Advanced Construction and Maintenance Modeling (ARE 520)
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Term Paper

The Use of Analytic Hierarchy Process in Risk Ranking and Maintenance Planning of Cross-country Pipelines

Prepared for

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Abstract

The oil and gas industry, which provides the largest source of income for the Arab countries, has been greatly expanded in the last three decades. The revenues from this industry are being used to develop the other aspects of public infrastructures. The increasing uncertainty in the global oil market calls for the need to sustain, preserve and prolong the operating lives of these huge investments through systematic and cost-effective maintenance efforts.

This paper describes a risk-based model using the analytical hierarchy process (AHP) for ranking the risk level associated with operating cross-country pipelines and Monte Carlo simulation technique to estimate the monetary value of pipeline failure. The AHP technique was used as a decision support system to prioritize the pipelines in order to determine the likelihood of failure while the Monte Carlo technique was used to determine the severity of the pipeline failures. This has helped in providing a risk management dosage that will ensure the expenditure of least costs for the highest levels of reliability and safety.

Data related to inspection records, design data, safety inspection sheets and experts' opinions on nine (9) cross-country pipelines used for transporting different products in Saudi ARAMCO were reviewed and evaluated for the study.

The results of the model provided an estimation of the possible cost of pipeline failure for the purpose of prioritizing the pipelines for annual maintenance planning.

1.1 Introduction

Cross-country pipelines are the most efficient, safest, environmentally friendly, and economical way to ship hydrocarbons over long distances. A significant portion of many nations' energy requirements is now transported through these pipelines and the economies of many countries depend on the smooth and uninterrupted operation of these pipelines. Saudi Aramco operates around 17000KM of cross-country pipelines, most of which are over 25 years old. Any failure of these pipelines could lead to substantial losses that will impact the overall national economy and may even pose environmental hazards to humans, as majority of them passes through residential area of the Eastern province of Saudi Arabia. The operators of these pipelines are continually developing in-house maintenance policies to replace the rules-of-thumb inspection and maintenance practices. This is because even though these pipelines are known to be the safest way of transporting these flammable and volatile materials with much lower failure rates compared to railroads and highway transportation, their failure can be very catastrophic. Fifty one people were burnt to death in Venezuela in 1993 as a result of gas pipeline failure and subsequent ignition of the escaping gas. The failure of a 914mm pipeline in New Jersey in 1994 caused a loss of one life and injuries to over 50 people. Similar failures have occurred in the UK, Canada, Russia, Pakistan, and India (Hopkins, 1994). Despite the less fatalities, pipeline failures results in interrupted operation, which leads to substantial business losses and environmental setbacks.

During the design phase, most pipeline companies ensure that safety requirements are met to provide a theoretical minimum failure rate for the life of the pipeline. Such safety requirements are considered when selecting rating and sizing of pipes and other fittings. Several techniques are periodically employed to monitor the status of a pipeline. These included the provision of high resistant external coating materials that will electrically isolate a pipeline, impressed current cathodic protection, injection of corrosion inhibitors with the products and regular patrolling of the right-of-way from the air as well as on the ground. Modern methodologies can ensure the structural integrity of an operating pipeline without taking it out of service (Jamieson, 1986).

1.2 Objective of the paper

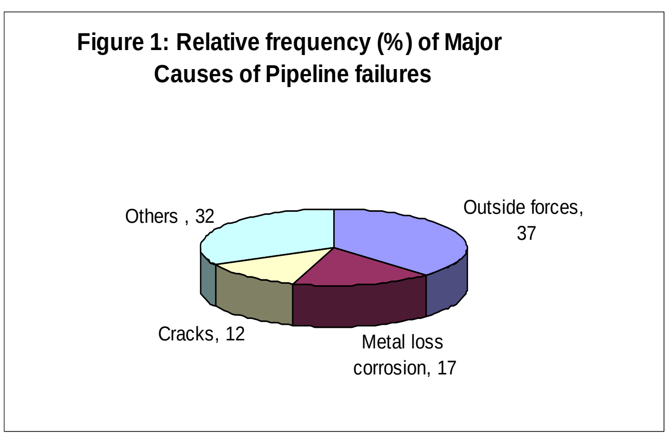
This paper seeks to develop a model for ranking the risk level associated with operating cross-country pipelines in order to be able to predict the likelihood of failure and estimate their severity for the purpose of annual maintenance planning.

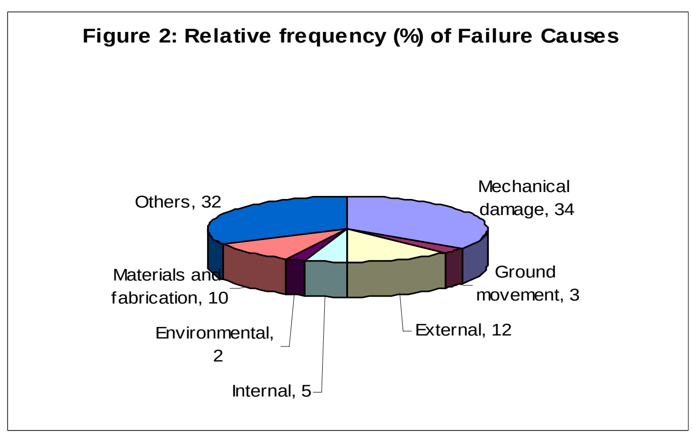
2.1 Causes of Pipeline failures

Estimates of pipeline failure rates in different parts of the world vary depending on the criteria used to define a reportable failure or incident. In Western Europe, the rate of occurrence of all natural gas incidents leading to the release product between 1988 and 1992 is 5.7x10E-4 (EGIG, 1993). In the USA, the rate of the natural gas pipeline failures leading to death, injury or major property damage between 1984 and 1990 is 1.3x10E-4 (EGA, 1992). Detailed analysis of the different failure data scores suggest that the difference between the USA and European figures is explained by differences in the requirements (Nessim and Pandey, 1997). The relative frequencies of the major failure causes and subcategories failure causes for USA pipelines are given in Figures 1 and 2 respectively. The summary of major and their sub categories are given in Table 1.

Table 1: Major and Sub-categorization of pipeline failure causes

Failure causes	
Outside forces	Mechanical damage
	Ground movement
Metal loss corrosion	External
	Internal
Cracks	Environmental
	Materials and fabrication
Others (e.g. operational error, mechanical component failure	



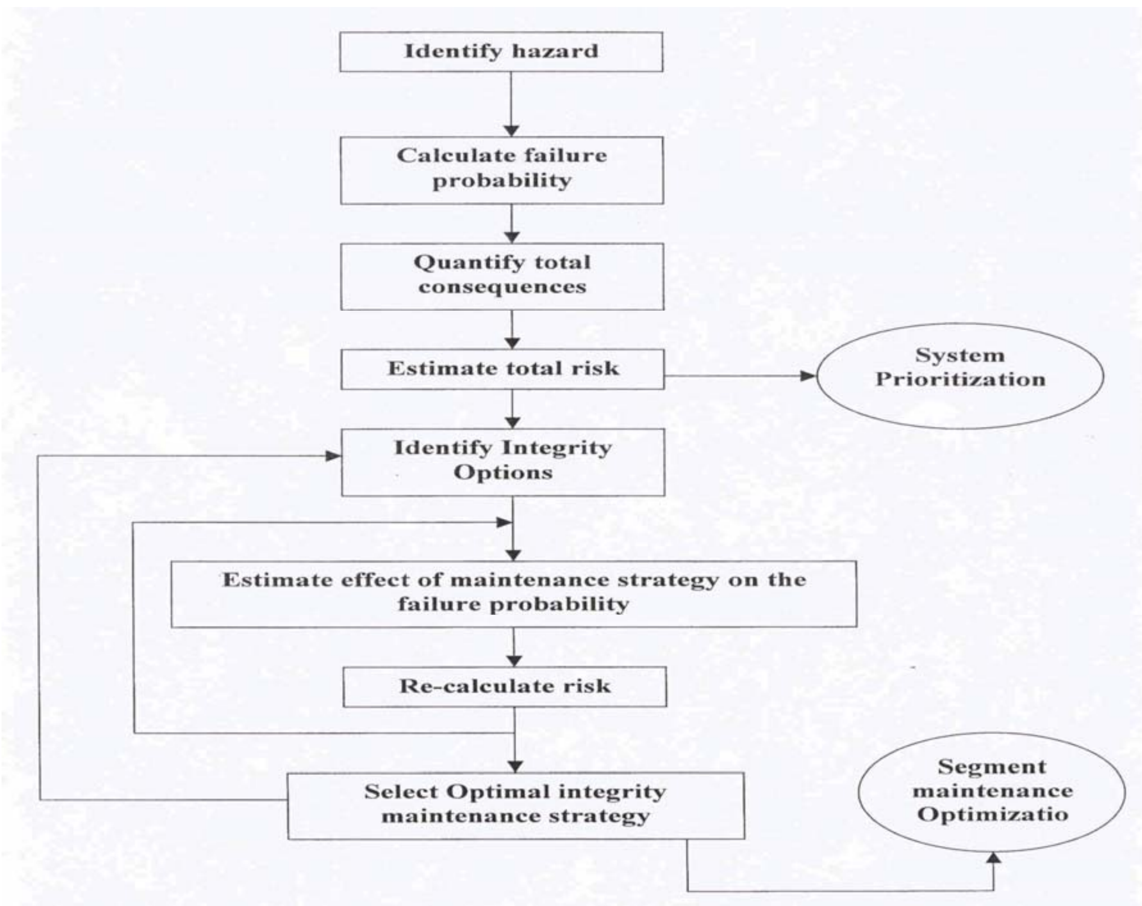


The figures show mechanical damage as the major cause of failure followed by metal loss corrosion. The frequency of corrosion leaks is low in the USA database because a large percentage of corrosion related failures involve small leaks, which are not reported in this particular database. The ratio of corrosion failures is significantly higher in databases that include incidents leading to small leaks (Caseley, 1994).

2.2 Risk-based Decision-making

The process of risk-based decision-making provided by Biagiotti and Goose (2000) is illustrated in Figure 3.

Figure 3: Overall Approach to Risk-Based maintenance Optimization



The total failure cost of pipelines consists of several components, some of which may be easy to calculate while others may be difficult to compute. The categories include:

1. Cost of lost product
2. Loss of revenue

3. Cost of the pipeline repair or replacement
4. Liability costs
5. Property damage costs
6. Socio-political costs
7. Benefit of replacing the pipe segment.

The first six items are added and the seventh is subtracted therefrom.

2.3 Methods of risk-based planning of pipeline maintenance

The approaches can be classified into two major categories:

2.3.1 Subjective Index Methods

Muhlbauer (1992) and Kiefner et al (1990) reported that qualitative risk approaches assign scores to different factors that are thought to influence the probability and consequences of pipeline failure. These scores are combined using simple formulae to give an index representing the level of risk. The risk indices are then used as a basis of prioritizing and planning maintenance activities. Index approaches are simple to implement and easy to use but Nessim and Pandey (1997) provided the following limitations:

1. The risk ranking produced by index systems may be inaccurate because the relative contributions of different factors that contribute to the total risk index are defined subjectively.
2. Subjective indices provide only relative ranking of different pipeline segments so that given two segments, one can determine (subject to the above limitation) which segment has a higher risk. They do not give any indication of whether the risk associated with either of the sections is unacceptable, and consequently no guidance whether any risk reduction action is necessary.

2.3.2 Quantitative Risk Assessment

a. **Consequence estimation**

The quantitative risk assessment approach estimates the level of risk based on direct estimates of the probability and consequences of failure, following the general framework shown in Figure 3. Consequence assessment is usually based on modeling the release of product from the pipeline. There are standard consequence analysis models that can be used to quantify releases, dispersion, hazard intensity, and the degree of damage of any particular release (Lees, 1980; Hanna and Drivas, 1987; Crosswaithe, 1988). Some of these models such as Cook et al (1987) and Brzustowski (1976) have been verified and calibrated with full-scale experiment results.

b. Probability estimation

Existing pipeline risk analysis models use the historical failure rate as a direct estimate of the failure probability for a given pipeline. While this approach appears to be reasonable, its accuracy is contingent on the fundamental assumption that the data used are representative of the pipeline being analyzed. However, since the historical failure databases do not allow extraction of the failure rates for pipelines with specific attributes (diameter, pressure, wall thickness, burial depth, age, etc.), the resulting failure probability tend to be averaged over the whole pipeline network. The second main limitation is that existing approaches do not consider the on-going maintenance actions in reducing the failure probabilities, since pipeline deterioration is a continuous and irreversible process.

3.1 Research Methodology

A comprehensive listing of failure causes were compiled from existing literature and through interview of 5 engineers having over 30 years experience in pipeline engineering, operation and maintenance. An AHP model of these failure causes was built and evaluation data such as repair history, inspection records, design parameters and current operating conditions were collected. A top-down pairwise comparison was then conducted by the engineers to determine the likelihood of pipeline failure. Elements at the criteria level were first compared followed by pairwise comparison at the sub-criteria level and then finally the alternative level.

The costs of failure of the pipelines under study were estimated for each failure cause to determine their severity. This estimation was based on previous failure costs and other industry resources. Monte Carlo simulation method, using the RandDiscrete function of a RiskSim spreadsheet, was then utilized to determine the total possible cost of failure using the estimated failure costs and the probabilities generated for each pipeline by the AHP model.

3.2 Analytic Hierarchy Process

AHP is one of the methods used to scale and quantify measurements. A useful feature of the AHP is its applicability to the measurements of both tangible criteria along with intangible ones. Three major principles of analytic thought associated with AHP include:

1. Constructing hierarchy descending from an overall goal to criteria, sub-criteria and alternatives in successive levels. When constructing hierarchies, one must include enough relevant detail to:
   - represent the problem as thoroughly as possible, but not at the expense of loosing sensitivity to change in the elements;
   - consider the environment surrounding the problem;
   - identify the issues or attributes that contribute to the solution; and
   - identify the participants associated with the problem.

   Structuring the problem into hierarchy serves two purposes. First, it provides an overall view of the complex relationship of variables inherent in the problem; and second; it helps the decision maker in making judgment on comparison of elements that are homogeneous and on the same level of the decision hierarchy.
2. Establishing priorities to show how much various elements are rated relative to each other and how much this level influences elements of the next higher level, so that the relative strength of the impact of the elements in the lower level on the overall hierarchy can be calculated (Saaty, 1980). Every input is rated on a 1-9 judgment scale to determine relative importance of the different attributes on one level of the hierarchy to one another. Table 2 below shows the scale of judgments and their definitions.

Table 2: Scale of Judgments

INTENSITY OF IMPORTANCE	DEFINITION	EXPLANATION
1	Equal importance	Two elements contribute equally to the property
3	Moderate importance of one over another	Experience and judgment slightly favors one element over the another
5	Essential or strong	Experience and judgment slightly strongly

	importance	favors one element over the another
7	Very strong importance	An element is strongly favorable and its dominance is demonstrated in practice
9	Extreme importance	The evidence of favoring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	Compromise is needed between two judgments

After scales of judgment have been identified for all levels of the hierarchy, matrices are constructed for each level starting from the top of the hierarchy. To find overall priorities, the subjective judgments (1-9) are synthesized to estimate the relative priorities of the objectives with respect to each other criterion. To do so, the values in each column of the comparison matrix are added, dividing each entry in the matrix by the total of the corresponding column to obtain the normalized matrix. Finally, the entries of each row of the normalized matrix are added, dividing the total by the number of entries of each row to obtain the averages. Those averages are the estimates of the overall priorities for the lower level alternatives. These values are between 0 and 1, and their total should be unity.

Next, a hierarchic composition (synthesis) is done by multiplying the vectors of priority by the weight of the criteria, and taking the sum over all weighted priority entries corresponding to those in the next lower level, and so on. The result is the overall priority for the lowest level of the hierarchy. The priorities are derived from the matrices of judgment based on the mathematical principles of the eigenvector and the corresponding eigenvalue. The eigenvector provides priority ordering while the eigenvalue is a measure of the consistency of judgment (Saaty, 1980)

3. Logical Consistency: Although perfect consistency is hard to achieve especially when considering multiple conflicting criteria, AHP provides a mechanism of measuring the consistency of the decision made, and allows for revisions of the decision in order to reach an acceptable level of consistency. AHP measures the

consistency of judgment by means of Consistency Ratio (CR). A value of 10 percent or less shows that the decision is "good". If the value exceeds 10 percent, it means that the judgment may somehow be random and should be revised (Saaty, 1980). Calculating the CR starts with multiplying each entry of the pairwise comparison matrix by the relative priority (the average) corresponding to the column, and then totaling the row entries. Next, the row totals are divided by the corresponding entry from the priority vector. The average of those entries is the eigenvalue λ_{max}.

Consistency Index (CI) is then measured using the formula

$$CI = (\lambda_{max} - n)/(n - 1)$$

Where n is the number of elements being compared in the matrix.

The CI is then divided by its random index (RI) to get the consistency ratio, which is a measure of how much variation is allowed.

Computer software based on the AHP principles, Expert Choice, was used for evaluation and analyses.

3.3 Monte Carlo Simulation

Monte Carlo Simulation is a mathematical technique for numerically solving mathematical equations. Monte Carlo technique for simulating events can be broken into four steps:

1. Establishing probability distribution
2. Setting random numbers intervals
3. Generating random numbers; and
4. Simulating the experiment.

Input parameters are expressed as probability distribution in the form of a histogram and the computer randomly chooses a number that is used together with an input probability distribution to generate an input value. This is repeated for each input parameter, using a new random number, until all input parameters are determined. The values are then used in the equation to obtain one "simulation" or "scenario". This is repeated over and over until the required number of simulations has been obtained (Michael, 1999).

3.4 RiskSim Excel Spreadsheet

RiskSim is a Monte Carlo simulation add-in for Microsoft Excel. It provides random number generator functions as inputs for the model, automates Monte Carlo simulation. Using RiskSim can help to simulate the uncertainty associated with the model output.

3.5 Study Data

The pipelines under study, provided in Table 3, are operated and maintained by Saudi Aramco. Substantial budgets are allocated for maintaining these pipelines annually in order to keep them operational and reliable for the prosperity of the kingdom's economy.

Table 3: listing of Pipelines under study

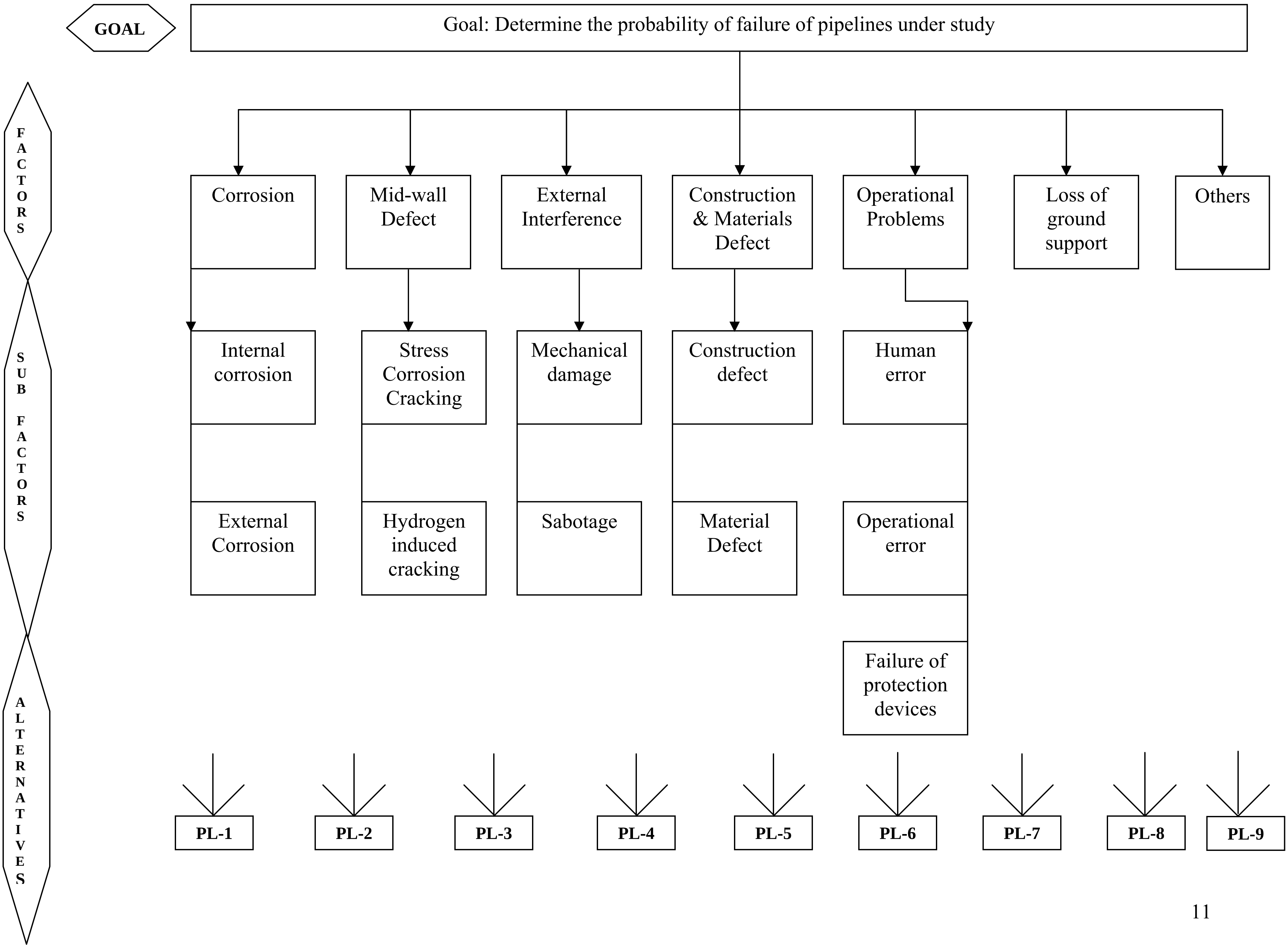
Pipeline Name	Primary service	Diameter (inches)	Pipeline Length (KM)	Coating type	Design temp.	Year built	Liquid or gas service
PL-1	SOUR GAS	32	42.443		0	1975	Gas
PL-2	NGL C3+	30	27.12	P2 SERVIWRAP	130	1976	Liquid
PL-3	NGL C3+	16	59.728	PLICOFLEX	120	1976	Liquid
PL-4	ARABLITE-SW	12	64.47	PLICOFLEX	120	1945	Liquid
PL-5	ARABLITE-SW	12	30.189	PLICOFLEX	120	1968	Liquid
PL-6	SWEETGAS	20	19.148	PLICOFLEX	120	1977	Gas
PL-7	SWEETGAS	24	18.46	PLICOFLEX	120	1974	Gas
PL-8	NGL C2+	28	212.059	PLICOFLEX	120	1978	Liquid
PL-9	PRODUCT	24	17.184	PLICOFLEX	120	1973	Liquid

The major categories of pipeline failure are:

- Corrosion – an electrochemical process that changes metal back to ore. Corrosion can either be internal or external depending on the location of initiation on the pipeline.
- Mid-wall defects - stress corrosion cracking and hydrogen induced cracking.
- External interference – malicious (sabotage or pilferage), third party or natural calamities
- Construction and Material defects
- Operational problems – human and operational error, equipment malfunction.
- Loss of ground support
- Others

The risk structure in AHP framework to determine failure characteristics of various pipelines is given in Figure 4.

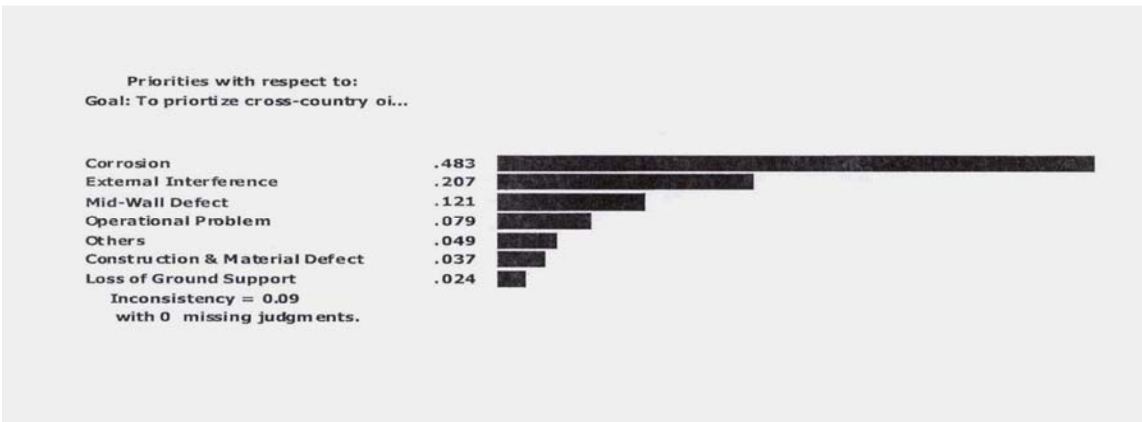
Figure 4: Risk Structure in AHP Framework to determine failure Characteristics of various Pipelines



4.1 Results and Discussion

1. The results of the pairwise comparison for the first level of the hierarchy shown in figure 5 indicate that corrosion contributes 48.3% to the likelihood of a pipeline failure. This corroborates with the real situation as indicated by the company experts and with global trend. External interference, sometimes called third party damage, is the second rated cause of a pipeline likelihood of a failure with a percentage of 20.7%. The other factors are mid-wall defects; operational problems; construction and materials defects; loss of ground support.

Figure 5: AHP Synthesis of Alternatives with respect to Goal



2. The results of the pairwise comparison of the second level of hierarchy showed that external corrosion (80%) has more impact on pipeline failure than internal corrosion (20%). This is observed in all Saudi Aramco pipelines, as most of the pipelines are old with tape wrap coating to protect them from the high saline soil of the eastern province of Saudi Arabia. Nowadays, these tape wraps are being replaced by fusion bonded coatings. On the other hand, all the factors that increase the internal corrosion are controllable through the removal of water and sulfides from petroleum products to acceptable contents. Furthermore, corrosion inhibitors are injected into pipelines that are operated with low velocity to mitigate the drop out of water in the bottom service of the pipeline. Hydrogen-induced cracking exists in most pipelines and the old industry codes are not strong enough to define pipelines materials that can resist such type of corrosion. On the other hand, stress corrosion cracking requires high operating pressure in order to produce high stress in the pipeline to accelerate

corrosion and most of the pipelines are operated well below their maximum allowable operating pressures. This justifies the pairwise results that hydrogen-induced cracking contributed 83.3% of the pipeline failure due to mid-wall defects whereas stress corrosion cracking contributes 16.7%. Further pairwise results showed that failure of protection devices is more likely to cause a pipeline failure than operational or human error. The sophisticated protection systems and strong operator training programs that limits failure resulting from operational and human errors explain this, but protection devices can fail mechanically due to malfunctioning. The above is supported by failure history, which shows rare cases of human or operational error as a cause of pipeline failure. Material defects showed a percentage of 80% over construction defects (20%). This is explained by the strong controls that are well established for pipeline construction industry.

3. After the pairwise comparisons were finalized, the synthesis of the AHP model was performed. Figure 6 shows results of the total likelihood of pipelines (alternatives) failures with respect to the goal. The final outcomes of each pipeline against the risk factors are summarized in Table 4. Both the local and global probabilities of each of the nine pipelines were computed against each of the risk factors. While local probability refers to the probability of failure in a section of the structure, global probability refers to the probability of failure in the entire structure. The global probabilities of each of the pipelines are summed up to derive the severity and the probability of the pipeline's failure and its position relative to the other eight pipelines.

Figure 6: AHP Synthesis of Alternatives with respect to Goal

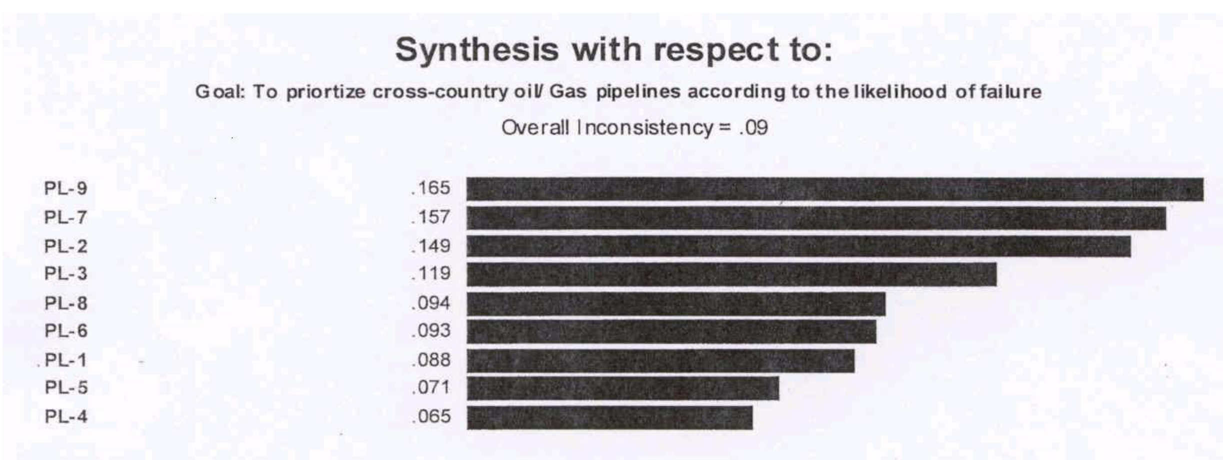


Table 4: Results of Synthesis across the hierarchy of Likelihood of Pipeline Failure

PIPELINES		AHP OUTPUT ON LIKELIHOOD OF FAILURE									
Level 1	Level 2	PL-1	PL-2	PL-3	PL-4	PL-5	PL-6	PL-7	PL-8	PL-9	Grand Total
Construction & Material Defect (L: .037 G: .037)	Construction Defect (L: .200 G: .007)	0.00021	0.00117	0.0012	0.00157	0.00051	0.00041	0.00064	0.00144	0.00017	0.00732
	Material Defect (L: .800 G: .029)	0.00084	0.00467	0.00479	0.00627	0.00202	0.00162	0.00256	0.00577	0.00069	0.02923
Construction & Material Defect (L: .037 G: .037) Total		0.00105	0.00584	0.00599	0.00784	0.00253	0.00203	0.0032	0.00721	0.00086	0.03655
Corrosion (L: .483 G: .483)	External Corrosion (L: .800 G: .386)	0.01093	0.05336	0.03276	0.02141	0.00792	0.02194	0.10572	0.01048	0.12188	0.3864
	Internal Corrosion (L: .200 G: .097)	0.02636	0.00813	0.00901	0.01522	0.02465	0.00181	0.00199	0.0032	0.00623	0.0966
Corrosion (L: .483 G: .483) Total		0.03729	0.06149	0.04177	0.03663	0.03257	0.02375	0.10771	0.01368	0.12811	0.483
External Interference (L: .207 G: .207)	Mechanical Damage (L: .889 G: .184)	0.0074	0.02455	0.02595	0.00354	0.00651	0.039	0.01434	0.04913	0.01395	0.18437
	Sabotage (L: .111 G: .023)	0.00439	0.00213	0.00275	0.00041	0.00486	0.00115	0.00084	0.00561	0.00091	0.02305
External Interference (L: .207 G: .207) Total		0.01179	0.02668	0.0287	0.00395	0.01137	0.04015	0.01518	0.05474	0.01486	0.20742
Loss of Ground Support (L: .024 G: .024)		0.00372	0.00676	0.00231	0.00146	0.00045	0.00063	0.00165	0.0023	0.00484	0.02412
Mid-Wall Defect (L: .121 G: .121)	Hydrogen Induced Cracking (L: .833 G: .101)	0.02563	0.02253	0.02284	0.00175	0.00397	0.00488	0.00571	0.00386	0.00982	0.10099
	Stress Corrosion Cracking (L: .167 G: .020)	0.00349	0.0059	0.0036	0.00138	0.00078	0.0017	0.002	0.00096	0.00039	0.0202
Mid-Wall Defect (L: .121 G: .121) Total		0.02912	0.02843	0.02644	0.00313	0.00475	0.00658	0.00771	0.00482	0.01021	0.12119
Operational Problem (L: .079 G: .079)	Failure of Protection Devices (L: .760 G: .060)	0.00291	0.00584	0.00435	0.00216	0.01044	0.0132	0.01321	0.00612	0.0015	0.05973
	Human Error (L: .096 G: .008)	0.00039	0.00044	0.00065	0.00018	0.00062	0.00162	0.00134	0.00133	0.00093	0.0075
	Operation Error (L: .144 G: .011)	0.00059	0.00066	0.00098	0.00028	0.00093	0.00245	0.00203	0.00201	0.00141	0.01134
Operational Problem (L: .079 G: .079) Total		0.00389	0.00694	0.00598	0.00262	0.01199	0.01727	0.01658	0.00946	0.00384	0.07857
Others (L: .049 G: .049) Total		0.00086	0.01241	0.0078	0.00906	0.00691	0.00296	0.00472	0.00183	0.00261	0.04916
Grand Total		0.08772	0.14855	0.11899	0.06469	0.07057	0.09337	0.15675	0.09404	0.16533	1.00001

4. The ranking of the failure probability for each factor and sub-factor based on the results of the synthesis was carried out and shown in column 2 of Table 7.

5. The pipelines' cost of failures, estimated based on the cause of the failure from each pipeline's failure record and history, were simulated using Monte Carlo. Failure intensity was classified into four groups on the basis of cost incurred as follows:
   - Small: assigned to pipelines transporting crude oil or having low pressure or having low impact on business if there are alternative flow routes e.g. corrosion.

- Medium: can take values between small failures and large failures
- Large: can take values between medium and very large failures
- Very large: assigned to pipelines transporting sour gas or any gas type/product operating under high pressure; or pipelines running through residential, industrial or agricultural areas due to involvement of high liability; e.g. mechanical damage or external interference.

Table 5 shows the cost of failure of the pipelines based on the above classification.

Table 5: Estimated Cost of Pipeline Failure with respect to Risk Factors (x1000 $)

RISK FACTORS LEVELS		FAILURE COST IN $ (X 1000)								
LEVEL 1	LEVEL 2	PL-1	PL-2	PL-3	PL-4	PL-5	PL-6	PL-7	PL-8	PL-9
Construction & Material Defect	Construction Defect	500	550	500	120	100	300	330	715	50
	Material Defect	500	550	500	120	100	300	330	715	50
Corrosion	External Corrosion	800	880	800	120	100	480	528	1144	50
	Internal Corrosion	500	550	500	180	150	300	330	715	75
External Interference	Mechanical Damage	2000	2200	2000	360	300	1200	1320	2860	150
	Sabotage	2000	2200	2000	360	300	1200	1320	2860	150
Loss of Ground Support		800	880	800	120	100	480	528	1144	50
Mid-Wall Defect	Hydrogen Induced Cracking	600	660	600	240	200	360	396	858	100
	Stress Corrosion Cracking	600	660	600	240	200	360	396	858	100
Operational Problem	Failure of Protection Devices	500	550	500	360	300	300	330	715	150
	Human Error	500	550	500	360	300	300	330	715	150
	Operation Error	500	550	500	360	300	300	330	715	150
Others		500	550	500	120	100	300	330	715	50

6. Monte Carlo simulation method was used to calculate the failure cost of each pipeline using the estimated failure costs in the above table and the probabilities generated for each pipeline by the AHP model. The simulation was done using the RandDiscrete function of RiskSim spreadsheet. The estimated cost of failure is the mean output of the simulation.
7. The overall output of the AHP and Monte Carlo simulation is tabulated in Table 6 for all the pipelines. Simulating the failure cost based on the AHP likelihood of each failure cause and each pipeline resulted in ranking pipelines with respect the risk as shown in Table 7.

Table 6: Monte Carlo Simulation Output for Estimated Cost of Pipelines Failure

PIPELINES / RISK FACTORS LEVELS		PL-1		PL-2		PL-3		PL-4		PL-5		PL-6		PL-7		PL-8		PL-9	
Level 1	Level 2	Cost of Failure 1000$	LH	Cost of Failure 1000$	LH	Cost of Failure 1000$	LH	Cost of Failure 1000$	LH	Cost of Failure 1000$	LH	Cost of Failure 1000$	LH	Cost of Failure 1000$	LH	Cost of Failure 1000$	LH	Cost of Failure 1000$	LH
Construction & Material Defect	Construction Defect	500	0.00021	550	0.00117	500	0.0012	120	0.00157	100	0.00051	300	0.00041	330	0.00064	715	0.00144	50	0.00017
	Material Defect	500	0.00084	550	0.00467	500	0.00479	120	0.00627	100	0.00202	300	0.00162	330	0.00256	715	0.00577	50	0.00069
Corrosion	External Corrosion	800	0.01093	880	0.05336	800	0.03276	120	0.02141	100	0.00792	480	0.02194	528	0.10572	1144	0.01048	50	0.12188
	Internal Corrosion	500	0.02636	550	0.00813	500	0.00901	180	0.01522	150	0.02465	300	0.00181	330	0.00199	715	0.0032	75	0.00623
External Interference	Mechanical Damage	2000	0.0074	2200	0.02455	2000	0.02595	360	0.00354	300	0.00651	1200	0.039	1320	0.01434	2860	0.04913	150	0.01395
	Sabotage	2000	0.00439	2200	0.00213	2000	0.00275	360	0.00041	300	0.00486	1200	0.00115	1320	0.00084	2860	0.00561	150	0.00091
Loss of Ground Support		800	0.00372	880	0.00676	800	0.00231	120	0.00146	100	0.00045	480	0.00063	528	0.00165	1144	0.0023	50	0.00484
Mid-Wall Defect	Hydrogen Induced Cracking	600	0.02563	660	0.02253	600	0.02284	240	0.00175	200	0.00397	360	0.00488	396	0.00571	858	0.00386	100	0.00982
	Stress Corrosion Cracking	600	0.00349	660	0.0059	600	0.0036	240	0.00138	200	0.00078	360	0.0017	396	0.002	858	0.00096	100	0.00039
Operational Problem	Failure of Protection Devices	500	0.00291	550	0.00584	500	0.00435	360	0.00216	300	0.01044	300	0.0132	330	0.01321	715	0.00612	150	0.0015
	Human Error	500	0.00039	550	0.00044	500	0.00065	360	0.00018	300	0.00062	300	0.00162	330	0.00134	715	0.00133	150	0.00093
	Operation Error	500	0.00059	550	0.00066	500	0.00098	360	0.00028	300	0.00093	300	0.00245	330	0.00203	715	0.00201	150	0.00141
Others		500	0.00086	550	0.01241	500	0.0078	120	0.00906	100	0.00691	300	0.00296	330	0.00472	715	0.00183	50	0.00261
Likelihood of No failure		0	0.91228	0	0.85145	0	0.88101	0	0.93531	0	0.92943	0	0.90663	0	0.84325	0	0.90596	0	0.83467
ESTIMATED FAILURE COST X 1000 $		104.33		165		124.67		14.2		16.67		82.4		85.36		269.79		9	

Table 7: Final Ranking of Pipelines for Maintenance planning

Pipeline	Severity rank	Likelihood rank
PL-8	1	4
PL-2	2	3
PL-3	3	5
PL-1	4	7
PL-7	5	2
PL-6	6	6
PL-5	7	8
PL-4	8	9
PL-9	9	1

Note that although, the likelihood of pipeline PL-8 encountering failure is ranked 4, its severity is the highest with the cost of the failure almost 29 times that of PL-9 whose likelihood of failure is highest. This suggests that PL-8 should be given the highest priority for maintenance during the next year budget. Possible reasons for this includes the high cost associated with losing the line resulting in major business interruption, and the vulnerability of the pipeline to external interference which results in major leakage that is aggravated by high pressure and subsequent increased gas loss into the atmosphere. On the other hand, PL-9 which has the highest likelihood of failure is operating only 15% of its maximum operating pressure and thus if failure occurs, rupture is not expected and the amount of product loss will be minimal.

5.0 Conclusions and Recommendations

This paper describes the use of AHP / Monte Carlo simulation to determine the risk level associated with operating the cross-country pipelines. The study reveals the effect of certain risk factors on the failure of pipelines/pipeline sections. The developed model will enable management formulate cost-effective, customized, flexible and systematic maintenance program.

In the light of the findings of this study, the following recommendations are being offered:

1. The risk level obtained in terms of monetary values should be a basis for maintenance planning and prioritization of pipelines
2. More attention should be given to pipelines that have higher failure consequences even though they have less likelihood of failure.
3. A semi-annual meeting should be held with representatives of operation, maintenance, and engineering departments to share ideas and in deciding the criteria and pairwise comparison.
4. A further work on the calculation of the benefits versus cost ratio of the recommended maintenance strategy is recommended.
5. The sensitivity analysis feature available in the expert choice can be used to resolve the conflicts that may occur when a team is assigned to conduct the pairwise comparison.

6.0 References

Biagiotti, B.F. and Gosse, S.F. (2000). Formalizing pipeline integrity with risk assessment methods and tools. 2000 International Pipeline Conference Proceedings, Vol. 1 ASME 2000.

Cassely, A.L. and Johnson, A. (1994). Pipeline performance in Alberta. Proceedings of the 1994 NACE International, Canadian Region Western Conference, National Association of Corrosion Engineers, February.

Crosswaith, P.J. Fitz, R.D. and urst, N.W. (1988). Risk assessment for the siting of development near liquefied petroleum gas installations. Symposium series No. 110, Institute of Chemical Engineers, 373-400.

EGIG (1993). Gas pipelines incident reports 1970-1992. European Gas Pipeline Incident Data Group.

Hanna, S.R. and Drivas, P.J. (1987). Guidelines for use of vapor cloud dispersion models. Center for Chemical Process safety, American Institute of Chemical Engineers.

Hopkins, P. (1994). Ensuring the safe operation of older pipelines and off-shore contractors associations, 28th Convention, September.

Jamieson, R.M. (1986). Pipeline integrity monitoring. Pipeline Integrity Conference, Aberdeen, Scotland, October.

Kiefner, J.F. Veith, P.H., Orban, J.E. and Feder, P.I. (1990). Methods for prioritizing pipeline maintenance and rehabilitation. Pipeline Research Council, Houston.

Lees, P.L. (1980). Loss prevention in the process industries. Butterworth Group, London.

Mahlbauer, W.K. (1992). Pipeline risk management manual. Gulf publishing company, Houston.

Michael, M.R. (1999). Monte Carlo Simulation using RiskSim. Decision Support services Inc., San Francisco.

Nessim, M.A. and pandey, M.D. (1997). Reliability based planning of inspection and maintenance of pipelines integrity, Center of Engineering Research inc., Alberta.

Saaty, T.L. (1980). The Analytic Hierarchy Process. McGraw-Hill, New York.