Risk Assessment and Integrity Management of Three Cross-Lake Pipelines

Abstract:
For the first time in Iran, a Pipeline Integrity Management (PIM) Program was developed for a set of cross-lake pipelines in Khuzistan province, south of Iran. The pipelines were being designed to carry oil, gas and condensate that contain up to 9,500 ppm of H2S. Since the design was still in its basic stage, it was the main objective of the study to determine the least risky way of crossing the lake through a traffic bridge. There were 3 main alternatives for each pipeline to study. In order to do so, a formal risk assessment of pipeline threats was performed using first a preliminary hazard analysis technique to identify hazardous situations. Next, the project team performed quantitative modeling of hazardous scenarios that lead to better understanding of the dimensions of fire and explosion threat to people, passing vehicles and the bridge itself. The tools used for this step were a professional modeling software and computational fluid dynamics (CFD). A comprehensive survey of pipeline accident statistics in USA, Europe, UK, and the former Soviet Union was made in order to relate the identified hazards to world statistical data headings. Then, the team derived typical failure rates from various scientific sources and assigned them to each failure scenario as a function of leak size. Subsequently, combining the above statistics with these data, allowed the team to establish a representative set of failure frequencies to each scenario as a function of failure type. A final risk ranking step that incorporated other important aspects like pollution potential, ease of maintenance, complexity of protective systems as well, allowed comparison of the three main alternatives in mitigated and non-mitigated states and determination of the best alternative. Based on the findings, and taking into consideration the specific characteristics of the pipelines under study, an integrity management program was developed. Although the current pipeline integrity management practices are used mainly for very long pipelines, their guidelines are very useful in preparation of PIM’s. The prepared PIM program was developed into a comprehensive framework incorporating instructions for pipeline data management, operational risk assessment methodology, typical defects of the pipelines, suitable testing and inspection techniques and tools, inspection schedule, in-line inspection data analysis and action-taking, corrosion control and monitoring, leak detection and remedial actions, accident prevention and mitigation methods, and applicable maintenance and repair methods.

Keywords: Pipeline Integrity Management (PIM), Pipeline Risk Assessment, Pipeline Risk Management, Fire and Explosion, Accident Simulation, Pipeline Inspection and Maintenance

Introduction
Objectives, Problem Definition and Alternatives
As a result of building a dam on river Lali, near Gotvand in Khuzistan Province, Iran, the level of water will rise and the locations of a number of oil and gas production units together with the interconnecting pipelines will be covered with water.

The operator of the units has decided to relocate the units in order to continue operation. It is planned to build a series of pipelines to cross the lake that will form behind the dam. The main purpose of the pipelines is to transport sour gas and oil to nearby Haft Shahidan Production Unit near Masjid Soleyman. Figure 1 is a schematic of the project area showing the path of the pipelines and the location of the bridge.

Alternatives of Pipeline Crossing over the Bridge
To cross the lake, the pipelines will be installed on a bridge that will also be used for public local road traffic.

The main alternative envisaged by the operator for building the pipelines is to install them in a corridor to be built under and along the bridge.

There is a second alternative in which the oil pipelines run on both sides of the upper surface of the bridge and gas pipelines to run beneath the extension of the two sides of the bridge.

As the third alternative, the operator had intended to install the pipelines on the top surface of the bridge along the road so that oil pipelines are on one side of the bridge and the gas pipelines on the other. Figure 2 shows the three alternatives. Dark lines depict oil/condensate pipelines, while grey lines show gas pipelines.
All the alternatives had to be studied and compared according to the criteria of the project, namely safety (risk), environmental pollution of the lake, and project economics. The diagram in Figure 3 shows how the initial risk assessment is used for preparation of project documents. Further details about the risk assessment step are given later in this paper.

Criteria and Scope of Work

Client required that the pipelines be designed and built in such a way that minimizes adverse safety and environmental impacts, based on a thorough risk assessment of alternatives. Some of the highlights of client requirements follow:

- To identify and analyze external risk factors
- To foresee any possible damage to pipelines where gas or oil could leak
- To determine qualitatively and quantitatively impacts of damage scenarios
- To envisage suitable measure for prevention/mitigation of accidents
- To make use of health, safety and environment criteria in analyzing risks
Risk Assessment

The Role of Risk Assessment

Very much like in process plant safety management, pipeline regulatory authorities in Canada, USA and the UK are moving away from prescriptive approaches to pipeline design and operation, to ‘risk management’ as the safest and most cost effective means of maintaining and improving safety levels in pipelines. [1] Risk management is a combination of risk assessment and risk control. Additionally, operators and regulators are recognizing the importance and usefulness of ‘management systems’. A Pipeline Integrity Management System is a requirement in the European Community, as well.

Risk management in pipelines is a cyclic development, in which risks are continuously monitored, assessed and managed (Figure 3). [1] Continuous improvement cycle like what is customary in piping integrity management [2], as depicted in Figure 4 helps operator of the pipeline to establish a system of in time repair and maintenance in order to assure safety and reliability of the pipeline.

The design phase is the best time to undertake a pipeline risk assessment and to prepare a pipeline integrity management program. It is true that at the design stage there are a number of unknowns that prevent accurate prediction of pipeline threats in actual conditions. But, at the same time, performing a risk assessment at this stage is a preventive measure in itself, as it reveals shortcomings, can lead to identification of improvement opportunities and makes possible implementation of remedial options while there is still time to correct any problems. It is much more cost-effective, as well, to correct the problems at this stage.

Models for Risk Assessment of Pipelines

Three general types of models are available for risk assessment in pipelines. From simplest to most complex, these are matrix, probabilistic, and indexing models. Each has strengths and weaknesses, as discussed below [3]:

Matrix models

One of the simplest risk assessment structures is a decision analysis matrix. It ranks pipeline risks according to the likelihood and the potential consequences of an event using a common risk matrix.
Each threat is assigned to a cell of the matrix based on its perceived likelihood and perceived consequence. This approach may simply use expert opinion or quantitative information to rank risks. While this approach cannot consider all pertinent factors and their relationships, it does at least break the problem into two parts (probability and consequence) for separate examination.

**Probabilistic models**

The most rigorous and complex risk assessment model is a modeling approach referred to as quantitative risk assessment (QRA). This technique is used in the nuclear, process, and aerospace industries. It is a rigorous mathematical and statistical technique that relies heavily on historical failure data and event analyses. Initiating events such as equipment failure and safety system malfunction are flowcharted forward to all possible concluding events, with probabilities being assigned to each branch along the way.

This technique is very data intensive. It yields absolute risk assessments of all possible failure events. These more elaborate models are generally more costly than other risk assessments.

**Indexing models**

Perhaps the most popular pipeline risk assessment technique in current use is the index model or some similar scoring technique. In this approach, numerical values (scores) are assigned to important conditions and activities on the pipeline system that contribute to the risk picture. This includes both risk-reducing and risk-increasing items or variables. Weightings are assigned to each risk variable. The relative weight reflects the importance of the item in the risk assessment and is based on statistics where available and on engineering judgment where data are not available. Among pipeline operators today, this technique is widely used.

Although each risk assessment method discussed has its own strengths and weaknesses, the indexing approach is especially appealing because it provides immediate answers with low cost, it is comprehensive and it identifies and places values on risk mitigation opportunities.

A drawback of this technique is the possible subjectivity of the scoring. Extra efforts must be employed to ensure consistency in the scoring and the use of weightings that fairly represent
real-world risks. A serious limitation of this technique is that it is most effective when the pipeline under study is actually in operation and suitable (automatic) data gathering means are in place.

The Selected Risk Assessment Approach

A team comprising process and safety engineers undertook semi-quantitative risk analysis of the project alternatives in order to establish a common basis for comparison of the alternatives.

The study was planned to be completed in four steps, as shown in Figure 5. First, a preliminary hazard analysis was performed to identify hazardous situations. Next, the project team performed quantitative modeling of hazardous scenarios that lead to better understanding of the dimensions of fire and explosion threat to people, passing vehicles and the bridge itself. The next step was to determine frequencies of identified hazard scenarios. A final risk ranking step incorporated other important aspects like pollution potential, ease of maintenance and complexity of protective systems as well.

This step allowed comparison of the three alternatives in mitigated and non-mitigated states and determination of the best alternative. Based on the findings, and taking into consideration the specific characteristics of the pipelines under study, an integrity management program and an emergency response plan were developed.

The project team decided to adopt a midline approach to risk assessment. Because, the level of knowledge about the pipeline was not so high to allow a full indexing method to be used and this was decided to be recommended for the operation phase. It was not so low, either, to rule out more accurate (quantitative) methods to be used. Therefore, it was decided to use QRA as the basis for the risk assessment step.

Figure 5. Risk assessment framework in this project

A. Hazard Identification:

As the first step in risk assessment for the project, the team undertook a HAZID study to identify hazardous situations pertinent to the pipelines under study. These included:

- Third-party damage (TPD)
- Internal corrosion
- External corrosion
- Geohazards
- Bad operation
The objectives of the study were:
- To identify critical problems and hazards
- To obtain better understanding of possible hazards, and
- To propose preliminary preventive and mitigation measures early in the design

The study was performed on each alternative, separately. A total of 25 recommendations were obtained as a result of this study.

B. Consequence Modeling

Understanding consequences of leak and rupture scenarios were crucial in later stages of the project. First, the nature of these scenarios could give the team a detailed insight on the nature of hazards that could be expected from the scenarios should they develop. Knowing this, the team could propose suitable prevention and mitigation measures to be included in the pipeline integrity management program. Another benefit of the approach was to make comparison between alternatives possible because at the end of this stage, it was required by the client to select the best alternative based on the level of risk as the main factor.

Comprehensive consequence modeling of was conducted for various leak and rupture scenarios. Process data (stream temp, press, flow rate, composition), meteorological data and geometry data were used to define the scenarios for each pipeline. A total of 22 scenarios were modeled using PHAST, a professional software tool for consequence modeling. Some detailed studies were also performed using FEMLAB, which is a CFD tool. The main reason for use of CFD was to study the behavior of toxic gas (H2S) after release from pipelines, and the effect of complex geometries on it.

The results of the modeling, which is commonly represented in graphical form (see Figure 6), gives concentration profile of H2S in space, toxic gas plume rise, maximum concentration of toxic gas in different points, radiation profile for jet fires, pool fires and flash fires and overpressure levels in explosion scenarios.

Figure 6. Sample results of consequence modeling using PHAST and FEMLAB
C. Frequency estimation, failure data and statistics

Failure statistics from the following sources were used in the study:

- EGIG: European Gas pipeline Incident data Group
- EUB: Alberta Energy and Utilities Board, Canada
- NEB: Canadian National Energy Board
- OPS: U.S. Office of Pipeline Safety
- PHMSA: Pipeline and Hazardous Materials Safety Administration

In addition to the above sources, statistics published by DNV that covers European pipelines including the former Soviet Union [4] were also used. These sources provided raw, average, failure frequency data for inclusion in the frequency estimation step.

Then, the complex outcomes of leak and rupture scenarios were captured, using Event Tree Analysis (ETA). ETA is an inductive method that describes and models different factors that can change the final outcome(s) of an accident. Here, the probabilities of immediate ignition, day or night occurrence of the accident, or a delayed ignition following release, among others, were considered. The failure frequencies obtained in the previous step were used as the starting point in the event trees for each scenario.

While event probabilities are normally recorded as frequency vs. hole size, the available pipeline failure frequencies were reported relative to failure mechanisms. So, a part of the study was to relate the available data to hole sizes of interest in the study.

To determine the impacts of each scenario, including fire, explosion and toxic release, the team first overlaid effect zones on the plot plan of the bridge. Then, using Probit approach, estimation was made of the probability of deaths in the vicinity of the accident point. For the estimation, it was necessary to take into account the difference between traffic load at night and during daytime.

D. Selection of the Best Alternative:

In order to evaluate relative advantage of each alternative, the team used a combined approach in which the risk level together with the following factors was taken into account:

- Pollution potential
- Ease of inspection, repair and maintenance
- Complexity of fire fighting system

To include all these items in final assessment, it was necessary to weigh each item against others. In other words, the team needed to assume a relative importance coefficient for each factor. For determination of these coefficients for each factor, two elements were considered:

- The reasonable absolute overall importance of the factor
- The reasonable relative priority of each factor compared to other factors

Each additional factor was given a range of 1 to 6 to make possible differentiating between alternatives in terms of these factors. Upon summation of all above contributions, an overall score was calculated for each alternative. The calculation was done once for each alternative without mitigation measures and once assuming they were implemented. The best alternative was the one with the lowest score.

The best alternative so determined was the third alternative, that is, to build the oil pipelines on one side of the bridge on its upper surface along the road and the gas pipelines on the other. The second best was the second alternative. However, the difference between scores of the best and second best alternatives was marginal.

In all circumstances, the role of mitigation was obvious: It clearly reduced the final score. Other factors to consider in the selection of the best alternative are engineering and construction costs, pipeline supporting, etc. These were not part of this study.
Pipeline Integrity Management (PIM) Program

Background

"Integrity" of pipe work means the absence of failure of pipe work. The goal of pipeline operators is to operate the pipeline in such a way that there are no adverse effects on employees, the environment, the public, or their customers as a result of their actions.

A modern integrity management program provides a means to improve the safety of pipeline system and allocate operator resources effectively to:
- Identify and analyze actual/potential prior events that can result in pipeline accidents
- Examine the likelihood and potential severity of pipeline incidents.
- Provide a comprehensive and integrated means for examining and comparing the spectrum of risks and risk reduction activities available.
- Provide a structured, easily communicated means for selecting and implementing risk reduction activities.
- Establish and track system performance in order to improve it.

This program is developed in order to protect “high consequence areas.” A high consequence area (HCA) is an urbanized area, as defined and delineated by the U.S. Census Bureau, that contains 50,000 or more people and has a population density of at least 1,000 people per square mile. [5] However, a given area is considered an HCA if certain environmental or otherwise sensitive or critical areas are concerned.

The rule requires that operators develop and implement a written integrity management program. This integrity management program must include [5]:
- An identification of all pipeline segments that could affect a high consequence area in event of a pipeline failure.
- A plan for conducting baseline assessment of the line pipe in these segments.
- A framework that addresses how each element of the operator's integrity management program will be implemented.

Pipeline integrity management is a continuous improvement process as demonstrated earlier, and the management plans are updated on the basis of the acquired data and information. So, PIM includes these major activities:
- Assess, evaluate, repair and validate through comprehensive analysis the integrity of pipeline segments.
- Prevent a leak or failure that could affect populated areas, areas unusually sensitive to environmental damage and commercially navigable waterways.
- Develop and follow a program that provides for continually assessing the integrity of all pipeline segments that could affect these high consequence areas.
- Provide for periodically evaluating the pipeline segments through comprehensive information analysis, remediation of potential problems found through the assessment and evaluation.
- Continue with devising additional protection to the segment and high consequence areas through preventive and mitigation measures.

Pipeline accidents have been highly influential in development of increasingly stringent regulations, as well. [6] Various standards have been developed or proposed in recent years to cover PIM for hazardous liquids [5] or gases [7].

PIM Framework in This Project

Integrity program is built into pipeline system from initial planning, design, and construction. It is a flexible program that may be changed and updated through the operation phase. Continuous evaluation is required to be sure the program takes appropriate advantage of
improved technology and that the program remains integrated with the operator's business practice and effectively supports the operator's integrity goals.

The framework of the PIM in this project comprises these categories:

- Data management
- Implementation of risk assessment
- Development of PIM
- Revision of the PIM
- Testing and inspection techniques, tools and schedule
- Maintenance and repair methods (suitable for hydrocarbon gases and liquids and using modern in-line data analysis system)

The preventive/mitigation activities that were incorporated into the integrity management program of the project are as follows:

1. Prevention of TPD:
   TPD is a major cause of pipeline releases. Current US DOT data indicates that roughly one-quarter of all reported pipeline incidents are caused by TPD. [5] The following mitigation activities are considered:
   - Using pipeline marking signs
   - Establishment of a one-call system
   - Employing a monitoring system (SCADA)
   - Right-of-way maintenance
   - Applying regular patrolling
   - Additional pipe wall thickness
   - Pipeline marker tape or warning mesh installed over pipeline

2. Controlling corrosion
   The impact of corrosion on pipeline failures is not the same in various parts of the world. However, it is by far the most influential factor in creation of mid-range leaks. These mitigation measures are considered against internal and external corrosion:
   - Monitor and maintain cathodic protection
   - Rehabilitation of pipeline coatings

3. Minimizing the consequence of unintended releases
   In event of an unintended product release from within a pipeline system, the consequence can be minimized by reducing the time required for detecting and/or locating the release, reducing the volume that can be released or reducing emergency response time. The following means were proposed for realization of these objectives:
   - Installation of release detection systems such as dynamic flow modeling, use of tracer chemicals, using release detection cables and shut-in (static) release detection systems.
   - Mechanical devices to enable pipeline shut-down (LBV’s)
   - Improved emergency response (an independent emergency response plan was also developed, see Figure 5)

4. Operating pressure reduction

5. Miscellaneous preventive measures
   These can be classified into the following categories:
   - Reducing probability of accidents that can lead to leakage, such as road side reinforce concrete guards
   - Reducing probability of leakage and ignition of sour gas by adequate ventilation and installing a gas detection and alarm system.
Conclusions

Client Requirements
Pipeline integrity management is a rapidly developing field, both inspired by experience and technological advancements. Benefits of such programs are various, including improved ability to manage risk, optimized operational and capital expenditures, conforming to the industry standards for operation and maintenance, elevated confidence of senior management, stakeholders, regulators, employees, and the community at large. However, since the standards are new to our country, these benefits are still to be realized.

A direct outcome of this is that the scope and objectives of these programs are not yet clear. One example is that PIM’s cannot be completed before operation starts and actual operating data are available. It requires therefore, that the operator adjusts its expectations from a PIM that is prepared at design stage, its data requirements, applicable methods, etc.

Another issue is the technological implications of a good PIM. Like in many other fields, good integrity management needs good tools, both hardware and software. Sophisticated smart pigs are just one example of important supporting tools in today’s PIM’s, especially in long pipelines. Management issues like leadership and commitment to pipeline inspection, monitoring, maintenance, etc. are another example. No PIM can be successfully implemented without intelligent, systematic use of these tools.

Data and Information
For this study, statistics of pipeline failure frequencies were available from nearly all parts of the industrialized world. Access to a local database, if such a database exists, would have helped more accurate analysis to be performed.

From the viewpoint of this study, it was not absolutely necessary to have such a database at hand because the project team believed local failure frequencies would not be fundamentally different from world statistics, given the level of experience of the Iranian operator in managing the already longest pipeline network in the region.

However, having such a database could have helped gain much better confidence as to accuracy of the results, although the main objective if the study was to compare a number of alternatives not calculating the absolute values of risk.

An additional point is the implications of creating and maintaining such a database, that the Iranian operator should be aware of. The advantages and the reason behind usability of international failure databases are their scientific approach, uniformity, continuity and ready availability.

Other Alternatives
Perhaps a shortcoming of the study was that of ignoring a less risky option: a dedicated pipeline bridge. However, the client had not considered this alternative.

Another option was to stick with the first alternative while employing a sophisticated monitoring and control system. Due to technical reasons, and also because of its cost, this option was not also of concern.

Risk criteria were another major concern. Since nationally approved risk criteria are not available, risk studies of this kind cannot be performed in absolute terms. While adopting these criteria is advised, this was not a particular concern or limitation because all risk assessments were done on relative terms for comparison between alternatives.

The final conclusion from this study was the necessity of coordination between stakeholders. In the current project, there were certain limitations due to differences between the client and public departments that govern the dam, the roads and the environment. Resolving these differences can greatly facilitate risk assessment and integrity management activities.
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