Developing Tolerable Risk Criteria for Gas Transmission Pipelines

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ABSTRACT
After completing an extensive risk assessment stage, PGPB’s Risk Management Team was ready to move towards Risk Management philosophy. Comparing PEMEX’s algorithm with the typical values of the industry enabled the risk assessment approach adopted in PGPB. As a result of a comprehensive study that gathered several of the users of the same analysis tool, an optimised and normalised algorithm was obtained to support the risk assessment programme and comply with the company’s policies.

The risk assessment stage included more than 1,700 kilometres of LPG pipelines and 3,500 kilometres of natural gas. This stage was granted as final until consistent risk values were achieved in every segment section. To move into the Risk Management stage a comprehensive study was performed to define tolerable risk criteria for PGPB pipeline network.

INTRODUCTION
This study included PGPB cumulated statistics of incidents to define a monetised Risk of Failure, ROF, as a function of the number of events per year of operation, associated with seven risk factors. For the Consequence of Failure, COF, it was decided that the best way to represent PGPB’s needs was through a Willingness to Pay to Avoid (WTPA) severe incidents in any pipeline segment. The metrics for Consequence of Failure are expressed as the cost for service interruption, repairs, product loss, injuries and fatalities, property and environment damage, all related to three types of impacts. The magnitude of the consequence is calculated as the cost per event, therefore the Total Risk value is obtained as a cost per year when multiplying the risk of failure value by the corresponding consequence. Some definitions were needed to measure risk values calculated from the risk assessment. A multidisciplinary engineering team participated to provide the input of the risk management programme. This group decided to issue a risk classification according to WTPA.

DEVELOPMENT OF A QUANTITATIVE RISK MODEL
The main purpose of a quantitative risk model is to close the gap between Risk Assessment and Risk Management stages to obtain Pro-Active Maintenance programmes. The risk assessment approach used in PGPB is based on an index model. One of the limitations inherent to any pure index based relative risk model is that the end result is a relative number with no link to absolute quantitative risk. An index based relative risk model can only suggest that one estimate of risk of failure is better or worst than another. The limitations identified in such a model were:

1) it is not possible to quantify the results in a meaningful way
2) does not indicate which values mean actual risk of failure and,
3) does not reflect clearly any improvement when lowering the relative risk score.

A more useful score is an output providing events per kilometre per year of operation. A quantified score may be used to support activities or projects selection to control or reduce risk in a pipeline.

PGPB goal is to focus its budget in those pipeline locations where risk reduction will provide the greatest benefit in terms of financial performance, safety, operation and environmental protection.

The risk management model developed for PGPB pipelines is based on a risk index model which results are transformed into a monetised form where total risk can be identified in terms of real money ($USD).

METHODOLOGY TO TRANSFORM RISK OF FAILURE – ROFS
To create a transformation for each index, a four step approach was used for every of the risk index model factors that have a contribution on the Risk of Failure value, ROF:
1. The middle points of Risk of Failure Data and actual PGPB incident statistics for the factor transformation were determined by taking the average of the available ROF scores.

2. ROF scores near to the lowest ROF value, middle ROF value and highest ROF value from the risk assessment were selected as representative risk values for every segment section.

3. Failure rates were calculated by using the change in pipeline risk of failure characteristics from the medium to low and medium to high in order to estimate the change of ROF for those low and high values.

4. Finally, a non-linear regression process was applied to the failure rates and ROF scores to estimate the required coefficients to transform ROF to ROF$.

This approach allows calculating a quantitative Total Risk Value (TR$) in US dollars per year of operation for one-mile sections of pipe for Natural Gas, LPG and petrochemicals. TR$ is calculated from:

$$TR$ = ROF$ \times COF$$

Where ROF$ is the expected frequency of pipeline failure in events per year and COF$ is the associated consequence of failure in thousands of US dollars per event. The expected frequency of failure is calculated as:

$$ROF$ = ECS + ICS + TPS + GMS + DMS + SO$$

The terms on the right-hand side of the equation are expected frequencies of failure in events per year per 1,000 miles of pipe for failures due to External Corrosion (ECS), Internal Corrosion (ICS), Third Party (TPS), Ground Movement (GMS), Design/Materials (DMS) and System Operation SO. Each of these factors is related to the Risk Assessment approach adopted by PGPB.

Risk of Failure (ROF) transformation curves and corresponding equations were derived from average ROF index values and PGPB average incident histories for the years 1990 to 1998. An average incident rate or event frequency for each risk factor was then calculated in terms of events per year in a system of 10,000 miles.

A summary of these results is provided in the following table:

<table>
<thead>
<tr>
<th>Risk Sub-Factor</th>
<th>Event Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eternal Corrosion</td>
<td>3.98</td>
</tr>
<tr>
<td>Internal Corrosion</td>
<td>0.57</td>
</tr>
<tr>
<td>Third Party</td>
<td>3.60</td>
</tr>
<tr>
<td>Ground Movement</td>
<td>0.57</td>
</tr>
<tr>
<td>Design / Materials</td>
<td>2.19</td>
</tr>
<tr>
<td>System Operation</td>
<td>1.14</td>
</tr>
<tr>
<td>Total Risk</td>
<td>12.05</td>
</tr>
</tbody>
</table>

Table 1. Event Frequency per Factor

Average ROF index value was related to the respective PGPB average event frequency for each risk factor. This provided a mid-point value for the transformed ROF versus the ROF index value as shown in Figure 1.

The low-point and high point event frequencies in events per 10,000 miles per year for the corresponding low and high index values were estimated based on an evaluation of the sub factor influences for each risk factor. The quantitative PGPB average incident history from 1990 to 1998 was used for the baseline for a given risk factor.

Sub-factors attributes were ranked to determine their influence on the value of 'Low' and 'High' event frequencies. The ranking was established by examining the sub-factors attributes from best to worst. The attributes are equally weighted from the average PGPB event frequency. The individual weight of each attribute is calculated as a percent change from the sub-factor attribute provided by the actual PGPB entries into the risk model for each ROF factor.
The process is repeated for each sub-factor influence for each risk factor. The variances for Low-Point and High-Point events are then added to the Medium event value. The resulting values are the Low and High event frequencies, respectively. These are combined with the Mid-Point event frequency to provide the three points needed to determine the risk factor curve and equation.

In some cases, the ranking of sub-factor influences as given on the risk model data sheets was complicated, particularly in those cases where the unknown option had to be selected. To avoid these complications a well balanced algorithm was obtained to compensate those variables where there was no input available.

For these cases the sub-factor attribute ranks are based on our experience in determining which factors are of greater or lesser impact. The contribution of the sub-factor attribute to the risk factor must be considered as well. For example, if the sub-factor is not believed to significantly contribute to the risk factor, then the sub-factor should not be included in this calculation. As a result of this study, we were able to identify sub-factors considered to be less significant when compared to other sub-factors in influencing each risk factor.

METHODOLOGY TO DETERMINE COF TRANSFORMATION – COFS

The risk model consequence of failure (COF) results, from a purely index-based relative risk model, are similar to the ROF results. The final result is a relative number with no link to absolute quantitative risk. The PGPB model determines consequence of failure (COFS) in a more useful quantified sense. This value for consequence is expressed in terms of dollars per event. The COFS may be used to make more effective project selections to reduce the consequence of failure and total risk associated with a pipeline.

This model enables PGPB to make informed risk reduction maintenance decisions based on dollars at risk, in lieu of the unit-less score derived from the risk assessment model.

The COF scores are transformed into quantified values in similar terms as calculating ROFS value. COFS scores are developed from actual data on event magnitudes and values of consequences developed for PGPB when setting the transformation equations then associated with past pipeline incident events. Using this input, a COFS value with an actual dollar interpretation can be calculated for a pipeline failure.

Description of General Approach

Each factor contributing to COFS was calculated as the value of the consequence (VOC) multiplied by the magnitude of the consequence (MOC). As VOC essentially remains constant, only MOC values required transformation. Similarly to the way the ROF transformations were calculated, a three step process was used for a majority of the factors that contribute to COFS.

1. Both average industry and average PGPB values for MOC were calculated and designated as 'ideal' averages.

2. Using non-linear regressions techniques, the coefficients for the transformation from risk assessment factors to MOC values to attain the 'ideal' averages were calculated.

3. The VOC values were multiplied with the MOC coefficients to obtain a COF to COFS transformation.

Data Collection

Industry average values of MOC were gathered from OPS statistics. PGPB provided input for those MOC values not available in OPS statistics.

The majority of the average VOC values used in the transformations were taken from a value model specially defined for PGPB needs and complemented with OPS figures where required.

The quantitative approach may be separated into three main components, just like the risk assessment model. These parts are defined as follows:

- IOB$ is the impact PGPB business from product loss (PROD$), repair cost (REP$), and shutdown cost (SHD$).
- IOE$ is the impact to PGPB from environmental damage in terms of property damage (DAM$).
- IOP$ is the impact on population as measured as the combination of fatalities (FATS) and injuries (INJ$).

All the variables to determine COFS were validated by PGPB's staff and supported with
real data of pipeline network. The variables description is as follows:

**PRODS** - represents product loss and is related to the impact in business. The estimates for the MOC transformation were calculated regressing non-linearly the product loss upon a factor score for one-mile section such the average resulting values matched the ideal MOC values. Product loss was calculated as the sum of the mean initial loss and mean stabilisation loss of the ranges in the index model. The final PRODS transformation was the MOC transformation multiplied by the VOC based on the PEMEX supplied product cost.

**REPS** - repair and rehabilitation costs were considered as constant per failure event.

**SHDS** - the highest impact rate was estimated from business impact of failure. The final SHDS transformation was the MOC multiplied by the VOC based on the PEMEX’s shut down costs.

**DAMS** - similarly to above cases, the average potential property damage was determined upon a factor score for each one-mile section. As the MOC is already expressed in dollars per event DAMS is equal to the MOC.

**FATS** - the final FATS transformation was the MOC multiplied by the VOC based on PGPB willingness to paid to avoid a fatality.

**INJS** - the estimates of this MOC was calculated by assuming that the expected number of injuries is just a multiple of the expect number of fatalities. This assumption is based on the ratio of the OPS injury rate to the OPS fatality rate. The VOC is based on PGPB willingness to paid to avoid.

To calculate COFS, each factor contributing to COFS was calculated as the value of consequence multiplied by its respective magnitude of consequence.

In a similar way to ROF transformation, a three step process was applied for most of the factors that have influence on COFS:

1. Both average industry and average PGPB values for each magnitude of consequence were calculated and designated as target averages.

2. Using non-linear regression techniques, the coefficients for the transformation form index values to MOC values to attain the target averages were calculated.

3. Values of consequences were multiplied by MOC coefficients to obtain consequence of failure transformation.

Industry average values of MOC were gathered from OPS statistics from 1984 to 1998.

The approach applied for both ROF and COF transformations is known within PGPB as the Value Model, which is basically a way to assign a quantitative value to risk of failure and consequence of failure scores.

As a final result the Total Risk score in any pipeline system is expressed as the annual cost per mile per year of operation. The following equation provides the units obtained once the transformations have been performed

\[
\text{Total Risk} = \text{ROFS} \times \text{COFS}
\]

\[
\text{Cost} = \frac{\text{Events}}{\text{Year}} \times \frac{\text{Cost}}{\text{Year}} \times \text{Events}
\]

**PGPB TOLERABLE RISK CRITERIA DEVELOPMENT AND RESULTS**

The development of the Tolerable Risk Criteria for PGPB’s use in pipeline risk assessment and decision making was accomplished by analysing information and data provided by several areas of the Pipeline Division. Several meetings were conducted to obtain and filter data from the Safety, Maintenance, Technology and Planning executives. These criteria are meant to be used by PGPB, together with the results of a quantitative Risk Model, to prioritise risk control/mitigation activities.

Staff from PGPB made inputs to the process of developing criteria to ensure that the results reflected PGPB’s risk tolerance basis.

Initially, PGPB had to review the risk criteria concepts and risk criteria used by other industries and organizations. Next, PGPB staff developed descriptions to define three risk criteria regions. These descriptions were accepted as company policy and described as follows:

**Intolerable Risk** – is the risk level that PGPB is not willing to keep in its facilities. Any pipeline segment located in this region will require immediate actions to reduce risk without taking into account any cost/benefit of the actions taken or planned to relocate the pipeline in another risk level.
Controllable Risk – is the region where control or reduction risk actions are required and investments are driven by cost/benefit ratio, among many other factors such as business impact and potential damage surrounding the pipeline.

Tolerable Risk – refers to any risk level in the system that does not require any immediate mitigation action or investment. In general, only monitoring and control actions are needed within this region.

The following Figure depicts PGPB Tolerable Risk Criteria. To apply these criteria in a real system all the pipeline segments have to be allocated in the graphic to establish a comparison between segments.

Those segments exceeding the upper limit of the RISK MANAGEMENT region must be attended to immediately. The risk management concept starts its application only in those segments where risk levels are considered manageable.

Segments under Intolerable Risk might require major investment in terms of maintenance activities and the obtained benefit is seen as a reduction in risk. Since a segment risk is classified in terms of average risk it is likely that only part of its length is affected by higher risk levels.

Figure 2. PGPB Tolerable Risk Criteria

An average segment length in PGPB is roughly 31 miles when they are defined from trap to trap. Then for the illustrated case less than 31 miles would be unacceptable and maintenance would mostly include preventative or monitoring actions, becoming a cost-effective activity.

Furthermore, PGPB performed an additional review to compare these results to actual insurance expenditures.

Previous Figure provides the PGPB Tolerable Risk Criteria adopted for Risk Management planning. When these criteria are applied and used to support decisions on needed remediation, budget limitations should be considered.

The following diagram shows the complete process applied in PGPB to obtain a quantitative risk approach.

Each block implied a comprehensive development, before establishing any relationship between risk assessment and risk management stages. A brief description is provided for each of the blocks that are part of the Risk Management process established by PGPB.

Figure 3. Risk Management Process

PGPB Input Data

To validate the above system diagram block three pipeline models were defined to include most of the products transported in the PGPB pipeline network. Three risk models were constructed according to the information and data required for the assessment program. The systems were:

- Natural Gas 48" inches with 1,252.5 Km
- LPG 24" – 20" – 14" inches with 1,231 Km
- Ethane 20" inches with 136 Km

For each model more than 80% of the needed data was collected, validated and input. This allowed a high degree of reliability in the results.

Index Factor Program

Once data bases of the models were consistent with the documentation available (printed and electronic media), the risk assessment was performed and risk factors were obtained.

Several reviews took place by different people to ensure the results were providing a logical
meaning, based on the knowledge of the system and experience of field engineers.

After several discussions it was agreed the results were reliable to carry on with the risk management stage. The graphic output was very useful to identify those areas creating conflicts between maintenance and operation divisions.

Index results calculated had a detailed review that included all the factors and every variable. The main values required to perform the transformation were related to ROF and COF.

Segment total risk is obtained from combination of weighted factors for each 1-mile section making up segment.

Transformation to Quantitative Values
The approach applied to perform the transformation uses ROF and COF results to obtain ROF$ and COF$. The ROF and COF values are obtained directly from the risk assessment model and filtered into a post-processor system that enables the transformation.

PGPB Pipeline Incident Data
PGPB actual data was used to match average actual accident rate and experienced consequence to average index results. This process was done to each risk factor calculated from the risk assessment.

PGPB statistics included data from 1990 to 1998. Events frequency was calculated to obtain number of events per year related to Corrosion, Material and Defects, Third Party Activities and others. The probability of occurrence for Operations and Procedures and Ground Movement factors was determined from detailed information provided by PGPB’s Safety and Environmental Protection Division.

Value Model
PGPB’s value model provides the willingness to pay to avoid (WTPA) consequence levels. These levels were established through several workshops and meeting between PGPB staff. The WTPA is a function of Health Impacts, Environmental Impacts and Business losses.

All the variables considered in this value model were explained earlier in this paper. The value model is normalised for a system of 10,000 miles.

Validation
The validation process was aimed to any potential change in all the assumptions established to quantify risk factors. Variation in index results versus changes in ROF$ and COF$ were identified to avoid inconsistencies when applying tolerable risk criteria. This validation provided enough support to assign number of events per factor, considering average, maximum and minimum risk values.

Transformation to Quantitative Values
Transformation of risk results was achieved by applying a computer program that interfaces with risk assessment software. This program utilises data inputs and results from index model and completes the transformation from section ROF and COF to section ROF$ and COF$.

Section results are combined to form segment ROF$, COF$, and TR$ (Total Risk), expressed with a metric that results quite simple to be interpreted by field engineers, operators and executives.

Once a pipeline is characterised in terms of risk through tolerable risk criteria a risk decision making was issued per each pipeline segment.

Figure 4 depicts a case study for an LPG pipeline with more than 1,200 kilometres of length. The graph shows the current conditions for this system before addressing any risk reduction activity.

Figure 4. Current Risk Conditions - LPG System

Figure 5 provides a picture of the benefits obtained in terms of risk reduction, after implementing specific actions in all the segments identified as intolerable. The investment simulated was equivalent to 9.1 million dollars.
The main purpose of any risk management programme is to obtain sufficient elements to provide a pro-active maintenance in a pipeline system.

By identifying pipeline segments where risk is intolerable and risk reduction projects are required the maintenance planning stage becomes a straight issue, since all those segments under these condition demand immediate attention regardless the investment required to mitigate risk.

For those segments located in an administratively controllable risk region, any activity or project will be selected on a cost-benefit basis.

The cost-benefit analysis is included in a computer program that evaluates every project cost and the corresponding benefit in risk reduction.

CONCLUSION
The risk management concept is a long-term type project. The risk assessment stage does not provide sufficient support for risk reduction making

After a comprehensive planning and development of the risk management stage, PGPB was able to quantify risk and provide results with a practical sense.

For instance any in-line inspection plan has to be supported by the corresponding risk management recommendations. The whole LPG pipeline network has been incorporated to the risk management philosophy.

For natural gas pipelines more than 5,000 kilometres have been modelled to evaluate risk conditions and apply tolerable risk criteria.

Some of the benefits measured as a function of pro-active maintenance and planning where clearly identified when the Operation and Commercial Divisions requested an increased in the operating pressure and flow. Several simulations where performed and a comparison was established to identify those scenarios increasing risk levels.

REFERENCES
- Development of PEMEX Gas y Petroquimica Basica (PGPB) Tolerable Risk Criteria - Final Report Task 1 - Mexico, July 16, 1999
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