Real-Time Risk Assessment and Management of Pipelines

Summer 2000 Report

To

H. Rosen Engineering

Minerals Management Service

By

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1. Introduction

1.1 Objective

The objective of this project is to develop, verify, and test procedures that can be used during the in-line instrumentation of pipelines to characterize their reliability (probability of not loosing containment). This project is sponsored by the U.S. Minerals Management Service (MMS) and ROSEN Engineering.

1.2 Scope

The Real-Time RAM (Risk Assessment & Management) of Pipelines project is addressing the following key aspects of criteria for in-line instrumentation of the characteristics of defects and damage in a pipeline.

1) Development of assessment methods to help manage pipeline integrity to provide acceptable serviceability and safety,

2) Definition of reliabilities based on data from in-line instrumentation of pipelines to provide acceptable safety and serviceability,

3) Development of assessment processes to evaluate characteristics of in-line instrumented pipelines,

4) Evaluation of the effects of uncertainties associated with in-line instrumentation data, pipeline capacity, and operating conditions,

5) Formulation of analysis of pipeline reliability characteristics in current and future conditions,

6) Validation of the formulations with data from hydrotesting of pipelines and risers provided by the POP (Performance of Offshore Pipelines) project.

7) Definition of database software to collect in-line inspection data and evaluate the reliability of the pipeline.

Important additional parts of this project provided by ROSEN engineering and MMS will be:

1) Provision of in-line instrumentation data and field operations data to test the real-time RAM formulations,

2) Conduct of workshops and meetings in Lingen, Germany and UCB to review progress and developments from this project and to share technologies,

3) Provision of a scholarships to fund the work of graduate student researchers that assist in performing this project, and

4) Provision of technical support and background to advance the objectives of the project.

1.3 Background

During the period of 1994 – 1998, the Marine Technology and Management Group of the University of California at Berkeley performed a project sponsored by U.S. Minerals Management Service (MMS), Chevron, Amoco, and Exxon to develop a database analysis program to assist in evaluation of the RAM based operating characteristics of corroded pipelines. This project is identified as the PIMPIS (Pipeline Inspection, Maintenance, and Performance Information System) project.

As part of the PIMPIS project, Farkas and Bea addressed following key aspects for RAM of pipelines.

1) Development of a qualitative methodology for predicting internal corrosion loss in non-instrumented pipelines including:

   - Corrosion loss formulation (time dependent)
   - Biocorrosion
   - Types of bacteria associated with sulfate reduction
   - Effect of pH on corrosion rates
   - Effect of flow regime on the corrosion rates

2) Development of quantitative formulation for risk assessment of non-instrumented pipelines including:

   - Calculation of flaw size distribution (e.g. 1 inch flaw size)
   - Impact assessment due to pipeline failure; Impact Scoring

3) Design of a computer database for performing qualitative and quantitative risk assessment of non-instrumented pipelines (PIMPIS; Pipeline Integrity, Maintenance, and Performance Information System) that included:

   - Main variables are the size and depth of flaws.
   - Reports on the probability of failure of the pipeline based upon the formulation that includes wall thickness and depth and size of flaws associated with demands (operating conditions) and capacity of pipeline pressure.

These works formed an important stating point for this project.

The Marine Technology and development Group of the University of California at Berkeley performed a project sponsored by PEMEX (Petroleos Mexicanos) and IMP (Instituto Mexicanos del Petroleo) to help develop first-generation Risk of Assessment and Management (RAM) based guidelines for design of pipelines and risers in the Bay of Campeche during the period 1996 - 2000. These guidelines were based on both Working Stress Design (WSD) and Load and Resistance Factor Design (LRFD) formats. The following guidelines were developed during this project:

1) Serviceability and Safety Classifications (SSC) of pipelines and risers,

2) Guidelines for analysis of in-place pipelines loadings (demands) and capacities (resistances), and

3) Guidelines for analysis of on-bottom stability (hydrodynamic and geotechnical forces).

4) Guidelines for installation design of pipelines.

During the period of 1998 – 2000, the Marine Technology and Management Group of the University of California at Berkeley performed a project sponsored by U.S. Minerals Management Service (MMS), Petroleos Mexicanos (PEMEX), and Instituto Mexicanos de Petroleo (IMP) to develop and verify Risk Assessment and Management (RAM) based criteria and guidelines for reassessment and requalification of marine pipelines and risers. This project is identified as the RAM PIPE REQUAL project.

The RAM PIPE REQUAL project addressed the following key aspects of criteria for requalification of conventional existing marine pipelines and risers:

1) Development of Safety and Serviceability Classification (SSC) for different types of marine pipelines and risers that reflects the different types of products transported, the volumes transported and their importance to maintenance of productivity, and their potential consequences given loss of containment,

2) Definition of target reliability for different SSC of marine risers and pipelines,

3) Guidelines for assessment of pressure containment given corrosion and local damage including guidelines for evaluation of corrosion of non-piggable pipelines,

4) Guidelines for assessment of local, propagating, and global buckling of pipelines given corrosion and local damage,

5) Guidelines for assessment of hydrodynamic stability in extreme condition hurricanes, and

6) Guidelines for assessment of combined stresses during operations that reflect the effects of pressure testing and limitations in operating pressures.

During the early phase of this project, 1st Rosen Risk Assessment and Management Workshop, "Risk Assessment for Pipelines Based on Inline Inspection Data", was held in Lingen, Germany on June 29 – 30, 2000. The objective of this workshop was to explore how RAM is important to Rosen engineering associated with in-line inspection service. RAM attempts to identify and remedy causes, detect potential and evolving events and bring them under control, and minimize undesirable effects. RAM pipe attempts to establish and maintain the integrity of a pipeline system at the least possible cost. However, comprehensive solutions may not be possible to implement them due to the limitation of funding and technology. Therefore, this project was started between Rosen Engineering, MMS, and U.C. Berkeley to develop a procedure that can characterize the reliability upon the results from in-line instrumentation.

1.4 Approaches

The fundamental approach used in this project is a Risk Assessment and Management (RAM) approach. This approach is founded on two fundamental strategies:

- Assess the risks (likelihood and consequence) associated with existing pipelines, and

- Management the risks so as to produce acceptable and desirable quality in the pipeline operations.

It is recognized that some risks are knowable (can be foreseen) and can be managed to produce acceptable performance. Also, it is recognized that some risks are not knowable (cannot be foreseen), and that management processes must be put in place to help manage such risks.

Applied to development of criteria for the requalification of pipelines, a RAM approach proceeds through the following steps (Bea, 1998):

1) Based on an assessment of costs and benefits associated with a particular development and generic type of system, and regulatory – legal requirements, national requirements, define the target reliabilities for the system. These target reliabilities should address the four quality attributes of the system including serviceability, safety, durability, and compatibility,

2) Characterize the physical conditions (e.g. corrosion, dents, gouges, and cracks), the internal conditions (e.g. pressures, temperatures), and the operational conditions (e.g. installation, production, and compatibility) that can affect the pipeline during its life,

3) Based on the unique characteristics of the pipeline system characterize the 'demands' (imposed loads, induced forces, displacements) associated with the environmental and operating conditions. These demands and the associated conditions should address each of the four quality attributes of interest (serviceability, safety, durability, and compatibility),

4) Evaluate the variabilities, uncertainties, and Biases (different between nominal and true value) associated with the demands. This evaluation must be consistent with the variabilities and uncertainties that were included in the decision process that determined the desirable and acceptable target reliabilities for the system,

5) For the pipeline system define how the elements will be designed according to a proposed engineering process (procedures, analyses, strategies used to determine the structure element sizes), how these elements will be configured into a system, how the system will be constructed, operated, maintained, and decommissioned (including Quality Assurance – QA, and Quality Control – QC process),

6) Evaluate the variabilities, uncertainties, and Biases (ratio of true or actual values to the predicted or nominal values) associated with the capacities of the pipeline elements and the pipeline system for the anticipated environmental and operating conditions, construction, operations, and maintenance activities, and specified QA – QC programs. This evaluation must be consistent with the variabilities and uncertainties that were included in the decision process that determined the desirable and acceptable target reliabilities for the system.

It is important to note that several of these steps are highly interactive. For some systems, the loadings induced in the system are strongly dependent on the details of the design of the system. Thus, there is a potential coupling or interaction between Steps 3, 4, and 5. The assessment of variabilities and uncertainties in Step 3 and 5 must be closely coordinated with the variabilities and uncertainties that are included in Step 1. The QA – QC processes that are to be used throughout the life-cycle of the system influence the characterizations of variabilities, uncertainties, and Biases in the capacities of the system elements and the system itself.

1.5 The Project Premises

The design criteria and formulation developed during this project are conditional on the following key premises:

1) The design and analytical models used in this project will be based on analytical procedures that are derived from fundamental physics, mathematics, materials, and mechanics theories.

2) The design and analytical models used in this project will be found on analytical procedures that result in un-biased assessment of the pipeline demands and capacities.

3) Physical test data and verified and calibrated analytical model data will be used to characterize the uncertainties and variabilities associated with the pipeline demands and capacities.

4) The uncertainties and variabilities associated with the pipelines demands and capacities will be concordant with the uncertainties and variabilities associated with the background used to define the pipeline reliability goals.

1.6 Project Tasks

The principal tasks defined for the conduct of this project are:

1) Develop, verify, and test procedures that can characterize the reliability upon the results from in-line instrumentation with various features including corrosion, cracks, gouges, dents, etc.

2) Evaluate available data from in-line instrumentation including the uncertainties associated with pigging tool itself and its specification.

3) Evaluate the uncertainties associated with in-line inspection data, pipeline demands (operating conditions), and capacities using simplified reliability based method.

4) Develop formulations to analyze reliability of pipeline in current condition. The consequence of pipeline failure will be included.

5) Develop formulations to determine time-dependent characteristics of pipeline capacities, demands, and uncertainties.

6) Develop formulations to determine reliability of pipeline due to time-dependent characteristics of pipeline capacities, demands, and uncertainties.

7) A parallel project (POP – Performance of Offshore Pipeline) will be utilized to verify the analytical procedures developed during this project.

8) Summarize comprehensively how to utilize this project into practical operations and service in the industry.

9) Document the forgoing results in four project phase reports

10) Transfer the forgoing results to project sponsors in five project meetings.

2. RAM Background

2.1 Reliability and Quality

Reliability (Ps) is the likelihood or probability that the structure system will perform acceptability. The probability of failure (Pf) is the likelihood that the structure system will not perform acceptably (Pf = 1 – Ps).
Reliability can be characterized with demands (S) and capacities (R). When the demand exceeds the capacity, then the structure system fails. The demands and capacities can be variable and uncertain.
Quality is defined as freedom from unanticipated defects. Quality is fitness for purpose. Quality is meeting the requirements of those who won, operate, design, construct, and regulate structure systems. These requirements include those of serviceability, safety, compatibility, and durability.

(1) Serviceability is suitability for the proposed purposes, i.e. functionality. Serviceability is intended to guarantee the use of the structure system for the agreed purpose and under the agreed conditions of use.

(2) Safety is the freedom from excessive danger to human life, the environment, and property damage. Safety is the state of being free of undesirable and hazardous situations.

(3) Compatibility is also the ability of the structure system to meet economic, time, and aesthetic requirements.

(4) Durability assures that serviceability, safety, and environmental compatibility are maintained during the intended life of the structure system. Durability is freedom from unanticipated maintenance problems and costs.

2.2 Probability of Success and Failure

The probability or likelihood that the structure system will survive the demand is defined as the reliability:

$$Ps = P\ (R > S)$$

where P is read as the probability that the capacity (R) exceeds the demand (S). Ps is the probability of success, or reliability.
The probability of failure (Pf) is the compliment of the reliability:

$$Pf = 1 - Ps \text{ or } Pf = P\ (R < S)$$

The probability of failure can be occurred in any four-quality attributes of the system to lead the system to fail.

The cumulative probability distribution function for the resistance can be expressed as:

$$F_R\,(s) = P\,(R < s)$$

where F_R (s) is read as the probability that the resistance, R, is equal to or less than a given value of the demand, s.
The probability density function for the loading can be expressed as:

$$fs\,(S) = p\,(s < S < s + \Delta s)$$

where p (S) is read as the probability that the loading is a particular value, S, in the interval from s to s + Δs.
Then, assuming independent demands and capacities:

$$Pf = \Sigma\, F_R\,[s]\, fs\,[S]\, \Delta s$$

In analytical terms, the reliability can be computed from:

$$Ps = \Phi\,(\beta)$$

where Φ (β) is the standard Normal distribution cumulative probability of the variants, β. β is commonly termed the Safety Index.

Given Lognormally distributed (these terms refer to the analytical model that describe the probability distribution of the parameter) independent demands (S) and capacities (R), β is computed as follows:

$$\beta = \frac{\ln(\underline{R} / \underline{S})}{\sqrt{\sigma_{\ln R}^{\;2} + \sigma_{\ln S}^{\;2}}} \text{ or } \frac{\ln(\underline{R} / \underline{S})}{\sqrt{\sigma_{\ln RS}^{\;2}}}$$

Given Normally distributed independent demands and capacities, β is computed as follows:

$$\beta = \frac{\ln(R - S)}{\sqrt{\sigma_R^{\;2} + \sigma_S^{\;2}}}$$

2.3 Central Tendency and Variability Measures

R̲ and **R** are the median and mean capacities of the structure system, respectively. S̲ and **S** are the median and mean demands in the structure system, respectively.

The mean of a variable, **X**, can be computed from n values of the variable, X, as follows:

$$\mathbf{X} = \Sigma \frac{X}{n}$$

For Normally distributed variables, the mean, mode, and median are all the same values (symmetrical distribution). For Lognormally, distributed variables, the mean, mode, and median generally are all different values. A Lognormal distribution is a Normal distribution of the logarithms of a variable.
A Normal distribution will result from the addition of a large number of random variables. A Lognormal distribution will result from the multiplication of a large number of random variables.
In the case of Lognormally distributed variables, the mean, **X**, is related to the median, $\underline{X}$, by:

$$\mathbf{X} = \underline{X} \exp\,(0.5\ \sigma_{\ln X}{}^2)$$

where $\sigma_{\ln R}$ is the standard deviation of the logarithm of the capacities. $\sigma_{\ln S}$ is the standard deviation of the logarithm of the demands. $\sigma_{\ln RS}$ is the standard deviation of the logarithms of the demands and capacities.

Coefficient of variation for Lognormal distribution, Vx, can be expressed as follows:

$$\sigma_{\ln X} = \sqrt{\ln(1 + Vx^2)} \ \text{ or } \ Vx = \sqrt{\exp^{\sigma \ln x^2} - 1}$$

$$\text{For } Vx < 0.3,\ \sigma_{\ln x} \cong Vx$$

2.4 Uncertainties

Uncertainties associated with structure loadings and capacities will be organized in two categories. The first category of uncertainty is identified as natural or inherent randomness (Type I uncertainty). Example of Type I uncertainty associated with loadings are the annual maximum wave height, earthquake ground acceleration, or ice impact kinetic energy that will be experienced by a structure at a given location during a given period of time in the future. Examples of Type I uncertainty associated with capacities are the yield strengths of steel, tensile strength of copper, and shear strength of any material.
A second category of uncertainty is identified as unnatural, cognitive, parameter, measurement, or modeling uncertainty (Type II uncertainty). This type of uncertainty applies to deterministic, but unknown value of parameters; to modeling uncertainty; and to the actual state of the system. Example of Type II uncertainty in loadings are the uncertainties in computed wind, wave and current, earthquake, and ice conditions and forces that are due to imperfections in analytical models. Examples of Type II uncertainty in capacities is the difference between the nominal yield strength of steel and the mean or median yield strength of the steel, and between the true buckling capacity of a column and that determined from an Euler buckling column formulation.
In this development, Type I uncertainty is characterized with two parameters:

(1) Central tendency measures of the parameter of concern, X (median, $\underline{X}$, and mean $\mathbf{X}$) and
(2) Dispersion measure of X, (coefficient of variation, Vx, standard deviation, σ_x)

Type II uncertainty is characterized with two parameters:

(1) Central tendency measures of the Bias, B (median, $\underline{B}$, mean, **B**) and,
(2) Dispersion measure of the Bias, the coefficient of variation, V_B

Bias is defined as the ratio of the true or actual value of a parameter to the predicted (design, nominal) value of the parameter:

$$B = \frac{\text{True or Measured Value}}{\text{Predcited or Nominal Value}}$$

2.5 Time Considerations

The time period that often is used to define the probability characteristics of the loadings and capacities is one year. If the capacity were changing as a function of time, for example, due to fatigue degradation of the strength, then Pf could be determined for discrete time intervals recognizing the change in the capacity, and the Pf is summed over the total exposure period (L).
Relating the annual risk, Pf_a, to the lifetime risk, Pf_L, is simple if each year is considered a statistically independent event (no correlation of trials from year to year). In this case, for a lifetime of L years:

$$Pf_L = 1 - (1 - Pf_a)^L$$

For small Pf_a, this gives:

$$Pf_L = L\ Pf_a$$

However, there is correlation of risk from year to year due to statistical dependence through several important variables in Pf including the structure resistance, some of its loadings (e.g. dead loadings), and some of the sources of uncertainty (e.g. methods of analysis). Many of the variables are independent of the natural randomness associated with such occurrences as storms or earthquakes, and may be considered constant during the lifetime. If one takes the other extreme assumption, and considers perfect dependence or correlation from year to year, then:

$$Pf_L = Pf_a$$

2.6 Evaluation of Variability and Correlations

To evaluate the variabilities of the demands and capacities from the components of the demands and capacities that contribute uncertainties, one can use the algebra of Normal Functions. This approach is equivalent to a first order – second moment (FOSM) method to propagate the central tendencies and uncertainties of multiple parameters. This approach is based on a first order Taylor Series expansion of the distribution characteristics and then retention of only the first two terms of the expansion.
For the addition or subtraction of two random variables, $(X \pm Y) = z$, the mean (same as mode and median) of the resultant distribution can be calculated as follows:

$$Z = X + Y$$

The standard deviation of the resultant distribution can be calculated as follows:

$$\sigma_Z = \sqrt{\sigma_X{}^2 + \sigma_Y{}^2 \pm 2\rho\sigma_X\sigma_Y}$$

ρ is the correlation coefficient between the two variables X and Y.

For the multiplication of two random variables, $(XY) = Z$, the mean of the resultant distribution can be calculated as follows:

$$Z = XY + \rho\,\sigma_X\sigma_Y$$

The standard deviation of the resultant distribution can be calculated as follows:

$$\sigma_Z = XY\sqrt{(1+\rho^2)[V_X{}^2 + V_Y^2 + (V_X^2V_Y^2)}$$

When the random variable X and Y can be considered independent ($\rho = 0$), and V_X and V_Y are small ($V \ll 1$), then:

$$Vz \cong \sqrt{V_X^2 + V_Y^2}$$

For the division of two random variables, $(X/Y) = Z$, the mean of the resultant distribution can be calculated as follows:

$$Z = X/Y$$

The standard deviation of the resultant distribution can be calculated as follows:

$$\sigma_Z = (X/Y)\sqrt{V_X{}^2 + V_Y^2 - 2\rho(V_XV_Y)}$$

When the random variable X and Y can be considered independent ($\rho = 0$), and V_X and V_Y are small ($V \ll 1$), then:

$$Vz \cong \sqrt{V_X^2 + V_Y^2}$$

To determine the product of two variables when one of the variables is raised to a power ε (Z = XY$^{\varepsilon}$):

$$Z = X\,(Y)^{\varepsilon} + \rho\, \sigma_X \sigma_Y$$

and

$$\sigma_Z = X(Y)^{\varepsilon} \sqrt{(1+\rho^2)[V_X{}^2 + V_Y^2 + (V_X^2 V_Y^2)}$$

When the random variable X and Y can be considered independent ($\rho = 0$), and Vx and V_Y are small (V<<1), then:

$$Vz \cong \sqrt{V_X^2 + (\varepsilon V_Y)^2}$$

The correlation coefficient, ρ, expresses how strongly two variables, X and Y, are related to each other. It measures the strength of association between the magnitudes of two variables. The correlation coefficient ranges between positive and negative unity ($-1 \leq \rho \leq 1$).
If $\rho = 1$, they are perfectly correlated, so that knowing X allows one to make perfect predictions of Y. If $\rho = 0$, they have no correlation, or are independent, so that the occurrence of X has no affects on the occurrence of Y and the magnitude of X is not related to the magnitude of Y.
The correlation coefficient can be computed from data in which the results of n samples of X and Y are developed:

$$\rho = \frac{\sum XY - nXY}{\sqrt{(\sum X2 - nX2)(\sum Y2 - nY2)}}$$

There can be correlations between demands and capacities. As the demands changes, the capacities can change. Increasing loadings resulting in decreasing capacities are an example of negative correlation in the demand and capacity.
Fro the case of Lognormally distributed correlated demands and capacities, β is computed as follows:

$$\beta = \frac{\ln(\underline{R}/\underline{S})}{\sqrt{\sigma_{\ln R}{}^2 + \sigma_{\ln S}{}^2 - 2\rho\sigma_{\ln R}\sigma_{\ln S}}}$$

2.7 Elements and Systems

In this development, the references are made to 'elements' and 'systems'. The design format developments were primarily focused on the elements that comprise a structure system. A pipeline structure system can be decomposed into sub-systems of series and parallel elements. A series sub-system is one in which the failure of one of the elements leads to the failure of the system. A parallel system is one in which the failure of the system only occurs when all of the elements have failed.

2.7.1 Parallel Systems

The probability of failure of parallel element system can be expressed in terms of the probabilities of failures in its N elements as:

$$Pf_{systems} = (P_{f1}) \text{ and } (P_{f2}) \text{ and } \ldots. (P_{fN})$$

The strength of characteristics of a parallel system are dependent on the ductility (deformation or strain capacity) and residual strength 9load or stress capacity after the yield strength has been developed) characteristics of the elements that comprise the system. A parallel system with N perfectly ductile elements, the expected capacity, R, of this system is determined by the sum of the expected capacities of the elements (i = 1 to N):

$$R = \sum_{i=1}^{N} R_i$$

If the capacities of the elements are positively correlated, the standard deviation of the capacity of the system will increase, and the probability of failure of the system will increase. An important conclusion that can be reached from these results is that if the degree of correlation between the capacities or the probabilities of failure of the parallel elements is high, then the probabilities of failure of the system is will be approximately the probabilities of failure of a single element.

2.7.2 Series Systems

A series system fails when any single element fails. The probability of failure of a series system can be expressed in terms of the probabilities of failures of its N elements as:

$$Pf_{systems} = (P_{f1}) \text{ or } (P_{f2}) \text{ or } \ldots. (P_{fN})$$

For a series system comprised of N elements, if the elements have the same strengths and the failures of the elements are independent ($\rho = 0$), then the probability of failure of the system can be expressed as:

$$Pf_{systems} = 1 - (1 - Pf_i)^N$$

If Pfi is small, as is usual, then approximately:

$$Pf_{systems} \approx N\, Pf_i$$

If the elements (independent) have different failure probabilities:

$$Pf_{system} = \sum_{i=1}^{N} Pf_i$$

If the elements are perfectly correlated then:

$$Pf_{system} = \text{maximum } (Pf_i)$$

2.8 Working Stress Design

The Working Stress Design (WSD) format, which is a traditional format for design guideline, utilizes a nominal static loading to define the serviceability response characteristics and strength of the structure. Linear elastic analyses are used to describe the structure response characteristics for the given nominal design loadings. Based on characterization of the demands and capacities as being Lognormally distributed, the traditional factor of safety (FS) in working stress design can be expressed as:

$$FS = Fe(B_S / B_R)\exp[(\beta\sigma_{\ln SR}) - (2.33\sigma_{\ln S})]$$

where Fe is a factor (median loading effect) that incorporates the interactive effects of dynamic – transient loadings and the nonlinear behavior of the system. Bs is the median bias in the maximum demand loading, B_R is the median bias in the capacity of the element, β is the annual Safety Index, $\sigma_{\ln SR}$ is the total uncertainty in the demands and capacities (standard deviation of the logarithms), and $\sigma_{\ln S}$ is the uncertainty in the annual maximum loadings. The number 2.33 is standard deviations from the mean value, or the 99th percentile. This is equivalent to the reference of the design loading to an average annual return period of 100 years.
The total uncertainty in the demands S and capacities R is determined from:

$$\sigma_{SR} = \sqrt{(\sigma_S^{\ 2} + \sigma_R^{\ 2})}$$

where σ_S is the uncertainty (standard deviation of the logarithms) in the annual maximum demands and σ_R is the uncertainty in the capacities of elements.
The FS is the ratio of the design capacity of a structure element (R_D) to design or demand (S_D):

$$FS = R_D/S_D$$

Generally, the true ultimate capacity of the element (R_U) is not used in the design process and another nominal or design capacity (R_D) is used. The capacity bias is introduced to recognize this difference:

$$B_R = R_U/R_D$$

In a similar manner, the loading bias is introduced to recognize the difference between the design or nominal demand (S_D) and the true maximum demand (S_M):

$$B_S = S_M/S_D$$

2.9 Load and Resistance Factor Design

Another format that is being used to design structures is known as the Load and Resistance Factor Design (LRFD) format. This format utilizes a load factor (γ), and a resistance factor (ϕ) as follows:

$$\phi R_D > \gamma S_D$$

The factoring is generally done such that the design engineer is still able to use linear elastic analysis methods in design computations.
To allow the load and resistance factors to be proportioned according to the uncertainties in the loading and resistance, the following approximation can be used:

$$c = \sqrt{(a^2 + b^2)} \approx 0.75(a + b)$$

Based on this approximation, the reliability approach can be used to determine the loading and resistance factors:

$$\gamma = \underline{Fe}\ \underline{Bs} \exp(0.75\ \beta\ \sigma_S - 2.33\ \sigma_S)$$
$$\phi = \underline{B_R} \exp(-0.75\ \beta\ \sigma_R)$$

If the design loading, S_D, were composed of two components: S_{dD} (for dead loading) and S_{SD} (for storm loading), then:

$$\phi\ R_I > \gamma_d\ S_{dD} + \gamma_S\ S_{SD}$$
$$\gamma_d = \underline{B_d} \exp(0.75\ \beta\ \varepsilon\ \sigma_d)$$
$$\gamma_S = \underline{B_S} \exp(0.75\ \beta\ \varepsilon\ \sigma_S)$$

where the 'splitting coefficient', ε, can be determined from:

$$\varepsilon = \frac{\sqrt{\sigma_d^{\ 2} + \sigma_S^{\ 2}}}{(\sigma_d + \sigma_S)}$$

The factor of safety is related to the Load and Resistance Factors as follows:

$$FS = \gamma/\phi$$

2.10 Risk Assessment and Management

The formal definition of risk is "The combination of probability that an undesired event will occur and the consequence that occur as a result of the undesired event" (Greenberg, 1991). Risk is also defined as the product of the likelihood that adequate or acceptable quality is not achieved and the consequences associated with lack of achieved quality (Aven, 1992). Risk results from uncertainties.

Uncertainties result from 1) Inherent variability (natural, random), 2) Professional or technical sources (analytical, modeling, parameter, epistemic), and 3) Human and organizational factors (Moan, 1993). The various characteristics of uncertainties can be categorized as 1) random vs. systematic, 2) manageable vs. unmanageable, 3) predictable vs. unpredictable, 4) static vs. dynamic, and 5) quantifiable vs. unquantifiable.

Consequences result from unrealized expectations and unanticipated lack of sufficient quality. Consequences can be expressed in terms of their frequency, their severity, their impacts, and their predictability. Consequences can be expressed in a variety of ways and with variety of metrics (Bea, 1997).

Risk can be perceived very differently by the public and by the experts. The public regards risks subjectively and qualitatively, from the individual standpoint, and often reacts from gut feeling rather than from rational thought. Very often under these conditions, the risk is perceived only as the potential consequence without regard to the likelihood of occurrence (Greenberg, 1991).

The following list present another view of how society perceives risk and what constitutes acceptable risks.

Table 1. Acceptable Risks Vs. Unacceptable Risks

Acceptable Risks	Unacceptable Risks
Known	Unknown
Old	New
Gradual	Sudden
Usual	Unusual
Natural	Manmade
Voluntary	Involuntary
Controlled by individual	Uncontrollable by individual
Necessary	Luxury
Profitable for individual	Not profitable for individual or company
Entertaining/Recreational	No entertainment value

Risk assessment includes perceptive risk identification, classification, analysis, and evaluation associated with the lack of achieved quality. Initiating events (direct causes), contributing events (background causes), and compounding events (propagating or escalating or arresting causes) should be identified and remedied properly. There are several methods are available to identify the hazards.

(1) Quantitative (probabilistic) approaches: Quantified Risk Assessment (QRA), Probabilistic Reliability Assessment (PRA), and Preliminary Hazards Analysis (PHA).
(2) Qualitative (Narrative) approaches: Failure Modes and Effects Analysis (FMEA), Hazards and Operability Analysis (HAZOP), and Safety Management Assessment System (SMAS).
(3) Checklists/Questions: Management Safety Systems Assessment, Guidelines in the Evaluation of Risk (MANAGER), and International Safety Rating System (ISRS)
(4) Rankings: Paired Comparison, Ranking/rating, Success Likelihood Indexing Methodology – Multi-Attribute Utility Decomposition (SLIM-MAUD), Operational Safety Review Team (OSART), and Analytical Hierarchy Process (AHP).
(5) Indexing Methods: Fire and Life Safety Assessment and Indexing Methodology (FLAIM), Human Error Safety and Indexing Method (HESIM), and Tripod Delta (Hudson et al., 1994).

Risk Management is 'how to manage' the risks identified in the assessment. Proactive risk management is concerned primarily with predictable and controllable risks (Swain, Guttman 1983). Reactive risk management is concerned primarily with preventing future accidents based on experience from past accidents (Rasmussen, 1996). Real-time risk management is concerned primarily with unpredictable risks (Bea, 1997).

A risk management system should be practical, realistic, and must be cost effective. A successful risk management plan must be credible, organized, thorough, relevant, doable, and economical, based on exiting technology with flexibility to adapt to later advances, and publicized. Key elements that should be presented in a risk management system include: 1) Hazard identification, 2) Consequence analysis, 3) Control or treatment responses, 4) Procedures (operation, maintenance, and testing and inspection), 5) Emergency planning 6) Training, 7) Accident Investigation, and 8) Audits (Myers et al. 1991).

Excellent risk management results from a combination of uncommon common sense, qualified experience, judgment, knowledge, wisdom, intuition, and integrity. Risk Management is largely a problem of doing what we know we should do and not doing what we know we should not do. The purpose of a risk management system should be to enable and empower those that have direct responsibility for the designing, building maintaining, and operating engineered systems (Bea, 1997).

2.11 Traditional and RAM Based Pipeline Criteria

"Whether Allowable Stress Design (ASD) or Load and Resistance Factor Design (LRFD) is considered (these are only different formats for engineering design guidelines), most existing offshore pipelines codes continue to address code development with a deterministic – experience based approach. The reluctance in using a probabilistic approach may be due to lack of understanding of the approach, a belief that sufficient data is not available for a fully valid reliability approach, that there are certain unknown variables which can not be quantified, or a combination of these.

At the outset, it must be recognized that the results of the pipeline engineering process is deterministic: a certain diameter of pipeline with a certain wall thickness must be evaluated. This is true no matter how the criteria have been derived.

It also must be recognized that a sound reliability approach is founded on the same principles as a sound deterministic approach. There must be a firm foundation of deterministic understanding of the physics and mechanics that underlie the important processes that determine the reliability of a pipeline. The traditional deterministic approach and the RAM approach should be complimentary. One builds on the foundation provided by the other.

The same problems that confront a reliability approach also confront a deterministic approach. A probabilities approach needs no more or no less data and information than a deterministic approach. If there are unknown variables, then these same unknown variables pervade the deterministic and probabilistic approaches. The need for qualified judgment and experience is present in both approaches. One of the biggest dangers to both approaches are 'number crunchers' that loose sight of the need for such qualified judgment and experience to act as a filter to provide adequate understanding and insight to make good engineering decisions.

Then, what does a RAM approach bring to the process of developing good engineering design and requalification guidelines that are not brought by a traditional deterministic approach? RAM provides disciplined and structured approaches to help recognize and incorporate explicit evaluation and assessment of uncertainties in an engineering design, decision, and management process. These uncertainties come from natural variabilities in pipeline properties, capacities, and loadings (external and internal) and the changes in these with time. They also come from limitations in the models, parameters, and knowledge used to evaluate the pipeline loadings and capacities. The most daunting source of these uncertainties are the future actions and inactions of people that influence the design, construction, operations, and maintenance of a pipeline during its lifetime. Once the presence of these uncertainties is recognized, then deterministic approaches must be modified and expanded to recognize and manage their effects.

One of the traditional methods used by engineers to mange uncertainties in a deterministic approach was to be conservative. But, problems develop when multiple conservatisms are implicitly introduced in a sequential engineering process such as is represented by engineering design guidelines and codes (certainly most uncoordinated design codes that ten to evolve with time). Similarly when new information indicates that what was thought to be conservative, no longer is conservative; the introduction of even more conservatism is the traditional response. The only active bounding influence on such conservatism is the traditional response. The only active bounding influence on such conservatism is economics and feasibility.

The other active bound on the deterministic approach legal-social-political. The deterministic approach cannot recognize that there is a finite probability that a pipeline will fail. But, we know that there is such a probability (history clearly shows this). No pipeline can be designed so that there is a zero probability of failure. The deterministic approach itself ahs encouraged such unrealizable expectations. The disappointment and disillusionment associated with such unrealized expectations encourages the legal – social – political response. The deterministic approach shields the real decision makers (managers, regulations that represent corporate interests) from developing an adequate understanding of the risks then making the decisions regarding what these risks should be. The deterministic approach has encouraged engineers to make such decisions.

By its very nature, a RAM approach must be very interdisciplinary. To be effective, a RAM approach must facilitate communications between very diverse fields and viewpoints. A RAM approach must involve both management and engineering. A Ram approach must consider not only the details of elements, but as well, the details of entire systems. Thus, if properly used, a RAM approach can provide another set of important dimensions to the traditional deterministic approach of developing engineering codes and guidelines.

The single biggest impediment to implementation of the RAM approach regards education of engineers. Engineers must learn the fundamental of statistics and probability and how these fundamentals can be applied to help identify and solve engineering problems. As often presented, the RAM approach appears to be extremely complex, involve new principles and methods, and highly mathematical. This does not have to be the presentation. The complexities can be reduced to terms that can be understood and used by practicing engineers and managers. The complexities can be reduced to terms that can be understood and used by practicing engineers and managers".

3. Corrosion

3.1 Fundamentals

Corrosion is a major problem for the engineering industry, and the potential for savings that corrosion control can provide constantly on the rise. Corrosion is also a complex process involving a large number of variables that both vary in space and time. The key to understanding the corrosion problem is to be able to accurately predict the nature of the reaction taking place at the interface of the corroding material and the environment.

Electrochemical corrosion of carbon steel will not occur unless these two requirements are met:

(1) Liquid water must exist as a free and separate phase. Water in oil as an emulsion will not cause corrosion

(2) Liquid water must wet the surface of the carbon steel equipment. The more continuous wetting, the greater the average corrosion rate.

A threshold water cut is required for corrosion to begin.

- The threshold waster cut for oil pipeline is strongly influence by the type of crude. Also, water is seldom uniformly distributed through the production flow. For horizontal lines in the slug regime, water may flow along the bottom of the lines even at low water cuts. Water may also settle out in the low points of lines when velocities are very low. Therefore, the threshold water cur for corrosion in oil pipeline is somewhere 30% to 60 %, with lower percentages for low flow rate conditions.

- For gas pipelines, the threshold water cut is even more difficult to define. As for oil pipelines, the water may not be uniformly distributed through the production flow and may exist as separate droplets at high velocities when in the annular mist flow regime. One rule-of-thumb is for the water to gas ratio to be >2.0 bbl/mmscf for corrosion to start.

- The water to condensate ratio is a better basis for predicting corrosion in gas pipeline. Water to condensate ratio to be > 50% will usually continuously water wet equipment.

The primary corrosion reaction for all iron-base alloys is the oxidation of iron to the ferrous ion:

$$Fe \rightarrow Fe^{+2} + 2e^-$$

The ferrous ions go into the water and the available electrons on the alloy surface are consumed by cathodic reactions in order to maintain electrical neutrality. For low pH water, the dominant cathodic reaction for flows is the reaction of the readily available hydrogen ions:

$$2H^+ + 2e^- \rightarrow H_2 \uparrow$$

Oxygen contamination above about 10 to 20 ppb will provide another cathodic reaction that will significantly increase general corrosion rates and chloride pitting:

$O^2 + 2H_2 + 4e^- \rightarrow 4OH^-$

The dominant corrosion mechanism is from CO_2 corrosion. The CO_2 will form carbonic acid with the overall corrosion reaction as:

$Fe + 2H_2CO_3 \rightarrow Fe^{+2} + 2HCO_3^- + H_2$

Farkas and Bea, Marine Technology and Management Group at UCB, well summarized the 'biocorrosion', 'types of bacteria associated with sulfate reduction', 'effect of pH', and 'effect of flow regime in the pipeline' in the Pipeline Inspection, Maintenance and Performance Information System Progress Report, Spring 1998.

3.2 Inspection

There are several methods in use today to obtain data on corrosion in pipelines with different levels of complexity and resolution of the results. Corrosion coupon installed in pig traps and manifold areas can be used to get general numbers on corrosion rate. There is limitation for the coupons to sense local corrosion condition since the coupons cannot be placed throughout the pipeline and they are only useful for general indications of corrosion rate.

For more detailed assessment on corrosion, inspection is only solution to detect corrosion features. Whereas outside gauging of the pipeline is one of the methods, intelligent pigging is a popular method in the current industry. These intelligent pigging methods have continuously improved on sensor technology and data processing, storage, and analysis. The techniques applied today on detecting metal loss of the pipeline are:

1) Magnetic Flux Leakage
2) Ultrasonic
3) High Frequency Eddy Current
4) Remote Field Eddy Current

The magnetic flux leakage is the most common method used by present industries. This method is based on relative measurements of the corrosion depths and shapes. Another method is ultrasonic pigs based on direct measurements of the corrosion depths. This method is only applicable for liquid transporting pipelines unless the pig is run in a bath of fluid during the inspection. For heavy wall and small diameter pipelines, the high frequency eddy current pigs can be used. It is important to realize the limitations on the inspection capabilities of the different instruments due to lack of technologies, and no methods are seen as being perfect. A certain amount of uncertainties that differs from one manufacture to another exist in all the methods. Good specifications of the pig manufacture are crucial to get a good quality of inspection results.

Bal and Rosenmoeller (1997) stated that there could be significant uncertainties in the depths of corrosion indicated by the inline instruments due to such factors as variable temperatures and degrees of magnetism, and the speed of movements of the instruments. Corrosion rates are naturally very variable in both space and tie. Thus, if instrumentation is used to determine the wall thickness and corrosion rates, the uncertainties in these characteristics needs to be determined and integrated into the evaluation of the fitness for purpose of pipeline.

3.3 Performance Specifications for In-Line Instrumentation

3.3.1 Detection and Sizing Capabilities

3.3.1.1 Manual Analysis

(Applicable for detailed analyzed features)

POD = Probability of Detection

	General Defect	Pitting Detect	Axial Grooving	Circumferential Grooving
Depth at POD = 90% (in fraction of t)	0.1	0.2	0.15	0.15
Depth sizing accuracy at 80% Confidence in -/+ fractions of t	±0.1	±0.15	±0.13	±0.11
Width sizing accuracy at 80% confidence in -/+ X mm	±15	±15	±10	±10
Length sizing accuracy at 80% confidence in -/+ X mm	±15	±15	±10	±10

3.3.1.2 Automatic Analysis

	General Defect	Pitting Detect	Axial Grooving	Circumferential Grooving
Depth at POD = 90% (in fraction of t)	0.2	0.2	0.3	0.2
Depth sizing accuracy at 80% Confidence in -/+ fractions of t	±0.15	±0.15	±0.25	±0.15
Width sizing accuracy at 80% confidence in -/+ X mm	±25	±25	±15	±15
Length sizing accuracy at 80% confidence in -/+ X mm	±25	±25	±15	±15

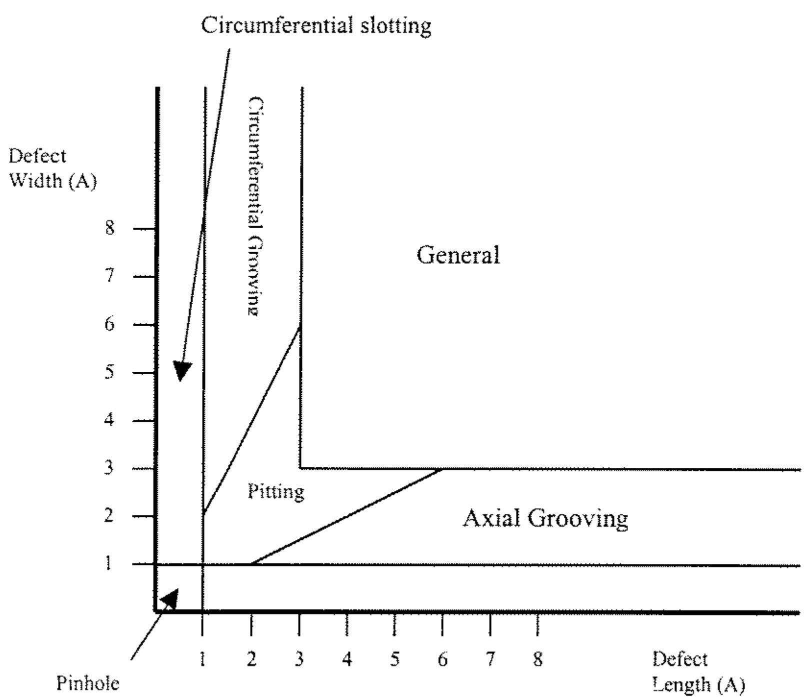
3.3.1.3 Wall Thickness Detection

± 1mm or ± 0.1t, whichever value is greater at 80% confidence.

3.3.2 Location and Orientation Capabilities

a. Axial position accuracy from reference marker: ± 1m
b. Axial position from closest weld: ± 0.1m
c. Circumferential position accuracy: ± 10°

3.3.3 Defect Dimension Definition



Note: t = wall thickness or 10mm, whichever value is greater

3.3.4 Identification of Features

POI: Probability of Identification

Feature	**Yes** **POI > 90%**	**No** **POI < 50%**	**May be** **50%<POI<90%**
Internal/External discrimination	X		
Metal loss corrosion defect	X		
Metal loss pipe mill defect	X		
Midwall defect			X
Grinding			X
Gouge			X
Dent	X		
Spalling	X		
Axial crack		X	
Circumferential crack	X		
Eccentric pipeline casing			X
Sleeve repair	X		
Fitting	X		
Valve	X		
Tee	X		

From above table, it can be that the probability of longitudinal cracks is less than 50%.

4. Summary of Current Practice

4.1 ASME B31G – 1991

ASME B31G criterion has been used the most commonly in the pipeline industry for the assessment of corrosion defects. As pointed out in several recent publications, this criterion is not proper to determine the strength of corroded pipelines. The ASME B31G is based on the NG-18 equation adjusted with available experimental data.

The safe maximum pressure P' is defined as:

$$P' = 1.1P\left[\frac{1-\frac{2}{3}\left(\frac{d}{t}\right)}{1-\frac{2}{3}\left(\frac{d}{t\sqrt{A^2+1}}\right)}\right] \quad \text{for A} = 0.893\left(\frac{L_m}{\sqrt{Dt}}\right) \leq 4$$

$$P' = 1.1P\left[1-\frac{d}{t}\right] \quad \text{for A} = 0.893\left(\frac{L_m}{\sqrt{Dt}}\right) > 4$$

where

L_m = measured longitudinal extent of the corroded area, in
D = nominal outside diameter of the pipe, in
t = nominal wall thickness of the pipe, in.
d = measured maximum depth of corroded area, in
P' = the safe maximum pressure for corroded area.
P = $\dfrac{SMYS * 2t * F}{D}$ and F is the design factor usually equal to 0.72

A limitation to this is that P' should not exceed P which is the maximum allowable design pressure for a non-corroded pipe.

4.2 DNV Recommended Practice for Corroded Pipelines

This document provides recommended practice for assessing pipelines containing corrosion. Recommendation are given for assessing corrosion defects subjected to:

1) Internal pressure loading only
2) Internal pressure loading combined with longitudinal compressive stresses.

The document describes two alternative approaches to the assessment of corrosion, and the document is divided into two parts. The first approach, which is based on Load and Resistance Factor Design (LRFD), is in accordance to the safety philosophy adopted in the

DNV Offshore Standard OS-F101, Submarine Pipeline System. The second approach is based on ASD (Allowable Stress Design) format.

The following types of corrosion defect can be assessed using this document:

1) Internal corrosion in the base material.
2) External corrosion in the base material.
3) Corrosion in seam welds.
4) Corrosion in girth welds.
5) Colonies of interacting corrosion defects.
6) Metal loss due to grind repairs

Internal pressure loading for:

1) Single defect
2) Interacting defects
3) Complex shaped defects

4.2.1. Partial Safety Factor – LRFD

The approach, which is based on Load and Resistance Factor Design (LRFD), is in accordance to the safety philosophy adopted in the DNV Offshore Standard OS-F101, Submarine Pipeline System. Partial safety factors are given for two general inspection methods, four different levels of inspection accuracy, and three different reliability levels corresponding to the Safety Class classification in DNV OS-F101.

The following safety classes are considered:

Table 2. Safety Class and Target Annual Failure Probability for ULS

Safety Class	Indicating a target annual failure probability of:
High	$< 10^{-5}$
Normal	$< 10^{-4}$
Low	$<10^{-3}$

The inspection sizing accuracy is commonly given relative to the wall thickness and for specified confidence level as follows:

Table 3. Standard Deviation and Confidence Level

Relative sizing accuracy	Confidence level	
	80%	90%
Exact	StD(d/t) = 0.00	StD(d/t) = 0.00
± 5% of t	StD(d/t) = 0.04	StD(d/t) = 0.03
± 10% of t	StD(d/t) = 0.08	StD(d/t) = 0.06
± 20% of t	StD(d/t) = 0.16	StD(d/t) = 0.12

The partial safety factors are given as functions of the sizing accuracy of the measured defect depth for inspections based on relative depth measurements and for inspections based on absolute depth.

The specified material requirement "U" shall be taken as not specified (NO) unless it can be documented that the requirements are fulfilled as defined as DNV OS-F101.

Partial safety factors are based on relative depth measurements where the defect depth measurement and the accuracy are given as a fraction of the wall thickness.

Table 4. Partial Safety Factors for Relative Depth Measurement

Requirement "U" specified	Safety Class		
	Low	Normal	High
No	$\gamma_m = 0.79$	$\gamma_m = 0.74$	$\gamma_m = 0.70$
Yes	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.73$

Table 5. Partial Safety Factor and Fractile value

Inspection sizing accuracy, StD(d/t)	ε_d	Safety Class		
		Low	Normal	High
0.00	0.0	$\gamma_d = 1.00$	$\gamma_d = 1.00$	$\gamma_d = 1.00$
0.04	0.0	$\gamma_d = 1.16$	$\gamma_d = 1.16$	$\gamma_d = 1.16$
0.08	1.0	$\gamma_d = 1.20$	$\gamma_d = 1.28$	$\gamma_d = 1.32$
0.16	2.0	$\gamma_d = 1.20$	$\gamma_d = 1.38$	$\gamma_d = 1.58$

Table 6. Partial Safety Factors for Absolute Depth Measurement

Requirement "U" specified	Safety Class		
	Low	Normal	High
No	$\gamma_m = 0.82$	$\gamma_m = 0.77$	$\gamma_m = 0.72$
Yes	$\gamma_m = 0.85$	$\gamma_m = 0.80$	$\gamma_m = 0.75$

Table 7. Partial Safety Factors for Circumferential Corrosion

Requirement "U" specified	Safety Class		
	Low	Normal	High
No	$\gamma_{mc} = 0.81$	$\gamma_{mc} = 0.76$	$\gamma_{mc} = 0.71$
Yes	$\gamma_{mc} = 0.85$	$\gamma_{mc} = 0.80$	$\gamma_{mc} = 0.75$

Table 8. Partial Safety Factors for Longitudinal Stress for Circum. Corrosion

Requirement "U" specified	Safety Class		
	Low	Normal	High
No	$\eta = 0.96$	$\eta = 0.87$	$\eta = 0.77$
Yes	$\eta = 1.00$	$\eta = 0.90$	$\eta = 0.80$

Table 9. Usage Factors for Longitudinal Stress

Safety Class	Usage Factor, ξ
Low	0.90
Normal	0.85
High	0.80

4.2.2 Single Defect

A defect is in the guidelines treated as a single defect if any of the following conditions are specified:

1) The depth of the defect, $\gamma_d(d/t)$ is less than 20%
2) The circumferential angular spacing between adjacent defects, ϕ, is larger than:

$$\phi > 360\sqrt{\frac{t}{D}} \text{ (Degrees)}$$

3) The axial spacing between adjacent defects, s, is lager than:

$$s > 2\sqrt{Dt}$$

If the pipeline is subject to internal pressure loading only, the allowable pressure is given by the following equation:

$$P_{corr} = \gamma_m \frac{2tSMTS}{D-t} \frac{\left[1 - \gamma_d (d/t)^*\right]}{\left[1 - \frac{\gamma_d (d/t)^*}{Q}\right]}$$

where:

$$Q = \sqrt{1 + 0.31\left(\frac{l}{\sqrt{Dt}}\right)^2}$$

$$(d/t)^* = (d/t)meas + \varepsilon_d \, StD(d/t)$$

If $\gamma_d(d/t)^* \geq 1$ then $P_{corr} = 0$, P_{corr} is not allowed to exceed $P_{mao.}$ The rules also state that measured defects depths exceeding 85% are not accepted. For longitudinal corrosion defects with internal pressure and superimposed compressive stresses, the following method applies:

Step 1) Determine longitudinal stress from external loads and calculate the nominal longitudinal elastic stresses in the pipe, based on the nominal wall thickness:

$$\sigma_A = \frac{F_x}{\pi(D-t)t}$$

$$\sigma_B = \frac{4M_x}{\pi(D-t)^2 t}$$

The combined nominal longitudinal stress is then:

$$\sigma_L = \sigma_A + \sigma_B$$

Step2. If the combined longitudinal stress is compressive, the allowable pipe pressure is given by:

$$P_{corr} = \gamma_m \frac{2tSMTS}{D-t} \frac{\left[1-\gamma_d (d/t)^*\right]}{\left[1-\frac{\gamma_d (d/t)^*}{Q}\right]} H_1$$

where:

$$H_1 = \frac{1+\frac{\sigma_L}{\xi SMTS}\frac{1}{A_r}}{1-\frac{\gamma_m}{2\xi A_r}\frac{1-\gamma_d (d/t)^*}{1-\frac{\gamma_d (d/t)^*}{Q}}}$$

$$A_r = 1-\frac{e}{t}\theta$$

For circumferential corrosion defects with internal pressure and superimposed longitudinal compressive stresses, the following procedure is given:

Step 1. Determine longitudinal stress as in the previous case.

$$P_{corr,circ} = \min[\gamma_{mc} \frac{2tSMTS}{D-t} \frac{\left[1+\frac{\sigma_L}{\xi SMTS}\frac{1}{A_r}\right]}{\left[1-\frac{\gamma_{mc}}{2\xi}\frac{1}{A_r}\right]},\ \gamma_{mc}\frac{2tSMTS}{D-t}]$$

where:

$$A_r = 1 - \frac{e}{t}\theta$$

The longitudinal stress in the remaining ligament is set to not exceed η*SMYS neither in tension nor compression:

$$|\sigma_L| \leq \eta SMYS(1-(d/t))$$

4.2.3 Interacting Defects

The rules on interacting defects are treating the load case including internal pressure only. A lot of information is also required for an assessment of interacting defects. The minimum information required is:

1) The angular position of each defect around the circumference of the pipe
2) The axial spacing between adjacent defects
3) Whether the defects are internal or external
4) The length of each individual defect
5) The depth of each individual defect
6) The width of each individual defect

The allowable operating pressure for a pipeline with a colony of interacting defects can be estimated using the following procedure:

Step 1. For regions where there is background metal loss, the local wall thickness and defect depths can be used.

Step 2. The corroded section of the pipeline should be divided into sections of a minimum length of 5 $\sqrt{Dt}$, with a minimum overlap of 2.5 $\sqrt{Dt}$

Step3 to 12 should be repeated for each sectioned length to assess all possible interactions

Step 3. Construct a series of axial projection lines with a circumferential angular spacing of:

$$Z = 360\sqrt{\frac{t}{D}} \text{ (degrees)}$$

Step 4. Consider each projection line in turn. If defects lie within ±Z they should be projected onto the current projection line

Step 5. Where defects overlap, they should be combined to form a composite defect. Taking the combined length and the depth of the deepest defect forms this. If the composite defect consists of an overlapping internal and external defect, then the depth of the composite defect is the sum of the maximum depth of the internal and external defects.

Step 6. Calculate the allowable pipeline pressure (p1, p2....Pn) of each defect to the N^{th} defect, treating each defect or composite defect as a single defect:

$$P_i = \gamma_m \frac{2tSMTS}{D-t} \frac{\left[1-\gamma_d (d/t)^*\right]}{\left[1-\frac{\gamma_d (d/t)^*}{Q}\right]} \quad i = 1 \ldots.N$$

where variables are as given in the assessment of a single defect.

Step 7. Calculate the combined length of all combinations of adjacent defects. For defects n to m the total length is given by:

$$l_{nm} = l_m \sum_{i=n}^{i=m-1} (l_i + s_i) \quad n,m = 1\ldots N$$

Step 8. Calculate the effective depth of combined defect formed from all of the interacting defects from m to n, as follows:

$$d_{n,m} = \frac{\sum_{i=n}^{i=m} d_i l_i}{l_{nm}}$$

Step 9. Calculate the allowable pipeline pressure of the combined defect from n to m (P_{nm}), using l_{nm} and d_{nm} in the single defect equation:

$$P_{nm} = \gamma_m \frac{2tSMTS}{D-t} \frac{\left[1-\gamma_d (d_{nm}/t)^*\right]}{\left[1-\frac{\gamma_d (d_{nm}/t)^*}{Q_{nm}}\right]} \quad n,m = 1\ldots N$$

where the variables are defined as for a single defect. Here, the definition of the standard deviation of d_{nm}/t is dependent on whether or not the depth measurements are correlated. For fully correlated depth measurements, the rules specify:

$$StD[d_{nm}/t] = StD[d/t]$$

For uncorrelated depth measurements, they give:

$$StD[d_{nm}/t] = \frac{\sqrt{\sum_{i=n}^{m} l_i^2}}{l_{nm}} StD[d/t]$$

Step 10. The allowable corroded pipe pressure for the current projection line is taken as the minimum of the failure pressures of all of the individual defects (p1 to pn), and of all the combination of individual defects (p_{nm}) on the current projection line.

P_{corr} =min (P_1, P_2,...P_N, P_{nm})

P_{corr} is not allowed to exceed $P_{mao.}$

Step 11. The allowable corroded pipe pressure for the section of the corroded pipe is taken as the minimum of the allowable corroded pipe pressures calculated for each of the projection lines around the circumference.

Step 12. Repeat steps 3 to 12 for the next section of the corroded pipe.

The assessment of complex shaped defects and ASD (Allowable Stress Design) format are not described here since those procedures are a quite long. The DNV guideline should be referred for the further descriptions.

4.3 RAM PIPE REQUAL

4.3.1. Pipeline Requalification Formulations & Criteria

The following table summarized the pipeline requalification criteria developed for in-place operating and accidental conditions. While the tables are not complete, these tables will provide the format that will be used to compile requalification formulations and criteria developed as a result of this project. At this stage, only one SSC (Safety and Serviceability Classifications) has been identified for requalification criteria.

Table 10. Pipeline Capacities

Loading States (1)	**Capacity Analysis Eqn.** (2)	**Data Bases** (3)	**Capacity Analysis Eqn. Median Bias** (4)	**Capacity Analysis Eqn. Coef. Var.** (5)
Single				
(Longitudinal) -Tension –Td	1	1.1	1.0	0.25
-Compression –Cd Local –Cld	2	1.2	1.0	0.25
-Compression Global – Cgd	3	1.3	1.0	0.25
(Transverse) -Bending –Mud	4	1.4	1.0	0.25
(Pressure) -Burst – Pbd	5	1.5	1.2	0.25
-Collapse – Pcd*	6	1.6	1.0	0.25
-Propagating – Pp*	7	1.7	1.0	0.12
Combined				
T –Mu	8	2.1	1.0	0.25
T – Pc*	9	2.2	1.0	0.25
Mu – Pc*	10	2.3	1.0	0.25
T-Mu-Pc*	11	2.4	1.0	0.25
C-Mu-Pb	12	2.5	1.0	0.25
C-Mu-Pc*	13	2.6	1.0	0.25

*Accidental Limit State (evaluated with 10-year return period conditions)

Table 11. Pipeline Loading & Pressures Biases and Uncertainties

Loading States (1)	**In-Place Loading Median Bias** B_{F50} (2)	**In-Place Loading Annual Coefficient of Variation** V_F (3)
Single		
(Longitudinal) -Tension –Td	1.0	0.1
-Compression –Cd Local –Cld	1.0	0.1
-Compression Global – Cgd	1.0	0.1
(Transverse) -Bending –Mud	1.0	0.1
(Pressure) -Burst – Pbd	1.0	0.1
-Collapse – Pcd*	0.98	0.02
-Propagating –Pp*	0.98	0.02
Combined		
T –Mu	1.0	0.10
T – Pc*	0.98	0.02
Mu – Pc*	0.98	0.02
T-Mu-Pc*	0.98	0.02
C-Mu-Pb	1.0	0.10
C-Mu-Pc*	0.98	0.02

*Accidental Limit State (evaluated with 10-year return period conditions)

Table 12. Pipeline Design and Reassessment Ultimate Limit State Annual Safety Indices

Loading States (1)	**Annual Safety Index In-Place ULS Pipelines** (2)	**Annual Safety Index In-Place ULS Risers** (3)
Single		
(Longitudinal) -Tension –Td	3.4	3.8
-Compression –Cd Local –Cld	3.4	3.8
-Compression Global – Cgd	3.4	3.8
(Transverse) -Bending –Mud	3.4	3.8
(Pressure) -Burst – Pbd	3.4	3.8
-Collapse – Pcd*	1.7	1.7
-Propagating –Pp*	1.7	1.7
Combined		
T –Mu	3.6	3.8
T – Pc*	2.0	2.0
Mu – Pc*	2.0	2.0
T-Mu-Pc*	2.0	2.0
C-Mu-Pb	3.6	3.6
C-Mu-Pc*	2.0	2.0

*Accidental Limit State (evaluated with 10-year return period conditions)

Table 13. In-Place Reassessment Working Stress Factors

WSD Single In-Place Loadings	Demand/ Capacity	Demand & Capacity	In-place Pipelines	In-place Risers
	Median Bias	Uncertainty V	ULS-f	ULS-F
Tension	1.00	0.27	0.40	0.36
Compression (local)	1.00	0.27	0.40	0.36
Compression (global)	1.00	0.27	0.40	0.36
Bending	1.00	0.27	0.40	0.36
Burst pressure (no corrosion)	0.91	0.27	0.44	0.39
Burst pressure (20yr corrosion)	0.83	0.27	0.48	0.43
Collapse pressure (high ovality)*	0.98	0.31	0.60	0.60
Collapse pressure (low ovality)*	0.98	0.27	0.64	0.64
Propagating Buckling*	0.98	0.12	0.83	0.83
WSD Combined In-Place Loadings				
Tension-Bending –Collapse Pressures*	0.98	0.27	0.64	0.64
Compression-Bending-Collapse Pre.*	0.98	0.27	0.64	0.64
Compression-Bending-Burst Pressure	1.00	0.27	0.40	0.36
*Accidental condition with 10yr demands				

Table 14. In-Place Reassessment Loading Factors

LRFD Single In-Place Loadings	Demand	Demand	In-place Pipelines	In-place Risers
	Median Bias	Uncertainty V	LRFD - γ	LRFD - ϕ
Tension	1.00	0.10	1.29	1.33
Compression (local)	1.00	0.10	1.29	1.33
Compression (global)	1.00	0.10	1.29	1.33
Bending	1.00	0.10	1.29	1.33
Burst pressure (no corrosion)	1.00	0.10	1.29	1.33
Burst pressure (20yr corrosion)	1.00	0.10	1.29	1.33
Collapse pressure (high ovality)*	0.98	0.02	1.01	1.01
Collapse pressure (low ovality)*	0.98	0.02	1.01	1.01
Propagating Buckling*	0.98	0.02	1.01	1.01
LRFD Combined In-Place Loadings				
Tension-Bending –Collapse Pressures*	0.98	0.02	1.01	1.01
Compression-Bending-Collapse Pre.*	0.98	0.02	1.01	1.01
Compression-Bending-Burst Pressure	1.00	0.10	1.29	1.33
*Accidental condition with 10yr demands				

Table 15. In-Place Reassessment Resistance Factors

LRFD Single In-Place Loadings	Demand	Demand	In-place Pipelines	In-place Risers
	Median Bias	Uncertainty V	LRFD - γ	LRFD - ϕ
Tension	1.00	0.25	0.53	0.49
Compression (local)	1.00	0.25	0.53	0.49
Compression (global)	1.00	0.25	0.53	0.49
Bending	1.00	0.25	0.53	0.49
Burst pressure (no corrosion)	1.10	0.25	0.58	0.54
Burst pressure (20yr corrosion)	1.20	0.25	0.63	0.59
Collapse pressure (high ovality)*	1.00	0.25	0.73	0.73
Collapse pressure (low ovality)*	1.00	0.25	0.73	0.73
Propagating Buckling*	1.00	0.12	0.86	0.86
LRFD Combined In-Place Loadings				
Tension-Bending –Collapse Pressures*	1.00	0.25	0.73	0.73
Compression-Bending-Collapse Pre.*	1.00	0.25	0.73	0.73
Compression-Bending-Burst Pressure	1.00	0.25	0.53	0.49
*Accidental condition with 10yr demands				

Table 16. Analysis Equation References

Loading States (1)	Analysis Eqn. (2)	Capacity Analysis Equation References (3)
Single		
(Longitudinal) -Tension –Td	1	Anderson, T.L., (1990), API RP 1111 (1997), DNV96 (1996), ISO (1999), Crentsil, et al (1990)
-Compression –Cd Local –Cld	2	API RP 2A(1993), Tvergaard, V., (1976), Hobbs, R.E., (1984)
-Compression Global – Cgd	3	API RP 2A(1993), Tvergaard, V., (1976), Hobbs, R.E., (1984)
(Transverse) -Bending –Mud	4	BSI 8010 (1993), DNV 96 (1996), API RP 1111 (1997), Stephens, D.R., (1991), Bai, Y.et al (1993), Bai, Y. et al (1997a), Sherman, D.R., (1993), Sherman, D.R., (1985), Kyriakides, S. et al (1991), Gresnigt, A..M., et al (1998)
(Pressure) -Burst – Pbd	5	Bea, R.G (1997), Jiao, et al (1996), Seward, G., (1994), ANSI/ASME B31G (1991), API RP 1111 (1997), DNV 96 (1996), BSI 8010 (1993)
-Collapse – Pcd	6	Timoshenko, S.P., (1961), Bai, Y., et al (1997a), Bai, Y., et al (1997b), Bai, Y., et al (1998), Mork, K., (1997), DNV 96 (1996), BSI 8010 (1993), API RP 1111 (1997), ISO (1996), Fowler, J.R., (1990)
-Propagating –Pp*	7	Estefen, et al (1996), Melosh, R., el al (1976), Palmer, A.C., et al (1975), Kyriakides, el al (1981), Kyridkides, S. el al (1992), Chater, E. (1984), Kyriakides, S. (1991)
Combined		
T –Mu	8	Bai, Y., et al (1993), Bai, Y., et al (1994), Bai, Y., (1997), Mork, K el al (1997), DNV 96 (1996), Wlker, A.C., (1995), Yeh, M.K., el al (1986), Yeh, M.K. et al (1988), Murphey, C.E. et al (1984)
T – Pc	9	Kyogoku, T., et al (1981), Tamano, et al (1982)
Mu – Pc	10	Ju, G.T., et al (1991), Kyriakides, S., (et al (1987), Bai, Y., et al (1993), Bai Y., et al (1994), Bai, Y., et al 91993), Corona, E., et al (1988), DNV 96 (1996), BSI 8010 (1993), API RP 1111 (1997), Estefen, S.F. et al (1995)
T-Mu-Pc	11	Li, R., et al (1995), DNV 96 (1996), Bai et al (1993), Bai, Y. et al (1994), Bai, Y. et al (1997), Kyriakides, et al (1989)
C-Mu-Pb	12	DNV 96 (1996), Bruschi, R., et al (1995), Mohareb, M.E. et al (1994)
C-Mu-Pc	13	Kim, H.O., (1992), Bruschi, R., et al (1995), Popv E. P., el al (1974)

Table 17. Capacity Database Reference

Loading States (1)	**Analysis Eqn.** (2)	**Capacity Analysis Equation References** (3)
Single		
(Longitudinal) -Tension –Td	1.1	Taby, J., et al (1981)
-Compression –Cd Local –Cld	1.2	Loh, J.T., (1993), Ricles, J.M., et al (1992), Taby, J., et al (1981)
-Compression Global – Cgd	1.3	Loh, J.T., (1993), Ricles, J.M., et al (1992), Smith, C.S., et al (1979)
(Transverse) -Bending –Mud	1.4	Loh, J.T., (1993), Ricles, J.M., et al (1992), Taby, J., et al (1981)
(Pressure) -Burst – Pbd	1.5	DNV (93-3637)
-Collapse – Pcd	1.6	
-Propagating –Pp*	1.7	Kyriakides, S., (1984), Estefen S.F., et al (1995), Mesloh, et al (1976)
Combined		
T –Mp	2.1	Dyau, J.Y., (1991), Wilhoit, Jr. J.C., et al (1973)
T – Pc	2.2	Edwards, S.H., et al (1939), Kyogoky, T., et al (1981), Tamano, T., et al (1982), Kyriakides, S., et al (1987), Fowler, J. R., (1990)
B – Pc	2.3	Kyriadides, S., et al (1987), Fowler, J.R., (1990), Winter, P.E. (1985), Johns, T. G., (1983)
T-Mp-Pc	2.4	Walker, G.E., Et al (1971), Langner, C.G., (1974)
C-Mp-Pb	2.5	Walker, G.E., Et al (1971), Langner, C.G., (1974)

Table 18. Formulation for Single Loading States

Loading States (1)	Formulation (2)	Formulation Factors (3)
Single		
(Longitudinal) -Tension –Td	Td =1.1SMYS (A-Δ)	
-Compression – Cd Local –Cld	Cl = 1.1 SMYS[2-0.28(D/t_{min})$^{1/4}$]A Kd	Kd = 1 + 3 fd (D/t)
-Compression Global – Cgd	Cg = 1.1 SMYS(1.2-0.25λ^2) A $\lambda = \frac{KL}{\pi r}\frac{SMYS}{E}^{0.5}$	$\frac{P_{crd}}{P_{crdo}} + \frac{P_{crd}\Delta Y}{(1-\frac{P_{crd}}{P_{Ed}})M_{ud}} \leq 1.0$ $\lambda_d = (P_{ud} / P_{ed})^{0.5}$ $P_{ud} = P_u \frac{A_d}{A_o} = P_u \exp\left(-0.08\frac{\Delta}{t}\right)$
(Transverse) -Bending –Mud	$\frac{M_d}{M_u} = \exp\left(-0.06\frac{\Delta}{t}\right)$	
(Pressure) -Burst – Pbd	$P_{bC} = \frac{2.2tSMTS}{(D-t)SCF_c}$ $P_{bD} = \frac{2t\sigma_u}{(D-t)SCF_D}$ $P_{bG} = \frac{2t\sigma_u}{(D-t)SCF_G}$ $P_{bDG} = \frac{2t\sigma_u}{(D-t)SCF_{DG}}$	SCFc = 1 + 2(d/R)$^{0.5}$ SCF_D = 1 + 0.2 (H/t)^3 SCF_G = 1 + 2(h/r)$^{0.5}$ SCF_{DG} = [1-d/t-(16H/D)(1-d/t)]$^{-1}$
-Collapse – Pcd	$P_c = 0.5\{P'_{ud} + P_{ed}K_d - [(P'_{ud}+P_{ed}K_d)^2 - 4P'_{ud}P_{ed}K_d]^{0.5}\}$ $P_c = 0.5\{P_{ud} + P_{ed}K_d - [P_{ud} + P_{ed}K_d]^2 - 4P_{ud}P_{ed}K_d\}^{0.5}\}$	$P_u' = 5.1\frac{\sigma_u t_d}{D_o}$ $P_E = \frac{2E}{1-\nu^2}\left(\frac{t_d}{D_o}\right)^3$ $K = 1 = 3f\left(\frac{D_o}{t_{nom}}\right)$ $P_{ud} = \frac{2SMTSt_{min}}{D_o}$
-Propagating – Pp*	$P_p = 34SMYS\left(\frac{t_{nom}}{D_o}\right)^{2.5}$	

Table 19. Formulation for Combined Loading States

Loading States (1)	**Formulation (2)**	**Formulation Factors (3)**
T –Mu	$\left[\left(\frac{M}{M_u}\right)^2+\left(\frac{T}{T_u}\right)^2\right]^{0.5}=1.0$	
T – Pc	$\frac{P}{P_c}+\frac{M}{M_u}=1.0$	
Mu – Pc	$\frac{P}{P_c}+\frac{M}{M_u}=1.0$ (load controlled) $(\frac{P}{P_c})^2+(\frac{M}{M_u})^2=1.0$ (displacement cont.)	
T-Mu-Pc	$\left[(\frac{T}{T_u})^2+(\frac{P}{P_c})^2+(\frac{M}{M_u})^2\right]\leq 1$	
C-Mu-Pb	$M_c = M_p F_M$ $M_p = SMYSD^2t(1-0.001\frac{D}{t})$ $\left[\left(\frac{P}{P_{co}}\right)^2+\left(\frac{M}{M_u}\right)^2+\left(\frac{C}{C_g}\right)^2-2\mu\left(\frac{P}{P_{co}}\bullet\frac{M}{M_u}+\frac{M}{M_u}\bullet\frac{C}{C_g}+\frac{P}{P_{co}}\bullet\frac{C}{C_g}\right)\right]^{0.5}\leq 1$	$f_M=k_1\cos\left[\frac{\frac{\pi}{2}\left(k_2-\frac{1}{2}\frac{\sigma_{he}}{SMTS}\right)}{k_1}\right]$ $k_1=\sqrt{1-\frac{3}{4}\left(\frac{\sigma_{he}}{SMTs}\right)^2}$ $k_2=\frac{C}{\pi SMTSDt}$
C-Mu-Pc	$\left(\frac{M}{M_{co}}\right)^2+\left(\frac{P}{P_{co}}\right)^2\leq 1$ $\left[\left(\frac{P}{P_{co}}\right)^2+\left(\frac{M}{M_u}\right)^2+\left(\frac{C}{C_g}\right)^2-2\mu\left(\frac{P}{P_{co}}\bullet\frac{M}{M_u}+\frac{M}{M_u}\bullet\frac{C}{C_g}+\frac{P}{P_{co}}\bullet\frac{C}{C_g}\right)\right]^{0.5}\leq 1$	$M_{co}=M_p\cos\left(\frac{\pi T}{2T_y}\right)$ $M_p=SMYS\bullet D_o^2t_{nom}(1-0.001\frac{D_o}{t_{min}})$ P_{co}: Timoshenko Ultimate or Elastic equation

5. Conclusion

This report summarized all the works performed during summer 2000 regarding on Real-Time RAM project. 1st Rosen Risk Assessment and Management Workshop, "Risk Assessment for Pipelines Based on Inline Inspection Data", was held in Lingen, Germany on June 29 – 30, 2000 to bring up why the RAM is important to Rosen engineering associated with in-line inspection service. RAM attempts to identify and remedy causes, detect potential and evolving events and bring them under control, and minimize undesirable effects. RAM pipe attempts to establish and maintain the integrity of a pipeline system at the least possible cost. However, comprehensive solutions may not be possible to implement them due to the limitation of funding and technology. Therefore, this project was started between Rosen Engineering, MMS, and U.C. Berkeley to develop a procedure that can characterize the reliability upon the results from in-line instrumentation. In-line inspection data can provide a large amount of data on damage and defects in a pipeline. This data must be properly interpreted to characterize the features in a pipeline. Any uncertainties associated with in-line inspection data and demand (operating conditions) and capacity of pipeline must be analyzed using reliability methods developed at the Marin Technology & Management Group at the University of California at Berkeley.
Most of summer works were to review the papers and works done by U.C.B. and other institution such as DNV, ASME B31G, BG_{plc}, etc. to build up the knowledge to understand the present technology and standard associated with the pipeline and continue my research.

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7. Appendix: Summary of Rosen Workshop

Summary of ROSEN Risk Assessment Workshop

Overview

The primary goal of this workshop was to discuss 'Risk Assessment and Management Approaches for Pipelines based on Inline Inspection Data'. This workshop was organized by Rosen Engineering in Germany to give a direction and idea to a new project called "Real-Time RAM Pipeline" working closely together with University of California at Berkeley and U.S. Minerals Management Service.

Engineered structures are systems that degraded with time and must be continuously assessed for their reliability. Among the many engineered structure, the pipeline experience the degradation upon entering the several environment, operational conditions, and time. Therefore, the deterioration of pipelines must be constantly inspected and maintained with proper instruments. In-line inspections provide information and data on the characteristics of defects in the pipeline and give the pipeline owners and operators a good understanding of how best to manage the pipeline integrity to provide an acceptable quality.

Given results from in-line inspection, it is required to develop an analysis and evaluation of the characteristics on the detected features for the pipeline's integrity. The project will result in development, verification, and testing of procedures that can be used to evaluate the reliability of a pipeline on results from the in-line instrumentation.
The discussions on the workshop indicated four main aspects about the project, which are:

A) Risk Assessment and Management Calculations,

B) Liability Issues,

C) Service to Clients, and

D) Software Development.

Followings are the points of contention addressed in the discussions.

Risk Assessment and Management Calculation

1. Data from Inline Inspection

What kind of data is required from the in-line inspection?

Actions

UCB: Preparation of forms with parameters (e.g. L,W,D) and the required statistical properties (e.g. variance, accuracy) that is necessary to perform the project. (e.g. Form of tables and figures)

ROSEN: Provide information. Fill in forms

2. Time Frame of Data – Comparison between Old and New Data

Is there an improvement for the calculation of the probability of failure using former inspection results?

How has the technical progress of the inspection service taken into account?

Improvement of liability of the pipeline including old data.

Actions

UCB: Preparation of a study addressing:
- Possible benefits from the assessment and analysis of old data.
- How old data is link to the probability of failure calculation on the present pipeline (example: corrosion rates).

3. Probability of Failure of Inspection Tool -

Minimization of the likelihood of failure.

Note: This issue is beyond the scope of work of the ongoing project. Maintenance issue.

4. Likelihood of Tool Damage Due to Pipeline Operation

Note: This issue is beyond the scope of work of the ongoing project. Operations issue.

5. Influence of the Different Pipe Sections on Risk Calculation

A pipeline consists of different pipe-sections like installations, riser, pipe sections with changing wt. Each of such a section may be associated with different inspection accuracies or different operational and environmental parameter. Therefore, in which way have this to be taken into account performing the risk assessment?

Section the risk associated with the pipeline such as the probability of failure for installation, external (e.g. Riser), and internal corrosion.

<u>Actions</u>

ROSEN: Categorize pipeline sections; Monitor accuracy for changes.

UCB: Assess the relevance and the risk associated with this issue.

6. Data from Pipeline Operation

Data from inline inspection are collected during pigging. In addition to that data from pipeline operation are required for conducting the risk calculation. The pigging company usually collect only those operational data which are essential for providing the pigging service (OD, wt, flow, pressure, medium,...).

Which information from the pipeline operation are essential for risk calculation?

In case of lack of information, would it be possible to adapt comparable databases for a general estimation (e.g. different scenarios based on different operational databases)?

-Database from other industries or regulation authorities if available;

-Database requirement for pigging data;

-Data From pipeline industries;

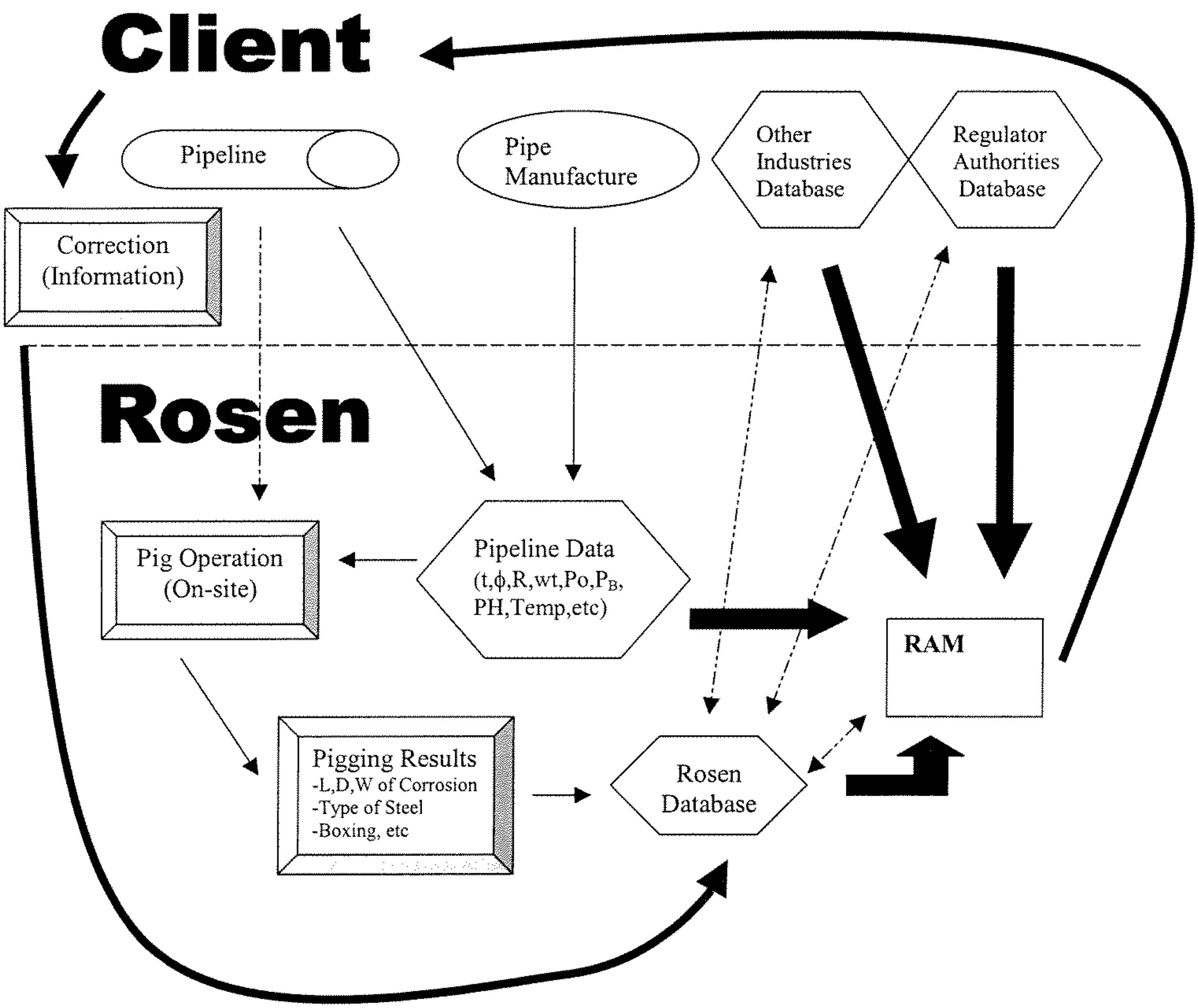
-Interface between industries' correction on the defects and Rosen's in-line instrumentation database to improve the accuracy of the detection.

<u>Actions</u>

ROSEN: Presentation of pipeline-operation data needed for the decision to launch the pig

UCB: Review and complete the list of data for the project.
Find out the availability of statistical database of other industries

The Flow of Data and Information



Check the accuracy of pigging by matching

7. Integration of Data Interpretation

How to integrate 'interpretations' of instrument data into Pf calculations?

- Focus on human factors of interpretation

8. Interfaces

- Data from intelligent pigging and fitness for pigging. Direct ROSEN input to the RAM system.
- Data from pipeline operation. Direct input from Client.
- Consequences of each of data. Clarification (Output) what a lack of data/information will imply for the RAM
- Options to improve data based on Cost/Benefit. (i.e. a better data base is more expensive, but may lead to a better and lower failure prediction)
- How to use external database to improve evaluations (e.g. liability implications. The external databases may be public. In case of missing operational data required for the RAM a general public database may be used, which is accepted as a reliable basis for the calculation.)

9. Implications of Providing Risk Based Analysis

How to deliver the project including this RAM technology to clients?

- Now and Future
- Need for standard to assess FFP (fit for purpose) and Pf.
- Explanation to Client. Prevention of confusion due to misunderstanding of the implications of RAM.
- What clients wants or think what they want

10. Rosen Presentations based on Local differences.

Clients' expectations to a RAM may vary by country and company.

Liability Issues

2. As engineers, may need to discuss with legal authorities to see possible concerns.
    - Liability issues may be different for different regions.

3. Need to state limitations of terms/conditions
    - Human factors

4. Would be providing a domestic difference
    - Currently note defect at a point in the pipeline

5. Discuss issue relative to insurance requirements – specifically with the insurance provider

6. Need to address legal liability issues

7. May consider as a certification document
    - Potential applications

Service to clients

8. What type of service we want to offer them?

9. Framework (Don't tell client what to do and give client what they want)

10. Strength of Rosen (What Rosen can provide which others can not?)

11. Purpose of calculation in RAM (Inspection and Maintenance and explain to client)

Software development

12. Implementation

13. No distinguish between Rosen and Clients

14. Access of other database

15. Input part form clients

16. Detail of calculation

17. New feature for Pf column to client (per joint basis)

18. Interactive (let user calculate the Pf and feedback to database to collect data)