.

It is assumed that interruption time will be proportional to the level of effort and hence cost associated with pipeline repair. It follows then that the pipeline system attributes that effect repair cost can also be assumed to effect interruption time. The system attribute matrix developed for repair cost is therefore assumed to be directly applicable to service interruption time. The corresponding interruption time matrix is shown in Table 10.2.

It is noted that in the context of service interruption time, as opposed to repair cost, the distinction between small leaks and large leaks or ruptures is based on the assumption that small leaks will involve only partial service interruption corresponding to a pipeline pressure drop during sleeve installation, whereas large leaks and ruptures will involve complete interruption of service while the cut-out replacement is performed.

As for repair cost, because the values that define the time attribute matrix are dependent upon the pipeline diameter range and other factors that are considered operator specific, it is assumed that the interruption time information necessary to define the matrix will best be defined by the operating company on a line by line basis or possibly on the basis of distinct line diameter ranges.

10.5 Interruption Cost

10.5.1 Introduction

The Interruption Cost node (basic node 8.4) and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 10.2. The specific node

parameter is the direct cost associated with service interruption cause by pipeline failure, c_{int}. The predecessor node arrows indicate that Interruption Cost is a functional node meaning that the value of the node parameter is calculated directly from the value of the parameters associated with its direct predecessor nodes which include: Product, Segment, Pipe Performance and Interruption Time.

Service interruption costs are calculated differently for liquid product and natural gas pipelines. Liquid product line operators are paid based on the amount of product delivered while natural gas line operators are paid based on the amount contracted unless they deliver less the a specified percentage of a shippers nomination during any given month.

10.5.2 Liquid Product Pipelines

Given the mass flow rate in the pipeline segment being considered, the interruption time and a reduction in flow volume for the specified pipe performance it is possible to calculate the reduction in product volume transported using the equation

$$V_{\text{int}} = \frac{\dot{m}_0 t_{\text{int}}}{\rho_s} r \qquad [10.1]$$

where $\dot{m}_0$ is the normal mass flow rate in the segment, t_{int} is the time duration of service interruption, ρ_s is the product density under standard conditions and r is the reduction in transported product resulting from the interruption. With the reduction in volume transported during the service interruption it is possible to calculate the total interruption cost with the equation

$$c_{\text{int}} = V_{\text{int}}\left(u_p - u_c - u_s\right) + C_{lump} \qquad [10.2]$$

where u_p is the unit price paid to the pipeline company for transporting the product, u_c is the unit cost incurred by the pipeline company for transporting the product, u_s is the unit volume savings resulting for not having to transporting the product, and C_{lump} is any lump sum cost associated with the service interruption. This formula uses the unit profit resulting from transporting the specified product, and takes into account any possible cost reductions (savings) and lump sum costs associated with a service interruption event.

10.5.3 Natural Gas Pipelines

Interruption costs for natural gas pipelines depend upon the reduction in volume received from each individual shippers during any month. Therefore, information on how a leak or rupture affect shippers in required for each pipeline segment. For each shipper a percentage of the flow in the segment, a percent reduction for small leaks and a percent reduction for large leaks and ruptures are required.

It is assumed that an interruption has an equal probability of occurring at any time within a month. It can be shown that depending upon when in a month the interruption starts, an interruption of less than one month in duration can either occur during a single month or may span over a month end. If the interruption extends beyond the month end its affect on nomination volumes during any single month is reduced. Likewise, an interruption with a duration of 1-2 months may affect either two or three monthly billing periods and for interruptions of over 2 months at least one complete month is affected by the interruption. It is therefore possible to calculate the length of an interruption in any month as a function of the start time and the resulting reduction in volume received from a given shipper. The basis for this calculation is given in Appendix G.

Having calculated the reduction in receipts from a shipper for a month the cost (or savings) of interruption for the shipper can be calculated. The volume of gas not delivered during a month can be calculated as:

$$V_{\text{int}}^{m} = \frac{\dot{m}_0 t_m}{\rho_s} r_m \qquad [10.3]$$

where $\dot{m}_0$ is the normal mass flow rate in the segment, t_m is the time in an average month (30.4 days), ρ_s is the product density under standard conditions and r_m is the reduction in flow for the shipper averaged over the month. The basic interruption cost (savings) for shipper during the month is:

$$C_{ib}^{m} = \dot{V}_{im}(-u_s) \qquad [10.4]$$

where u_s is the unit volume savings resulting for not having to deliver the natural gas. If the abatement cut-off has been exceeded in the month then abatement cost can be calculated using the equation

$$C_{ab}^{m} = V_{rm} u_{ccs} \qquad [10.5]$$

where u_{ccs} is a per unit volume company cost of service given in the Gas Transportation Tariff agreement. The total interruption cost can be calculated by adding the interruption costs to individual shippers for all months in which they were affected. This is done using the following equation

$$c_{\text{int}} = \sum_{shippers} \sum_{m} \left(C_{lb}^{m} + C_{ab}^{m} \right) + C_{lump} \qquad [10.6]$$

where C_{lump} is any additional lump sum cost associated with the service interruption.

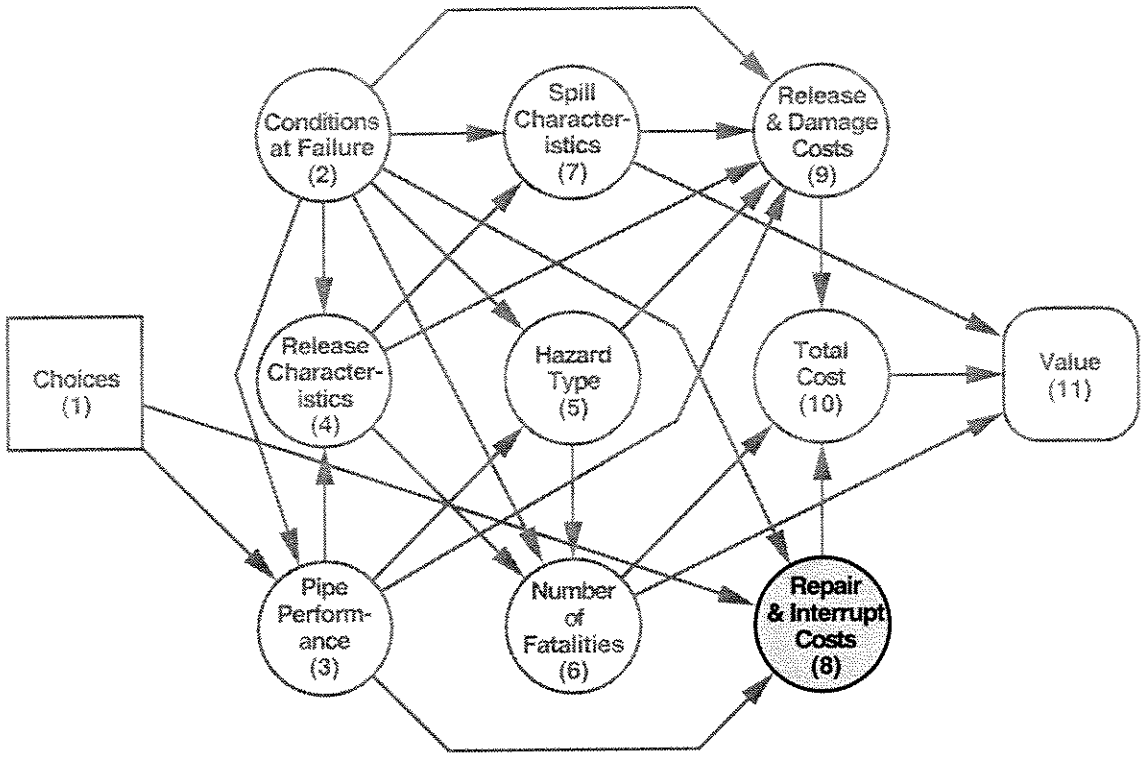

Figure 10.1 Compound node influence diagram highlighting Repair & Interrupt Costs node group

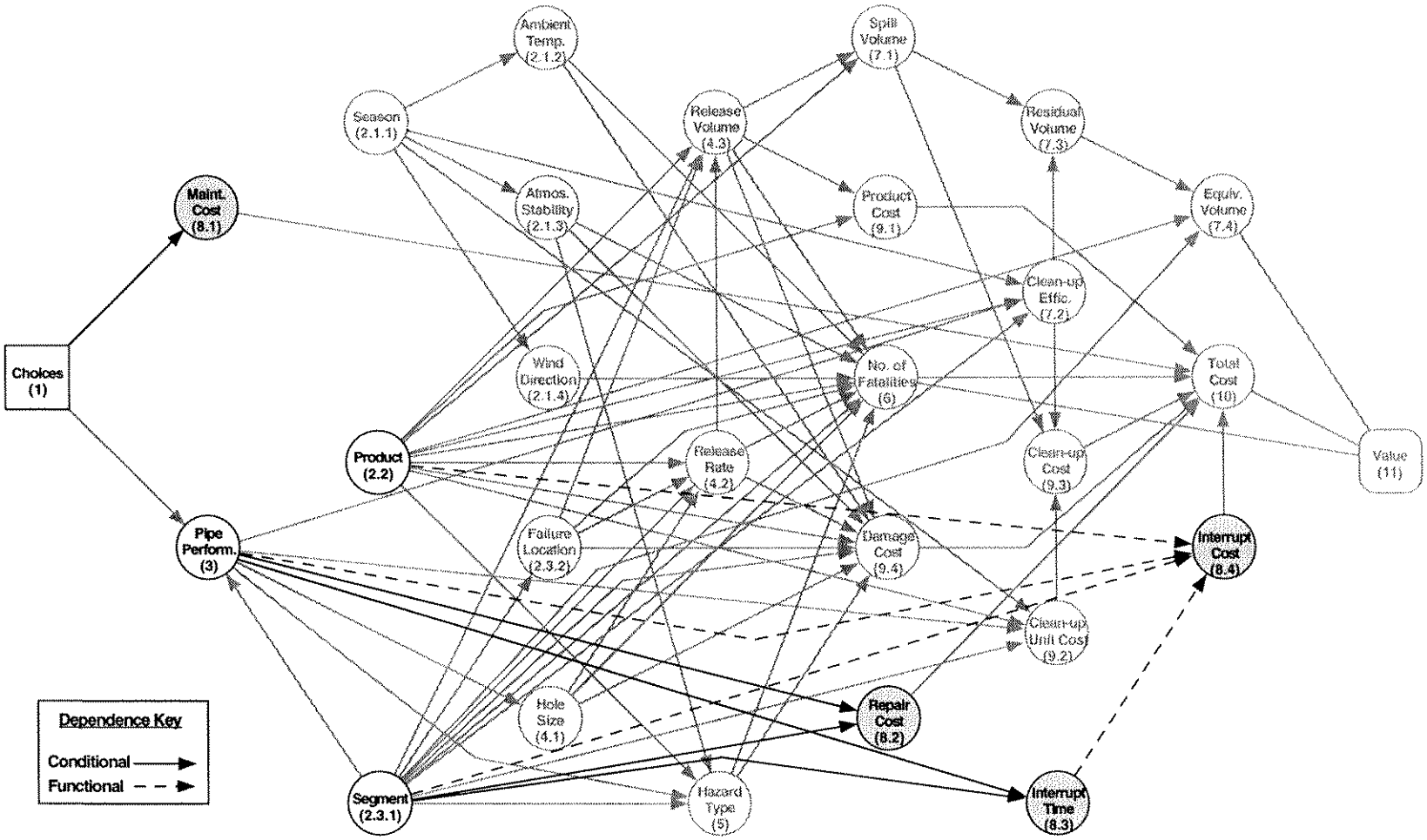

Figure 10.2 Basic node influence diagram highlighting Repair & Interrupt Costs nodes and associated immediate predecessor nodes

Terrain and Crossings	Accessibility	Repair Cost ($1000's)	
		Small Leak (i.e. sleeve repair)	**Large Leak / Rupture** (i.e. cut-out repair)
Typical (cross-country)	easy access		
	difficult access		
Bog / Muskeg	easy access		
	difficult access		
Marsh / Swamp	easy access		
	difficult access		
Lake	easy access		
	difficult access		
Roadway / Railway (uncased)	easy access		
	difficult access		
Roadway / Railway (cased)	easy access		
	difficult access		
River / Stream (unprotected)	easy access		
	difficult access		
River / Stream (protected)	easy access		
	difficult access		
Aerial	easy access		
	difficult access		

Table 10.1 Pipeline repair cost matrix

Terrain and Crossings	Accessibility	Service Interruption Time (hrs)	
		Small Leak (i.e. sleeve repair)	**Large Leak / Rupture** (i.e. cut-out repair)
Typical (cross-country)	easy access		
	difficult access		
Bog / Muskeg	easy access		
	difficult access		
Marsh / Swamp	easy access		
	difficult access		
Lake	easy access		
	difficult access		
Roadway / Railway (uncased)	easy access		
	difficult access		
Roadway / Railway (cased)	easy access		
	difficult access		
River / Stream (unprotected)	easy access		
	difficult access		
River / Stream (protected)	easy access		
	difficult access		
Aerial	easy access		
	difficult access		

Table 10.2 Pipeline service interruption time matrix

11.0 RELEASE AND DAMAGE COSTS

11.1 Overview

The Release and Damage Cost node group (group 9) is shown in a highlighted version of the compound node influence diagram in Figure 11.1. This node group involves parameters that represent the cost of lost product, liquid spill clean-up costs and the costs associated with property damage. The individual parameters associated with the Release and Damage Costs node group, as identified by the shaded nodes in a highlighted version of the basic node influence diagram shown in Figure 11.2, are discussed in the following sections.

11.2 Cost of Lost Product

The Product Cost node (basic node 9.1) and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 11.2. The specific node parameter is the direct cost associated with the product lost at the time of pipeline failure. The predecessor node arrows indicate that Product Cost is a functional node meaning that the value of the node parameter is calculated directly from the value of the parameters associated with its direct predecessor nodes, Product and Release Volume.

The product cost, c_{prod}, is calculated using the following equation

$$c_{prod} = u_p V_R \qquad [11.1]$$

where V_R is the total release volume and u_p is the unit product cost.

The release volume is defined at the Release Volume node leaving unit product cost (u_p) which must be defined for all products carried in the pipeline. This supplementary product data does not constitute an additional set of influence diagram parameters but rather it represents a set of deterministic data that must be available to the Product Cost node to facilitate evaluation of the node parameter.

As part of this project a survey of recent energy statistics was carried out to develop a representative set of unit prices for the product groups of interest. The cost information and reference sources are given in Table 11.1 for each of the main product groups of interest.

11.3 Unit Clean-up Cost

11.3.1 Node Parameter

The Clean-up Unit Cost node (basic node 9.2) and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 11.2. The specific node parameter is the unit cost of spill clean-up associated with liquid product pipeline failure, u_{clean}. The predecessor node arrows indicate that Clean-up Unit Cost is a conditional node meaning that the value of the node parameter is conditionally dependent upon the values of its direct predecessor nodes which include Pipe Performance, Product, Season and Segment. The Clean-Up Unit Cost node parameter must therefore be defined explicitly for all combinations of pipe performance states involving failure (i.e. leak and rupture), for both summer and winter (i.e. frozen and unfrozen) seasons, and for selected combinations of product and pipeline attributes which are considered to have a significant impact on spill clean-up cost. In the context of this project the node parameter is defined for each combination by specifying a continuos probability distribution for the expected unit clean-up cost (u_{clean}) that can take any value within a defined range.

A literature review was carried out to identify the specific product and pipeline right-of-way attributes that can have a potentially significant effect on the costs associated with liquid spill clean-up. The relevant attributes identified include:

- product viscosity;
- ground surface permeability for spills on land; and
- water flow characteristics for spills into water.

In the context of this project product viscosity is used to distinguish between light and heavy liquid products. Light products are assumed to include the lighter refined products such as gasoline and the middle distillates (e.g. kerosene based products and gas oils) which spread quickly and easily penetrate permeable soils, whereas the heavy products are assumed to

include the heavier refined products and crude oils which tend to spread more slowly and in the short term generally do not penetrate as far as the lighter products.

Ground surface permeability (as it affects ground based spills) and water flow characteristics (as they affect water based spills) are combined into a single composite attribute that is defined by eight discrete choices:

- ground of low permeability (i.e. clayey soil or shale);
- ground of moderate permeability (i.e. silt or glacial till);
- ground of high permeability (i.e. clean sand or gravel);
- waterlogged ground masses (i.e. bog or muskeg);
- water covered vegetation (i.e. marsh or swamp);
- static water (i.e. pond or lake);
- slow flowing water (i.e. laminar river flow); and
- fast flowing water (i.e. turbulent stream flow).

It is assumed that the effect of the above ground and water characteristics on clean-up actions will be directly influenced by the season with frozen winter conditions reducing the effective permeability of the ground surface and providing a physical barrier that will affect the spreading and recovery of spills that occur either onto the surface of or under the surface of frozen water.

In addition, it is assumed that pipeline failure modes can be divided into two separate categories: small leaks and large leaks or ruptures. The distinction being made on the basis that a small leak will typically involve subsurface release and spreading of liquid product whereas a large leak or a rupture will produce a crater providing for surface spreading of released product.

The product and ground/water attributes, when combined with the two distinct season and failure modes, define a matrix of 64 possible attribute combinations, each of which is potentially associated with a different unit clean-up cost. The resulting unit clean-up cost matrix is shown in Table 11.2.

11.3.2 Unit Clean-up Cost Estimates

It is assumed that unit clean-up cost estimates can be developed for generic spill scenarios involving each of the product and spill site attributes identified in the efficiency matrix shown in Table 11.2 to a degree of accuracy that depends on the level of effort involved. As a first stage in the development of a realistic and set of unit clean-up cost estimates, a subjective approach was adopted based on the judgement of experts in the environmental field. To this end representatives from the Calgary offices of the consulting engineering firms of O'Connor Associates Environmental Inc. and AGRA Earth & Environmental Limited were asked to provide subjective estimates of the likely range of unit clean-up costs (i.e. the 90% confidence interval on clean-up cost) associated with each spill scenario based on previous experience. The responses obtained from each consultant are summarized in Appendix J.

The clean-up cost range estimates provided by the environmental consultants were then averaged (see Appendix J) and the resulting average lower bound and average upper bound values for each case were taken to represent the 5 percentile and 95 percentile values of a standard normal probability distribution. The normal probability distribution type was chosen because in the absence of additional information it represents the simplest and most reasonable way to characterize the parameter uncertainty using a continuous distribution. The resulting distribution parameters associated with each case (i.e. the mean and standard deviation) are included in Table 11.2.

11.4 Total Clean-up Cost

The Clean-up Cost node (basic node 9.3) and its direct predecessor nodes are shown in a highlighted version of the basic node influence diagram in Figure 11.2. The specific node parameter is the total cost associated with spill clean-up resulting from liquid product pipeline failure. The predecessor node arrows indicate that Clean-up Cost is a functional node meaning that the value of the node parameter is calculated directly from the value of the parameters associated with its direct predecessor nodes, Spill Volume, Clean-up Efficiency and Unit Clean-up Cost.

The total spill clean-up cost, c_{clean}, is calculated using the following equation

Release and Damage Costs

$$c_{clean} = \kappa_c V_s u_{clean} \qquad [11.2]$$

where V_S is the total spill volume, κ_c is the clean-up efficiency and u_{clean} is the unit clean-up cost. All of the information necessary to calculate the node parameter is available from preceding node parameter calculations.

11.5 Cost of Property Damage

11.5.1 Introduction

Figure 11.2 shows the node representing cost of property damage and its relationship to other influence diagram nodes. This is a functional node in which the cost of property damage is calculated from such parameters as the product (and its characteristics), the failure location, the ambient temperature and wind conditions, and the release rate and release volume. The node has the same direct predecessors as the node representing the number of fatalities, and uses a similar approach to calculate the node parameter. It uses release models to estimate the areal extent of a hazard or spill, and combines this with unit costs of damaged property and land to calculate the total cost of damage.

In calculating the cost of damage different damage scenarios are considered, namely fires, explosions and spills. Fires and explosions are possible for all product types, whereas spills are only relevant for LVP liquids. The methods used to calculate the cost of property damage are described in Sections 11.5.2 and 11.5.3.

11.5.2 Assumptions and Basic Approach

For a given hazard scenario, the total property damage cost is the sum of two components:

1. The cost of replacing damaged buildings and their contents.
2. The cost of site restoration. This relates to land around buildings in developed areas, agricultural land, parks and undeveloped land. The damage costs in this case covers immediate clean up and remediation for all lands, as well as replacement of landscaping for developed land.

The type of damage that could occur depends on the product released. For gas or HVP liquids there are no spills associated with the release. Damage caused by these products therefore results only from fires or explosions, which can damage both buildings and land. Land damage in this case corresponds to loss of vegetation, forests or landscaping. The costs associated with this are the costs of replacing landscaping or re-seeding forests.

LVP products result in a liquid release that could evaporate and/or ignite, causing a subsequent fire or explosion. If the spill does not ignite, no damage to buildings will occur. Only damage to the soil will occur due to seepage of the spill into the ground. The costs associated with this damage are the costs of clean up and remediation of affected land. If the spill ignites, damage to buildings and land will occur due to the fire as in the case of gas and HVP products. In addition, seepage of the liquid into the ground could occur before or during the fire, causing damage of the soil as in the case of unignited spills. It is therefore assumed that if an LVP spill ignites the costs of land damage will be the sum of remediation of the site and replacing landscaping or forests.

For a given hazard scenario (fire, explosion or spill), the total cost of property damage is calculated as follows:

$$c_{dmg} = \sum c_u \times g_c \times A \qquad [11.3]$$

where Σ indicates a summation of the costs for damage associated with each type of property, namely buildings and their contents, and land; and the symbols in the equation are defined as follows:

c_u is the cost of restoration per unit area;

Lg_c is the effective ground coverage defined as the ratio between the total area of the property type considered as a ratio of the total ground area. In the case of buildings for example, this would be the total floor area (total of all stories in multi-story developments) divided by the total ground area; and

A is the total ground area for which property will be damaged by the hazard.

In order to implement Equation [11.3] the values of c_u, g_c and A must be defined for different types of hazard and different types of land use that occur around pipelines. The definition of these parameters are addressed in Sections 11.5.3 to 11.5.4.

11.5.3 Calculation of Hazard Area

The ground area affected by a given hazard (A in Equation [11.3]) is calculated using the release models discussed in Appendix C. The hazards considered here include thermal radiation from jet or pool fires, vapour cloud fires, vapour cloud explosions and spills. It is noted that asphyxiation which was considered as a hazard to human life does not pose a risk of property damage and is therefore not considered here.

The approach used to define the extent of damage due to fires and explosions is similar to that used for calculating the number of fatalities (see Section 8.2 and Figure 8.2). Two hazard intensity thresholds are defined: an upper bound threshold defining the hazard intensity above which all property is destroyed; and a lower bound threshold below which no damage occurs. Between the two thresholds the probability of damage is assumed to vary linearly from 1 to 0. Based on a similar analysis to that described in Section 8.2, it can be shown that the equivalent area A based on these assumptions is given by:

$$A = 0.5(A_1 + A_0) \qquad [11.4]$$

where A_1 is the total area within the upper bound threshold and A_0 is the total area within the lower bound threshold.

The upper and lower bound thresholds used for fires and explosions are given in Table 11.3. The assumptions and justifications behind these values are discussed in Appendix E. Fire damage thresholds for buildings are based on the heat intensity that causes wood to ignite. The lower bound threshold for building damage due to explosions is based on the pressure that causes breakage of glass and the upper bound threshold on the pressure that causes total destruction of houses. For damage to land the thresholds for igniting vegetation and trees are assumed to be the same as those for people in outdoor locations.

For LVP liquid spills, the damaged area is equal to the spill size. The spill size for this purpose is calculated as the release volume divided by an assumed average pool depth of 1 cm. A similar value of pool depth was used by other researchers in the past (e.g. Ramsay and Hilbert 1994). The release volume is calculated using the method described in Section 6.3.

11.5.4 Unit Costs and Effective Ground Coverage

Table 11.4 gives a summary of the unit damage costs and effective ground coverage for different categories of land use. The following comments are relevant to the values in the table:

- In industrial, commercial and urban residential areas the ground coverage under the site restoration category corresponds to landscaped areas. The total ground coverage for buildings and landscaped area does not add up to 100%. The remainder consists of roads and parking lots that are assumed not to be affected by a release.
- The value of building contents is given as a percentage of the unit cost of the building. This cost is added to the building unit cost to get the total cost of damaging the building and its content. For example, the unit cost of damage to a building and its contents in a residential area is \$700x(1+75/100) per m^2.
- For developed land (landscaped or parkland), the costs of site restoration are assumed to be the same for a liquid spill, fire or blast. This is based on the assumption that the land will be immediately restored to its original state. For undeveloped or agricultural land, the cost of fire or blast is much lower than the cost of a liquid spill because the former involves only re-planting costs, whereas the latter involves removal of contaminated soil.

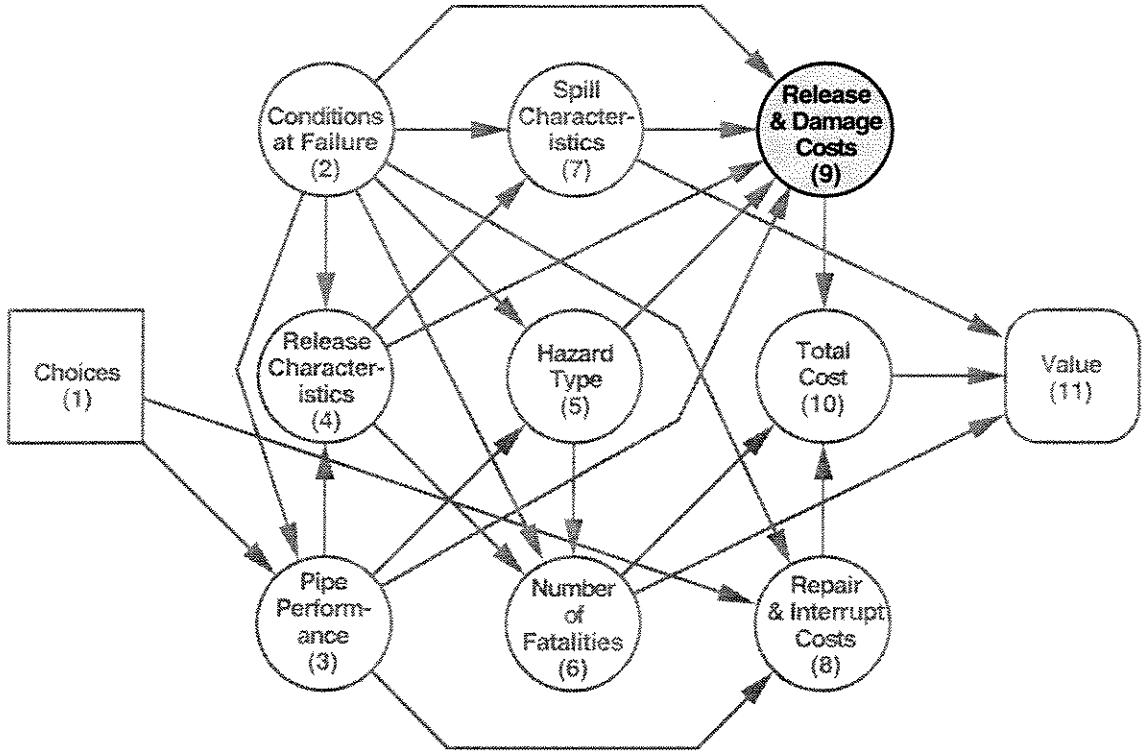

Figure 11.1 Compound node influence diagram highlighting Release & Damage Costs node group

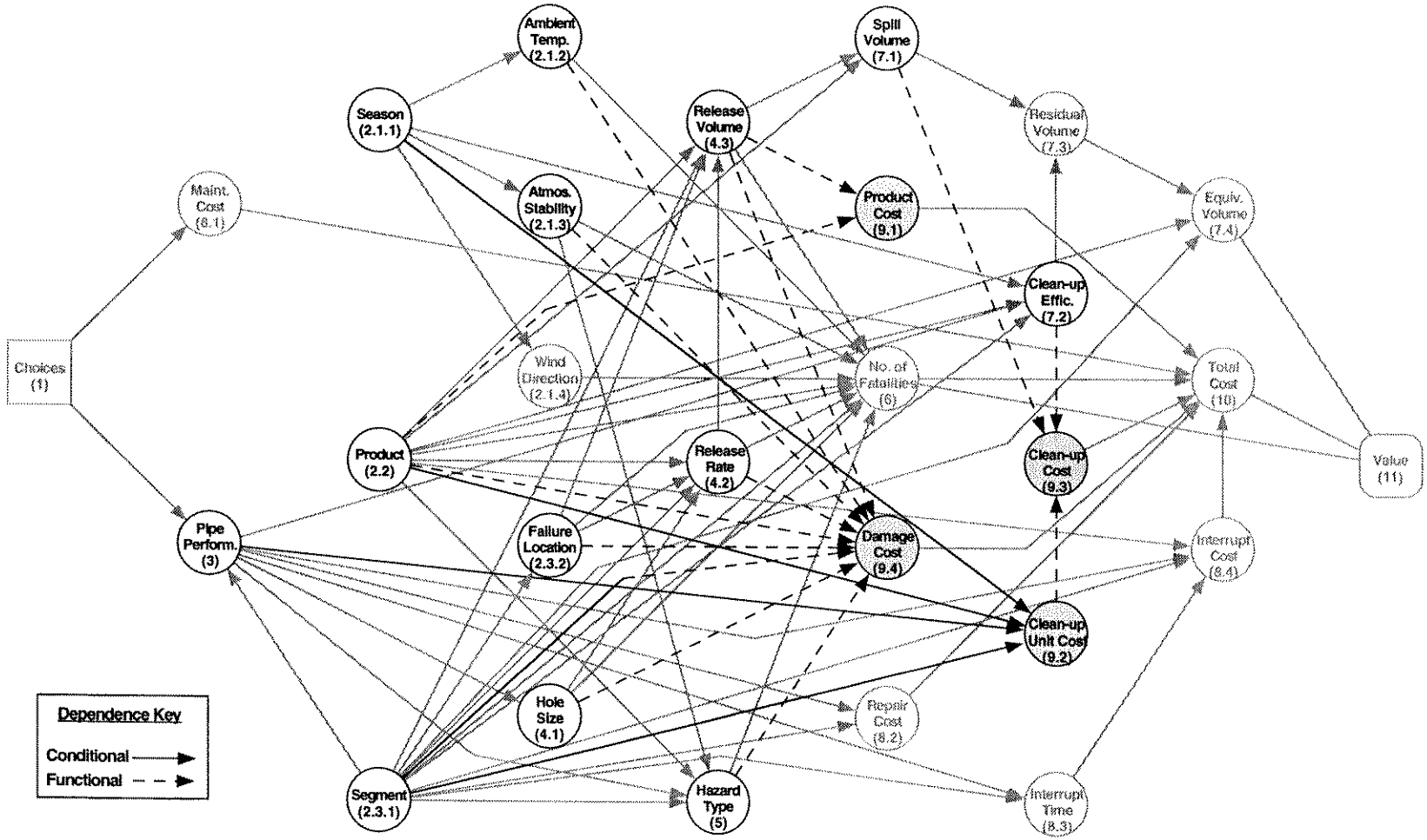

Figure 11.2 Basic node influence diagram highlighting Release & Damage Costs nodes and associated immediate predecessor nodes

Petroleum Fraction	Product Group	Cost ($/m^3)
Natural Gas	methane	0.055[1]
Natural Gas Liquids	ethanes	60[2]
	propanes butanes	85[3]
	pentanes (condensate)	120[5]
Gasolines	automotive gasoline aviation gas	200[4]
Kerosenes	jet fuel (JP-1) range oil (Fuel Oil - 1)	
Gas Oils	heating oil (Fuel Oil - 2) diesel oil (Fuel Oil -2D)	
Crude Oils	_____	120[1]

Notes:

1. representative wellhead/plant gate price: 1990 - 1993
   (CAPP statistical handbook, July 1994)
2. representative F.O.B. Alberta plant price: 1990 - 1993
   (CAPP statistical handbook, July 1994)
3. representative F.O.B. Alberta plant price: 1990 - 1993
   (Energy Statistics Handbook, Statistics Canada, Dec. 1994)
4. representative F.O.B. export price: 1989 - 1993
   (National Energy Board Annual Report, 1994)
5. the price of pentanes plus is historically comparable to that of crude oil
   (Canada Year Book, Statistics Canada, 1990)

Table 11.1 Unit cost estimates for representative petroleum products

Terrain Character	Season	Unit Clean-Up Cost * ($ per cubic metre of recovered product)			
		Light Refined Product		Heavy Unrefined Product	
		Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)	Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)
Ground	summer	530, 119	775, 228	300, 106	273, 93
Low Permeability	winter (i.e. frozen)	363, 99	663, 175	410, 161	381, 148
Ground	summer	1000, 365	1075,350	494, 125	675, 167
Moderate Perm.	winter (i.e. frozen)	563, 220	838, 251	385, 100	660, 161
Ground	summer	2575, 1170	1468, 385	713, 175	713, 144
High Permeability	winter (i.e. frozen)	500, 182	1375, 380	475, 67	680, 119
Waterlogged	summer	675, 198	1395, 429	775, 319	688, 190
Groundmass	winter (i.e. frozen)	669, 118	1300, 380	710, 298	563, 129
Water Covered	summer	1075, 410	not applicable (see note)	488, 114	not applicable (see note)
Vegetation	winter (i.e. frozen)	588, 160	1375, 380	373, 93	1225, 365
Static	summer	1063, 312	not applicable (see note)	1053, 315	not applicable (see note)
Water	winter (i.e. frozen)	278, 53	1300, 426	270, 55	1300, 426
Slow Flowing	summer	1075, 319	not applicable (see note)	813, 160	not applicable (see note)
Water	winter (i.e. frozen)	383, 117	1550, 426	378, 117	1450, 456
Fast Flowing	summer	1788, 403	not applicable (see note)	1200, 365	not applicable (see note)
Water	winter (i.e. frozen)	1613, 327	3175, 1110	1058, 315	1975, 380

Note: for spills in water, subsurface release and spread refers to liquid spreading beneath the ice surface and applies in winter only
* Parameter defined by a Normal distribution type with the tabulated means and standard deviations (i.e., Normal [mean, standard deviation])

Table 11.2 Characterization of unit clean-up costs for liquid petroleum product spills

Hazard	Parameter	Unit	Building Damage Thresholds		Land Damage Thresholds	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Thermal Radiation	Heat Intensity	kW/m^2	15.7	27	6.3	15.7
Vapour cloud fire	Volume Concentration	Ratio	N/A	N/A	0.5 C_L(1)	C_L(1)
Vapour cloud explosion	Volume Concentration	kPa	2.069	34.475	2.069	34.475

(1) Lower flammability limit.

Table 11.3 Upper and Lower bound Hazard Thresholds for Property Damage

Land Use	Building Reconstruction Costs			Site Restoration Costs		
	Unit Cost ($ per sq. m.)	Value of Contents (% of bldg.)	Effective Gnd. Coverage (% of total area)	Unit Cost for Fire or Blast ($ per sq. m.)	Unit Cost for Liquid Spill ($ per sq. m.)	Effective Gnd. Coverage (% of total area)
Industrial (1)	325	200	28 (2)	14.20 (8)	14.20 (8)	20
Commercial (1)	550	200	32 (3)	14.20 (8)	14.20 (8)	20
Residential - urban (1)	700	75	24 (4)	20.50 (9)	20.50 (9)	70
Residential - rural	700	75	0.2 (5,7)	5.50 (7,10)	5.50 (7,10)	100
Agricultural	700	150	0.0062 (6,7)	0.054 (7,11)	3.60 (7,12)	100
Parkland	700	0	0	5.40	5.40	100
Parkland - forested	700	0	0	0.07	3.60	100
Remote	700	0	0	0.00	3.60	100
Remote - forested	700	0	0	0.07	3.60	100

Notes:

1) ground coverage assumption: 80% lot, 10% landscaped easement and greenspace, 10% sidewalks and roadways
2) effective coverage based on a building floor area of 35% of lot area (see also note 1)
3) effective coverage based on a building floor area of 40% of lot area (see also note 1)
4) effective coverage based on a building floor area of 30% of lot area (see also note 1)
5) effective coverage based on 12.36 dwelling units per sq. km. (8 dwelling per quarter section)
6) effective coverage based on 0.386 dwelling units per sq. km. (1 dwelling per section)
7) assumes a representative dwelling area of 160 sq. m. with a heavily landsacaped surrounding area of 480 sq. m.
8) unit cost based on 10% @ $23 per sq. m. (setback @ LR) and 10% @ $5.40 per sq. m. (easement @ LP)
9) unit cost based on 60% @ $23 per sq. m. (yard @ LR) and 10% @ $5.40 per sq. m. (easement @ LP)
10) unit cost based on 0.6% @ $23 per sq. m. (immediate yard @ LR) and 99.4% @ $5.40 per sq. m. (remainder @LP)
11) unit cost based on 0.0186% @ $23 per sq. m. (immediate yard @ LR) and 99.98% @ $0.05 per sq. m. (cropland @ CA)
12) unit cost based on 0.0186% @ $23 per sq. m. (immediate yard @ LR) and 99.98% @ $3.60 per sq. m. (cropland @ LM)

Basic Unit Costs:

Buildings:	BR	Residential Building - $700 per sq. m. (~$65/sq. ft.)
	BC	Commercial Building - $550 per sq. m. (~$50/sq. ft.)
	BI	Industrial Building - $325 per sq. m. (~$30/sq. ft.)
Landscaping & Crops:	LR	Residential Standard - $23.00 per sq. m. (~$2.10/sq. ft.)
		(includes: grading, 100 mm top soil, sod, and allowance for shrubs, trees and fencing)
	LP	Parkland Standard - $5.40 per sq. m. (~$0.50/sq. ft.)
		(includes: grading, 100 mm top soil, sod, and trees as per urban development standards)
	LM	Miscellaneous Standard - $3.60 per sq. m. (~$0.33/sq. ft.)
		(includes: grading,150 mm top soil and seed)
	CA	Agricultural Crop - $0.05 per sq. m. (~$200/acre)
		(based on average value for canola, wheat, peas, oats, etc.)
	CF	Forest- $0.07 per sq. m. (~$280/acre)
		(based on an average timber value for mixed forest and replanting cost)

Table 11.4 Property damage costs associated with building reconstruction and site restoration

Total Cost

12.0 TOTAL COST

12.1 Node Parameter

The Total Cost node group (group 10) is shown in a highlighted version of the compound node influence diagram in Figure 12.1. The node group consists of a single Total Cost node (node 10) which is shown together with its direct predecessor nodes in a highlighted version of the basic node influence diagram in Figure 12.2. The specific node parameter is the total financial cost which is taken to be the sum of the direct costs associated with pipeline inspection and maintenance and the risk related costs associated with pipeline failure including the value of compensation for property damage and human casualties. Total Cost is a functional node meaning that the value of the node parameter is calculated directly from the values of its direct predecessor nodes which include: nodes in the Repair and Interruption Cost group, the Release and Damage Cost group, and the Number of Fatalities node.

The total cost, c, is calculated from the following equation

$$c = c_{main} + c_{prod} + c_{rep} + c_{\text{int}} + c_{clean} + c_{dmg} + a_n n \qquad [12.1]$$

where c_{main} is the direct cost associated with pipeline inspection and maintenance, c_{prod} is the market value of the lost product, c_{rep} is the cost of pipeline repair, c_{int} is the cost associated with service interruption, c_{clean} is the cost associated with spill clean-up where liquid spills are involved, c_{dmg} is the cost of site restoration and the value of compensation associated with property damage, and a_n is a constant that converts the number of human fatalities, n, into a financial cost.

All of the information necessary to calculate the total cost is available from preceding node parameter calculations except for the constant a_n which, in the context of the total cost node parameter, is intended to represent the cost of direct compensation to be paid for a human fatality. It is noted that the cost of compensation for loss of life (a_n) is not the same as the "value of a human life" which is intended to serve as a much broader measure of the financial

impact of a human fatality on society as a whole. This societal impact of human fatality is addressed separately in the value node calculation (see Section 13).

12.2 Cost of Compensation for Human Fatality

As part of this project a literature review was carried out and discussions were held with legal professionals working in the area of injury compensation. This review led to the basic understanding that within Canada, compensation payments for loss of life are based primarily on estimates of the economic value of a human life, *EVOL*, as obtained using a 'human capital approach' wherein the compensation reflects the present capital value of the loss of earnings of the person whose life has been lost. The *EVOL* of an average Canadian is calculated to be approximately $732,000 based on employment and retirement income information and statistical life tables available from Statistics Canada. A detailed discussion of the calculation method and the associated assumptions are given in Appendix H.

The total compensation award package paid to dependants and other claimants generally also included an allowance to account for the costs of pain, grief and suffering to the casualty, relatives and friends. Studies conducted in the U. K., where a similar approach to compensation payments applies (Marin 1986), suggest that a reasonable estimate of the 'pain and suffering' allowance is on the order of 25% to 30% of the *EVOL*.

In addition, it is noted that in Canada a 20% to 25% contingency reduction is often applied by the court to compensation awards. This contingency reduction is intended to reflect factors that are not specifically addressed in the formal calculation of the *EVOL*, including for example: consideration of the fact that the deceased person may not have chosen to work continuously to the standard retirement age of 65; or the possibility that a dependent spouse may chose to remarry.

Finally, the cost to the operator of compensation for human fatalities will also include legal fees for both parties because the fees for the party seeking compensation are usually built into the settlement award. The combined cost of legal fees is typically estimated to be on the order of 25% of the basic compensation award.

Total Cost

The above suggests that, on average, the added compensation for pain and suffering is offset by contingency reductions. The total cost of compensation for loss of life is therefore assumed to be equal to the *EVOL* plus legal fees. The equation for a_n is therefore

$$a_n = 1.25 \ \ EVOL \ \ = \$915{,}000 \text{ for an } EVOL = \$732{,}000 \qquad [12.2]$$

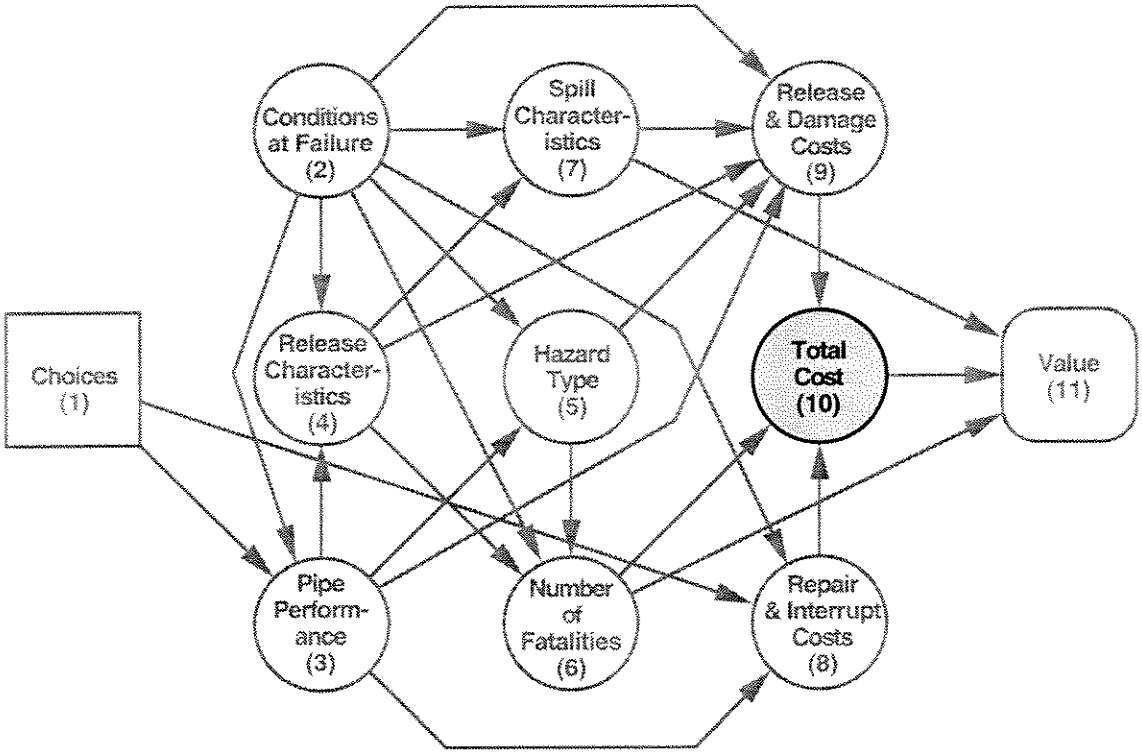

Figure 12.1 Compound node influence diagram highlighting Total Cost node group

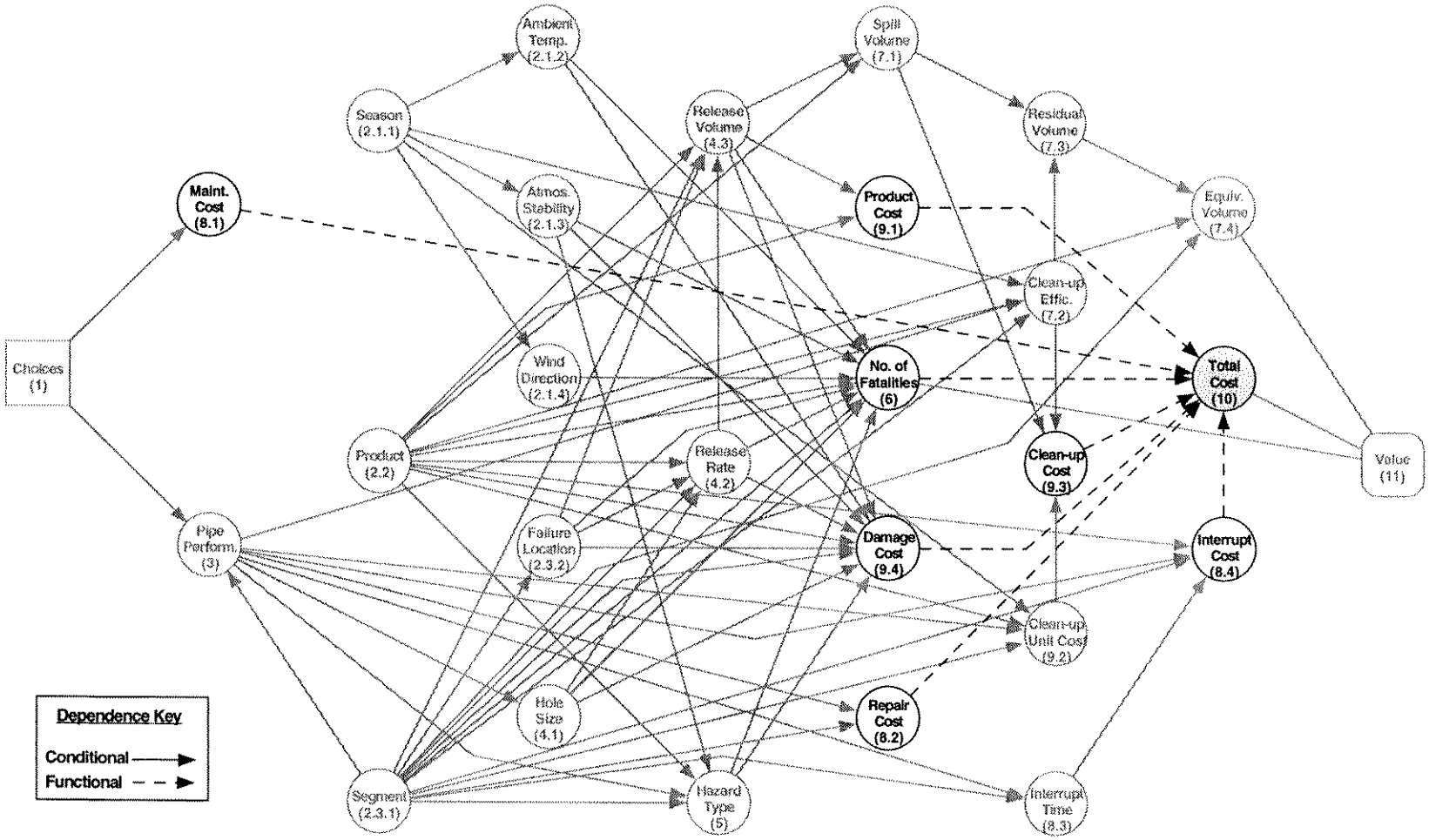

Figure 12.2 Basic node influence diagram highlighting Total Cost node and associated immediate predecessor nodes

Value

13.0 VALUE

13.1 Introduction

The value node defines the criterion used to make the final choice on integrity maintenance action. This criterion must take into account the three major objectives associated with the decision problem, namely 1) a high levels of *safety* for those exposed to risk from the pipeline, 2) a high level of *environmental protection* from potential product spills and 3) a low *economic* cost. Each objective is characterized by a specific parameter (called an attribute) that measures the degree to which the objective is achieved. As described in Stephens et al. (1994), the attributes selected for the present problem are:

1. Number of Fatalities n measuring safety.
2. Equivalent spill volume v measuring environmental protection.
3. Total cost c measuring economic aspects.

Figures 13.1 and 13.2 show how this parameter relates to the influence diagram in its compact and expanded forms. Figure 13.2 shows that the value node is a functional node, with the nodes representing the above three parameters as its direct predecessors.

Two approaches for defining the value function have been developed for this program (Stephens et al. 1994). These are:

- Utility Optimization. A utility measure is defined as a function of n, v and c. This function is defined such that higher expected values of the utility are preferred, and therefore the optimal choice is the one that leads to the maximum expected utility. In this approach, the value node calculates the utility u as a function of n, v, and c. Solution of the influence diagram provides the expectation of c for each choice and this information can be used to identify the choice that leads to the maximum expected utility.
- Constrained cost optimization. Cost is optimized subject to life safety and/or environmental constraints. This is achieved by first eliminating choices that do not meet the imposed safety and environmental constraints. The optimal action is then selected from among the remaining choices as the one with the lowest expected total cost.

Calculation of the value function is discussed in detail in Section 13.2 for the utility approach and in Section 13.3 for the constrained cost optimization approach.

Value

13.2 The Utility Approach

13.2.1 Introduction

13.2.1.1 Why Utility Functions?

A commonly used basis for decision making under uncertainty is to optimize the total expected cost c_t defined as:

$$c_t = an + bv + c \qquad [13.1]$$

where the constants a and b convert losses of life and equivalent spill volumes into monetary equivalents. This approach implies that the decision maker finds any two choices with the same expected total cost equally attractive. While this appears reasonable, the presence of uncertainty causes the preferences of most people and corporations to deviate from this approach.

To illustrate this consider the choices in Figure 13.3. Choice 1 represents a 0.01 chance of paying \$20,000, whereas choice 2 represents a sure cost of \$ 200. The expected cost for choice 1 is 0.99 x \$0.0 + 0.01 x \$20,000 = \$200, which is equal to that of choice 2. Therefore, based on the expected cost approach the two choices would be equivalent. In reality, however, most decision makers find a payment of \$200 to be more attractive than a 1% chance of losing \$ 20,000. In fact most people would be willing to pay more than the expected value of \$200 to avoid the risky choice. This attitude is referred to as *risk aversion* and is widely accepted in financial risk analysis.

Another limitation of the expected total cost approach relates to tradeoffs between different attributes. This is illustrated by considering the two choices in Figure 13.4. Choice 1 represents a 0.50 chance at paying \$10 million and causing 5 fatalities, and a 0.50 chance at having no losses. Choice 2 represents a 0.50 chance at losing \$10 million (with no losses in life) and a 0.50 chance at having 5 fatalities (with no financial losses). Using Equation [13.1] (with $v = 0$ and a = \$1 million per life) the expected value of the total cost c_t can be calculated for the first choice as 0.5 x (\$10 million + \$1 million x 5 fatalities) + 0.5 x (\$0 + 0) = \$7.5

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million. Similarly, choice 2 can be shown to have a total expected cost of $7.5 million as well, so that optimization of the total expected cost would mean indifference between the two choices. It can be seen however that some decision makers may prefer choice 1 because it includes a chance of no losses, whereas choice 2 is assured to have some loss (either financial or human). This attitude relates to *tradeoffs* between costs and losses in life.

The foregoing discussion shows that the expected cost approach may lead to poor choices because it cannot reflect appropriate risk aversion and tradeoff attitudes of decision makers. Utility theory can overcome this limitation by incorporating these attitudes in the optimization process. Formal definitions of the preference attitudes alluded to in this section and the manner in which they can be represented in a utility function is addressed in Section 13.2.2.

13.2.1.2 Defining a Utility Function

The development of a utility function for a problem with multiple attributes involve two main steps.

1. Definition of individual utility functions for each attribute based on the appropriate risk attitudes.
2. Combining the individual utility functions in an overall utility function , that takes into account tradeoff attitudes between the different attributes.

Sections 13.2.2 and 13.2.3 describe the above two steps for the problem of pipeline risk-based decision making. Each section gives the basic concepts needed before describing the analysis undertaken and the conclusions reached.

13.2.2 Single Attribute Utility Functions

13.2.2.1 Risk Attitudes - Concepts and Definitions

To generalize the risk aversion concept introduced in Section 13.2.1.1, risk aversion is said to apply for a certain attribute if the expected value of an uncertain choice (or lottery) is more attractive than the lottery itself for the whole range of attribute values. Risk aversion can be reflected in risk management choices by defining the objective function (called the utility function u) as a concave function of the attribute. This is illustrated in Figure 13.5a for the

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cost attribute c. The utility function u(c) is a decreasing function of c and this reflects the fact that higher costs are less desirable. The figure can be used to verify that, because the function is concave, the expected utility of any option involving uncertainty is lower than the utility associated with the expect value of the option. Therefore, using a concave utility function over cost results in risk averse choices.

Risk proneness is the opposite of risk aversion. It is said to apply to a certain attribute if the decision maker prefers each lottery to its expected value over the whole attribute range. Risk proneness can be modeled by a convex utility function as shown in Figure 13.5b. It is noted that a linear utility function would correspond to optimizing the cost itself, and that this case is referred to as a *risk neutral* attitude.

The sure cost deemed by the decision maker to be equivalent to a certain lottery l is called the *certainty equivalent* of that particular lottery, and is denoted $\hat{c}$. The difference between the expected value of the lottery and its certainty equivalent, represents the amount of money which the decision-maker is willing to pay in order to avoid the risk, and is called the *risk premium* $\pi(l)$ for this particular lottery. The risk premium represents the degree of risk aversion (see Figure 13.5a).

Consider a lottery represented by a 0.50 chance of paying $c - \Delta c$ and a 0.50 chance of paying $c + \Delta c$. The amount c is called the *reference amount* of the lottery, while the *range* of the lottery is $2\Delta c$. The variation of the risk premium with the reference amount for the same lottery range represents another significant attitude of risk behaviour. If the risk premium increases (decreases) monotonically with c for any fixed range $2\Delta c$, the decision maker is said to be *increasingly (decreasingly) risk averse*. Otherwise, if the risk premium is constant for all h, the decision-maker is *constantly risk averse*. Similar definitions apply to increasing, decreasing, and constant risk proneness.

Mathematical functions can be proposed to satisfy the ranking and risk characteristics that are judged to be appropriate for a certain attribute. These functions contain constants that can be determined by the decision maker's certainty equivalents for a number of lotteries equal to the number of the required constants. The characteristics of the utility functions used for the attributes used in the present study are given in Sections 13.2.2.2 and 13.2.2.4.

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13.2.2.2 Utility Function for Cost

Money is the most frequently appearing attribute in utility theory applications. Hax and Wiig (1975), for example, dealt with a capital investment decision problem of bidding on a project taking into consideration the possibilities of a high or low bid, and bidding alone or with a partner. "Net present value" of the investment was taken as an attribute. Another example is a study for selecting a site for a nuclear power plant constructed by Keeney and Nair (1975). They considered the attribute "annual differential cost" for the different proposed sites. Bell (1977) analyzed the problem of dealing with forest pests in New Brunswick, based on the attribute "single year's profit". In a decision analysis study for the development of the Mexico City Airport, Keeney (1973) used "cost" as an attribute.

All the above authors and many others agree, regardless of the nature of the problem or the exact definition of the attribute, on monotonicity and risk aversion. The function is either monotonically increasing in case of gain, or monotonically decreasing in case of cost. In addition Keeney and Raiffa (1976) and Schlaifer (1969) suggest that an increasingly risk averse function (as defined in Section 13.2.2.1) would be appropriate.

In summary, the utility function over cost is 1) monotonically decreasing, 2) risk averse, and 3) increasingly risk averse. A function that satisfies the above conditions is given plotted in Figure 13.6. Appendix I describes how the function is defined by asking the decision maker to give his or her certainty equivalent to a simple lottery. It also shows how the function is verified by using to calculate some equivalent options and presenting them to the decision maker to ensure their consistency with his or her choices.

13.2.2.3 Utility Function for Number of Fatalities

Several authors have reported using losses in life as an attribute in decision analysis. For example, Keeney (1973) for example used the "number of people killed or seriously injured" in a study of the development of Mexico City Airport. The attribute was used in the range of 0 to 1000. A linear utility function was selected although in his discussion, Keeney suggests that a rational utility function should be risk averse.

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A study of hazardous materials transportation for the Maritimes Administration by Kalelkar and Brooks (1974) used the "number of people killed" as an attribute in the range of 0 to 60. A decreasingly risk prone function was assigned to the attribute by an experienced person in the field of safety, who was asked to represent the point of view of society. The authors explained the risk proneness for small numbers of deaths by the fact that the decision maker was willing to take high chances to avoid even one certain death. So he was willing to take a 50-50 chance between 0 to 60 deaths, rather that accept 10 sure deaths. As the number of sure deaths increased, his risk proneness declined and his function became risk neutral. This explanation holds only for uncertain choices that involve a chance of no deaths, while the function still implies risk proneness for a large range of uncertain choices that do include sure deaths (e.g. the certainty equivalent for a 50-50 lottery between 10 or 60 deaths is about 25). It is interesting here to note that the utility function of the same decision-maker over property damage in dollars was decreasingly risk prone. Tversky (1977) also suggested that a risk prone utility function is appropriate for losses in life.

A risk averse function was suggested by Jordaan (1982) in a study of the transportation of hazardous goods through the City of Calgary, Alberta, Canada. The function is intended to expresses the aversion of society to a catastrophe involving a large number of deaths. The function used by Jordaan was constantly risk averse (i.e., the degree of risk aversion was not dependent of the number of lives lost).

The foregoing discussion shows that there is no consistency in previous work regarding risk attitudes associated with losses in life. In fact, all possible risk attitudes (risk averse, risk prone and risk neutral) have been suggested. In evaluating this information to choose an appropriate utility function, the following points were considered:

1. References that suggested a risk prone function indicate that the degree of risk proneness decreases rapidly as the number of fatalities increase, and the functions become almost risk neutral. The risk prone attitude in the low values of the attribute can be explained by the attractiveness of lotteries which involve a chance at zero deaths or injuries.
2. Risk aversion was justified on the basis of society's aversion to large catastrophes. Such catastrophes are unlikely to result from a pipeline failure.
3. Any deviation from a straight line behaviour does not minimize the expected number of deaths since it means the willingness to pay a certain premium in order to avoid or seek risk. A risk averse behaviour, for example, reflects the fact that society is more shaken by 100 deaths in one accident than 10 accidents, each resulting in 10 fatalities. Most people

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would agree with this attitude. What is questionable, however, is the validity of accepting a higher expected number of deaths (sacrificing lives) in order to ensure that the rest of the society is informed of these deaths in a more acceptable manner.

Based on this it was decided that a risk neutral (linear) utility function is most suitable. This corresponds to minimizing the expected number of fatalities directly. The utility function is given in Appendix I.

13.2.2.4 Equivalent Spill Volume

The equivalent spill volume represents the residual spill volume remaining in the environment after clean up. This volume is calculated the actual volume in the environment in question to a volume that is judged to have the same impact in a reference environment for which the characteristics are defined by the user. Details of this parameter are described in Section 9.4.

Discussions with some of the organizations that were consulted to obtain input on environmental issues (see Section 9.0) indicate that decision makers place much more importance on prevention of spills than on limiting the spill size if one occur. In other words, the utility drops at a high rate for low spill volumes and this rate decreases as the spill volume increases. This trend implies that the utility function is convex or risk prone.

The function used is plotted in Figure 13.7. Details of the derivation and verification of the function are given in Appendix I.

13.2.3 Multi-attribute Utility Function

13.2.3.1 Tradeoff Attitudes - Concepts and Definitions

A multi-attribute utility function is defined as a function of the individual utility functions for each attribute, and a number of constants representing tradeoffs between the individual attributes. The multi-attribute utility function can represent different assumptions regarding how the attributes interact. Interaction between attributes relates to such questions as: do preferences over lotteries involving cost c depend on the number of fatalities n or the volume of spill v?, or do tradeoffs between c and n depend on the values of v. If all such interactions are

permitted, the form of the multi-attribute utility function becomes very complex. With some constraints, however, significant simplifications to the function can be made. Two types of constraints are discussed in the following paragraphs.

The first constraint relates to *preferential independence*, which means that preferences over a given subset of the attributes are independent of the values of the remaining attributes. For example, if tradeoffs between the cost c and number of fatalities n are unaffected by the equivalent spill volume v, then if can be stated that the subset $\{c,n\}$ is preferentially independent of v. It is noted that preferential independence relates to tradeoffs under certainty and therefore it can be established without consideration of any uncertain choices.

The other constraint that can be exploited to simplify the utility function is called *utility independence*. A given attribute is utility independent of another attribute if preferences under uncertainty for the former are not affected by the value of the latter. For example, cost c is utility independent of the number of fatalities n if preferences regarding cost lotteries (such as the one in Figure 13.3) are not affected by the number of fatalities.

The utilization of these independence characteristics to select an appropriate form of the multi-attribute utility function in discussed in Section 13.2.3.2.

13.2.3.2 The Multi-attribute Utility Function

Figure 13.8a shows two equivalent choices involving cost c. Since this equivalence does not take into consideration the number of fatalities n, it is valid for $n = 0$, and the equivalence in Figure 13.8b holds. Now, if the value of n is changed from zero to 5 say, would this change the above equivalence in c ? In other words, does the indifference relation in Figure 13.8a imply the one in Figure 13.8d for any value of n ? It is reasonable to answer the above questions positively, and this implies that c is Utility Independent (UI) of n A similar arguments can be developed to show that it is reasonable to assume that c is UI of v. Therefore it can be stated that c is UI of $\{n, v\}$.

Now consider tradeoffs between c and n for a certain value of v. Assume that the consequence $\{c = \$50$ million, $n = 0$ fatalities, $v = 0$ m$^3\}$ is equivalent to $\{c = \$0$, $n = 5$ fatalities,

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$v = 0$ m^3}. This means that a loss of \$50 million is equivalent to 5 fatalities provided that $v = 0$ m^3 (i.e., there is no spill). Assume that the value of v is changed to 1000 m^3, would this affect the values of c and n in the above equivalence relationship? In other words, does the tradeoff between c and n depend on the value of v ? A negative answer is reasonable, implying that $\{c,n\}$ is preferentially independent on v, denoted $\{c, n\}$ is PI of v. A similar arguments can be used to show that $\{c, v\}$ is PI of n.

The above-mentioned conditions are sufficient to justify a simplified form of the utility function called the multiplicative form. This function and the input required to define and verify it is given in Appendix I. It is noted that, as is shown in the Appendix, defining the multiattribute utility function involves indirect definition of the monetary equivalents of losses in life and spills.

13.3 Constrained Cost Optimization

13.3.1 Introduction

As discussed earlier, the constrained cost optimization approach is based on selecting the lowest expected cost option that meets a pre-defined minimum level of life safety or environmental protection. This approach eliminates the need to consider the tradeoffs discussed in Section 13.2, which may be considered an advantage by some decision makers who find it difficult to explicitly consider such issues as the monetary value of human life and environmental protection. It must be mentioned, however, that such values are implied by the decision made regardless of the method used. For example, the value of human life implied by a given choice can be calculated using the decision influence diagram. Therefore, it can be argued that since these issues cannot be avoided it is better to consider them explicitly in order to ensure consistency and understand the implications of a given decision.

The constrained expected cost optimization approach is best suited to cases where policy or regulations are in place that dictate certain levels of human safety or environmental protection. In such cases, this approach allows meeting these regulations at the lowest possible cost.

Value

Calculation of the total cost is addressed in Section 12.0, and need not be repeated in this section. The remaining information necessary to use this method is how the constraints are defined.

13.3.2 Life Safety Constraint

13.3.2.1 Selecting Acceptable Risk Levels

Two aspects are usually considered in defining acceptable risk levels:

1. *Individual Risk*, defined as the annual probability of death due to a pipeline failure for any exposed individual (based on HSE 1989). This risk is determined by exposure time and the probability that a given failure will lead to fatal consequences. Individual risk is independent of the number of people exposed to risk.
2. *Societal (or Collective) Risk*, defined as the annual probability of a given number of fatalities due to a given source of risk. To take society's aversion to large accidents into account, acceptable societal risk is often defined as a decreasing function of the number of fatalities (HSE 1989).

Suggested acceptable individual and societal risk levels for the present project were developed based on a review of criteria set out by governments and the industry for similar industrial facilities.

Individual Risk Criteria

In the U.K. acceptable individual risk levels specified by the Health and Safety Executive are in the range of 10^{-6} to 10^{-4} per year (HSE 1988, 1989). The maximum tolerable risk level recommended by HSE (1988) for existing nuclear power stations is 10^{-4} per year. Risks above this level are considered unjustifiable on any grounds. Risks between 10^{-6} and 10^{-4} per year are considered tolerable only if risk reduction is impractical, or if the cost of reduction is grossly disproportional to the improvement gained. Risks below 10^{-6} per year were considered acceptable without additional reductions. For new developments the HSE (1989) suggests an upper limit for acceptable risk of 10^{-5} per year, which is one tenth of the maximum level used for existing nuclear stations. The HSE guidelines are applicable to individuals with an average (rather than maximum) level of exposure to the risk.

Value

In Canada, the Major Industrial Accidents Council of Canada (MIACC 1993) is developing Land Use Guidelines for Pipeline Corridors. It is proposed that the type of land use in the proximity of an industrial facility is defined as a function of the risk level. The MIACC approach is based on risk contours that define how the risk decreases with increasing distance from the facility. High density residential developments are allowed beyond the risk contour corresponding to 10^{-6} per year. This implies that, similar to the HSE guidelines, 10^{-6} per year is acceptable without limitation. Commercial land use and low density residential housing are permitted in areas where the risk is 10^{-6} to 10^{-5} per year, and industrial developments in areas where the risk is 10^{-5} to 10^{-4} per year. This indicates that the highest acceptable annual individual risk levels are 10^{-4} for industrial developments, 10^{-5} for low density residential areas and 10^{-6} for high density residential areas.

Societal Risk Criteria

The purposes of defining societal risk criteria is to recognize society's aversion to large accidents. A common method to express acceptable societal risk is the so-called *F-N* curves (Farmer 1967), in which *N* is the number of fatalities in an accident and *F* is the probability of accidents causing more than *N* fatalities. However, *F-N* curves are dependent on the total population exposed to a given type of accident. This is a severe draw back with respect to using *F-N* curves for pipeline systems, which due to their linear nature expose a number of people that is, on average, proportional to their length. Therefore, everything else being equal, the acceptability of a given pipeline with respect to a given *F-N* curve would be dependent on its length. Due to this unreasonable trend, *F-N* curves are not used further in this project.

Another method to consider societal risk is to define individual risk as a function of the number of people exposed to a given accident. This is the approach adopted in HSE's Guidelines for Land-Use Planning (HSE 1989), in which an individual risk level of 10^{-5} per year was considered acceptable for developments housing more than 25 and less than 75 people. If the development houses 75 people or more, the acceptable individual risk is reduced to 10^{-6} per year. HSE suggested that the individual risk of 10^{-6} per year is acceptable even for very large facilities (e.g., hospitals, schools, and large shopping centres).

Value

In Canada, MIACC's draft guideline (MIACC 1993) refers to the acceptable risk level associated with railway transportation of dangerous goods in Toronto. This level was specified as 10^{-5} per year if more than 25 people are exposed. This is essentially the same as the HSE approach. MIACC's approach in defining individual risk is also based on the number of people exposed and therefore it implies partial consideration of societal risk.

Suggested Tolerable Risk Levels

Based on the information presented earlier in this section, it was decided that an approach based on a variable individual risk depending on the number of people exposed in a given accident should be used to account for both individual and societal risk aspects. Consistent with both the U.K. HSE and the Canadian MIACC recommendations, the basic individual risk levels suggested are 10^{-6}, 10^{-5} and 10^{-4} for urban, industrial and rural land use classifications, respectively.

13.3.2.2 Definition of the Constraint

The basic criterion used to apply a life safety constraint is that the maximum individual risk along the pipeline should be lower than the tolerable risk level. Because of potential variations in land use along the pipeline, the tolerable individual risk level will vary as discussed in Section 13.3.2.1. This makes it necessary to use a reference tolerable individual risk level and normalize the actual calculated individual risk levels for different land use types to correspond to the land use associated with the reference tolerable risk.

The reference tolerable individual risk level R_{tr} is defined as the maximum for all land uses associated with the pipeline. This means that:

$$R_{tr} = \max(R_{ti}) \ , \ i = 1,2,....,m \qquad [13.2]$$

where R_{ti}, is the tolerable individual risk level for the i^{th} land use type, and m is the number of land uses associated with the pipeline. The normalized maximum individual risk R_{nj} for a given segment j is then calculated from:

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$$R_{nj} = R_j(d_{\min})(R_{tr} / R_{ij}) \qquad [13.3]$$

where $R_j(d_{\min})$ is the individual risk for segment j calculated at the minimum offset from the pipeline at which a development is permitted ($d_{\min}$). Calculation of individual risk is discussed in detail in Section 8.0. The maximum normalized reference individual risk is then calculated as:

$$R_{\max} = \max(R_{nj}) \ , \ j = 1,2,...,k \qquad [13.4]$$

where k is the number of pipeline segments. The constraint is then defined as $R_{\max}<R_{tr}$, so that choices that do not satisfy this constraint are inadmissible.

13.3.3 Environmental Impact Constraint

The environmental constraint is defined in terms of the expected total equivalent volume per km length of the pipeline. Recall that the equivalent spill volume is a measure of the environmental impact of the residual spill after clean up of as much of the spill as possible (see Section 9.4 for details of how this parameter is calculated). Use of the total expected value of the equivalent spill volume per km of the pipeline results in a measure of the total expected environmental impact due to a unit length of the pipeline. Any choice that leads to an average per km equivalent spill volume greater than the tolerable value is considered inadmissible.

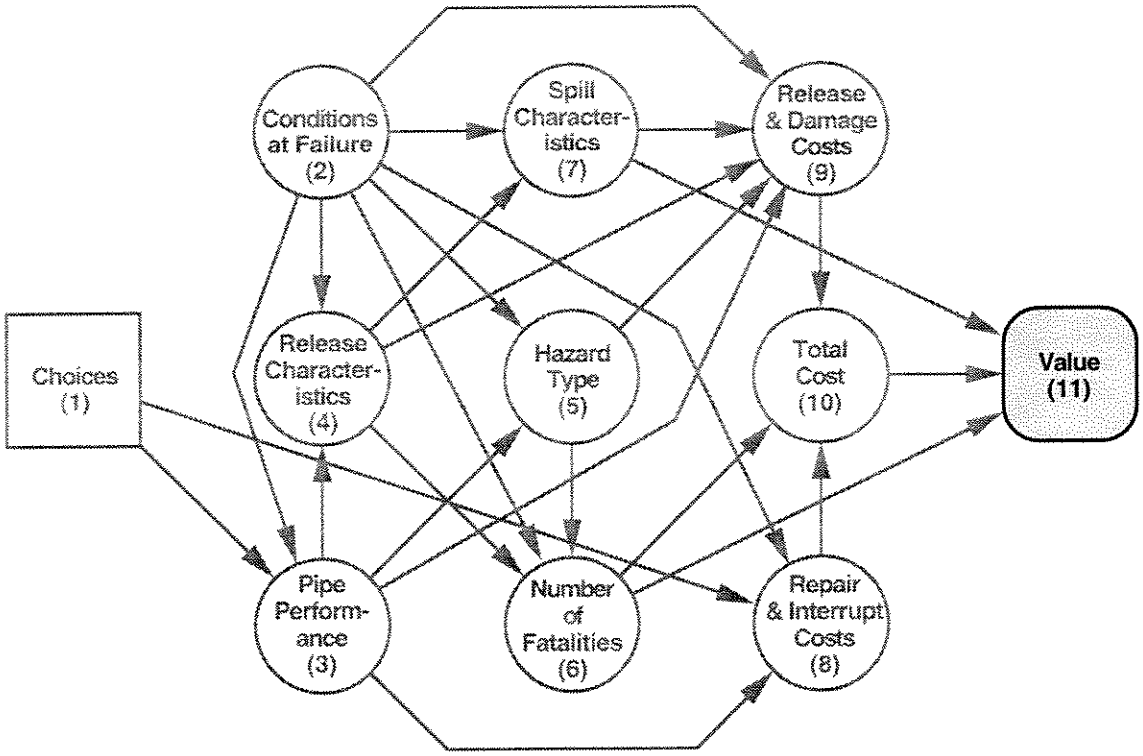


Figure 13.1 Compound node influence diagram highlighting Value node group

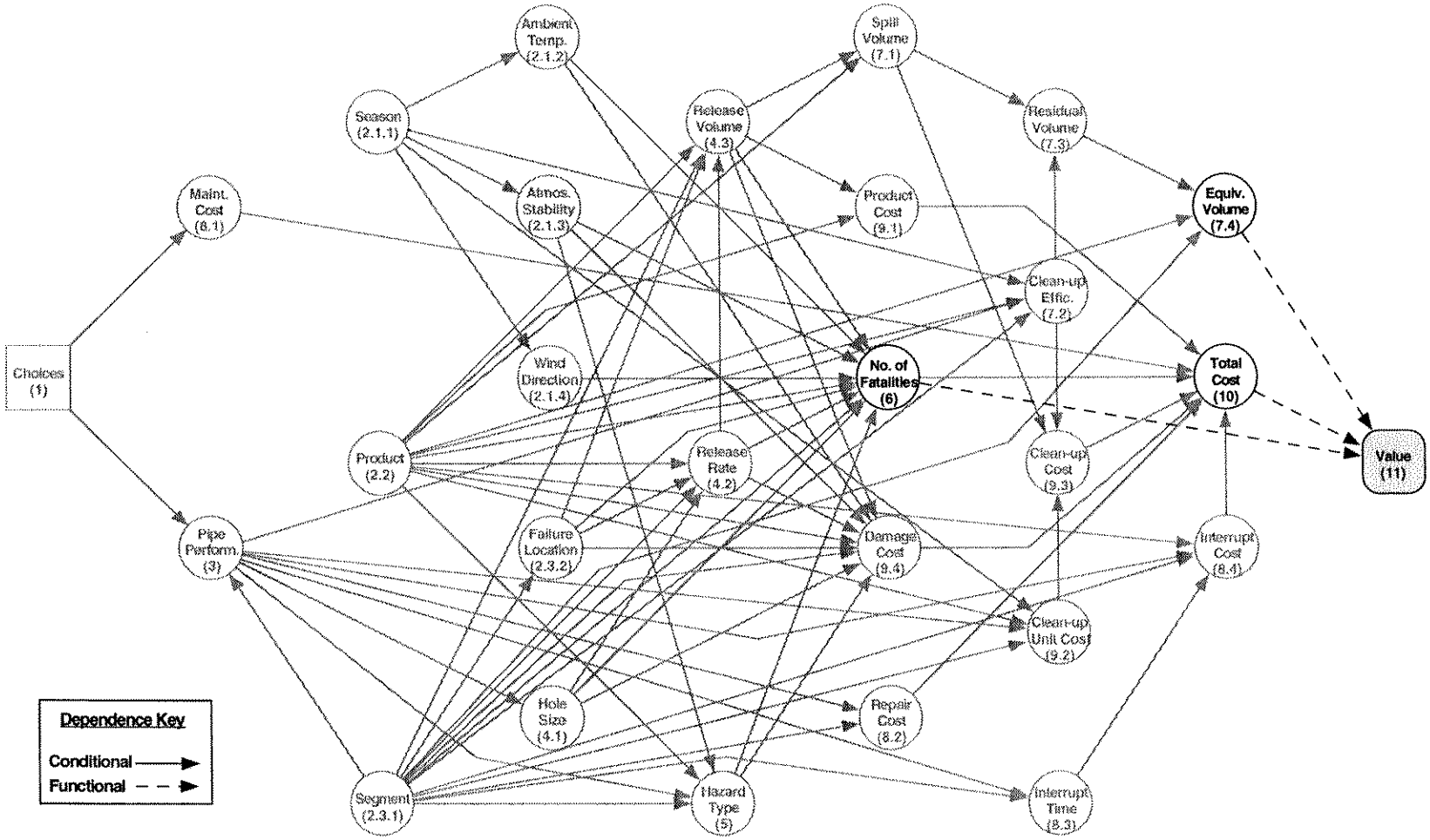
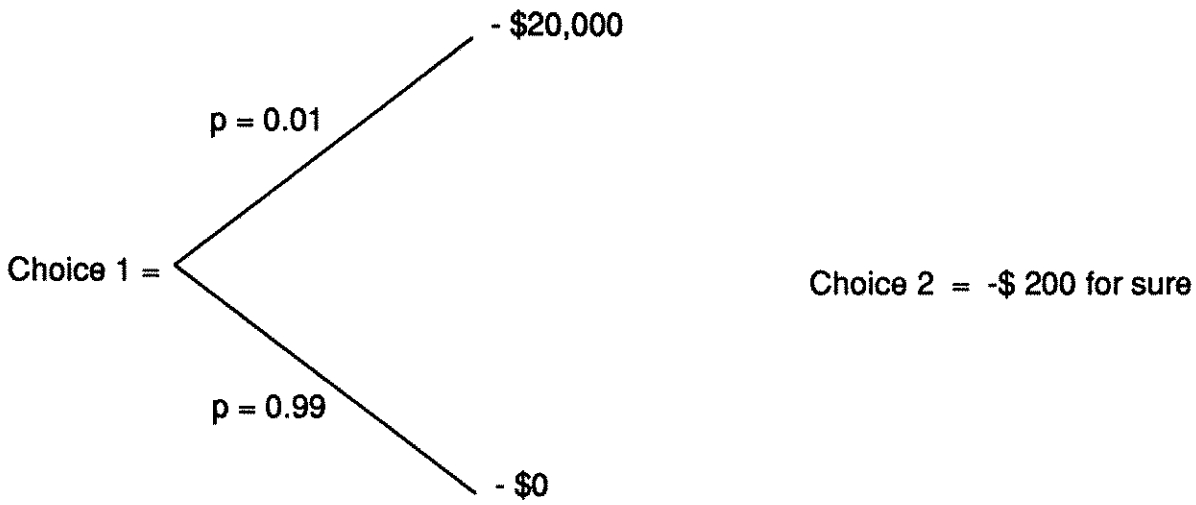


Figure 13.2 Basic node influence diagram highlighting Value node and associated immediate predecessor nodes



E (C) = 0.01 x -$20,000 + 0.99 x 0. = -$200

Figure 13.3 Choices With Equivalent Expected Costs and Different Risk Levels.

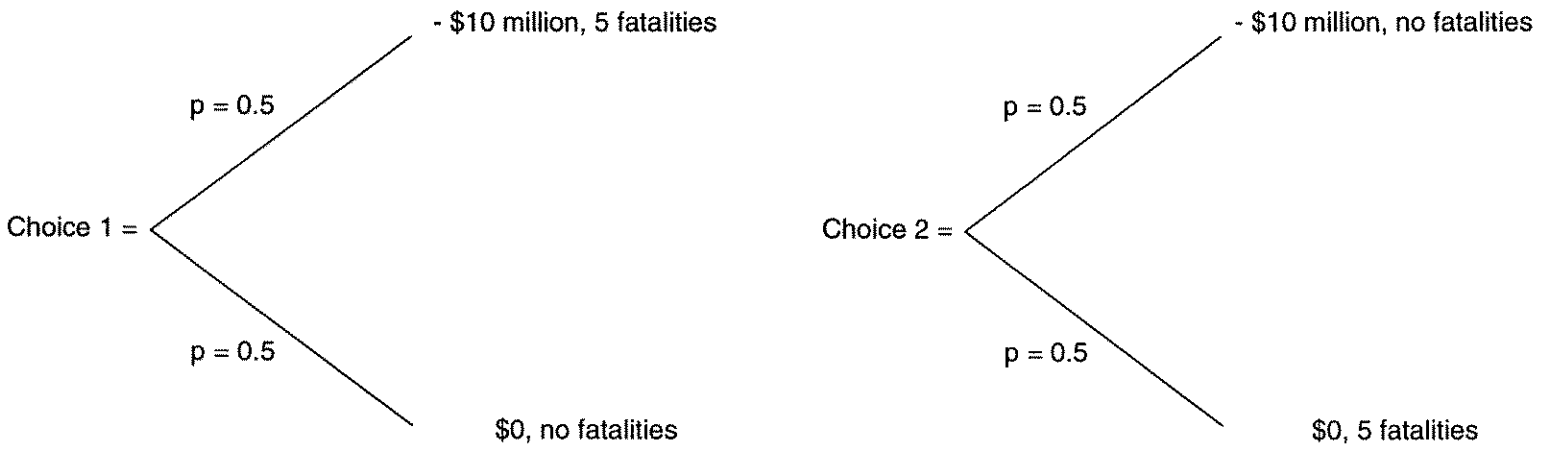
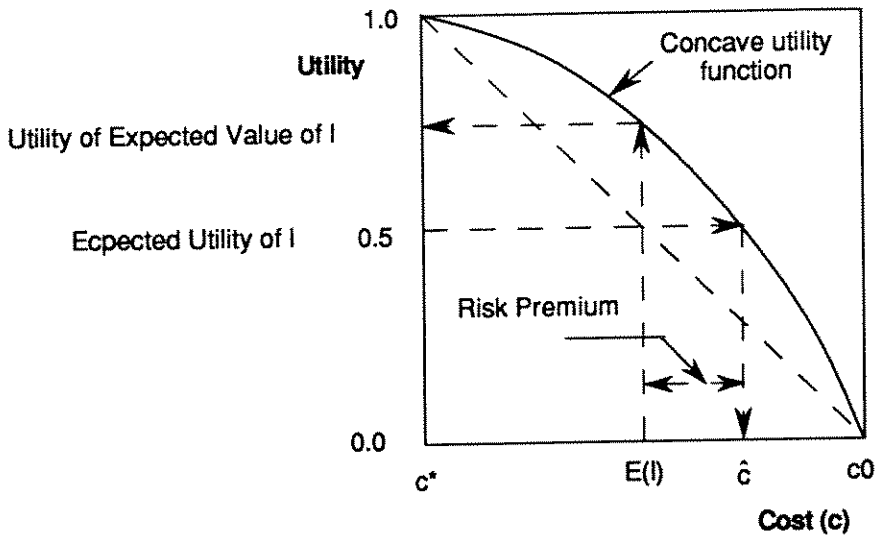
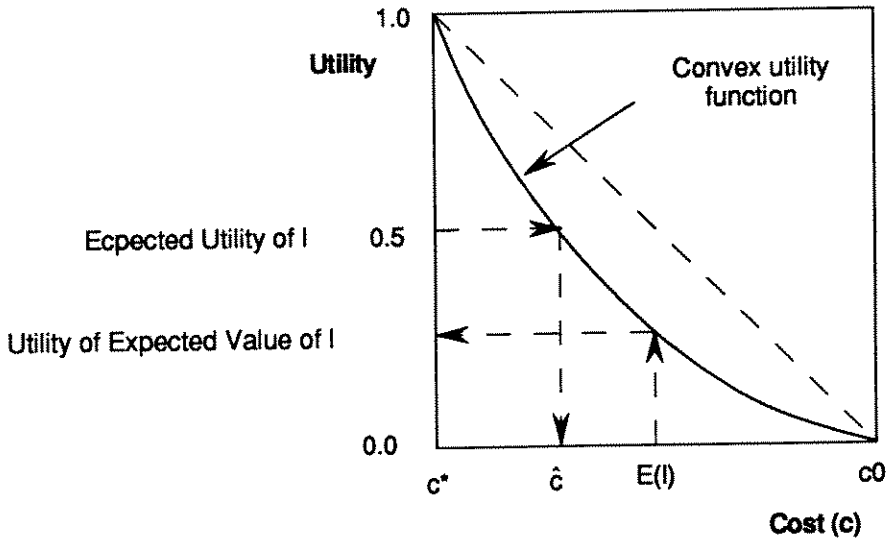


Figure 13.4 Uncertain Choices Involving Combinations of Costs and Fatalities



a) Risk Averse: Utility of the Expected Value > Expected Utility of Lottery



a) Risk Averse: Utility of the Expected Value < Expected Utility of Lottery

c*	= Minimum cost
c0	= Maximum cost
I	= a 50-50 chance of c* or c0
E(I)	= Expected value of lottery = (c*+c0)/2
E[u(I)]	= Expected utility of the lottery = [u(c*)+u(c0)]/2 = 0.50
ĉ	= Certainty Equivalent of I

Figure 13.5 Illustration of Risk Averse and Risk Prone Utility Functions

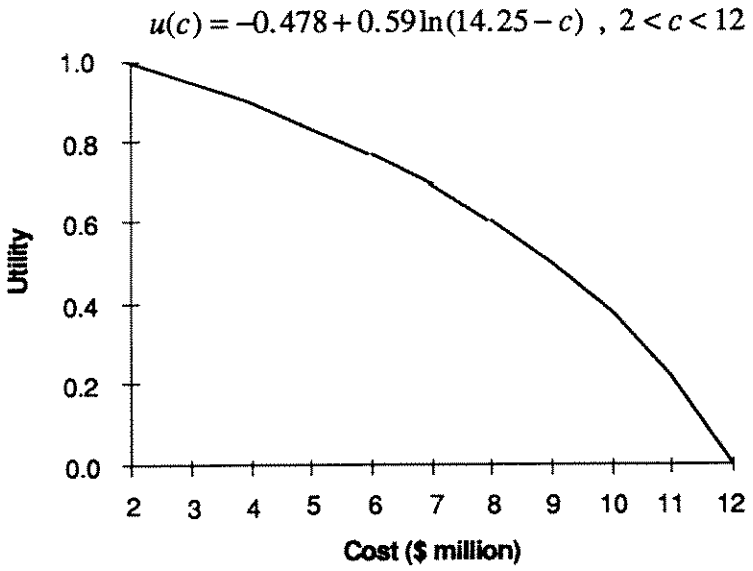


Figure 13.6 Example of an Increasingly Risk Averse Utility Function Over Cost

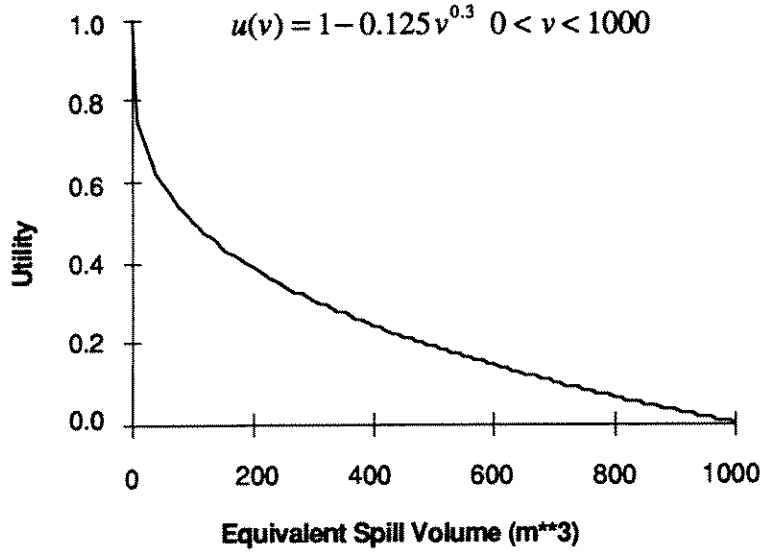
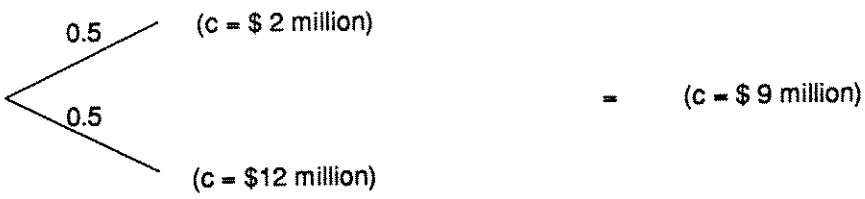
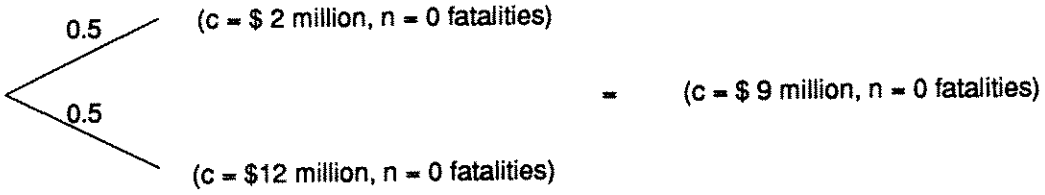


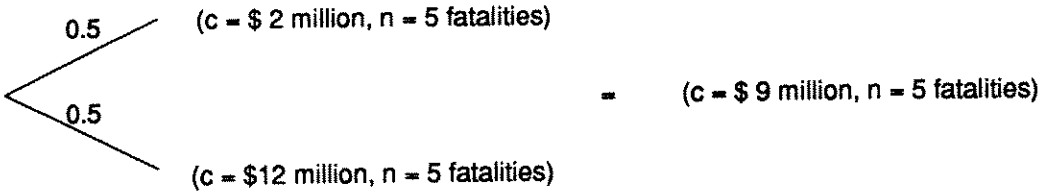
Figure 13.7 Example of a Risk Prone Utility Function Over Equivalent Spill Volume



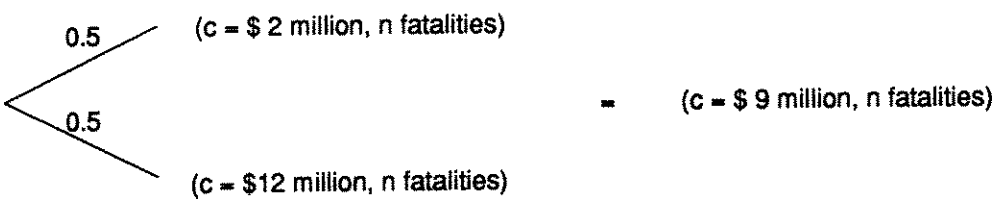
a)



b)



c)



d)

Figure 13.8 Illustration of the Conditions Necessary to Justify Preferential Independence

14.0 APPLICATION TO DECISION MAKING

14.1 Introduction

Sections 3.0 to 13.0 of this report give a description of the data and models used to define each influence diagram node. Once this information is defined, the influence diagram can be solved to produce the decision making aids that are required to make an optimal choice. The solution methodology and resulting outputs are described in Nessim and Hong (1995). This section gives a description of the main outputs for the consequence analysis problem and discusses their use in decision making.

14.2 The Main Decision Making Tools

The main decision making tool obtained by solving the influence diagram is the expectation of the value node for each choice. As discussed in Section 13.0, three different methods for defining the value node are available. Each of these methods corresponds to a different decision making criterion. These are as follows:

- *Utility optimization.* The result of this method is illustrated in Figure 14.1, in which the expected utility is plotted for each choice. Since the utility function is defined in such a way as to incorporate all of the decision maker's preferences, risk attitudes and tradeoffs between different attributes, the optimal choice in this case is the one that achieves the maximum expected utility.
- *Constrained cost optimization.* Figure 14.2 illustrates the format of the results for the constrained cost optimization approach using a life safety constraint. This plot shows the expected cost versus the criterion used to define the constraint for each choice. In this case, the expected total cost is plotted against the maximum individual risk associated with the choice. The constraint, defined by the maximum allowable individual risk, is also plotted on the figure. A strict application of the constrained cost optimization would mean that all choices that do not meet the constraint should be eliminated. Among the choices that meet the constraint, the one with the lowest expected cost is optimal. In practical terms, Figure 14.2 can be used in a more flexible sense to compare different options with respect to their expected total cost and their deviation from the constraint. For example, if the absolute lowest cost option does not meet the constraint, the expected cost associated with meeting the constraint can be defined as the difference between the absolute lowest cost and the lowest cost for an option that meets the constraint (see Figure 14.2). The figure can also be used to determine how far the lowest cost option is from meeting the constraint. Subjective assessment can then be made regarding which option should be selected. A similar plot can be produced for an environmental constraint.

In addition, the influence diagram can be used for *sensitivity analyses*. By changing the value of a given parameter and repeating the calculation, the impact of this parameter on the final choice can be determined. This type of sensitivity analysis can be performed for input parameters that are not well defined. It can increase the confidence of the decision maker that the best decision has been made. For example, if a parameter that cannot be defined with accuracy is changed within a reasonable range without affecting the optimal choice, confidence in the appropriateness of this choice is increased. Similarly, sensitivity analysis can be used to determine the ranges of a given parameter for which different choices are optimal. The optimal choice in this case can be obtained by placing the parameter in a given range instead of giving it a precise value or probability distribution, which is an easier way of characterizing parameters with high uncertainty. The user of the methodology can develop many similar applications of sensitivity analysis, producing valuable information to understand and substantiate the final choice.

14.3 Information on Other Parameters

In addition to the main decision aids described in Section 14.2, probabilistic descriptions can be obtained for any node parameter in the diagram. Such information can be useful in assessing the contributions of different factors to the overall risk and understanding all the implication of a certain choice. This information includes:

1. *Expected values of node parameters for all choices.* Any node in the influence diagram can be treated as the final (or pseudo-value) node, creating a truncated diagram that includes only the predecessors of that node. Analysis of this new diagram allows the user to calculate the expected value of the node parameter in question for the different choices. For example, by treating the number of fatalities node as the final node (see Figure 14.3), the total expected number of fatalities and the individual risk curves for each decision can be obtained. Similarly, the total expected cost and equivalent spill volume can be calculated for each decision by treating the corresponding nodes as the final nodes. This information gives insight into the actual consequences contributing to the total risk as characterized by the value node. Similar outcomes can also be obtained for hazard and release characteristics and individual cost components.

2. *Conditional probability distributions of functional node parameters.* For any intermediate node, the probability distribution of the node parameter for any combination of the direct conditional predecessors of the node can be obtained. For example, the probability distributions of the hazard type and the number of fatalities can be obtained for any selected combination of season, segment, product and failure mode. This information is useful in

understanding the relative contributions of different factors to the risk t human life (e.g., the risk may be dominated by one product).

14.4 Risk Assessment Applications

It must be recognized that although this approach is geared toward decision problems in which different choices are being evaluated, the methodology can also be used for *risk assessment.* In this type of analysis, a quantitative estimate of the risk associated with an existing pipeline is required, without consideration of any specific maintenance choices. In this case, the influence diagram can be developed with only one choice (representing the status quo), and the results would represent the financial, environmental, life and overall risks associated with the pipeline. For example, the individual risk contours mentioned in Section 8.0 are often used in risk assessment studies as a measure of risk to life safety. Similarly the total cost and residual spill volume nodes can be used to assess the expected level of financial an environmental risks posed by a certain pipeline segment.

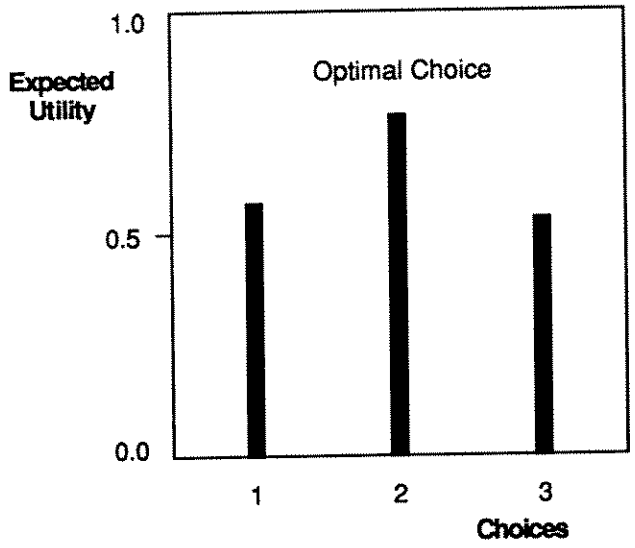


Figure 14.1 Expected Utility Plot for Different Choices

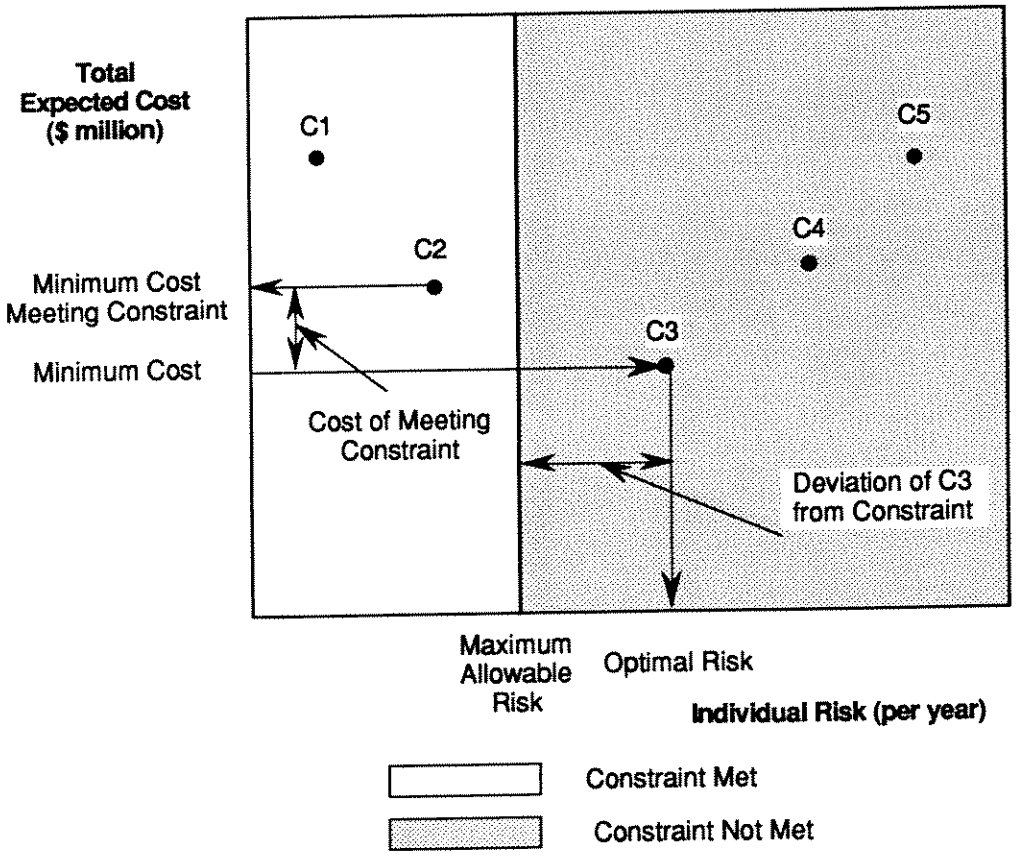


Figure 14.2 Illustration of the Output for the Constrained Cost Optimization Approach

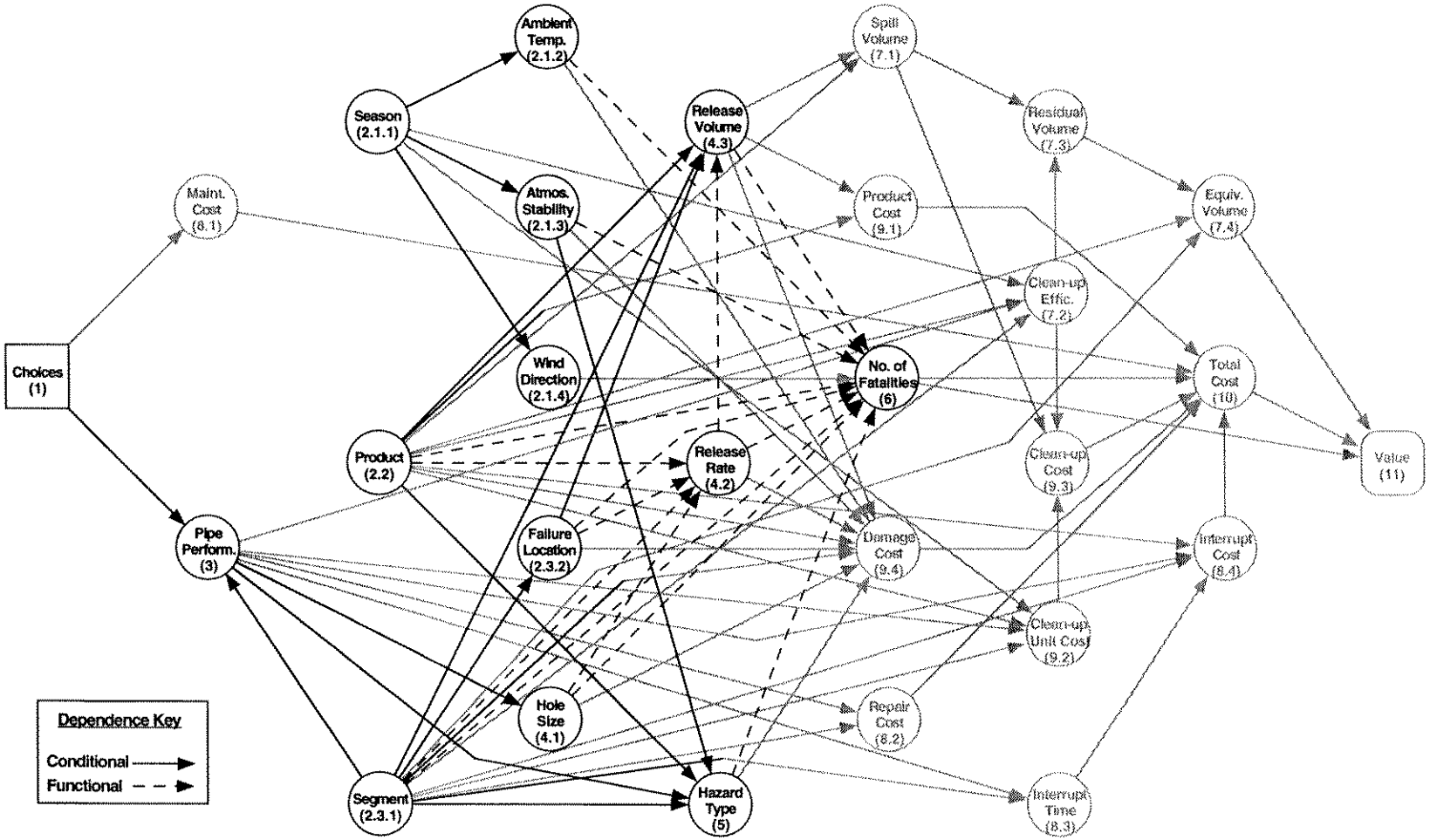


Figure 14.3 Influence Diagram Used to Analyze Number of Fatalities as a Target Node

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Appendix A

PHYSICAL PROPERTIES OF REPRESENTATIVE PRODUCT GROUPS

The following describes the information sources and calculation methods employed to define representative petroleum products for each product group identified in Table 4.7, and to develop the physical properties data base given in Table 2.8.

(1) For all product groups the following properties are based on Weiss (1980):

- lower flammability limit (Clfl);
- heat of combustion (Hc);
- heat of vaporization (Hvap);
- normal boiling point (Tb);
- specific gravity ratio (SGR); and
- specific heat ratio of vapour (SHR).

For gasolines, kerosenes and gas oils, the normal boiling point is taken as the lower value of the given range. Since crude oil has a particularly broad range of boiling points, its mid-point value of 290 °C (IARC 1989) is used as a representative value.

(2) For product groups involving compounds with a single carbon number (e.g. methane, ethane, propane, butane and pentane), molecular weight (molwt), specific heat of liquid (SHL), and the parameters used for vapour pressure calculation are taken from Reid *et al.* (1987).

The vapour pressure parameters include:

- critical temperature (Tc);
- critical pressure (Pc); and

Appendix A

- constants VPa, VPb, VPc and VPd.

The equation for vapour pressure (Pv) is

$$\ln(Pv/Pc) = (1-x)^{-1} [(VPa)\, x + (VPb)\, x^{1.5} + (VPc)\, x^3 + (VPd)\, x^6)] \qquad [A.1]$$

where: x = T/Tc, T and Tc are in °K, and Pv and Pc are in bars.

The properties given for propanes are based on n-propane (C_2H_6), properties for butanes are based on n-butane (C_4H_{10}), and those for pentane are based on n-pentane (C_5H_{12}). Since pentane is the major constituent of condensate, the properties of pentane may be used to represent condensate.

(4) Selected properties for petroleum products involving a mixture of hydrocarbon compounds with varying carbon numbers (e.g. crude oils, gasolines, kerosenes, and gas oils) can be determined in a rigorous manner if an accurate analytical report of product composition is available (e.g. Reid *et al.* 1987). However, a simplified approximate approach was adopted in developing the product database for the following reasons: the exact composition of a given product type or product group will exhibit considerable variation; and, variations in the properties of interest, such as vapour pressure and liquid specific heat will not critically affect the outcome of acute hazard analysis for these low vapour pressure (LVP) products.

For each product mixture, a representative n-alkane was selected by examining the normal boiling point and the major hydrocarbon compounds present in the mixture. The following n-alkanes were selected because their boiling points are considered representative of the mixture as a whole (i.e. boiling points are approximately in the middle of the range for the dominant hydrocarbon compounds):

- n-hexane (C_6H_{14}) for gasolines;
- n-dodecane ($C_{12}H_{26}$) for kerosenes; and
- hexadecane ($C_{16}H_{34}$) for gas oils and crude oil.

Appendix A

Molecular weight (molwt), specific heat of liquid (SHL), and the vapour pressure parameters for the above n-alkanes were then used to represent the respective product mixtures. For gasolines, Eqn. [A.1] was then used to calculated vapour pressure. For all other product mixtures, the following equation was used (Reid *et al.* 1987):

$$\ln (Pv) = (VPa) - (VPb)/T + (VPc) \ln(T) + (VPd)\, Pv/T^2 \qquad [A.2]$$

(6) The explosive yield factor (Yf) for vapours and gases produced by all of hydrocarbon products considered was taken to be 0.03 (FEMA/DOT/EPA 1989).

(5) The kinematic viscosity (Vs) of all liquid hydrocarbon product mixtures considered was taken from Fingas et al. (1979).

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Appendix B

Appendix B

REPRESENTATIVE FAILURE RATES FOR PETROLEUM GAS AND LIQUID PIPELINES

Based on natural gas and crude oil pipeline performance in Alberta for the ten year period from 1983 to 1992 as compiled by the ERCB (Cassley et al. 1994) the annual failure incident rate ranges between 0.6 and 3 per 1000 km•year with a representative incident rate being on the order of 1 per 1000 km•year (i.e. 1×10^{-3} per km•year). The ERCB reporting criteria requires the reporting of all pipeline failure incidents on pipelines in Alberta under their jurisdiction "without limitation of cause, magnitude, or consequence" suggesting that the reported failure rates include all leaks and ruptures. There are currently ~100 000 km of natural gas pipeline and ~25 000 km of crude oil pipeline under ERCB jurisdiction which is considered sufficient to yield a representative failure rate estimate.

The ERCB data further indicates that approximately 85% of all failures are leaks and 15% of all failures are ruptures, where leaks are defined as "a small opening, crack, or hole in the pipeline causing some product loss but not immediately impairing the operation of the line", and ruptures are defined as "an instantaneous tearing or fracturing of the pipe material causing immediate impairment of the operation of the pipeline". Assuming the ERCB definition of leak to be consistent with the 'small leak' category adopted in this project, and the ERCB definition of rupture to be consistent with the 'large leak' or 'rupture' category, the following representative failure rates are indicated by the data:

- 8.5×10^{-4} per km•year for small leaks; and
- 1.5×10^{-4} per km•year for large leaks and ruptures.

Historical incident data reported by British Gas (Fearnehough 1985) gives an indication of the effective hole size associated with reported failure incidents. The frequency of hole size distribution is given by Fearnehough as:

Appendix B

Hole Size	Relative Frequency
less than 20 mm	87%
20 to 80 mm	10%
greater than 80 mm	3%

Holes smaller than 20 mm are said to typically be pin-holes, which are analogous to the 'small leak' category adopted in this project. Holes larger than 80 mm are said to typically involve very large openings analogous to the 'rupture' category. Assuming, based on the above that the relative frequency of 'large leaks' is analogous to incidents involving effective hole sizes in the 20 to 80 mm range; the relative frequency of small leaks vs. large leaks and ruptures (i.e. 87% to 13%) is very similar to that indicated by the ERCB data.

Based on the representative failure rate indicated by the ERCB data (i.e. 1×10^{-3} per km•year), and the relative frequencies of small leaks, large leaks and ruptures inferred from the hole size frequency data reported by Fearnehough, the following failure rates are indicated as representative values for both natural gas and crude oil pipelines:

Failure Mode	Failure Rate
small leak	8.7×10^{-4}
large leak	1.0×10^{-4}
rupture	0.3×10^{-4}

In assessing the validity of the representative failure rates given above consider the following:

- The failure rate for natural gas gathering and transmission lines in the United States, based on USDOT incident data for the period from 1984 to 1990 processed and summarized by the American Gas Association (AGA 1992), is reported to be $\sim 1.6 \times 10^{-4}$ per km•year. Given that the USDOT incident reporting criteria for gas lines only involves incidents that cause major property damage and/or injury or death, it is reasonable to assume that the reported failure rate does not include 'small leaks'. If it is therefore assumed that the

reported rate applies to large leaks and ruptures only, the value is seen to compares favourably with the effective rate calculated from the proposed reference large leak and rupture rate, which is 1.3 x 10^{-4} per km•year.

- The failure rate for natural gas transmission lines in Western Europe, based on incident data for the period from 1988 to 1992 compiled by the European Gas Pipeline Incident Data Group (EGIG 1993), is reported to be ~5.8 x 10^{-4} per km•year. Given that the EGIG incident reporting criteria is currently intended to apply to all release incidents, it is assumed that the reported rate applies to small leaks, large leaks and ruptures. The value is seen to compares favourably with the proposed reference failure rate which is 10 x 10^{-4} per km•year.
- The failure rate for crude oil and petroleum product gathering and transmission lines in Canada, based on incident data, excluding equipment failures, for the period from 1982 to 1991 compiled by the Canadian Association of Petroleum Producers (CAPP 1992), is reported to be ~8.3 x 10^{-4} per km•year. Given that the CAPP incident reporting criteria is currently intended to apply to all incidents involving the release of more than 1.5 m^3 of product, it is assumed that the reported rate applies to all large leaks and ruptures and some of the small leaks. If it is assumed that the reported rate applies to all large leaks and ruptures and say half of all small leaks, the value is seen to compares favourably with the effective rate calculated from the proposed reference failure rates for leaks and ruptures, assuming only half of the small leaks are counted, which is 5.7 x 10^{-4} per km•year.
- The failure rate for crude oil trunk lines in Western Europe, based on incident data for the period from 1988 to 1992 compiled by the Oil Companies European Organization for Environmental and Health Protection (CONCAWE 1993), is reported to be ~6.2 x 10^{-4} per km•year. Given that the CONCAWE incident reporting criteria is currently intended to apply to all incidents involving the release of more than 1 m^3 of product, it is assumed that the reported rate applies to all large leaks and ruptures and some of the small leaks. If it is assumed that the reported rate applies to all large leaks and ruptures and say half of all small leaks, the value is seen to compares favourably with the effective rate calculated from the proposed reference failure rates for leaks and ruptures, assuming only half of the small leaks are counted, which is 5.7 x 10^{-4} per km•year.

Appendix B

The preceding comparisons suggest that the proposed reference failure rates are both reasonable and in a broad sense supported by historical incident data in the public domain.

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Appendix C

Appendix C

PRODUCT RELEASE AND HAZARD ZONE CHARACTERIZATION MODELS

C.1 Introduction

This Appendix describes the analytical models that have been chosen to characterize product release and the associated acute hazards resulting from failure of a gas or liquid pipeline. The models presented address the following:

- the release of gas and liquid products (*i.e.* release rate and release volume);
- the evaporation of liquid pools;
- the dispersion of gas or liquid vapour;
- the heat intensity associated with fire hazards (*i.e.* jet fire, pool fire and flash fire); and
- the overpressure associated with explosions (*i.e.* vapour cloud explosion).

The models described in this appendix are based primarily on the models described in the 'Handbook of Chemical Hazard Analysis Procedures' (FEMA/DOT/EPA 1989) and implemented in the accompanying public domain software program, ARCHIE. Supplementary reference sources include: the 'Guidelines for Use of Vapour Cloud Dispersion Models' published by the Center for Chemical Process Safety (Hanna and Drivas 1987); Brzustowski's work on hydrocarbon flares (Brzustowski 1971, 1973, and 1976); evaporation models developed by the Engineering and Service Laboratory of U. S. Air Force (Kahler et al. 1989); and Lees' standard reference text on loss prevention in the chemical process industry (Lees 1980).

Each of the following sections provides the technical basis for a particular model, including a detailed description of the associated equations and any major assumptions. The sections are organised as follows:

Section C.2 Gas Release
Section C.3 Liquid Release
Section C.4 Evaporation of Liquid
Section C.5 Jet Fire

Appendix C

C.2 Gas Release

C.2.1 Overview

- Scenario description: Discharge of gas from a pressurized pipeline.
- Output: Release rate and total release volume.
- Sources: Model for release rate is based on ARCHIE.

C.2.2 Assumptions

- Release rate is 75% of the maximum value and is constant with respect to time (Eqn. C.2.4).
- The maximum release rate is the initial rate under the sonic flow condition (Eqn. C.2.1).
- Quantity of release is jointly controlled by the release rate, pipeline characteristics (e.g. valve spacing and flow rate) and time for emergency response (e.g. time to close values and time to plug holes).
- All types of friction are taken into account by a friction factor of 0.62.
- Release process is adiabatic (without heat exchange).
- The hole shape is circular.
- Release direction is vertical.

C.2.3 Model Description

Equation for release rate. The equation for the maximum rate is the widely used formula (FEMA/DOT/EPA 1989, Hanna and Drivas 1987, Lees 1980):

$$(\dot{m}_{RG})_{max} = C_d \, A_h \left[\gamma P_0 \, \rho \left(\frac{2}{1+\gamma} \right) \right]^{1/2} \qquad [C.2.1]$$

where $\dot{m}_{RG}$ = mass release rate of gas (kg/s);

C_d = 0.62, friction factor (Lees 1980);

Appendix C

A_h = $\pi \frac{d_h^2}{4}$, area of the hole (m^2); [C.2.2]

d_h = effective hole size (m);

γ = specific heat ratio of the product;

P_0 = pipeline operating pressure (Pa);

ρ = $\frac{P_0 M_w}{R T_0}$, density of the product (kg/m^3); [C.2.3]

M_w = molecular weight (kg/mol);

R = gas constant (8.314 $Pa \cdot m^3/mol \cdot °K$);

T_0 = product flow temperature (°K).

The model uses a constant release rate associated with the initial pipeline pressure. Such a constant value will in general overestimate release rate but underestimate release duration.

C.2.4 Calculation Algorithm

1. Calculate gas density [Eqn. C.2.3].

2. Calculate release rate.

$$\dot{m}_{RG} = 0.75\, C_d\, A_h \left[\gamma P_0\, \rho \left(\frac{2}{1+\gamma} \right) \right]^{1/2} \qquad [C.2.4]$$

Note that for a full rupture, a hole size equivalent to twice the cross sectional area of the pipe is used to represent a double-end release.

3. Calculate total amount available for release.

$$M_{R0} = M_0 + \min \{ \dot{m}_{RG}, \dot{m}_0 \} t_1 \qquad [C.2.5]$$

where M_{R0} = total amount available for release (kg);

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$$M_0 = \rho\pi\frac{(D_P - 2t_P)^2}{4}S_V, \text{ total amount between valves (kg);} \quad [C.2.6]$$

D_P = pipe diameter (m);

t_P = pipe wall thickness (m);

$\dot{m}_0$ = pipeline flow rate (kg/s).

and $$t_1 = \min\{t_{detect},\ \rho V_{detect}/\dot{m}_{RG}\} + t_{close} \quad [C.2.7]$$

where t_{detect} = time to detect release (s);

V_{detect} = detectable release volume (m^3);

t_{close} = time to close block valves (s).

4. Calculate release duration.

$$t_R = \min\{M_{R0}/\dot{m}_{RG},\ t_2\} \quad [C.2.8]$$

where t_R = duration of release (s).

and $$t_2 = \min\{t_{detect},\ \rho V_{detect}/\dot{m}_{RG}\} + t_{stop} \quad [C.2.9]$$

where t_{stop} = time to stop release (s).

5. Calculate total release amount (kg).

$$M_R = \dot{m}_{RG}\, t_R \quad [C.2.10]$$

6. Calculate total release volume at standard conditions (m^3).

$$V_R = \dot{m}_{RG} t_R/\rho_S \quad [C.2.11]$$

where ρ_S = product density at standard temperature and pressure.

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C.3 Liquid Release

C.3.1 Overview

- Scenario description: Discharge of liquid product from a pipeline.
- Output: Release rate and total release volume.
- Sources: The equation for release rate is based on ARCHIE but the calculation of HVP flashing and aerosol fraction are based on other sources (Lees 1980, Hanna and Drivas 1987).

C.3.2 Assumptions

- The release rate is affected by both pipeline pressure and hydrostatic pressure which is dependent on the elevation profile of a pipeline.
- The average liquid height is used to calculate the steady-state release rate.
- All types of friction are taken into account by a friction factor of 0.62.
- Release rate is determined by momentum balance. Energy exchange through heat transfer is not considered.
- The liquid release model is used for both HVP and LVP liquids. It may overestimate release rate for HVP products because two phase release is not considered.
- Release volume is jointly controlled by release rate, pipeline characteristics (e.g. elevation and flow rate) and time for emergency response (e.g. time to close valves and time to plug holes).
- The hole shape is circular.
- If the pipeline temperature exceeds the product boiling point, a fraction of liquid immediately flashes to vapour and an equal amount of liquid becomes aerosols and evaporates rapidly in the air

C.3.3 Model Description

Release rate from a liquid pipeline can be calculated by the Bernoulli equation based on momentum balance (FEMA/DOT/EPA 1989, Hanna and Drivas 1987, Lees 1980):

$$\dot{m}_R = C_d A_h \rho \, [2 \, (P_l - P_a)/\rho + 2 \, g \, H]^{1/2} \qquad [C.3.1]$$

where P_l = $\max\{P_{v0}, P_a\}$ (Pa);

P_{v0} = vapour pressure in the pipeline (Pa);

P_a = ambient pressure (Pa);

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g = acceleration due to gravity (9.8 m/s^2);

H = height of hydrostatic head (m).

C.3.4 Calculation Algorithm

1. Calculate release rate

$$\dot{m}_R = C_d A_h \rho [2 (P_1 - P_a)/\rho + g H]^{1/2} \quad [C.3.2]$$

Note that the term $2gH$ in Eqn. [C.3.1] becomes gH in Eqn. [C.3.2]. This is because the average liquid height of $H/2$ is used for an average release rate. Similar to Eqn. [C.2.3], a hole size equivalent to twice the cross sectional area of the pipe is used for a double-end release when a full rupture failure occurs.

2. Calculate total amount available for release.

$$M_{R0} = \min \{M_0, M_1\} + \min \{\dot{m}_R, \dot{m}_0\} t_1 \quad [C.3.3]$$

where M_{R0} = total amount available for release (kg);

M_1 = total amount in the pipeline between the failure location and the next or previous elevation crest along its route (kg);

$\dot{m}_0$ = pipeline flow rate (kg/s);

and $$t_1 = \min\{t_{detect}, \rho V_{detect}/\dot{m}_R\} + t_{close} \quad [C.3.4]$$

where t_{detect} = time to detect release (s);

V_{detect} = detectable release volume (m^3);

t_{close} = time to close block valves (s).

3. Calculate release duration.

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$$t_R = \min \{M_{R0}/\dot{m}_R, t_2\} \quad [C.3.5]$$

where t_R = duration of release (s);

and $$t_2 = \min\{t_{dtect}, \rho V_{dtect}/\dot{m}_R\} + t_{stop} \quad [C.3.6]$$

where t_{stop} = time to stop release (s).

4. Calculate total release volume (m^3).

$$V_R = \dot{m}_R t_R / \rho \quad [C.3.7]$$

5. If the product temperature, which is taken to be equal to the pipeline temperature, exceeds the product boiling point (i.e. $T_0 > T_b$), the total fraction (including flashing fraction and aerosol fraction) of vapour release is given by (Lees 1980, Hanna and Drivas 1987)

$$\dot{m}_{RG}/\dot{m}_R = 2\, c_P\, (T_0 - T_b)/L \quad [C.3.8]$$

where $\dot{m}_{RG}$ = average release rate of gas or vapour (kg/s);

c_P = specific heat of the liquid (J/kg °K);

T_b = normal boiling point of the liquid (°K);

L = heat required to evaporate the liquid (J/kg).

The average release rate for the liquid portion that does not flash is $\dot{m}_{RL} = \dot{m}_R - \dot{m}_{RG}$. The gas release rate ($\dot{m}_{RG}$) will be used for jet fire calculation, and the liquid release rate ($\dot{m}_{RL}$) will be used to calculate evaporation and liquid pool fire consequences.

C.4 Evaporation of Liquid

C.4.1 Overview

- Scenario description: A spilled liquid evaporates either as a volatile liquid or as a cold boiling liquid, depending on the pool temperature and the boiling point of the liquid. LVP hydrocarbon liquids usually evaporate in a volatile manner while HVP liquids are more likely to behave as a cold boiling liquid.

- Output: Rate of evaporation.
- Sources: Models in ARCHIE are used for pool spreading and evaporation of cold boiling liquids. The volatile evaporation model developed by the Engineering and Service Laboratory of U.S. Air Force (Kahler et al. 1989) is adapted for LVP liquids.

C.4.2 Assumptions

- Pool shape is circular and the size is assumed to be constant during evaporation.
- Variables such as ground slope and soil penetration that may affect pool size are not considered.
- Rate of evaporation is approximated as constant.
- The total spill amount is assumed to evaporate (ground absorption is not modeled).

C.4.3 Model Description

1. Evaporation of a volatile liquid (Kahler et al. 1989)

$$f_V = 2.22\text{x}10^{-5}\, u_a^{0.75}\, (1+0.0043 T_p^2)\, \frac{P_v\, M_w}{P_{vh}\, M_{wh}} \qquad \text{[C.4.1]}$$

where f_V = evaporation flux (kg/s/m^2);

u_a = wind speed (m/s);

P_{vh} = vapour pressure of hydrazine (Pa);

M_{wh} = molecular weight of hydrazine (kg/mol);

T_p = pool temperature (°C). It is assumed that T_p is the higher of ambient temperature and pipeline temperature and $T_p \geq 0$ °C.

Comparison with other models shows that this model gives an average to conservative evaporation rate (Hanna and Drivas 1987). Note that ARCHIE uses the same model with a modified pool temperature.

2. Evaporation of a cold boiling liquid (FEMA/DOT/EPA 1989)

$$f_V = 1.597\text{x}10^{-6}\, (514.2 - T_b)\, M_w\, e^{-0.0043 T_b} \qquad \text{[C.4.2]}$$

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where T_b is the normal boiling point in degree Celsius.

3. Pool size from an instantaneous spill (FEMA/DOT/EPA 1989)

$$D_{max} = 1.798 \left[\frac{V_L{}^2 \rho}{f_V} \sqrt{\frac{g}{C_f}} \right]^{2/11} \qquad [C.4.3]$$

where V_L = total release volume of liquid (m^3);

C_f = 0.5, ground friction coefficient.

4. Pool size from a continuous spill

$$D_{max} = 1.128 \sqrt{\frac{\dot{m}_{RL}}{f_V}} \qquad [C.4.4]$$

in which the evaporation rate is assumed to be equal to the spill rate.

4.4 Calculation Algorithm

1. Calculate evaporation flux. First identify whether the liquid is volatile or cold boiling by comparing the pool temperature with the boiling point. The evaporation flux can then be calculated by using Eqn. [C.4.1] or [C.4.2].

2. Calculate pool size using Eqn. [C.4.3] or [C.4.4]. Identify the spill scenario as instantaneous or continuous by examining (FEMA/DOT/EPA 1989)

$$\tau = t_R f_V / \rho \, V_L{}^{1/3} \qquad [C.4.5]$$

It is assumed to be an instantaneous spill if $\tau < 0.002$, or a continuous spill if $\tau \geq 0.002$.

3. Calculate evaporation rate by

$$\dot{m}_V = f_V \pi (D_{max}/2)^2 \qquad [C.4.6]$$

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C.5 Jet Fire

C.5.1 Overview

- Scenario description: Gas or vapour emerging from a gas or HVP pipeline forms a jet at the puncture which becomes a jet flame when ignited.
- Output: The distribution of thermal radiation intensity.
- Sources: Dimensions of a jet fire were based on a model developed by Brzustowski (1976). Thermal radiation is calculated using a point source model.

C.5.2 Assumptions

- Centre of the flame is located halfway between the release hole and the tip of flame.
- The total radiant heat of the fire is concentrated at the flame centre and radiates as a point source. Such a model gives very approximate results in the vicinity of the jet fire, however, the validity of the model increases as the distance from the fire centre increases.

C.5.3 Model Description

Equations for the dimensions of a jet fire are given by Brzustowski (1976). The non-dimensional curvilinear length of the flame is

$$\overline{S}_L = 2.04\ \overline{C}_L^{-1.03} \qquad (\text{if } \overline{C}_L < 0.5) \qquad \text{[C.5.1a]}$$

or $$\overline{S}_L = 2.51\ \overline{C}_L^{-0.625} \qquad (\text{if } \overline{C}_L \geq 0.5) \qquad \text{[C.5.1b]}$$

where

$$\overline{C}_L = C_L \frac{\dot{m}_{RG}\ M_w}{A_h\ \rho\ u_a M_{wa}} \qquad \text{[C.5.2]}$$

The term of $(\dot{m}_{RG}/A_h\ \rho)$ gives the velocity of the released product u_j (m/s). M_{wa} is the molecular weight of air (about 29 g/mol), and C_L is the lower flammability limit.

The non-dimensional vertical and horizontal distances ($\overline{Z}_L$ and $\overline{X}_L$) corresponding to $\overline{S}_L$ can be calculated by

$$1.04\ \overline{X}_L{}^2 + 2.05\ \overline{X}_L{}^{0.28} = \overline{S}_L \qquad (\text{if } \overline{C}_L \geq 0.5 \text{ and } \overline{S}_L \leq 2.35) \qquad \text{[C.5.3a]}$$

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or $\overline{X}_L = \overline{S}_L - 1.65$ (if $\overline{C}_L < 0.5$ or $\overline{S}_L > 2.35$) [C.5.3b]

and $\overline{Z}_L = 2.05\ \overline{X}_L^{0.28}$ [C.5.4]

They can be converted into vertical and downwind horizontal distances between the flame tip and the release source by

$$Z_L = k\ \overline{Z}_L \quad [C.5.5]$$

and $X_L = k\ \overline{X}_L$ [C.5.6]

where $k = \dfrac{\dot{m}_{RG}\ d_h}{u_a\ A_h \sqrt{\rho\ \rho_a}}$ [C.5.7]

is the conversion factor (m) and d_h is the diameter of the hole (m).

C.5.4 Calculation Algorithm

1. Calculate the dimension of jet flame using Eqn. [C.5.1] to [C.5.7];

2. Calculate the total radiant power

$$P = \chi\ \dot{m}_{RG}\ \Delta H_c \quad [C.5.8]$$

where ΔH_c is the heat of combustion (J/kg) and χ is the fraction of radiant heat (Table C.1, Brzustowski 1971).

Table C.1 Fraction of Radiant Heat for Hydrocarbon Fires

Product	Methane	Ethane	Propane	Butane	Pentane and higher
χ	0.2	0.25	0.3	0.3	0.4

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3. Locate the radiant source at the centre of the flame and calculate the intensity of thermal radiation using a point source model

$$I_F = P / 4 \pi r^2 \qquad [C.5.9]$$

where r is the distance from the assumed fire centre to the target (m), and I_F is heat intensity (W/m^2).

C.6 Pool Fire

C.6.1 Overview

- Scenario description: A pool of flammable hydrocarbon liquid is ignited and burns as a three dimensional radiant heat source.
- Output: Distribution of heat intensity.
- Sources: The pool fire model is based on ARCHIE, which includes calculations of pool size, burning rate and heat intensity.

C.6.2 Assumptions

- Pool size and burning rate are constant.
- Pool shape is assumed to be circular.
- Pool is ignited soon after release.
- Pool size is estimated as a continuous spill.
- Total spill volume will eventually be consumed in pool fire.

C.6.3 Model Description

Burning rate in a pool fire is given by (FEMA/DOT/EPA 1989)

$$\dot{m}_B = 1.543 \times 10^{-3} A_p M_w e^{-0.0043 T_b} \qquad [C.6.1]$$

in which $\dot{m}_B$ is the burning rate (kg/s), A_p is the pool area (m^2), M_w is the molecular weight (g/mol) and T_b is the boiling point in °F.

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C.6.4 Calculation Algorithm

1. Calculate the burning flux (FEMA/DOT/EPA 1989).

$$f_B = 1.543\text{x}10^{-3}\, M_w\, e^{-0.0043Tb} \qquad [C.6.2]$$

2. Estimate pool size using the model for continuous spill.

$$D_{max} = 1.128 \sqrt{\frac{\dot{m}_{RL}}{f_B}} \qquad [C.6.3]$$

3. Calculate heat intensity using the model for a three dimensional fire (FEMA/DOT/EPA 1989).

$$I_F = E\, F\, \tau \qquad [C.6.4]$$

where the transmissivity τ is assumed to be unity. The surface emission power E (kW/m^2) and view factor F are defined as

$$E = 117 - 0.313\, T_b \qquad [C.6.5]$$

$$F = 1.143\, (D_{max}/2\, r)^{1.757} \qquad [C.6.6]$$

The boiling point T_b in Eqn. [C.6.5] is in degrees Fahrenheit.

C.7 Dispersion of Naturally Buoyant Gas

C.7.1 Overview

- Scenario description: Gas or vapour discharged into the atmosphere disperses in the downwind direction. The dispersing gas forms a cloud which may burn or explode if ignited.
- Output: Concentration distribution at ground level.
- Sources: Similar to ARCHIE, the Gaussian model for short duration release is used for neutral buoyant gases.

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C.7.2 Assumptions

- The model considered is a plume model for continuous release.
- Air mixing is assumed to occur in the cross wind directions.
- The plume moves downwind at average wind speed.
- Initial momentum and buoyant rise are not considered since an overestimation of release rate may overestimate the rise and thus underestimate the dispersion effects. The initial jet rise ceases after traveling a short distance from the source.

C.7.3 Model Description

At a given location (ξ, η) in which ξ and η are the respective downwind and cross wind distances from the dispersion source, the maximum concentration at ground level is given by the Gaussian dispersion model (FEMA/DOT/EPA 1989)

$$C_{max} = 0.5\, C_c \left[\text{erf}\left(\frac{\xi}{\sqrt{2}\sigma_x}\right) - \text{erf}\left(\frac{\xi - u_a t_s}{\sqrt{2}\sigma_x}\right)\right] \quad \text{if } \xi \le 0.5\, u_a\, t_s \qquad \text{[C.7.1a]}$$

$$C_{max} = C_c\, \text{erf}\left(\frac{u_a\, t_s}{2\sqrt{2}\sigma_x}\right) \quad \text{if } \xi > 0.5\, u_a\, t_s \qquad \text{[C.7.1b]}$$

where $C_c = \dfrac{\dot{m}_s}{\pi\sigma_y\sigma_z u_a} \exp(-\eta^2/2\sigma_y^2)$ (kg/m^3); [C.7.2]

$\dot{m}_s = \dot{m}_{RG} + \dot{m}_V$, supply rate of the dispersion source (kg/s);

t_s = duration of source dispersion;

σ_x, σ_y, σ_z = dispersion coefficients at the downwind direction, cross wind direction, and vertical direction, respectively (m);

and erf() is the error function defined as $\text{erf}(x) = \dfrac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$.

For a given concentration, the Gaussian model defines the boundary of an area within which the gas concentration is higher than the given level. The shape of this area is approximately an ellipse with the downwind distance and maximum crosswind width as the major and minor axes.

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C.7.4 Calculation Algorithm

1. For a given (ξ, η), calculate the values of σ_x, σ_y and σ_z.

2. Use Eqn. [C.7.1] and [C.7.2] to calculate the concentration level at (ξ, η).

C.8 Dispersion of Dense Gas

C.8.1 Overview

- Scenario description: Vapours discharged into the atmosphere and those evaporated from liquid pools disperse in the downwind direction. The dispersing vapour forms a cloud which may burn or explode if ignited.
- Output: Downwind and crosswind distances for a given concentration at ground level. These distances can be used to define the ellipse that encompasses the area where the concentration is higher than the given level.
- Sources: Equations for dense gas dispersion are based on the ARCHIE program.

C.8.2 Assumptions

- Buoyant rise and momentum rise are not considered.
- Dispersion is affected by atmospheric stability but not wind speed.
- Crosswind width is estimated by some simplified rules which characterize the shape of a dense gas cloud.

C.8.3 Model Description

For a given volume concentration C in volume percent, the downwind distance D and the maximum crosswind width W can be estimated by the following equations.

1. For neutral or unstable weather,

$$D = 98\,(\dot{m}_s / M_w C)^{0.54} \quad \text{and} \quad W = 0.5\,D \quad \text{(continuous release)} \qquad [C.8.1]$$

$$D = 380\,(\dot{m}_s t_s / M_w C)^{0.24} \quad \text{and} \quad W = D \quad \text{(instantaneous release)} \qquad [C.8.2]$$

The boundary between the two release modes is

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$$t_s = 0.0035\ (\dot{m}_s / M_w C)^{1.25} \qquad [C.8.3]$$

where $\dot{m}_s$ is in lb/min, t_s is in minutes, M_w is in g/mol, and D and W are in ft.

2. For stable weather,

$$D = 165\ (\dot{m}_s / M_w C)^{0.54} \quad \text{and} \quad W = 0.9\,D \quad \text{(continuous release)} \qquad [C.8.4]$$

$$D = 240\ (\dot{m}_s\, t_s / M_w C)^{0.27} \quad \text{and} \quad W = 1.4\,D \quad \text{(instantaneous release)} \qquad [C.8.5]$$

The boundary between the two release modes is

$$t_s = 0.25\ (\dot{m}_s / M_w C) \qquad [C.8.6]$$

C.8.4 Calculation Algorithm

1. For a given concentration level C and dispersion duration t_s, determine whether it is an instantaneous release or a continuous release according to Eqn. [C.8.3] or [C.8.6].
2. For a given weather condition, use corresponding equations to calculate downwind distance D and maximum crosswind width W.

C.9 Vapour Cloud Fire

- Scenario description: Dispersion of gas or vapour forms a cloud of flammable gas. A delayed ignition causes the cloud (in the concentration range between the lower and upper flammability limits) to burn as a flash fire.
- Output: Shape and size of the burning area in a flash fire.
- Sources: Models for flash fire, including the one used in ARCHIE, use the shape and size of the flammable cloud for the burning area. The extent of the flammable cloud can be determined using dispersion models such as those given in Sec. 7 and 8. These models, as implemented, assume that the contour of equal concentration can be approximated by an elliptical shape. The effective burning area is therefore an ellipse corresponding to the concentration of lower flammability limit.

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C.10 Vapour Cloud Explosion

C.10.1 Overview

- Scenario description: Dispersion of gas or vapour forms a cloud of flammable gas. A delayed ignition of the vapour cloud may cause an explosion under certain circumstances .
- Output: Distribution of overpressure from vapour cloud explosion
- Sources: Vapour cloud explosion model in ARCHIE.

C.10.2 Assumptions

- Only the flammable portion of total release volume will contribute to a vapour cloud explosion.
- Overpressure from the explosion is calculated based on the equivalent amount of TNT.
- Confinement and weather conditions are not considered.

C.10.3 Model Description

Equation for overpressure (FEMA/DOT/EPA 1989, Lees 1980)

$$P_E = \exp(9.097-(25.13\ \ln(r/M_{TNT}^{1/3})-5.267)^{1/2}) \quad \leq 14.7 \text{ psi} \qquad [C.10.1]$$

where P_E is the overpressure in psi, r is the distance (ft), and M_{TNT} is the equivalent mass of TNT (lb) given by (FEMA/DOT/EPA 1989)

$$M_{TNT} = Y_f M_C \Delta H_c / 1155 \qquad [C.10.2]$$

In Eqn. [C.10.2], Y_f is the yield factor (0.03 for hydrocarbon products), ΔH_c is the heat of combustion (kcal/kg) and M_C is the total mass of the flammable cloud (lb).

C.10.4 Calculation Algorithm

1. Calculate total mass of the flammable cloud M_C by

$$M_C = \dot{m}_s L_1 / u_a \qquad [C.10.3]$$

where $L_1 = \min \{\xi_{LFL}, u_a t_s\}$ and ξ_{LFL} is the dispersion distance for lower flammability limit.

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2. Calculate explosive overpressure for a given distance by Eqn. [C.10.1] and [C.10.2].

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Appendix D

Appendix D

CONDITIONAL EVENT PROBABILITIES FOR ACUTE RELEASE HAZARDS

D.1 Overview

This Appendix describes the basis for the conditional event probabilities given in Table 7.1 which are associated with the branches in the acute release hazard event trees shown in Figures 7.3.

D.2 Liquid Product Pipelines

Representative release event and hazard frequency models were developed for use in risk assessments of Liquified Petroleum Product (LPG) installations by the UK Health and Safety Executive (HSE) based on historical incident data review and release modelling. Key findings relevant to the modelling of liquid product pipeline release incidents, as reported by Crossthwaite et al. (1988), includes the following:

- The probability of immediate ignition is taken to be 0.05 for all failure modes.
- The probaility of delayed ignition of a large vapour cloud (assoiciated with vessel rupture) passing over industrial land is taken to be ~1 and 0.9 for unstable and stable weather conditions, respectively.
- For a large cloud passing over urban land the delayed ignition probabilities are 80% of the values applicable to industrial land uses.
- For a large cloud passing over rural land the delayed ignition probabilities are 4% of the values applicable to industrial land uses.
- For limited releases involving holes in piping systems (as opposed to vessel ruptures) the delayed ignition probabilities associated with a relatively high density of surrounding ignition sources are taken to be 0.8, 0.45, and 0.24 for release rates associated with hole diameters of 50 mm, 25 mm, and 13 mm respectively.

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- The ratio of vapour cloud fire to vapour cloud explosion is taken to be 3:1 during unstable weather conditions and 10:1 during stable weather condition.

The above information can be used to develop a set of conditional event probabilities for liquid product pipelines if the following assumptions are made:

- The delayed ignition probabilities given for piping systems with holes apply to vapour clouds passing over urban land during unstable weather conditions.
- The three hole sizes associated with piping sytem releases correspond to rupture, large leak, and small leak failure modes.
- The ignition probabilities given for large vapour clouds are taken to apply to pipeline rupture events and the corresponding probabilities for large and small leaks are obtained by prorating the ruture probabilities using the values given for piping system releases.

The resulting conditional event probailities are given in Table D.1. It is noted that the conditional probabilities developed from the HSE data are most applicable to high vapour pressure (HVP) liquid products that form a heavier than air vapour under atmospheric condtions (e.g. propane and butane). The probabilities given will therefore be conservative for HVP liquid products that form a bouyant vapour under atmospheric conditions (e.g. ethane). The probabilities given in Table D.1 are also conservative for low vapour pressure (LVP) liquid products because they produce significantly less vapour than HVP products for a given mode of pipeline failure and thereby form smaller vapour clouds which have a lower probability of iteracting with distributed ignition sources.

D.3 Natural Gas Pipelines

Historical incident data compiled by the Euopean Gas Pipeline Incident Data Group for gas transmission pipelines suggests that the immediate ignition probability (P_i) is highly dependent on the mode of failure. Incident data from the operating period covering 1970 to 1992 indicates the following (EGIG 1993):

Failure Mode (hole size)	Immediate Ignition Probability
pinhole / crack ($\leq$ 20 mm)	0.027
significant hole (20 mm to line dia.)	0.019

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rupture (line dia. ≤ 400 mm)	0.099
rupture (line dia. > 400 mm)	0.235

A world-wide review of pipeline failure incident data carried out by British Gas suggests ignition probabilities in the range of 0.1 for leaks and 0.5 for ruptures (Fearnehough 1985).

Based on the above, representative values of the probability of immediate ignition will be taken to be 0.03, 0.10, and 0.25 for small leaks, large leaks and ruptures, respectively.

No specific historical information regarding the delayed ignition probability of natural gas was found in the literature. It is noted, however, that due to the bouyant nature of natural gas, which tends to rise quickly thereby minimizing its potential interaction with ground based ignition sources, the ignition probabilities will in general be much lower than for the dense, ground hugging vapour clouds associated with liquid product releases. Based on the above and in the absence of specific incident data it will be assumed that the delayed ignition probabilities for natural gas releases are 0.5 times the values calculated for liquid product releases.

No specific historical information regarding the delayed explosion probability of natural gas was found in the literature. In the absence of relevant historical data the ratio of vapour cloud fires to vapour cloud explosions for natural gas will be assumed to be the same as for liquid products.

The conditional event probabilities for natural gas pipeline releases based on the above are given in Table D.1.

References

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Fearnehough, G. D. 1985. "The control of risk in gas transmission pipelines", Symposium Series No. 93, Institute of Chemical Engineers, 25-44.

Appendix D

EGIG 1993. Gas pipeline incidents, Report 1970-1992, European Gas Pipeline Incident Data Group.

Probability of Immediate Ignition		
small leak	large leak	rupture
0.05	0.05	0.05

Probability of Immediate Ignition		
small leak	large leak	rupture
0.03	0.1	0.25

Probability of Delayed Ignition - small leak		
weather	unstable	stable
urban	0.24	0.22
rural	0.012	0.011
industrial	0.30	0.27

Probability of Delayed Ignition - small leak		
weather	unstable	stable
urban	0.12	0.11
rural	0.006	0.0054
industrial	0.15	0.14

Probability of Delayed Ignition - large leak		
weather	unstable	stable
urban	0.45	0.41
rural	0.02	0.02
industrial	0.56	0.51

Probability of Delayed Ignition - large leak		
weather	unstable	stable
urban	0.23	0.20
rural	0.011	0.010
industrial	0.28	0.25

Probability of Delayed Ignition - rupture		
weather	unstable	stable
urban	0.8	0.72
rural	0.04	0.036
industrial	1	0.9

Probability of Delayed Ignition - rupture		
weather	unstable	stable
urban	0.4	0.36
rural	0.02	0.018
industrial	0.5	0.45

Probability of Explosive Conditions		
weather	unstable	stable
urban	0.33	0.1
rural	0.33	0.1
industrial	0.33	0.1

Probability of Explosive Conditions		
weather	unstable	stable
urban	0.33	0.1
rural	0.33	0.1
industrial	0.33	0.1

Liquid Products

Natural Gas

Table D.1 Conditional event probabilities for acute release hazards

Appendix E

Appendix E

HAZARD TOLERANCE THRESHOLDS

E.1 Overview

This document summarizes the acute hazard tolerance thresholds that have been established based on a review of relevant literature. Thresholds are required for the calculation of the Number of Fatalities node parameter (node 6) and the Damage Cost node parameter (node 9.4).

E.2 Thresholds for Human Fatality

Hazard	Exposure	Parameter	Unit	Lower Bound Tolerance Threshold	Upper Bound Tolerance Threshold
Thermal radiation	Outdoor	Heat Intensity	kW/m^2	6.3	27
Thermal radiation	Indoor	Heat Intensity	kW/m^2	15.7	27
Asphyxiation	Outdoor or Indoor	volume concentration	ratio	0.306	0.713
Vapour cloud fire	Outdoor	volume concentration	ratio	0.5xLFL(1)	LFL
Vapour cloud fire	Indoor	volume concentration	ratio	N/A	N/A
Vapour cloud explosion	Outdoor or Indoor	Pressure	kPa	10.35	68.95

(1) Lower flammability limit of the product

Appendix E

The thresholds tabulated above are based largely on publications by the U.K. Health and Safety Executive (HSE) on risk assessment. The rationale behind each of the threshold values is given below.

1. Threshold for vapour cloud explosion

- Based on a probit equation given by HSE (Crossthwaite *et al.* 1988), overpressure levels of 1.5 psi and 10 psi are assumed to associated with a 0.1% and 99.9% chance of fatality, respectively. As an approximation, people within the 10 psi (68.96 kPa) overpressure contour are assumed to be fatalities, and people beyond the 1.5 psi (10.35 kPa) contour are assumed to be safe.
- The 10 psi (68.96 kPa) peak overpressure will result in total destruction of buildings (Lees 1980) and thus represents the threshold for indoor exposure. This threshold is conservatively applied to outdoor exposure as well.

2. Threshold for thermal radiation

- For indoor exposure, the ignition probability of wood is frequently used as the threshold for indoor receptors (Jones and Fearnehough 1986, Pape 1989). A heat intensity of 15.7 kW/m^2 is sited as the critical heat intensity for the pilot ignition of wood. At or below this intensity level people located inside a dwelling will be protected indefinitely and escape would not be necessary (Jones and Fearnehough 1986). A heat intensity of 27 kW/m^2 will cause spontaneous ignition of wood in 5 to 15 minutes and slow moving people would not be able to escape at this intensity level (Jones and Fearnehough 1986, Pape 1989).
- For outdoor exposure the threshold relates to the probability of evacuation without sustaining fatality. There is variation in the lower limits of the outdoor exposure threshold reported in literature. A threshold of 10 kW/m^2 is proposed by the SFPE (1988) based on a 1% chance of fatality for an assumed exposure time of 40 seconds (ARCHIE uses 10 kW/m^2 for fatality and 5 kW/m^2 for injury). The chosen level of 6.3 kW/m^2 is sited by Jones and Fearnehough (1986) as the level at which a receptor only needs to travel a short distance in order to escape.

- The literature review does not provide an upper bound for the outdoor exposure threshold. However, it can be assumed that fatalities associated with outdoor exposure may result from:

  a.) an intensity so high that the individual sustains fatality before reaching shelter;

  b.) an intensity so high that the potential shelter ignites.

  Threshold associated with *b.* (i.e. 27 kW/m^2) is lower than that obtained from *a.* if the required evacuation distance suggested by the HSE and the 99% fatality threshold for thermal radiation given by Lees (1980) are employed in the calculation.

- Thresholds listed above are generally conservative because:

  a.) for outdoor exposure the thermal radiation data for skin burns is usually based on the assumption of bare skin which does not take into account the protection of clothing.

  b.) for indoor exposure a large percentage of people in ignited building will survive.

3. Threshold for vapour cloud fire

- Models for vapour cloud or flash fire often use the shape and size of the flammable cloud as the burning area. The extent of the flammable cloud can be determined using dispersion models. The models adopted in this program assume that contours of equal vapour concentration can be approximated by an elliptical shape. The effective burning area is therefore taken to be an ellipse corresponding to the concentration contour associated with the lower flammability limit, C_{LFL}.
- Flash fire burns quickly and secondary ignition within the fire zone is very unlikely (Craven 1976), people inside buildings are therefore assumed not to sustain any fatalities. This assumption has also been adopted in work reported by DnV Technica Ltd. (1988).
- For outdoor exposure the assumption of 100% fatality within the C_{LFL} concentration contour has been used by HSE (Pape 1989).
- Acknowledging that fire may spread beyond the C_{LFL} contour, ARCHIE assumes that a plume has the potential to burn out to the boundaries of the area encompassed by a concentration contour that is associated with approximately one-half of the C_{LFL}

(FEMA/DOT/EPA 1989). This concentration level is adopted herein to account for the spread of heat intensity. People outside this area are assumed to survive a flash fire.

4. Threshold for asphyxiation

- Most references list methane, ethane, propane and butane as simple asphyxiants (Lees 1980, Matheson 1971). The legal limits for oxygen concentration in working environments are between 16% to 19%. It is however generally considered that oxygen deficiency symptoms become evident when blood haemoglobin becomes 90% saturated, which occurs at the oxygen concentration level of 14.5% (NIOSH 1980). The lower limit on asphyxiating vapour concentration of 30.6% adopted herein corresponds to this 14.5% oxygen concentration.
- An oxygen concentration of 6% or less, which corresponds to an asphyxiating vapour concentration of 71.3% or more, will cause death in 6 to 8 minutes (FEMA/DOT/EPA 1989). This concentration is adopted as the upper limit.

Appendix E

E.3 Thresholds for Property Damage

Hazard	Parameter	Unit	Building Damage Thresholds		Land Damage Thresholds	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Thermal Radiation	Heat Intensity	kW/m^2	15.7	27	6.3	15.7
Vapour cloud fire	Volume Concentration	Ratio	N/A	N/A	0.5 C_L(1)	C_L(1)
Vapour cloud explosion	Volume Concentration	kPa	2.069	34.475	2.069	34.475

(1) Lower flammability limit.

The basis for the thresholds tabulated above is as follows:

1. *Thresholds for thermal radiation and vapour cloud fire*

- Thresholds for buildings exposed to thermal radiation are based on the ignition of wood (see thresholds for fatality). No significant damage is assumed for vapour cloud fires due to the lack of secondary ignition potential (see thresholds for fatality).
- Thresholds for landscape (i.e. trees and other plants) exposed to thermal radiation and flash fire will vary with the season and the type of vegetation (no relevant data was found in the literature). The tabulated values are the same as the values adopted for people outdoors on the basis that both involve the potential for damage to living tissue.

2. *Threshold for vapour cloud explosion*

Appendix E

- The overpressure thresholds for vapour cloud explosions are based on Lees (1980). An overpressure of 0.3 psi (2.069 kPa) is sited as the level necessary to cause glass breakage, and 5 psi (34.475 kPa) is sited as the level that would cause nearly total destruction of wood framed houses and breakage of timber telephone poles (which are taken to be analogous to trees).

References

Crossthwaite, P. J., Fitzpatrick, R. D. and Hurst, N. W. (1988), "Risk assessment for the siting of developments near liquefied petroleum gas installations",

Fearnehough, G. D. (1985), "The Control of Risk in Gas Transmission Pipeline", Institute of Chemical Engineers, Symposium, No.93, 25-44.

FEMA/DOT/EPA (1989) Handbook of Chemical Hazard Analysis Procedures, U.S. Federal Emergency Management Agency, U.S. Department of Transportation, U.S. Environmental Protection Agency, Washington, DC.

Jones, D. A. and Fearnehough, G. D. (1986), "Natural gas transmission by pipelines", Fifth International Symposium on Loss Prevention and Safety.

Lees (1980), Loss Prevention in the Process Industries.

Matheson (1971), Matheson Gas Data Book, Matheson Gas Products.

NIOSH (1980), Working in Confined Spaces, Criteria for a recommended standard, Notional Institute for Occupational Safety and Health, U.S. Department for Health, Education, and Welfare, Washington, D.C. (MED: RC962.3 N277 1980)

SFPE (1988), SFPE Handbook of Fire Protection Engineering, P. J. DiNenno *et al.* ed., Society of Fire Protection Engineers, Boston, Massachusetts.

Technica Ltd. (1988), Techniques for Assessing Industrial Hazards.

NIOSH (1980), Working in Confined Spaces, Criteria for a recommended standard, Notional Institute for Occupational Safety and Health, U.S. Department for Health, Education, and Welfare, Washington, D.C. (MED: RC962.3 N277 1980)

Pape (1989), "HSE Assessment for Consultation Distances for Major Hazard Installations", Safety Cases, F. P. Lees and M. L. Ang ed., Butterworths, Sevenoaks, U.K.

Appendix F

POPULATION DENSITY ESTIMATES

This Appendix summarizes the estimated population density ranges and suggested representative values for the land use categories defined within this project.

Land Use Category		Population Density (people per hectare*)	
Major Use Category	**Sub-Categories**	**Typical Range**	**Representative Value**
Industrial	Industrial	2 to 50	10
Urban	Commercial	10 to 50	50
	Urban Residential	10 to 50	50
Rural	Rural Residential	0.1 to 5	0.5
	Agricultural	0.01	0.01
	Parkland	0.01 to 50	none (highly variable)
	Parkland - forested	0.01 to 50	none (highly variable)
	Remote	0	0
	Remote - forested	0	0

* 1 hectare = 100 m x 100 m = 10,000 m^2

The population density ranges tabulated above were established based on the following reference population density estimates (in people per hectare):

50 - average value for urban residential suburb consisting of mixed single and multi-family dwelling units (~5000 people per sq. km., City of Edmonton Planning Dept.)

- maximum design value for typical light industrial land or industrial park (18 to 28 people per acre, De Chiara and Koppelman, 1975)

- representative value for land area immediately surrounding a high density campground or trailer park sites (10 sites per acre, 3 to 4 people per site, with sites occupying 50% of the total land area, De Chiara and Koppelman, 1975)

- representative value for land area designated as nature trail (2 miles of trail on 2.4 acres designed for 50 people per mile of trail, assuming 50% utilization,

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DeChiara and Koppelman, 1975)

10 - overall average value for major urban centre (~160,000 dwelling units within city limits, total land area ~700 sq. km., City of Edmonton Planning Dept.)

2 - representative value for land area designated as heavy industrial in the U.K. (200 people per sq. km., Crossthwaite et al. 1988)

- representative value for land area designated as golf course (18 holes on 150 acres used by approximately 120 people at a time, De Chiara and Koppelman, 1975)

0.5 - maximum value for unrestricted county development (8 dwellings units per quarter section of land, Provincial guidelines)

0.01 - typical value for farmland (1 dwelling unit per section of land)

The representative densities tabulated above, as developed from the sited density ranges, are considered to be reasonable and conservative order of magnitude estimates of population densities for typical cases of the designated land use categories. Given the extreme variability associated with the Parkland land use categories it is recommended that densities be established on a case by case basis.

References

Crossthwaite, P. J., Fitzpatrick, R. D. and Hurst, N. W. 1988. "Risk assessment for the siting of developments near liquefied petroleum gas installations", Symposium Series No. 110, Institute of Chemical Engineers, 373-400.

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Appendix G

SERVICE INTERRUPTION FOR NATURAL GAS PIPELINES

If a service interruption with a duration of less than one month starts at or near the beginning of the month, a flow reduction only occurs in the month in which it started. However, if the service interruption started late enough in the month the interruption would not end until sometime into the following month. When this occurs the effect of interruption on the month in which it starts is reduced and a reduction starts to occur in the following month. If the service interruption starts very late in the month (e.g. 11:59 P.M. on the last day) there is virtually no reduction in the month in which the interruption starts although there can be a significant reduction in the following month. The effect of interruption start time is illustrated in Figure G.1. The left side of the figure shows a service interruption of approximately 15 days starting at three different times during the "first" month. The right hand side of the figure shows the monthly reduction as a function of start time for the first and second months.

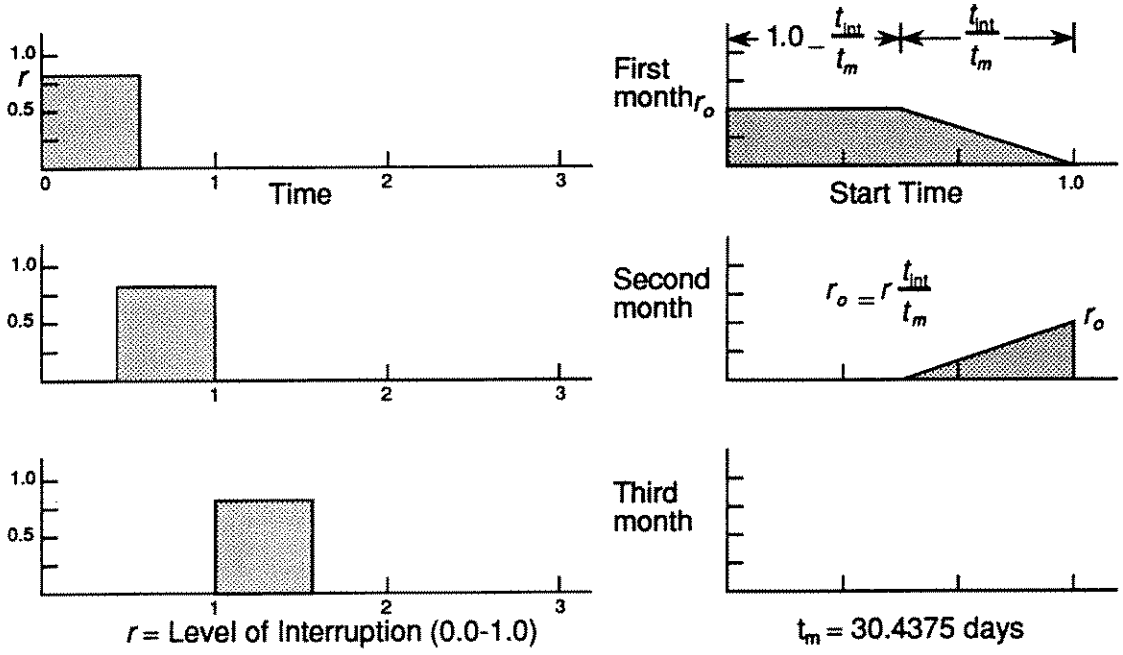

Figure G.1 - Average Monthly Reduction for Natural Gas Pipelines (t_{int} < 1 month)

It is possible to calculate the average monthly flow reduction by integrating the monthly reduction over the range of possible start times multiplied by the probability of the service

interruption starting at that time. If it is assumed that there is an equal probability of a failure starting at any time during a month, this integration is equal to the area under the monthly reduction curves shown in Figure G.1.

If a service interruption with a duration of between one and two months starts at the beginning of the month, the monthly reduction during the first month is equal to the level of the basic service interruption. However if the interruption duration is greater than one month a reduction will also occur in the second month. As the possible interruption start time occurs later in the month, reduction for the month is less in the first month and the reduction in the second month increases up to the level of the basic service interruption. Once this level of interruption is reached the interruption starts to affect the third month. The affect of interruption start time for interruption durations between one and two months is illustrated in Figure G.2. The left side of the figure shows a service interruption of approximately 45 days starting at three different times during the "first" month. The right hand side of the figure shows the monthly reduction as a function of start time for the first, second and third months.

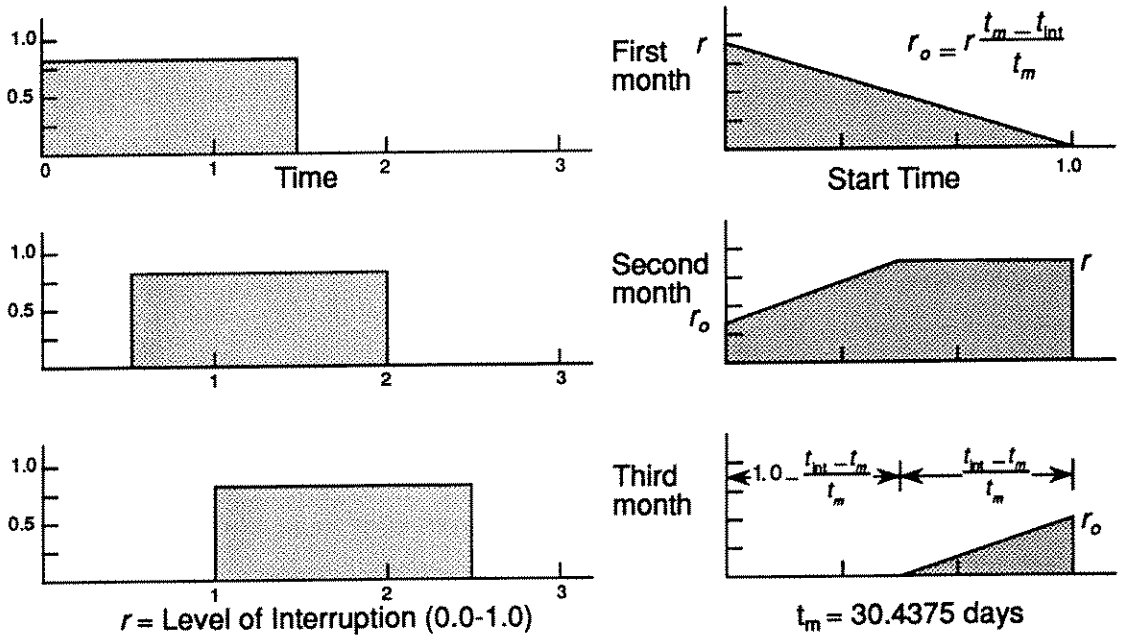

Figure G.2 - Average Monthly Reduction for Natural Gas Pipelines ($1 < t_{int} < 2$ months)

Appendix G

It is possible to calculate the average monthly flow reduction in the manner previously described for interruption times of less than one month.

For service interruptions with durations longer than two months, the duration is reduced by an even number of months until the new duration is between one and two months. The average monthly flow reductions for the first, second and third months can then be calculated using the method described above. However, in addition you also have the number of months by which the original duration was reduced that have an average monthly flow reduction equal to the level of the basic service interruption.

Appendix H

HUMAN CAPITAL APPROACH TO LIFE VALUATION

H.1 Introduction

The human capital approach is a commonly used method of estimating the economic value of a statistical life (Mooney 1977, Marin 1986, Royal Society 1992). In this approach, the value of life is taken to be equivalent to the present capital value of the loss of the output or earnings of the person whose life will be lost as a result of higher level of risk (Marin 1986).

The economic value of life (EVOL) based on this criterion is calculated in the following way: if the economic value of the output (*i.e.* the earnings) in year i is E_i and the probability of surviving until year i is P_i, then the EVOL of a person who would die at age n is given by (Acton 1976)

$$EVOL = \sum_{i=n}^{N} \frac{P_i E_i}{(1+r)^{i-n}} \qquad [H.1]$$

where r is a discount rate is used to obtain the present value of the earnings that would be lost in future, and N denotes the total length of life in years. Note that the discount rate represents a compound growth rate by which an amount of money invested at present will grow to a prescribed value over certain period of time.

H.2 Computation of the Economic Value of an Average Life

In this section, the EVOL is calculated for an average Canadian person. For this purpose, the probability of survival (P_i,) data is obtained from the life tables published by Statistics Canada (1990c). The annual average income of $22,810 and $14,532 for male and female, respectively, is considered in the analysis (Statistics Canada 1990b). For people of age 65 and over, average retirement earning of $18,624 and $13,376 for male and female, respectively, is included in the calculation.

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The age at death, n, is considered to be equal to the average population age which is 34 years for males and 36 years for females based on the population group surveyed in the year 1988 (Statistics Canada 1990a). The total length of life, N, is taken as 100 years which is consistent with the Canadian life table. The EVOL is calculated separately for an average male and female based on the conservative assumption that the rate of growth of the economic output of a person and the discount rate are the same. (This assumption is conservative in the sense that it overestimates the value of life due to the fact that the discount rate is usually higher than the income growth rate.) Eqn.[H.1] therefore reduces to the following simple expression:

$$EVOL = \sum_{i=n}^{100} P_i E_o \qquad [H.2]$$

in which E_o is the average annual income per person which, as noted above, is assumed to take one constant value prior to age 65 to reflect the earning years, and a lower constant value after age 65 to reflect the retirement years.

The economic value of life based on Eqn. [H.2] and the stated income levels is calculated to be $847 000 for an average Canadian male and $616 000 for an average Canadian female. The final estimated EVOL of $732,000 is obtained by averaging the two values. It is noted that there is considerable uncertainty is associated with the estimated EVOL due to variability in earnings and earning potential, age at time of death, and the discounting rate. The calculated value is, however, considered to be representative of the economic value of a statistical life.

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Statistics Canada (1990a). *CANADA Year Book*, Statistics Canada, Ottawa.

Statistics Canada (1990b). "Income after Tax, Distributions by Size in Canada". Catalogue No. 13-210, pp.85.

Appendix H

Statistics Canada (1990c). Life Tables, Canada and Provinces, 1985-1987. Vol.2(4), 82-003S13.

Appendix I

Appendix I

THE UTILITY FUNCTION

I.1 Introduction

This appendix contains the mathematical descriptions of the utility functions selected for the project. Utility theory defines different functional forms that can represent different attitudes toward risk and tradeoffs between attributes. The attitudes and trends that are considered applicable for the present problem are discussed in Section 13.2 of the main report. The functional forms corresponding to these attitudes are given in this Appendix. In each case, the function contains some constants that can be determined from the decision maker's response to questions regarding simple choices involving uncertain options or tradeoffs between attributes. The information required to define and verify these constants is given in each case. In addition, the Appendix gives examples that demonstrate the application of utility functions in evaluating different choices.

I.2 Single Attribute Utility Functions

I.2.1 Cost

As discussed in the main report, the utility function for cost is required to be 1) monotonically decreasing, 2) risk averse, and 3) increasingly risk averse. A function that satisfies the above conditions are given as follows (Keeney and Raiffa 1976):

$$u(c) = k_{c1} + k_{c2} \ln(k_{c3} - c), \quad c < k_{c3} \qquad [I.1]$$

where k_{c1}, k_{c2}, k_{c3} are constants. To evaluate these three constants, three points on the utility function must be given. The first two points are defined by scaling the function between two arbitrary values. Utility is usually scaled in the range of 0 to 1.0, where a zero utility is assigned to the worst possible outcome (i.e., maximum possible cost, denoted c_0) and a utility of 1.0 is assigned to the best possible outcome (i.e., the minimum possible cost, denoted $c*$).

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Note that the subscripts 0 and * are consistently used to denote the worst and best possible values of an attribute, respectively. These two conditions lead to:

$$u(c_0) = k_{c1} + k_{c2} \ln(k_{c3} - c_0) = 0 \qquad [I.2a]$$

and

$$u(c_*) = k_{c1} + k_{c2} \ln(k_{c3} - c_*) = 1.0 \qquad [I.2b]$$

The third condition can be determined by asking the decision maker to specify the certain cost that would be equivalent to a 50-50 chance at paying c_0 or c_*. This is called the certainty equivalent of that lottery and is denoted c_{ce}. By definition, c_{ce} must be greater than $(c_0+c_*)/2$ for a risk averse function. Because the utility associated with the certainty equivalent is equal to the expected utility of the lottery, a third point on the utility function can be defined as:

$$k_{c1} + k_{c2} \ln(k_{c3} - c_{ce}) = 0.5[k_{c1} + k_{c2} \ln(k_{c3} - c_0)] + 0.5[k_{c1} + k_{c2} \ln(k_{c3} - c_*)] \qquad [I.2c]$$

Solving Equations [I.2] gives

$$k_{c3} = (c_0 c_* + c_{ce}{}^2) / (c_0 + c_* - 2c_{ce}), \quad k_{c3} > c_0 \qquad [I.3a]$$

$$k_{c2} = 1 / \ln[(k_{c3} - c_*) / (k_{c3} - c_0)] \qquad [I.3b]$$

$$k_{c1} = 1 - k_{c2} \ln(k_{c3} - c_*) \qquad [I.3c]$$

After defining the utility function, it can be checked by calculating the certainty equivalents of a number of lotteries and confirming that they are consistent with the decision maker's preferences.

As an example, consider a case in which c_* = \$2 million and c_0 = \$12 million. Also assume that the certainty equivalent of a 50-50 lottery at \$2 million or \$12 million is \$9 million. Equations [I.3] can be used to calculate k_{c1} = -0.478, k_{c2} = 0.59, and k_{c3} = 14.25. The utility function is then given by

$$u(c) = -0.478 + 0.59 \ln(14.25 - c), \quad 2 < c < 12 \qquad [I.4]$$

This function is plotted in Figure 13.6 of the main report. Confirmation of the appropriateness of the function can be achieved by calculating the certainty equivalents of some arbitrary

lotteries and verifying that they are consistent with the decision maker's preferences. For example, the certainty equivalent of a lottery l_1 defined as a 50-50 chance at c = \$2 million or c = \$7 million is \$4.83 million. This is calculated by finding the expected utility of the lottery using Equation [I.4] and then finding the fixed cost that has the same utility value using the inverse of Equation [I.4]. Similarly, the certainty equivalent of a lottery l_2 defined as a 50-50 chance at c = \$7 million or c = \$12 million is \$10.21 million. If these values are consistent with the decision maker's preferences, then the utility function is adequate. Otherwise, the value of c_{ce} can be redefined, the utility function re-evaluated and the confirmation process repeated.

It is also worth noting that the lotteries l_1 and l_2 have the same range of \$5 million, but l_1 has a reference value of \$4.5 million and l_2 a reference value of \$9.5 million (see Section 13.2.2.1 for the definitions of reference value and range). The risk premiums for these lotteries are \$0.33 million for l_1 and \$0.71 million for l_2 (see Section 13.2.2.1 for definition of risk premium). It can therefore be seen that the risk premium increases with the reference value for lotteries having the same range, confirming that this utility function is increasingly risk averse.

I.2.2 Number of Fatalities

Based on the discussion in Section 13.2.2.3 it was decided that a risk neutral (linear) utility function should be used for the number of fatalities. This utility function is given by:

$$u(n) = 1 - n / n_0 \qquad [I.5]$$

where n_0 is the maximum possible (highest) number of fatalities. Equation [I.5] assumes that the minimum number of fatalities $n*$ is 0. It can be verified that this equation satisfies the scaling conditions $u(n_0) = 0$ and $u(n*) = 1.0$. If n_0 is equal to 10 for example Equation [I.5] gives

$$u(n) = 1 - n/10 \ , \ 0 < n < 10 \qquad [I.6]$$

Appendix I

I.2.3 Equivalent Spill Volume

A risk prone utility function was selected for the equivalent spill volume. The function used is as follows:

$$u(v) = k_{v1} + k_{v2} v^{k_{v3}} , \quad 0 < k_{v3} < 1 \qquad [I.7]$$

where k_{v1}, k_{v2}, k_{v3} are constants. As in the case of cost, these constants can be evaluated from the following conditions:

$$u(v_0) = k_{c1} + k_{c2} v_0^{k_{c3}} = 0 \qquad [I.8a]$$

$$u(v_*) = k_{c1} + k_{c2} v_*^{k3} = 1.0 \qquad [I.8b]$$

and

$$k_{c1} + k_{c2} v_{ce}^{k_{c3}} = 0.5[k_{c1} + k_{c2} v_0^{k_{c3}}] + 0.5[k_{c1} + k_{c2} v_*^{k_{c3}}] \qquad [I.8c]$$

where v_* is the minimum spill volume, v_0 is the maximum spill volume, and v_{ce} is the certainty equivalent of a 50-50 lottery at a spill volume of v_0 or v_*. Solving Equations [I.8] and assuming that $v_* = 0$, leads to

$$k_{v3} = \ln(0.5) / (v_{ce} / v_0) , \quad 0 < k_{v3} > 1 \qquad [I.9a]$$

$$k_{c2} = -1 / v_0^{k_{v3}} \qquad [I.9b]$$

$$k_{v1} = 1 \qquad [I.9c]$$

Consider for example a case in which $v_* = 0$ and $v_0 = 1000$ m^3. Also assume that the certainty equivalent v_{ce} of a 50-50 lottery at 0 or 1000 m^3 is 100 m^3. Equations [I.9] can be used to calculate $k_{v1} = 1$, $k_{v2} = -0.125$, and $k_{v3} = 0.3$. The utility function is then given by

$$u(v) = 1 - 0.125 v^{0.3} \quad 0 < v < 1000 \qquad [I.10]$$

This function is plotted in Figure 13.7 of the main report. As in the case of cost, the appropriateness of the function can be confirmed by calculating the certainty equivalents of some additional lotteries. For example, the certainty equivalent of a lottery l_1 defined as a 50-50 chance at v= 0 million or v = 500 m^3 is 50 m^3. Similarly, the certainty equivalent of a lottery l_2 defined as a 50-50 chance at v= 500 m^3 or v = 1000 m^3 is 720 m^3. If these values

are consistent with the decision maker's preferences, then the utility function is adequate. It is noted that this function is decreasingly risk prone as can be verified by calculating the risk premiums for lotteries l_1 and l_2. These values are -200 m^3 and -30 m^3.

I.3 Multi-attribute Utility Function

Based on the preferential and utility independence trends explained in Section 13.2.3.2, it can be shown that a multiplicative utility function is appropriate (see Theorem 6.2 in Keeney and Raiffa 1976). This form is given by:

$$u(c,n,v) = [(k k_c u(c)+1)(k k_n u(n)+1)(k k_v u(v)+1)-1]/k \qquad [I.11]$$

where $u(c)$, $u(n)$, $u(v)$ are the single attribute utility functions discussed in Section ??.2, and k, k_c, k_n, k_v are constants. The utility function is scaled between 0 and 1 so that:

$$u(c_0,n_0,v_0) = 0 \qquad [I.12a]$$

$$u(c_*,n_*,v_*) = 1 \qquad [I.12b]$$

The constants k_c, k_n, and k_v are given by:

$$k_c = u(c_*,n_0,v_0)\ ,\ 0<k_c<1 \qquad [I.13a]$$

$$k_n = u(c_0,n_*,v_0)\ ,\ 0<k_n<1 \qquad [I.13b]$$

$$k_v = u(c_0,n_0,v_*)\ ,\ 0<k_v<1 \qquad [I.13c]$$

These values can be assessed directly by the decision maker. Recall that the subscripts 0, * represent the worst and best possible values of each attribute, respectively. Equations [I.12] define the scale of the utility function: a utility of 0 corresponds to an outcome that consists of the worst values of all attributes, and a utility of 1 corresponds to an outcome consisting of the best values of all attributes. The constants in Equations [??.13] represent the utility value, on that scale of 0 to 1, associated with an outcome consisting of the best value of one attribute and the worst values of the other two attributes. To determine k_c, for instance, the decision maker must assign a utility value between 0 and 1 to an outcome consisting of the best consequences in $c = c_*$ combined with the worst consequences in n and v (i.e., $n = n_0$ and $v = v_0$). The relative magnitude of the utility increases attached to improvements in single attributes reflect

the tradeoffs between these attributes. For example if the decision maker assigns a utility value of 0.2 to a cost saving of $10 million and a utility value of 0.4 to a reduction in the number of fatalities of 10, it can be concluded that saving 5 lives in twice as desirable as saving $20 million, indicating that the value of a human life is approximately $2 million.

Once k_c, k_n, and k_v are determined, k can be obtained by substituting $c = c*$, $n = n*$ and $v = v*$ in Equation [I.11], and observing that $u(c*) = u(n*) = u(v*) = u(c*,n*,v*) = 0$. This lead to a quadratic equation from which k can be calculated as:

$$k = \frac{-(k_c k_n + k_n k_v + k_v k_c) + \sqrt{(k_c k_n + k_n k_v + k_v k_c)^2 - 4 k_c k_n k_v (k_c + k_n + k_v - 1)}}{2 k_c k_n k_v} \qquad [I.14]$$

It is noted that if $k_c+k_n+k_v = 1$, then $k = 0$. This results in simplifying the utility function to a weighted sum of the three single attribute functions, and this means that there is no interaction between the three attributes. If $k_c+k_n+k_v < 1$, then $k > 1$. In this case it can be verified from the utility function that raising all attributes simultaneously from their worst to their best values has a more positive impact on the utility function than the sum of the impacts of raising each attribute to its best value individually. It is therefore said that the three attributes are *complimentary*, indicating that there is some added benefit in achieving good results simultaneously in more than one attribute. A typical example of this trend is that of the general who is fighting on both fronts. Winning on both fronts is a must, otherwise the war will be lost. On the other hand , if $k_c+k_n+k_v > 1$, then $k < 1$. In this case raising each attribute from its worst to its best value has a more positive impact on the utility function than raising all attributes from their worst to their best values simultaneously. In this case it is said that the attributes are *substitutive*. It indicates that there is some importance attached to achieving good results in any of the attributes. A typical example is a corporation that markets two products, and although it is desirable to do well in both, it is essential to do well at least in one in order to remain in business.

Once the utility function is defined, it can be used to calculate some equivalent combinations of the three attributes. As discussed for the single attribute utility functions, these values can be used for verification or modification of the constants defined by the decision maker (Equations[I.13]).

Appendix I

I.4 Example

An example can be developed by considering the three single attribute utility functions defined in the examples given in Sections I.2.1 to I.2.3 (Equations [I.4], [I.6] and [I.10]). For these functions, the scale for the multi-attribute utility function is defined by substituting the minimum and maximum values of the attributes in Equations [I.12], leading to:

$$u(\$12\,\text{million}, 10\,\text{fatalities}, 1000\,\text{m}^3) = 0 \qquad \text{[I.15a]}$$

$$u(\$2\,\text{million}, 0\,\text{fatalities}, 0\,\text{m}^3) = 1 \qquad \text{[I.15b]}$$

The constants k_c, k_n, and k_v are assessed subjectively based on Equations [I.13] as:

$$k_c = u(\$2\,\text{million}, 10\,\text{fatalities}, 1000\,\text{m}^3) = 0.2 \qquad \text{[I.16a]}$$

$$k_n = u(\$12\,\text{million}, 0\,\text{fatalities}, 1000\,\text{m}^3) = 0.8 \qquad \text{[I.16a]}$$

$$k_v = u(\$12\,\text{million}, 10\,\text{fatalities}, 0\,\text{m}^3) = 0.2 \qquad \text{[I.16a]}$$

Equation [I.14] gives k = -0.585. The utility function is then obtained by substituting these constants into Equation [I.11]. This gives:

$$u(c,n,v) = 1.709[1 - \{1 - 0.117u(c)\}\{1 - 0.468u(n)\}\{1 - 0.117u(v)\}] \qquad \text{[I.17]}$$

where $u(c)$, $u(n)$, and $u(v)$ are given by Equations [I.4], [I.6] and [I.10].

Equation [??.17] can be verified by calculating the utility values in Equations [I.16] and verifying that they are equal to the values defined by the decision maker. In this case u(\$2 million, 10 fatalities, 1000 m^3) = 0.2, u(\$12 million, 0 fatalities, 1000 m^3) = 0.8, and u(\$12 million, 10 fatalities, 0 m^3) = 0.2. The utility function can then be used to calculate the utility associated with any combination of c, n, and v. For example, u(\$5 million, 2 fatalities and 100 m^3) = 0.80, and u(\$2 million, 7 fatalities and 500 m^3) = 0.44. It is noted that u(\$12 million, 0 fatalities, 1000 m^3) = u(\$5 million, 2 fatalities and 100 m^3) = 0.80, indicating that these two combinations are equivalent.

Appendix I

Reference

Keeney, R.L., and Raiffa, H. (1976). Decisions With Multiple Objectives: Preferences and Value Trafeoffs

Appendix J

Appendix J

SUBJECTIVE EVALUATIONS OF CLEAN-UP EFFICIENCY AND COST

Terrain Character	Season	Clean-Up Efficiency (fraction of spilled product recovered)			
		Light Refined Product		Heavy Unrefined Product	
		Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)	Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)
Ground	summer	0.75 - 0.8	0.4 - 0.5	0.8 - 0.95	0.8 - 0.95
Low Permeability	winter (i.e. frozen)	0.8 - 0.95	0.4 - 0.5	0.8 - 0.95	0.8 - 0.95
Ground	summer	0.5 - 0.6	0.3 - 0.5	0.8 - 0.95	0.75 - 0.9
Moderate Perm.	winter (i.e. frozen)	0.6 - 0.8	0.3 - 0.5	0.8 - 0.95	0.75 - 0.9
Ground	summer	0.2 - 0.3	0.05 - 0.3	0.7 - 0.9	0.3 - 0.7
High Permeability	winter (i.e. frozen)	0.3 - 0.5	0.05 - 0.3	0.7 - 0.9	0.3 - 0.7
Waterlogged	summer	0.05 - 0.2	0.05 - 0.2	0.3 - 0.5	0.3 - 0.5
Groundmass	winter (i.e. frozen)	0.2 - 0.5	0.05 - 0.3	0.5 - 0.7	0.4 - 0.6
Water Covered	summer	0.02 - 0.1	not applicable (see note)	0.15 - 0.4	not applicable (see note)
Vegetation	winter (i.e. frozen)	0.15 - 0.3	0 - 0.05	0.3 - 0.7	0.05 - 0.2
Static	summer	0.03 - 0.1	not applicable (see note)	0.15 - 0.3	not applicable (see note)
Water	winter (i.e. frozen)	0.15 - 0.3	0 - 0.05	0.3 - 0.6	0.05 - 0.1
Slow Flowing	summer	0 - 0.1	not applicable (see note)	0.5 - 0.7	not applicable (see note)
Water	winter (i.e. frozen)	0.2 - 0.45	0 - 0.05	0.5 - 0.8	0.15 - 0.3
Fast Flowing	summer	0 - 0.05	not applicable (see note)	0.05 - 0.2	not applicable (see note)
Water	winter (i.e. frozen)	0 - 0.05	0 - 0.05	0.05 - 0.2	0.05 - 0.1

Note: for spills in water, subsurface release and spread refers to liquid spreading beneath the ice surface and applies in winter only

Table J.1 Characterization of clean-up efficiency for liquid petroleum product spills by O'Connor Associates Environmental Inc.

Terrain Character	Season	Clean-Up Efficiency (fraction of spilled product recovered)			
		Light Refined Product		Heavy Unrefined Product	
		Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)	Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)
Ground	summer	0.45 - 0.55	0.2 - 0.5	0.6 - 0.75	0.3 - 0.6
Low Permeability	winter (i.e. frozen)	0.55 - 0.75	0.3 - 0.6	0.7 - 0.85	0.35 - 0.65
Ground	summer	0.2 - 0.4	0.2 - 0.4	0.4 - 0.6	0.25 - 0.5
Moderate Perm.	winter (i.e. frozen)	0.55 - 0.75	0.25 - 0.5	0.65 - 0.85	0.3 - 0.6
Ground	summer	0.05 - 0.2	0.1 - 0.3	0.2 - 0.4	0.25 - 0.5
High Permeability	winter (i.e. frozen)	0.5 - 0.75	0.2 - 0.4	0.6 - 0.85	0.3 - 0.5
Waterlogged	summer	0.4 - 0.6	0.3 - 0.6	0.5 - 0.7	0.25 - 0.5
Groundmass	winter (i.e. frozen)	0.45 - 0.65	0.4 - 0.6	0.55 - 0.85	0.4 - 0.6
Water Covered	summer	0.3 - 0.6	not applicable (see note)	0.4 - 0.7	not applicable (see note)
Vegetation	winter (i.e. frozen)	0.35 - 0.65	0.4 - 0.6	0.5 - 0.8	0.4 - 0.6
Static	summer	0.65 - 0.8	not applicable (see note)	0.8 - 0.9	not applicable (see note)
Water	winter (i.e. frozen)	0.75 - 0.85	0.2 - 0.5	0.85 - 0.95	0.2 - 0.5
Slow Flowing	summer	0.4 - 0.7	not applicable (see note)	0.5 - 0.8	not applicable (see note)
Water	winter (i.e. frozen)	0.75 - 0.85	0.1 - 0.3	0.85 - 0.95	0.15 - 0.3
Fast Flowing	summer	0.1 - 0.4	not applicable (see note)	0.25 - 0.5	not applicable (see note)
Water	winter (i.e. frozen)	0.65 - 0.85	0.05 - 0.3	0.75 - 0.95	0.1 - 0.3

Note: for spills in water, subsurface release and spread refers to liquid spreading beneath the ice surface and applies in winter only

Table J.2 Characterization of clean-up efficiency for liquid petroleum product spills by AGRA Earth & Environmental Limited

Terrain Character	Season	Clean-Up Efficiency (fraction of spilled product recovered)			
		Light Refined Product		Heavy Unrefined Product	
		Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)	Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)
Ground Low Permeability	summer	0.6 - 0.675	0.3 - 0.5	0.7 - 0.85	0.55 - 0.775
	winter (i.e. frozen)	0.675 - 0.85	0.35 - 0.55	0.75 - 0.9	0.575 - 0.8
Ground Moderate Perm.	summer	0.35 - 0.5	0.25 - 0.45	0.6 - 0.775	0.5 - 0.7
	winter (i.e. frozen)	0.575 - 0.775	0.275 - 0.5	0.725 - 0.9	0.525 - 0.75
Ground High Permeability	summer	0.125 - 0.25	0.075 - 0.3	0.45 - 0.65	0.275 - 0.6
	winter (i.e. frozen)	0.4 - 0.625	0.125 - 0.35	0.65 - 0.875	0.3 - 0.6
Waterlogged Groundmass	summer	0.225 - 0.4	0.175 - 0.4	0.4 - 0.6	0.275 - 0.5
	winter (i.e. frozen)	0.325 - 0.575	0.225 - 0.45	0.525 - 0.775	0.4 - 0.6
Water Covered Vegetation	summer	0.16 - 0.35	not applicable (see note)	0.275 - 0.55	not applicable (see note)
	winter (i.e. frozen)	0.25 - 0.475	0.2 - 0.325	0.4 - 0.75	0.225 - 0.4
Static Water	summer	0.34 - 0.45	not applicable (see note)	0.475 - 0.6	not applicable (see note)
	winter (i.e. frozen)	0.45 - 0.575	0.1 - 0.275	0.575 - 0.775	0.125 - 0.3
Slow Flowing Water	summer	0.2 - 0.4	not applicable (see note)	0.5 - 0.75	not applicable (see note)
	winter (i.e. frozen)	0.475 - 0.65	0.05 - 0.175	0.675 - 0.875	0.15 - 0.3
Fast Flowing Water	summer	0.05 -0.225	not applicable (see note)	0.15 - 0.35	not applicable (see note)
	winter (i.e. frozen)	0.325 - 0.45	0.025 - 0.175	0.4 - 0.575	0.075 - 0.2

Note: for spills in water, subsurface release and spread refers to liquid spreading beneath the ice surface and applies in winter only

Table J.3 Average characterization of clean-up efficiency for liquid petroleum product spills

Terrain Character	Season	Unit Clean-Up Cost ($ per cubic metre of recovered product)			
		Light Refined Product		Heavy Unrefined Product	
		Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)	Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)
Ground Low Permeability	summer	300 - 600	400 - 600	100 - 400	100 - 400
	winter (i.e. frozen)	100 - 600	400 - 600	100 - 400	100 - 400
Ground Moderate Perm.	summer	300 - 1500	400 - 1500	400 - 700	600 - 900
	winter (i.e. frozen)	100 - 1000	400 - 1000	300 - 600	600 - 900
Ground High Permeability	summer	300 - 3000	1000 - 3000	600 - 800	750 - 900
	winter (i.e. frozen)	100 - 1000	1000 - 3000	600 - 800	750 - 900
Waterlogged Groundmass	summer	300 - 1000	1000 - 3000	300 - 2000	500 - 1000
	winter (i.e. frozen)	600 - 1000	1000 - 3000	300 - 2000	500 - 1000
Water Covered Vegetation	summer	300 - 2000	not applicable (see note)	400 - 600	not applicable (see note)
	winter (i.e. frozen)	300 - 700	1000 - 3000	300 - 600	1000 - 3000
Static Water	summer	1000 - 3000	not applicable (see note)	1000 - 3000	not applicable (see note)
	winter (i.e. frozen)	300 - 600	1000 - 3000	300 - 600	1000 - 3000
Slow Flowing Water	summer	1000 - 3000	not applicable (see note)	1000 - 2000	not applicable (see note)
	winter (i.e. frozen)	300 - 1000	1000 - 3000	300 - 1000	1000 - 3000
Fast Flowing Water	summer	2000 - 4000	not applicable (see note)	1000 - 3000	not applicable (see note)
	winter (i.e. frozen)	2000 - 4000	2000 - 4000	1000 - 3000	2000 - 4000

Note: for spills in water, subsurface release and spread refers to liquid spreading beneath the ice surface and applies in winter only

Table J.4 Characterization of unit clean-up costs for liquid petroleum product spills by O'Connor Associates Environmental Inc.

Terrain Character	Season	Unit Clean-Up Cost ($ per cubic metre of recovered product)			
		Light Refined Product		Heavy Unrefined Product	
		Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)	Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)
Ground Low Permeability	summer	370 - 850	400 - 1700	150 - 550	140 - 450
	winter (i.e. frozen)	300 - 450	350 - 1300	190 - 950	175 - 850
Ground Moderate Perm.	summer	500 - 1700	600 - 1800	175 - 700	200 - 1000
	winter (i.e. frozen)	300 - 850	450 - 1500	140 - 500	190 - 950
Ground High Permeability	summer	1000 - 6000	670 - 1200	250 - 1200	200 - 1000
	winter (i.e. frozen)	300 - 600	500 - 1000	130 - 370	220 - 850
Waterlogged Groundmass	summer	400 - 1000	380 - 1200	200 - 600	250 - 1000
	winter (i.e. frozen)	350 - 725	350 - 850	140 - 400	200 - 550
Water Covered Vegetation	summer	500 - 1500	not applicable (see note)	200 - 750	not applicable (see note)
	winter (i.e. frozen)	350 - 1000	500 - 1000	140 - 450	250 - 650
Static Water	summer	100 - 150	not applicable (see note)	70 - 140	not applicable (see note)
	winter (i.e. frozen)	80 - 130	200 - 1000	60 - 120	200 - 1000
Slow Flowing Water	summer	100 - 200	not applicable (see note)	100 - 150	not applicable (see note)
	winter (i.e. frozen)	80 - 150	700 - 1500	70 - 140	400 - 1400
Fast Flowing Water	summer	250 - 900	not applicable (see note)	200 - 600	not applicable (see note)
	winter (i.e. frozen)	150 - 300	700 - 6000	80 - 150	700 - 1200

Note: for spills in water, subsurface release and spread refers to liquid spreading beneath the ice surface and applies in winter only

Table J.5 Characterization of unit clean-up costs for liquid petroleum product spills by AGRA Earth & Environmental Limited

Terrain Character	Season	Unit Clean-Up Cost ($ per cubic metre of recovered product)			
		Light Refined Product		Heavy Unrefined Product	
		Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)	Small Leak (subsurface release & spread)	Large Leak / Rupture (surface release & spread)
Ground Low Permeability	summer	335 - 725	400 - 1150	125 - 475	120 - 425
	winter (i.e. frozen)	200 - 525	375 - 950	145 - 675	137.5 - 625
Ground Moderate Perm.	summer	400 - 1600	500 - 1650	287.5 - 700	400 - 950
	winter (i.e. frozen)	200 - 925	425 - 1250	220 - 550	395 - 925
Ground High Permeability	summer	650 - 4500	835 - 2100	425 - 1000	475 - 950
	winter (i.e. frozen)	200 - 800	750 - 2000	365 - 585	485 - 875
Waterlogged Groundmass	summer	350 - 1000	690 - 2100	250 - 1300	375 - 1000
	winter (i.e. frozen)	475 - 862.5	675 - 1925	220 - 1200	350 - 775
Water Covered Vegetation	summer	400 - 1750	not applicable (see note)	300 - 675	not applicable (see note)
	winter (i.e. frozen)	325 - 850	750 - 2000	220 - 525	625 - 1825
Static Water	summer	550 - 1575	not applicable (see note)	535 - 1570	not applicable (see note)
	winter (i.e. frozen)	190 - 365	600 - 2000	180 - 360	600 - 2000
Slow Flowing Water	summer	550 - 1600	not applicable (see note)	550 - 1075	not applicable (see note)
	winter (i.e. frozen)	190 - 575	850 - 2250	185 - 570	700 - 2200
Fast Flowing Water	summer	1125 - 2450	not applicable (see note)	600 - 1800	not applicable (see note)
	winter (i.e. frozen)	1075 - 2150	1350 - 5000	540 - 1575	1350 - 2600

Note: for spills in water, subsurface release and spread refers to liquid spreading beneath the ice surface and applies in winter only

Table J.6 Average characterization of unit clean-up costs for liquid petroleum product spills