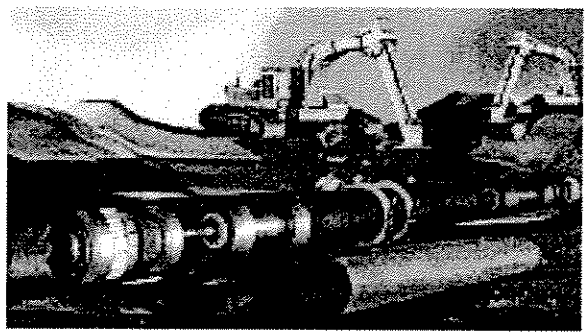
Real-Time Risk Assessment and Management of Pipelines Project



Sponsored by:

Rosen Engineering and the U.S. Minerals Management Service

Report Two

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Introduction

In-line inspections provide information on the characteristics of defects and damage in a pipeline. Given this information, the pipeline owner/ operator wants to know ho best to manage the pipeline integrity to provide acceptable serviceability and safety.

Objective

The objective of the Real-Time RAM Project is to develop, verify, and test procedures that can be used during the in-line instrumentation of pipelines to characterize their reliability. The sponsors of the Real-Time RAM project are the U.S. Minerals Management Service and Rosen Engineering.

Project Background

Pipeline in-line instrumentation data can provide a large amount of data on damage and defect (features) in a pipeline. This data must be properly interpreted before the features can be characterized. The detection of features varies as a function of the size and geometry of the features, the in-line instrumentation used, and the characteristics of the pipeline.

Given results from in-line instrumentation, it is desirable to develop an evaluation of the effects of the detected features on the pipeline's integrity. This evaluation requires and analysis of how the detected features might affect the ability of the pipeline to maintain containment.

Evaluation of the effects of uncertainties associated with in-line instrumentation data, pipeline capacity, and operating conditions on a pipeline's abilities to maintain containment can be analyzed using structural reliability methods. During the past five years, the Marine Technology and Management Group at the University of California at Berkeley have been using such methods to evaluate the reliability of pipelines. This work has addressed a variety of types of defects and damage including corrosion, denting, gouging, and cracking. The work has also included development of database structures that can allow storage and use of information gathered from in-line instrumentation in developing improved reliability evaluations for both instrumented and non-instrumented pipelines. One of the products of these studies has been development of a generic framework for the reassessment and requalification of pipelines. This framework involves a three-tiered process that includes qualitative indexing methods (tier 1), simplified reliability based methods (tier 2), and sophisticated probability risk analysis based methods (tier 3). The objective of this approach is to allow pipelines to be reassessed and requalified at the simplest tier possible, utilizing the more advanced tiers only when it is necessary. This project would be focused on development and verification of a tier 2 method.

A parallel project, titled the Performance of Offshore Pipelines Project will provide information on the burst pressure capacities on in-place pipelines. The pipelines will be in-line instrumented prior to hydrotesting. The ruptured sections of the pipeline will be retrieved and subjected to laboratory tests. This project will provide data to verify the analytical procedures developed during this project.

Scope of Work

The Real-Time RAM (Risk Assessment and Management) of Pipelines addresses the following key aspects of criteria for in-line instrumentation:

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.

Project Tasks

1. Develop, verify and test procedures that can characterize the reliability upon the results from in-line instrumentation with various features including corrosion, dents and gouges.
2. Evaluate available data from in-line instrumentation including the uncertainties associated with the in-line instrumentation 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 methods.
4. Develop formulations to analyze reliability of a pipeline in its 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. The POP Project will be used to verify the analytical procedures developed during this project.
8. Summarize comprehensively how to utilize this project into practical operations and service in industry.
9. Document the results in four project phase reports.
10. Transfer the forgoing results to project sponsors in five project meetings.

Risk Assessment and Management

Introduction

Risk is defined as the likelihood that adequate or acceptable quality is not achieved and the consequences associated with the lack of achieved quality. Quality is formed by the combination of serviceability, safety, durability, and compatibility. Risk results from uncertainties. Uncertainties result from inherent variability, technical sources (information, modeling) and human and organizational factors. Risk assessment attempts to understand and identify the risks, and how they may be mitigated. Risk management evaluates alternative measures for risk mitigation, identify those that should be implemented, and act (Bea, 1995).

Risk assessment and management of pipelines should be practical in nature, thus embodying the following key attributes:

- Simplicity: ease of use and implementation.
- Versatility: the ability to handle a wide variety of real problems,
- Compatibility: readily integrated into common engineering and operations procedures,
- Workability: the information and data required for input is available or economically attainable, and the output is understandable and can easily be communicated,
- Feasibility: available engineering, inspection, instrumentation, and maintenance tools and techniques are sufficient for application of the approach,
- Consistency: the approach can produce similar results for similar problems when used by different engineers.

(Bea, 1999)

Reliability Engineering

A significant advancement in modern science is the study of systems in a probabilistic, rather than deterministic, framework. The conventional, deterministic paradigm neglects the potential range of variables that exist for a given term in an equation. The modern practitioner of engineering is becoming more aware that deterministic models are inadequate for designing the complex systems of the modern age. Furthermore, the performance of supposedly identical systems differs because of differences in components and differences in the operating environment. Reliability engineers speak of "statistical distributions," instead of a peak value, a maximum load, or expected load. Instead of saying that a component is not expected to fail, during a given time, engineers now talk about the probability of failure of a system, or a system component.

It is more conservative to use a single, deterministic value, representing a worst case scenario, rather than to calculate with statistical methods. The application of statistical models in engineering stems from the use of statistics in World War Two. Unfortunately, university engineering curriculums have failed to teach statistics to their students. Probability refers to the chances that various events will take place, based on an assumed model. In statistics, we have some observed data and wish to determine a model that can be used to describe the data. Both situations arise in engineering. For example, if we wish to predict the performance of a system of known design, before building, by assuming various statistical models for the components that make up a system. When test data on system performance is given, statistical techniques are then used to construct an appropriate model and to estimate its parameters. Once a model is obtained, it may be used to predict future performance (Hahn, 1968).

The basic premise of a reliability approach is recognition of the statistical variations in the loading of a structural element (pipeline), and the capacity of the element to withstand these loadings, within a specified performance criteria. The reliability process begins with a statistical description of the loadings to which the structure will be subjected. This description provides, in statistical terms, the occurrence of loadings that the structure will experience during its lifetime.

The capacity of a pipeline system can be characterized by the pipeline material properties: the elastic and inelastic strength properties of the linepipe. The demands on the system are obtained from the statistical characterization of the internal pressure loadings.
The following figure, Figure 1, shows the pipeline structure as a composition of segments and elements.

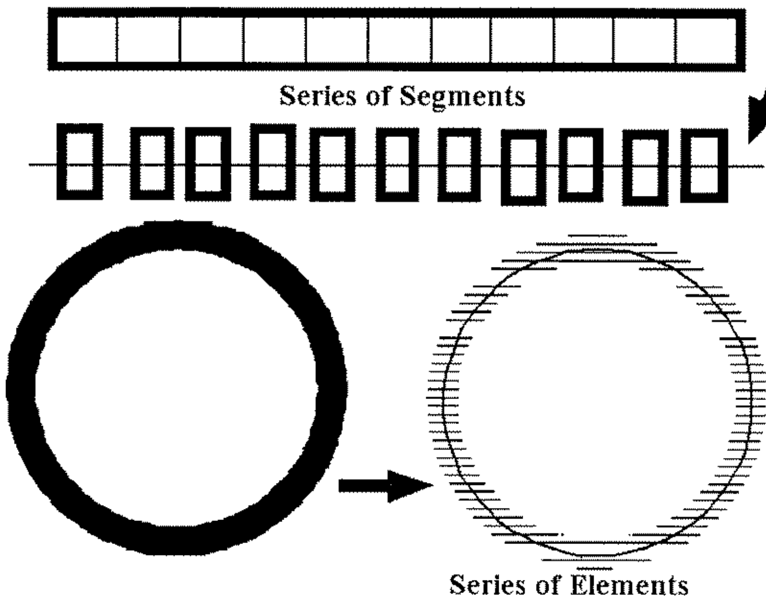

Figure 1: Pipeline System, Composed of Segments and Elements (Bea, Xu, 1999)

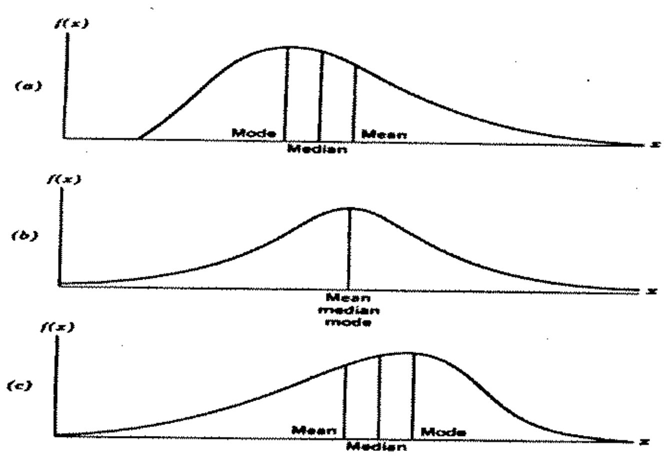

Figure 2: Central Tendency Measures (Bea, 1995)

As previously mentioned, the demand (load) and capacity (strength), are statistically described, based on the reliability approach. The statistical description of demand and capacity is referred to as a 'distribution,' which are shown graphically in figure 1. The best known measure of the central tendency of a distribution, whether this distribution describes the demand or capacity of a pipeline system, is the expected value, or the arithmetic mean, or the average. This point is the center of gravity of the distribution, since it is that point around which the sum of the distance to the left times the probability weight balances out the corresponding sum of weighted values to the right. The median or mid-point is a second measure of the central tendency of a distribution. The median is that value of the random variable that has exactly one half of the area under the probability density function to its left and one half to its right. The last measure of central tendency is the mode, which is that value of the random variable that has the highest probability. The mode is the value associated with the maximum of the probability density function. (Han and Shapiro, 1992) Figure 2 demonstrates full distributions; curves with fully developed tails on both ends. Another capacity scenario exists, which acts to truncate the capacity distribution.

Reliability and Quality

Reliability (Ps) is the likelihood or probability that the structure system will perform acceptably. The probability of failure (Pf) is the likelihood that the structural system will not perform acceptably. Reliability can be characterized with demands (S) and capacities (R). When the demand exceeds the capacity, then the structural system fails. The demands and capacities can be variable and uncertain (Bea, 1995).

Quality is defined as freedom from unanticipated defects. Quality is also fitness for purpose. Quality is also meeting the requirements of those who design, construct, operate, and regulate systems. These requirements include those of serviceability, safety, compatibility, and durability.

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. Safety is the freedom from excessive danger to human life, the environment and property. Safety is the state of being free of undesirable and hazardous situations. Compatibility assures that the structure system does not have unnecessary or excessive negative impacts on the environment and society during its life cycle.

Compatibility is the ability of the structure system to meet economic, time, and aesthetic requirements. Durability assures that serviceability, safety, and environmental compatibility are maintained during the intended life of the marine structure system. Durability is freedom from unanticipated maintenance problems costs.

Reliability is defined as the probability that a given level of quality will be achieved during the design, construction, and operating life-cycle phases of a structure. Reliability is the likelihood that the structure will perform in an acceptable manner. Acceptable performance means that the structure has desirable serviceability, safety, compatibility, and durability. (Bea, 1995)

Probability of Failure

The probability that a structural system will survive the demand is defined as the reliability:

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

Where Ps is the probability of success, or reliability. And P (R > S) is read as the probability that the capacity (R) exceeds the demand (S).

In analytical terms, the reliability can be computed from:

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

Where Φ is the standard normal distribution cumulative probability of the variable β. β is referred to as the safety index. Given lognormally distributed, independent demands (S) and capacities (R), the safety index, β, is computed as follows:

$$\beta = \frac{\ln\left(\frac{\underline{R}}{\underline{S}}\right)}{\sqrt{\sigma_{\ln R}{}^2 + \sigma_{\ln S}{}^2 - 2 \cdot \rho_{RS} \cdot \sigma_{\ln R} \cdot \sigma_{\ln S}}}$$

$\underline{R}$ = median capacity

$\underline{S}$ = median demand

$\sigma_{\ln S}$ = standard deviation of the demand

$\sigma_{\ln R}$ = standard deviation of the demand

ρ_{RS} = correlation coefficient

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). Examples of Type I Uncertainties include annual maximum wave height, earthquake peak ground acceleration, or ice impact kinetic energy that will be experienced by a structure at a given location during a given period of time. Type I Uncertainties associated with capacities are the yield strength of steel, the tensile strength of aluminum, and the shear strength of a material. The second type of uncertainty, Type II Uncertainties, are identified as unnatural, cognitive, parameter, measurement, or modeling uncertainties (Bea, 1995).

Type II Uncertainties apply to deterministic, but unknown value of parameters, to modeling uncertainty, and to the actual state of the system. Examples in loading uncertainties, Type II, include uncertainties in computed wind, wave, current, earthquake, and ice conditions and forces that are due to imperfections in analytical models. Examples of Type II Uncertainties in capacities is the difference between the nominal yield strength of steel and the median yield strength of steel. Type II Uncertainties are characterized by a measure of the bias, which is the ratio of the measured value to the nominal value (Bea, 1995).

M.E. Pate'-Cornell discusses uncertainties in the oil and gas industry, in her article titled "Organizational Aspects of Engineering System Safety: The Case of Offshore Platforms," published in *Science*. She mentions the unique environment, which is often poorly known, and highly variable. A common strategy to cope with large uncertainties is to eliminate uncertainties from decisions, by redefining the problem. When this cannot be done, incentives and culture often lead to denial, biases in interpretation of information, and overconfidence in either the most likely or most favorable hypothesis. The natural tendency in the communication of incomplete information is to tell people what they prefer to hear. (M. E. Pate'-Cornell, 1990)

Elements and Systems

Figure 1 refers to a pipeline system composed of elements and segments. A series system is one in which the failure of one of the elements leads to the failure of the system. In the case of a pipeline, which is composed of a system of elements and segments, the probability of failure of the pipeline can be expressed as the probability of failure of its N elements as:

$$P_{f\,SYSTEM} = (P_{f1})or(P_{f2})or...(P_{fN})$$

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

$$P_{f_{SYSTEM}} = 1 - (1 - P_{fi})^N$$

If P_{fi} is small, as is typical, then approximately:

$$P_{f_{SYSTEM}} \approx N \cdot P_{fi}$$

If the independent elements have different failure probabilities:

$$P_{fSYSTEM} = \sum_{i}^{N} P_{fi}$$

If the elements are perfectly correlated, then:

$$P_{fSYSTEM} = Maximum(P_{fi})$$

(Bea, 1995)

Pipeline Inspection Technology

Introduction

As the pipeline infrastructure system ages, it is important that pipeline operators have the technology to inspect and assess the state of their pipelines. Information on inspection techniques can be found in literature.

Fundamentals of In-Line Instrumentation

An intelligent pig, or a 'smart pig,' or in-line inspection tool, is a self-contained inspection tool that flows through a pipeline with the product. Pipeline operators use smart pigs to evaluate the integrity of transmission pipelines. Smart pigs, or in-line inspection tools, inspect the full thickness of the pipe wall. These tools are designed to look for conditions such as metal-loss corrosion, cracks, gouges, and other anomalies.

The two main objectives of smart pigs are to detect potential defects, and then determine the size of the detected defect.

It should be noted that detection requirements depend upon the overall goal of the pipeline inspection. One operator may be interested in using inspections to uncover problem areas in a pipeline; hence the objective of the inspection is to locate defects in the initial stages of their growth life. Another operator may want to ensure that their lines have no defects which threaten pipeline integrity; therefore, they are interested in larger ($d/t>50\%$) defects only (Bubenik, 2001).

According to Batelle, magnetic flux leakage (MFL) is the oldest and most commonly used in-line inspection method for pipelines. The magnetic flux leakage technique provides an indication of the general condition of a pipeline section. MFL is a mature technique, extensively used in self-contained smart pigs. A permanent magnet generates a magnetic field in the pipe wall, so that a reduction in material will cause flux to leak. Most of the magnetic flux field lines pass through the pipe wall. The pipe wall is the preferred path for the flux. In the region of metal-loss region, the sensor records a higher flux density or magnetic field, thus indicating the presence of an anomaly. Furthermore, defects distort the applied magnetic field, producing flux leakage. The amount of flux leakage depends on the size and shape of the defect, as well as the magnetic properties of the pipeline steel. Sensors measure flux leakage, and record the measurements inside the pig. The measurements taken by the pig are analyzed after the inspection is completed to estimate the defect geometry depth.

An MFL pipeline inspection tool is a self-contained unit, containing magnets, sensors, data recording systems, and a power system. The systems used in most MFL tools include:

- A drive system, which uses the pressure differential in the pipeline to propel the tool.
- A power system, which provides battery power for the sensors, and data recording system.
- A magnetization system for magnetizing the pipe.
- A sensor system to measure the flux-leakage signal.
- A data recording system, which amplifies, filters, and stores the measured signals (Bubenik, 2001).

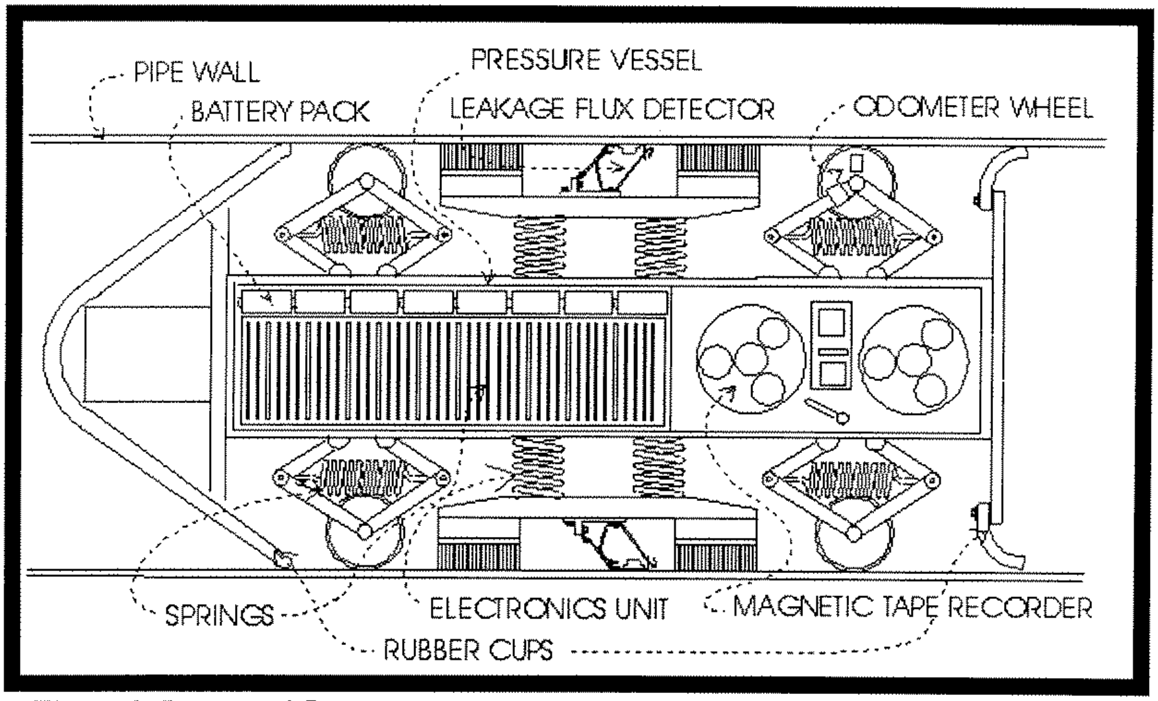

Figure 3: Layout of Components of MFL Pipeline Pig (www.phy.queensu.ca)

Standard Definitions

The following standard definitions are used throughout this report:

Applied Magnetic Field: The strength of the magnetization field that is produced in a pipe wall by a magnetizing system in an in-line inspection tool.

Anomaly: An indication, generated by non-destructive examination of base pipeline material, which may or may not be an actual flaw.

Bellhole: An excavation in a local area to permit a survey, inspection, maintenance, repair, or replacement of pipe sections.

Buckle: A partial collapse of the pipe due to excessive bending associated with soil instability, land slides, washouts, frost heaves, earthquakes, etc.

Characterize: To quantify the type, size, shape, orientation, and location of an anomaly or defect.

Configuration Pig: An instrumented pig that collects data relating to the inner contour of a pipe wall or of the pipeline. Geometry pigs, are a type of configuration pigs.

Corrosion: An electrochemical reaction of the pipe wall with its environment, causing a loss of metal.

- *General External* - Metal loss due to electrochemical, galvanic, microbiological, or other attack on the pipe due to environmental conditions surrounding the pipe.
- *General Internal* - Metal loss due to chemical or other attack on the steel from liquids on the inside of the pipe. Electrochemical attack can also occur in local cells, but this condition is less frequent.
- *Pit* - Local concentrated-cell corrosion on the external or internal surfaces that results from the generation of a potential (voltage) difference set up by variations in oxygen concentrations within and outside the pit. The oxygen-starved pit acts as the anode and the pipe surface acts as the cathode.

Defect : an undesirable property of a pipeline, capable of being identified and measured by an intelligent pig.

Dent: Distortion of the pipe wall resulting in a change of the internal diameter but not necessarily resulting in localized reduction of wall thickness.

Detection: The process of obtaining an inspection signal that is recognized as coming from a defect. An in-line inspection tool can detect only those defects that produce signals that are both measurable and recognizable. Not all defects are detectable with all inspection systems.

Dummy Run: A preliminary run of a utility pig to verify safe passage of a fully instrumented tool through a section of pipeline. Dummy runs may also be used to remove debris from inside the pipeline.

Erosion: Destruction or removal of material by abrasive action of moving fluids (or gases) usually accelerated by the presence of solid particles or matter in suspension.

False Call: An indication from an inspection that is classified as an anomaly where no imperfection, or defect exists.

Flux: The (scalar) number of flux lines crossing a unit area at right angles to the unit area. See magnetic flux.

Flux Density:A measure of the intensity of magnetization produced by a magnetic field.

Flux Leakage: The flow of flux out of a magnetic material, such as the wall of a pipe, into a medium with lower permeability, such as gas or air.

Gauging Pig: A utility pig that is permanently deformable by obstructions in the pipeline and thus, upon retrieval from the line, provides evidence of the worst-case obstruction in a given pipeline segment.

Geometry Pig: A configuration pig designed to record conditions, such as dents, wrinkles, ovality, bend radius and angle, and occasionally indications of significant internal corrosion, by making measurements of the inside surface of the pipeline.

Gouge: Mechanically induced metal-loss, which causes localized elongated grooves or cavities.

Heat Affected Zone: The area around a weld where the metallurgy of the metal is altered by the rise in temperature caused by the welding process.

Identification: The process of differentiating a signal caused by one type of defect from signals caused by other types of defects or pipeline features.

Induction Coil Sensor: A type of sensor that measures the time rate of change in flux density. Induction coils do not require power to operate.

In-Line Inspection Tool: The device or vehicle, also known as an intelligent or smart pig, that uses a nondestructive testing technique to inspect the wall of a pipe.

Instrumented Tool or Pig: A vehicle or device used for internal inspections of a pipe, which contains sensors, electronics, and recording or output functions integral to the system. Instrumented tools are divided into two types: (a) configuration pigs, which measure the pipeline geometry or the conditions of the inside surface of the pipe, and (b) in-line inspection tools that use nondestructive testing techniques to inspect the wall of the pipe for corrosion, cracks, or other types of anomalies.

Launcher: A pipeline facility used for inserting a pig into a pressurized pipeline.

Magnetic Flux: A measure of the amount of magnetization carried by a material.

Magnetic Flux Leakage: An inspection technique in which a magnetic field is applied to a pipe section and measurements are taken of the magnetic flux density at the pipe surface. Changes in measured flux density indicate the presence of a possible defect. Also called MFL.

Maximum Allowable Operating Pressure (MAOP): The maximum internal pressure permitted the operation of a pipeline as defined by the Code of Federal Regulations.

Maximum Operating Pressure (MOP): The maximum internal pressure expected during the operation of a pipeline, which cannot normally exceed the maximum allowable operating pressure.

Measurable: Producing an inspection signal that is above the noise level inherently present in the pipe.

Obstructions: Any restriction or foreign object that reduces or modifies the cross section of the pipe to the extent that gas flow is affected or in-line inspection pigs can become stuck (ovality, collapse, dents, undersized valves, wrinkles, bends, weld drop through). Also any foreign object in the pipeline.

Ovality: A condition in which a circular pipe forms into an ellipse, usually as the result of external forces.

Pig: A generic term signifying any independent, self-contained device, tool or vehicle that moves through the interior of the pipeline for purposes of inspecting, dimensioning, or cleaning. All pigs in this report are either or instrumented tools.

Pipe Mill Feature: A defect that arises during manufacture of the pipe, as for instance a lap, sliver, lamination, non-metallic inclusion, roll mark and seam weld anomaly.

Pipeline: That portion of the pipeline system between the compressor stations including the pipe, protective coatings, cathodic protection system, field connections, valves and other appurtenances attached or connected to the pipe.

Pipeline System: All portions of the physical facilities through which gas moves during transportation including pipe, valves, and other appurtenances attached to the pipe, such as compressor units, metering stations, regulator stations, delivery stations, holders and other fabricated assemblies. (See 49 Code of Federal Regulations 192)

Probability of Detection: The probability of a feature being detected and recorded by the intelligent pig.

Pig call: a pipeline anomaly detected and recorded in the data of the instrumented pipeline, which may or may not actually exist.

Radius Bends: The radius of the bend in the pipe as related to the pipe diameter (D). Example: A 3D bend would have a radius of three times the diameter of the pipe measured to the centerline of the pipe.

Receiver: A pipeline facility used for removing a pig from a pressurized pipeline.

Remanent Magnetization: The magnetization level left in a steel pipe after the passage of a magnetic in-line inspection tool.

Rerounding: The process of changing the dent depth and shape by internal pressure in the pipe. Generally, dents due to third-party contact will reround, while dents due to rocks will not unless the rock causing the dent is removed.

Residual Stresses: Elastic stresses that were not present within the pipe wall before mechanical damage but that are present after the damage has occurred.

Saturation: The degree of magnetization where a further increase in magnetic field strength produces a decrease in permeability of a material.

Sizing: See characterization.

Smart Pig: See in-line inspection tool.

Specified Minimum Yield Strength or Stress (SMYS): A required strength level that the measured yield stress of a pipe material must exceed, which is a function of pipe grade. The measured yield stress is the tensile stress required to produce a total elongation of 0.5 percent of a gage length as determine by an extensometer during a tensile test.*Tool:* A generic term signifying any type of instrumented tool or pig.

Trap: pipeline facility for launching and receiving tools and pigs.

(Bubenik, 2001)

Probability of Detection

There are four contributing factors, which directly influence the probability of detection of an MFL inspection tool (Beuker, 2001):

1. Inspection Tool Capability: mechanical parameters, such as magnetization level and configuration.

2. Calibration of Inspection Tool: defect population should be taken into account in calibration.

3. Interpretation of Results: interpreting the data printouts provided by the intelligent pig.

4. Defect Population: Adjacent defects make signal analysis difficult because the leakage fields overlap and affect each other.
    a. Distribution of depth.
    b. Noise Level
    c. Noise Parameter

Inspection Tool Capability: Mechanical Limitations

The characterization accuracy, including the probability that the pig will simply detect a metal-loss defect (POD), is related to the mechanical properties of the pig. For example, applied magnetic field strength produce stronger leakage fields, which improve the performance of the pig's detection and characterization abilities. The applied flux density in a pipe also depends upon the coupling efficiency between the magnet, the pipe, and on the local wall thickness. For the same applied magnetic field, an increase in wall thickness decreases the flux density in the pipe. Therefore, the strength of the magnetization system must be tailored to the wall thickness of the pipe to be inspected. Thick-walled pipe requires a larger magnetization (magnet) level in order to achieve saturation. Furthermore, variations in the wall thickness will change the applied field strength. Flux density is also a function of the local permeability of the pipe. Small changes in carbon content, alloying elements, and impurities create variations in permeability. The magnetization level strongly affects both detection and characterization accuracy. Magnet strength and magnetic coupling have the strongest affect on the applied field. Velocity, stress, repeated magnetizations of the line-pipe, and changes in the material properties of the pipe along the length of the pig run also affect the applied magnetic field. Ideally, the magnetization system in an MFL tool should produce a magnetic field that is strong enough to cause a measurable amount of flux leakage at defects; uniform from the inside surface to the outside surface of the pipeline wall thickness, and consistent in magnitude along the length of a pipe, so that measurements can be compared at different locations during an inspection run.

Sensors located on-board the pig convert the magnetic flux leakage field measurements into electrical signals that can be stored, analyzed, and reviewed. The sensor must optimize the information that it collects, as it balances the quantity and quality of the data that it collects. Sensors are spring-loaded against the pipe surface, allowing the sensors to ride over weld beads, dents, and debris. The stiffness of the mounting system and the mass of the sensors affect how closely the sensors ride the internal pipeline wall. A sensor wear plate protects the sensor from damage but provide a built-in stand-off between the sensor and the pipe wall, which affects POD. Furthermore, sensors filter the incoming data, and the size of the sensor affects the resolution of the system. Important sensor parameters include circumferential width of the sensor, sensor type, its axial position between magnet poles, and the ability of the sensor to reduce background noise levels (Bubenik, 2001).

Data storage devices located on–board the pig require battery power to operate. Therefore, the available battery power limits the mileage that can be inspected at any time. The power system is constrained by the size and shape of the interior of the inspection tool.

False Pig Calls

False pig calls are indications of defects in the collected data, where no defect actually exists. Two common causes of false calls are metal objects near the pipeline, and pipeline repair sleeves (Bubenik, 2001). False pig calls can lead to costly excavations, and repair work being performed, without it being needed. The rate of false calls is related to the interpretation and use of the inspection results. If all indications of defects are to be excavated, the number of false calls should be minimized.

Parametric Study

A parametric study was undertaken, in order to display the decision process made by the pig, while in operation. As the pig makes a run through a pipeline, there are probabilities associated with the pig's ability to detect and identify defects in a pipe. Figures 4 and 5 demonstrate the decision paths available for the pig. The following definitions are used in the study, and are consistent with other definitions throughout this report:

Definitions:

Actual Decision Tree:

1. Pig call: a pipeline anomaly detected and recorded in the data of the instrumented pipeline, which may or may not actually exist.
2. Defect: an undesirable property of a pipeline, capable of being identified and measured by an intelligent pig.
3. Defect Classes*:
    a. Class I: corrosion pit
    b. Class II: pipeline dent
    c. Class III: pipeline gouge
    d. Class IV: combination of any of the above classes of defects
4. POD: Probability of detection
5. POI.X: Probability of identification of a given class of defect.

* Class I defects (corrosion) are the only defect types capable of being predicted, given that the defect is not detected by the pig.

*Ideal Decision Tree***:

1. POF: Probability that the detected defect actually exists.
2. POM: Probability of missing an existing defect

** The ideal decision tree will not be used at this time for the real-time probability of failure calculation. The ideal decision tree requires data that does not yet exist.

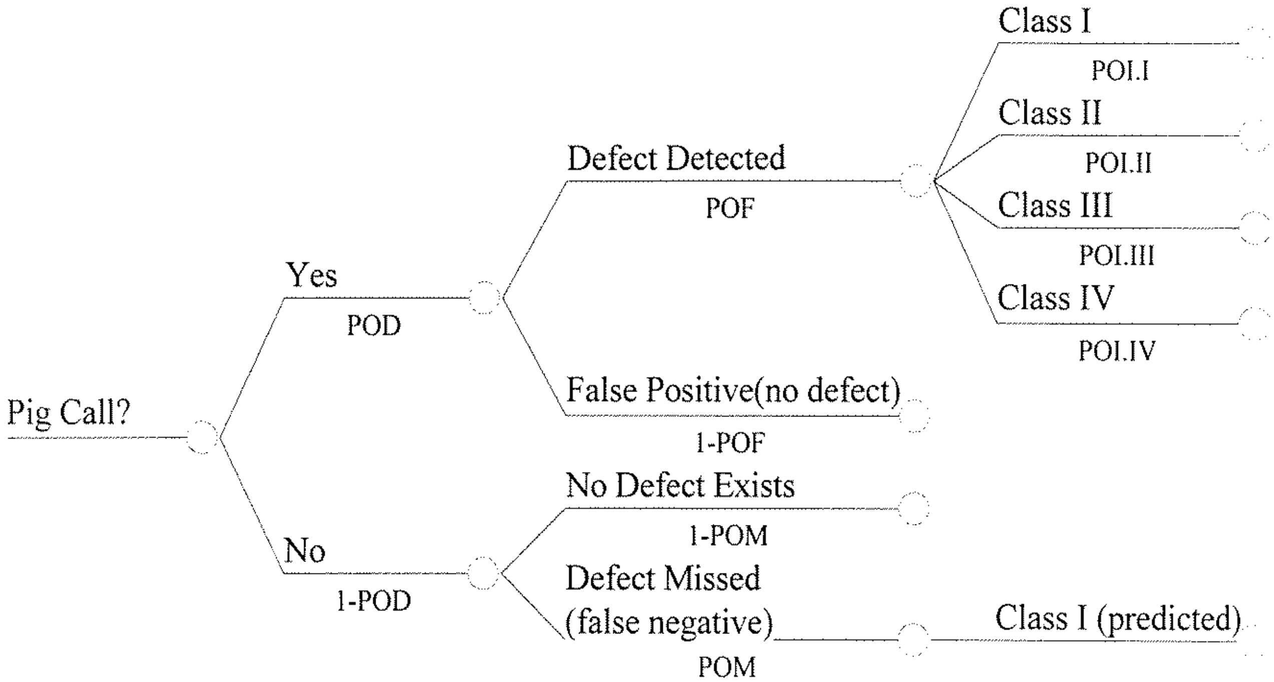

Figure 4: Ideal Decision Tree

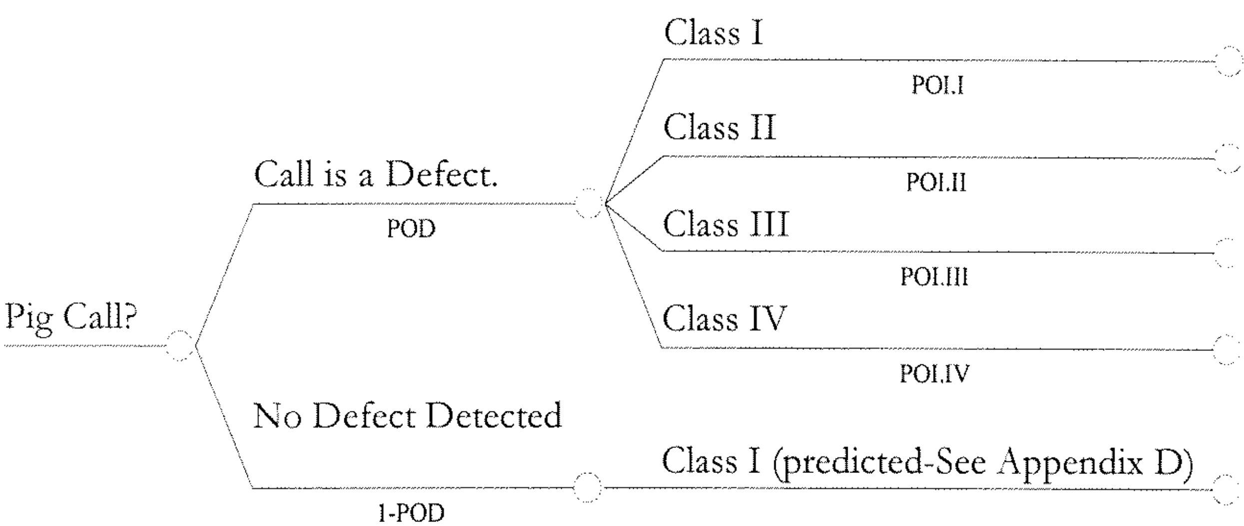

Figure 5: Actual Decision Tree

Real-Time Risk Assessment and Management

The integrity of aging pipeline systems is a major concern for pipeline operators. The pipeline operator must decide as to how to optimize their available maintenance resources. Optimal resource allocation involves identification of the highest risk pipeline segments, and determination of maintenance activities that will lead to the highest reduction in overall risk (Bea, 1999).

The three areas pertaining to probability of failure calculations on a real-time basis are: burst pressure formulations of damaged pipelines, inspection accuracy, and reliability theory. Pipelines undergo nearly constant degradation, from the time they are put into service, until the decommissioning phase of the pipeline's lifecycle. The degradation of pipelines in the offshore environment is commonly caused by internal and external corrosion.

The pipeline operator must identify high-risk segments, and quantify the probability of failure of these segments. Furthermore, the operator must evaluate the consequences of failure, which may vary with pipeline segment location (Beuker, 2001).

The first key task in the RAM paradigm is to prioritize the pipeline system, based on level of risk. This step involves the processing of key pipeline attributes in order to calculate the probability of failure for a given section of pipe.

Pipeline	Pipe SegmentBend	Pipe Segment Normal Condition	Pipe Segment Survey Condition
Pipeline Code	Location	Minimum Velocity	Segment Number
Section Name	Type	Ave Velocity	Minimum Velocity
Size	Radius	Max Velocity	Ave Velocity
Overall Length	ID	Min Liquid Flowrate	Max Velocity
Year Installed	Remarks	Ave Liquid Flowrate	Min Liquid Flowrate
On Shore	**Pipe SegmentFlange**	Max Liquid Flowrate	Ave Liquid Flowrate
Off Shore	Flange No	Min Gaseous Flowrate	Max Liquid Flowrate
Remarks	Type	Ave Gaseous Flowrate	Min Gaseous Flowrate
Pipeline Contents	Class	Max Gaseous Flowrate	Ave Gaseous Flowrate
Medium	Remarks	Min Pressure	Max Gaseous Flowrate
Detailed Medium	**Pipe Segment Material**	Ave Pressure	Min Pressure
Phase Flow	Segment Number	Max Pressure	Ave Pressure
Paraffin	Material Number	Min Inlet Temp	Max Pressure
Salt Water	Type	Ave Inlet Temp	Min Inlet Temp
FeCO	Internal Coating	Max Inlet Temp	Ave Inlet Temp
H_2S	Wall thickness	Min Outlet Temp	Max Inlet Temp
Pipe Segment	Joint Length	Ave Outlet Temp	Min Outlet Temp
Segment Name	Weld Type	Max Outlet Temp	Ave Outlet Temp
On Shore	Detailed Weld Type	Expected Cleanness	Max Outlet Temp
Off Shore	Design Pressure	Slug Flow	Expected Cleanness
Nominal Outer Diameter	Design Factor		
Minimum Inner Diameter	SMYS		
Nominal Inner Diameter	SUTS		
Constan Inner Diameter	Remarks		
Minimum Bend Radius			
Minimum Wall thickness			
Nominal Wall thickness			
Maximum Wall Thickness			
MAOP			

Figure 6: Key Pipeline Risk Assessment and Management Attributes (Rosen, 2001)

The next step in RAM is to calculate the probability of failure of the pipeline, given the existence of a defect. Pipeline pigging companies commonly supply pipeline data, describing the various types of flaws that exist in a pipeline. In order to extend the knowledge supplied by the pigging company to its client, the probability of failure formulation is being developed, on a 'real-time' basis.

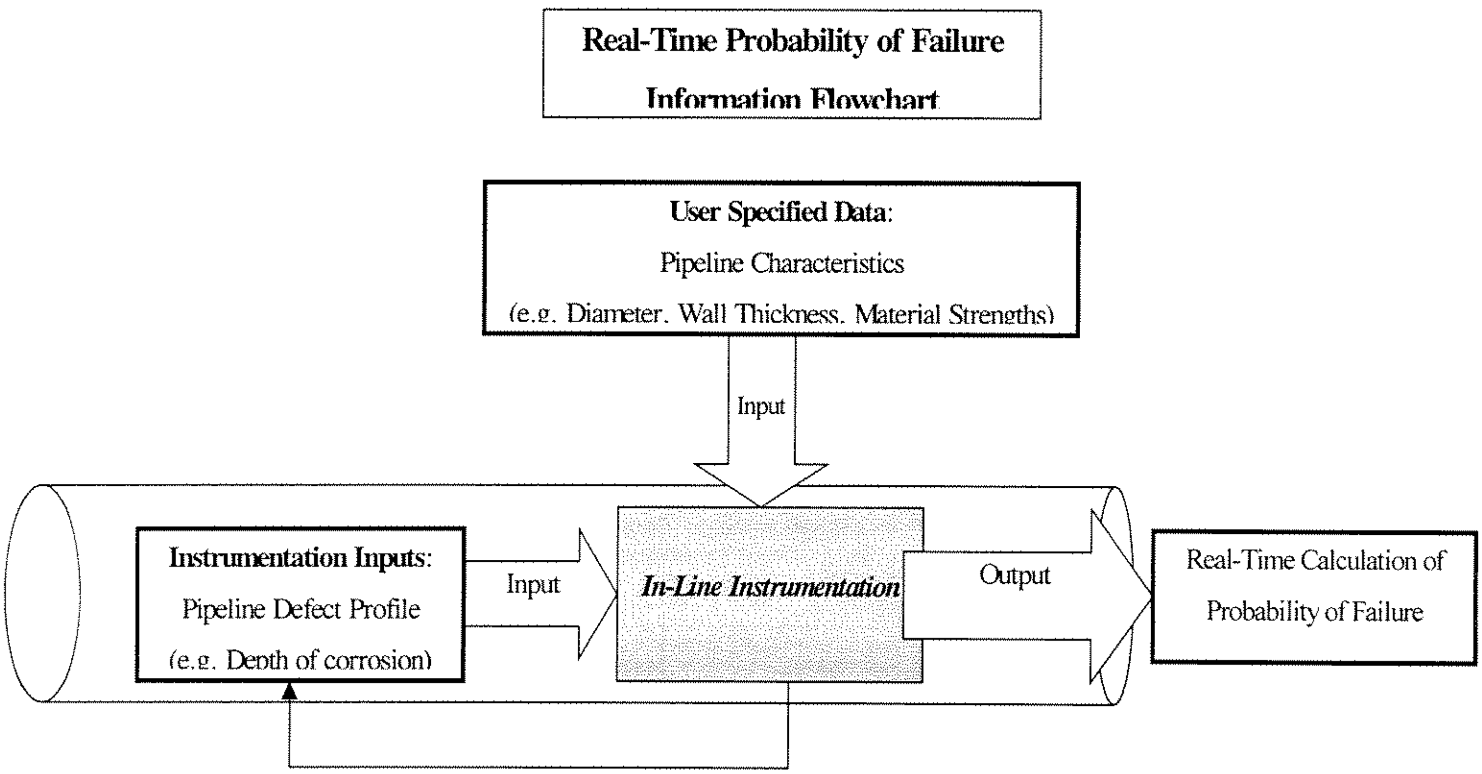

Figure 7: Real Time Probability of Failure Information Flow

RAM PIPE Formulations

Significant advancements have been made in the requalification and reassessment of offshore pipelines. The fundamental strategy used in U.C. Berkeley's RAM PIPE REQUAL approach is based on two strategies (Bea, 1999):

- Assess the risks (likelihoods, consequences) associated with existing pipelines, and
- Manage the risks so as to produce acceptable and desirable quality and reliability in pipeline operations.

RAM PIPE REQUAL formulations are based on the following key premises (Bea, Xu, 1999):

- The design and reassessment-requalification analytical models are based on analytical procedures that are founded on fundamental physics, materials, and mechanics formulations.
- The requalification analytical models are based on analytical procedures that result in unbiased (the analytical results equals the median measured values) assessments of the pipeline demands and capacities.
- Physical test data and verified – calibrated analytical model data are used to characterize the uncertainties and variabilities associated with the pipeline demands and capacities; data from numerical models are used only if there is sufficient physical test data to validate the numerical models over a sufficiently wide range of parameters.
- The uncertainties and variabilities associated with pipeline demands and capacities are concordant with the uncertainties and variabilities involved in definition of the pipeline reliability goals.

Refer to Appendix A, page 41, for an Excel spreadsheet to calculate burst pressure of pipelines containing corrosion defects, dents, and gouges.

Burst Pressure, Corroded Pipelines:

RAM PIPE developed a burst equation for a corroded pipeline as:

$$p_{bd} = \frac{3.2 \cdot t_{nom} \cdot SMYS}{D_o \cdot SCF_C} = \frac{2.4 \cdot t_{nom} \cdot SMTS}{D_o \cdot SCF_C}$$

Where:

t_{nom} = nominal pipe wall thickness
D_o = mean pipeline diameter (D-t)
SMYS = Specified Minimum Yield Strength of pipeline steel
SMTS = Specified Minimum Tensile Strength of pipeline steel
SCF_C = Stress Concentration Factor for corrosion, defined by:

$$SCF_C = 1 + 2 \cdot (d / R)^{.5}$$

Burst Pressure, Dented and Gouged Pipelines:

$$P_{b_{DG}} = \frac{2 \cdot t \cdot \sigma_U}{(D - t) \cdot SCF_{DG}} \qquad SCF_{DG} = \left[1 - \frac{d}{t} - \frac{16 \cdot H}{D}\left(1 - \frac{d}{t}\right)\right]$$

σ_U = Ultimate strength of the pipeline material

h = depth of gouge

H= depth of dent

SCF_{DG} = Stress Concentration Factor due to dents and gouges

(Bea, Xu, 1999)

Applied Reliability Theory

One of the primary deliverables in this phase of the Real-Time RAM Project involves the development of an algorithm to calculate the probability of failure. Appendix A contains deterministic RAM PIPE formulations for calculation the burst pressure of pipelines. Appendices B and C contain Excel spreadsheets for the purpose of calculating the probability of failure of a pipeline. In order to calculate the probability of failure for a pipeline with a known corrosion defect, the initial step is to choose the distribution type for the burst pressure (capacity, R) and operating pressure (demand, S) of the pipeline. Based on previous work in this area of pipeline reliability, the lognormal distribution will be used in the calculation. Therefore, using the lognormal distribution, the probability of failure for any individual defect can be calculated by the use of Equation 1.

$$P_f = 1 - \Phi(\beta)$$

The total probability of failure of a pipeline is equal to the sum of the individual probabilities of failure for detected defects, and undetected, yet existing defects, and is expressed as follows:

$$P_f = P_f\big|_D + P_f\big|_{ND} \qquad \text{(Bea, 1999)}$$

Where $P_f\big|_D$ is probability of failure based on detected pipeline defects.

$P_f\big|_{ND}$ is probability of failure based on undetected pipeline defects. Refer to Appendix D for the prediction of non-detected (yet existing) corrosion defects.

In Equation 1, β is the safety index and Φ is the standard normal cumulative function. β can be further broken down into its components, which is shown in the following equation:

$$\beta = \frac{\ln\left(\dfrac{B_b \cdot P_b}{B_o \cdot P_o}\right)}{\sqrt{\sigma^2_{\ln b} + \sigma^2_{\ln o} - 2\rho\sigma_{\ln b}\sigma_{\ln o}}}$$

B_b is the bias in the burst pressure, and B_o is the bias in the operating pressure. $\sigma_{\ln b}$ is the standard deviation of the lognormally distributed burst pressure. $\sigma_{\ln o}$ is the standard deviation of the operating pressure, and ρ is the correlation coefficient. In the case of these calculations, the correlation between the burst pressure and operating pressure is zero, and therefore the third term under the radical can be neglected. Appendix G presents an analysis of the sensitivity of the variables that compose β, the safety index.

The bias is defined as the ratio of true or measured value to predicted or nominal value, attempting to 'bridge the gap' between the truth and 'what we know.'

$$Bias = \frac{MeasuredValue}{\Pr edictedValue}$$

Given appropriate data, the standard deviation is a trivial calculation. Beginning with the coefficient of variation (COV):

$$COV = V = \frac{\sigma_x}{\bar{x}}$$

σ_x is the standard deviation of the variable x, and $\bar{x}$ is the mean or expected value of the variable. Given the lognormal assumption, as previously stated, the lognormal standard deviation can be derived through the following equation:

$$\sigma_{\ln x} = \sqrt{\ln\left(1 + V_x^{\ 2}\right)}$$

The total coefficient of variation is equal to the sum of the squares of the Type I and Type II uncertainties, and the total COV is represented by the following equation:

$$V_{Total}^2 = V_I^2 + V_{II}^2$$

In order to further illustrate the probability of failure calculation, a table of user-specified variables needed to determine the probability of failure is shown:

Pipeline Characteristics (median values)			
Diameter, D_{50}	$V_{D,I}$	Wall Thickness, t50	$V_{t,I}$
Inches		Inches	
16	0.10	0.332	0.12
Steel Material Strengths (median values)			
Yield Strength, YS_{50}	$V_{YS,I}$	Tensile Strength, TS_{50}	$V_{TS,I}$
PSI		PSI	
35000	0.08	52000	0.08
Pipeline Defect		**Biases**	
Defect Type: Corrosion		Demand	Capacity
Depth, d	$V_{d,I}$	B_S	B_R
0.20	0.08	1.1	1
Pipeline Demand		**Pipeline Capacity**	
Operating Pressure		RAM PIPE, Corroded Pipelines	
PSI	$V_{P,I}$	PSI	$V_{BP,I}$
4000	0.1	2009	0.1

Table 1: User Specified Inputs for Real-Time Probability of Failure Calculation

Table 1 summarizes the user-specified inputs, which would be supplied by the in-line inspection tool operator. Refer to Appendix E for more detailed information on pipeline pressure demands, including maximum and minimum operating pressures experienced by the pipeline. In the 'pipeline characteristics' section of the table, D_{50}, median diameter, is entered, with its associated 'Type I' uncertainty, $V_{D,I}$. The user enters wall thickness, t_{50}, and wall thickness uncertainty, $V_{t,I}$. Next, the user must enter the median yield strength of the pipeline, YS_{50}, and Type I uncertainty of yield strength, $V_{YS,I}$. TS_{50}, median tensile strength, is entered, along with its uncertainty, $V_{TS,I}$. Pipeline defect information, supplied by the intelligent pig, is the next input parameter for the probability of failure calculation. $V_{d,I}$ is the uncertainty in the depth measurement. Appendix H addresses the problem of 'converting' an uncertainty based on an 80% confidence level to a Type I uncertainty, used in the RAM PIPE formulation.

Biases in demand and capacity, B_S and B_R, respectively, are entered as reliability parameters. The user must specify the pipeline pressure demand, and the uncertainty of demand, $V_{p,I}$. Lastly, the pipeline capacity must be known. Using the RAM PIPE Equation for corroded pipelines, the burst pressure of the pipeline is calculated, and entered in the table as a 'user specified' value.

Once the appropriate data has been collected by the pig, the probability of failure can be calculated. The denominator of the safety index equation (β) is first calculated. Using the values listed in Table 1, the coefficient of variation is calculated for Type I uncertainties, associated with the pipeline capacity.

$$\begin{aligned} V_I^2 &= V_D^2 + V_t^2 + V_{TS}^2 + V_d^2 + V_{BP}^2 \\ &= .1^2 + .12^2 + .08^2 + .08^2 + .1^2 \\ &= .047 \end{aligned}$$

For this particular example, Type II uncertainties of capacity, due to modeling, are non-existent. The total uncertainty for the capacity (R) becomes:

$$V_{Total}^2 = V_I^2 + V_{II}^2 = .057 + 0 = .047$$

The standard deviation of the lognormally distributed capacity variables is:

$$\sigma_{\ln R} = \sqrt{\ln\left(1 + V_{Total}^{\ 2}\right)} = .215$$

These steps are repeated for the lognormally distributed demands:

$$\sigma_{\ln S} = \sqrt{\ln\left(1 + V_{Total}^{2}\right)} = .100$$

Now that all of the necessary terms are present, the probability of failure for a given corrosion pit can be calculated:

$$\beta = \frac{\ln\left(\frac{B_b \cdot P_b}{B_o \cdot P_o}\right)}{\sqrt{\sigma^2_{\ln b} + \sigma^2_{\ln o} - 2\rho\sigma_{\ln b}\sigma_{\ln o}}} = \frac{\ln\left(\frac{1.0 \cdot 2009}{1.1 \cdot 2500}\right)}{\sqrt{.215^2 + .100^2}} = -1.32$$

$$P_f = 1 - \Phi(\beta) = 1 - .093 = 90.7\%$$

Therefore, for the conditions presented in Table 1, for this single corrosion pit, detected by the pig, the probability of failure of the pipeline at this location is 91%. There may be other flaws present, which correspond to a given probability of failure. Refer to Appendix B, page 39, for an Excel spreadsheet to calculate the probability of failure of a pipeline, based on full demand and capacity distributions.

Probability of Failure: Truncated Distribution

In the beginning of this section, a full distribution was used to develop the probability of failure of a pipeline given a corrosion pit. Another situation arises, where the probability of failure will be calculated based on a truncated capacity distribution. The following graph shows the principle of the truncated distribution:

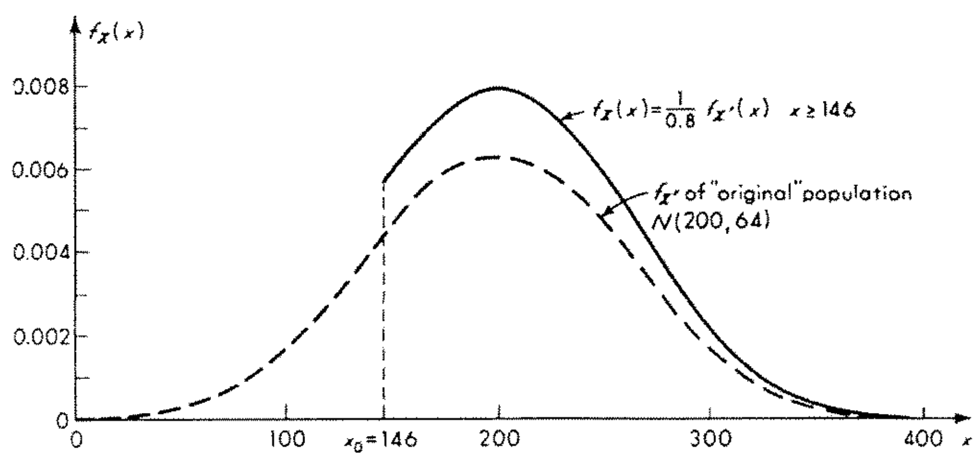

Figure 8: Truncated Distribution (Benjamin and Cornell, 1970)

The tails of both the demand and capacity distributions are lost, due to three primary reasons:

1. Pressure relief valves installed in the pipeline.
2. Pressure operating parameters specified by the pipeline operator.
3. Hydrotesting of the pipelines: Refer toAppendix F, page 56, which discusses pipeline hydrotesting, as it relates to pipeline capacity distributions.

The resulting 'truncated' distribution has been truncated below x_o. The original population had a probability density function (PDF) of $f_x(x)$, and a cumulative distribution function of $F_x(x)$, and the variable of interest Y (demand or capacity variable), has been truncated below x_o, the PDF is zero up to x_o, and $f_x(x)$ is renormalized for $x>x_o$.

$$f_Y(y) = \left| \frac{0 \quad for \quad y < x_o}{k \cdot f_x(y) \quad for \quad y \geq x_o} \right.$$

$$where:$$

$$k = \frac{1}{[1 - F_x(x_o)]}$$

The PDF for the lognormal distribution is:

$$f(x, \mu, \sigma) = \frac{1}{\sigma \cdot x \cdot \sqrt{2\pi}} \exp\left[\frac{-1}{2\sigma^2} (\ln x - \mu)^2 \right]$$

Where:

$$\mu = mean$$
$$\sigma = s\tan dard\ deviation$$

The lognormal cumulative distribution function (CDF) is:

$$F(x) = \Phi\left[\frac{\ln(x)}{\sigma}\right]$$

Where:

$$\Phi = \textit{cumulative distribution function of the normal distribution}$$

The probability of failure calculation, given a detected flaw, and a truncated capacity distribution, is calculated by the following equation:

$$P_f = \sum\left[P_f \mid p\right]\cdot\left[P(p)\right]\cdot\left[\Delta P\right]$$

This equation is read as "the probability of failure equals the summation of probability of failure, given a pressure, times the probability of the pressure occurring, times a pressure increment." (Bea, 1995)

The following graph shows the region of interest for the probability of failure calculation.

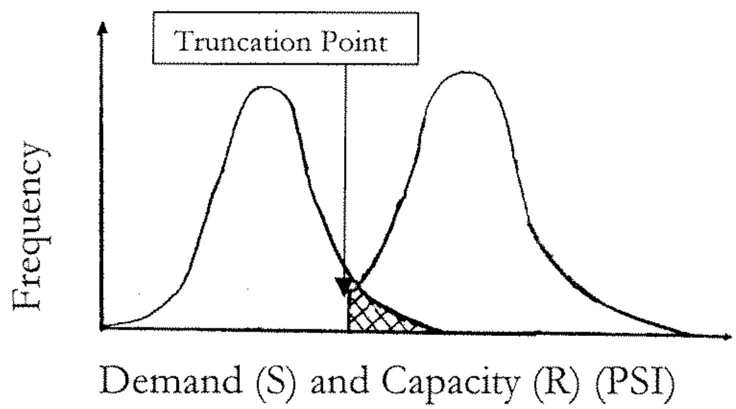

Figure 9: Demand and Capacity Distribution

The cross-hatched region represents the overlap between the demand and capacity distributions. This is the region of interest for the probability of failure calculations, given a corrosion pit in a pipeline, and a truncated demand distribution for the pipeline.

As in the previous sample calculation, information regarding the pipeline characteristics, must be assembled.

It should be noted that $P_f|p = 1 - \Phi(\beta)$, where β is the safety index. The probability of the pressure occurring, P_p, is equal to the probability density function for lognormally distributed variables. The pressure increment, ΔP, is specified by the user. Appendix C contains an Excel spreadsheet for the purpose of calculating pipeline probability of failure, based on truncated distributions.

The extent to which the tail of the probability distribution is truncated directly affects the probability of failure of a corroded pipeline. Refer to Appendix I, page 66, for a parametric study that demonstrates the effects of truncating the pipeline pressure demand distribution.

Conclusion

Methods for calculating the probability of failure of a pipeline, on a real-time basis, based on inputs from an intelligent pig, have been presented. The real-time probability of failure calculation requires several inputs from the intelligent pig. Based on the user inputs, a probability of failure calculation has proven to be feasible. The availability of metrics used for calculating probability of failure of a pipeline has been validated. That is, an intelligent pig, of the magnetic flux leakage type, produces data that is suitable for a probabilistic calculation.

Tables 4 and 5, the decision analysis trees, demonstrate the decision process inherent to the intelligent pig. The results of the decision analysis tree are used to assess the risk associated with a depth of corrosion in the presence of a pig call and in the absence of a pig call.

Future considerations for in-line tool technical standards are summarized in the following table:

In-Line Tool Technical Information Standard
Probabilities
Probability of Detection, POD
Probability of Identification of a given type of defect, POI
Probability of False Call, POFC
Data Interpretation
Characterization of Human Data Interpretation/Conversion
Calibration Standard
Descriptive Statistics for Normal Distribution of Calibration Data
Factors Which May Influence Pig Performance
External Factors
Pipeline Wall Grade
Pipeline Wall Stress
Remanent Magnetization Effects
Internal Factors
Tool Velocity
Pig Magnet Size, Relative to Pipeline Wall Thickness

Table 2: MFL In-Line Tool Technical Standard

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Appendix A: Burst Pressure of Pipelines—RAM PIPE Formulations

Pipeline Burst Pressure: RAM PIPE Formulations				
New Pipeline				
Pipeline Characteristics				Burst Pressure
Diameter, D	Wall Thickness, t	SMYS	SMTS	
Inches	Inches	PSI	PSI	PSI
48	0.422	35000	46000	1941

Corroded Pipeline						
Pipeline Characteristics				Pipeline Defect	Burst Pressure	
				Corrosion		
Diameter, D	Wall Thickness, t	SMYS	SMTS	Depth, d	PSI	
Inches	Inches	PSI	PSI	Inches	SCF	PSI
24	0.322	42000	55000	0.2	1.12	1609

Dented-Gouged Pipeline							
Pipeline Characteristics				Pipeline Defect		Burst Pressure	
				Dent	Gouge		
Diameter, D	Wall Thickness, t	SMYS	SMTS	Depth, H	Depth, d	PSI	
Inches	Inches	PSI	PSI	Inches	Inches	SCF	PSI
24	0.422	35000	46000	1	0.1	3.93	503

SMYS = Specified Minimum Yield Strength
SMTS =Specified Minimum Tensile Strength
SCF = Stress Concentration Factor

Figure A-1: Burst Pressure of Pipelines, Based on RAM PIPE Formulations

Appendix B: Probability of Failure—Full Distribution

Variable	*Definition*
D_{50}	Median Diameter
$V_{D, I}$	Diameter Uncertainty
t_{50}	Median Wall Thickness
$V_{t, I}$	Wall Thickness Uncertainty
YS_{50}	Median Yield Strength
$V_{YS,I}$	Yield Strength Uncertainty
TS_{50}	Median Tensile Strength
$V_{TS, I}$	Tensile Strength Uncertainty
d	Depth of Corrosion
$V_{d, I}$	Corrosion Depth Uncertainty
H	Depth of Dent
$V_{H,I}$	Depth of Dent Uncertainty
h	Depth of Gouge
$V_{h, I}$	Depth of Gouge Uncertainty
σ_{lnS}	Standard Deviation of Lognormal Demand Variables
σ_{lnR}	Standard Deviation of Lognormal Capacity Variables
S_{50}	Median Demand
$V_{S, I}$	Uncertainty in Capacity
R_{50}	Median Capacity
ρ_{rs}	Correlation Coefficient
β	Safety Index
$\Phi(\beta)$	Standard Cumulative Normal of Variable Beta
P_f	Probability of Failure

Table B-1: List of Variables used in Real-Time Probability of Failure Calculation

Probability of Failure
New (Uncorroded) Pipeline

Pipeline Characteristics (median values)				Steel Material Strengths (median values)			
Diameter, D50	$V_{D,I}$	Wall Thickness, t50	$V_{t,I}$	Yield Strength, YS50	$V_{YS,I}$	Tensile Strength, TS50	$V_{TS,I}$
Inches		Inches		PSI		PSI	
16	10%	0.332	12%	35000	8%	52000	8%

	Reliability Parameters				
	Uncertainty Summary		Biases	Standard Deviation	
	Type I	Type II		$\sigma_{\ln S}$	$\sigma_{\ln R}$
Demands, S_{50}	12%	0%	1	0.120	0.215
Capacities, R_{50}	19%	10%	1.2		

Default Values	Type I	Type II	Biases	Standard Deviation	
				$\sigma_{\ln S}$	$\sigma_{\ln R}$
Demands, S_{50}	15%	10%	1.0		
Capacities, R_{50}	10%	10%	1.0	0.10	0.10

Distrubution Type: Lognormal
Correlation: $\rho_{rs} = 0$

Loading State			Probability of Failure		
Uncorroded Pipeline Capacity	Pipeline Demand	$V_{S,I}$			
R_{50}	S_{50}		β	$\Phi(\beta)$	P_f
2158	1000	12%	3.13	0.9991	0.001

Note 1: Pipeline demand is user specified (normal pump pressure, accidental pressure loads: shut-ins)
Note 2: Pipeline characteristics and steel material strengths are median values
Note 3: Shaded boxes represent user specified values

Figure B-2: Excel Spreadsheet to Calculate Probability of Failure of New Pipeline, Lognormal Format

Probability of Failure
Corroded Pipeline

Pipeline Characteristics (median values)				Steel Material Strengths (median values)				Pipeline Defect	
Diameter, D_{50}	$V_{D,I}$	Wall Thickness, t50	$V_{t,I}$	Yield Strength, YS_{50}	$V_{YS,I}$	Tensile Strength, TS_{50}	$V_{TS,I}$	Defect Type: Corrosion	
Inches		Inches		PSI		PSI		Depth, d	$V_{d,I}$
16	10%	0.332	12%	35000	8%	52000	8%	0.20	0.08

	Reliability Parameters				
	Uncertainty Summary		Biases	Standard Deviation	
	Type I	Type II		$\sigma_{\ln S}$	$\sigma_{\ln R}$
Demands, S_{50}	12%	0%	1.0	0.120	0.229
Capacities, R_{50}	21%	10%	1.0		

Default Values	Type I	Type II	Biases	Standard Deviation	
				$\sigma_{\ln S}$	$\sigma_{\ln R}$
Demands, S_{50}	15%	10%	1.0	0.10	0.10
Capacities, R_{50}	10%	10%	1.0		

Distrubution Type: Lognormal
Correlation: $\rho_{rs} = 0$

Loading State			Probability of Failure		
Corroded Pipeline Capacity	Pipeline Demand	$V_{S,I}$			
R_{50}	S_{50}		β	$\Phi(\beta)$	P_f
2009.1	1000	12%	2.71	0.9966	0.003

Note 1: Pipeline demand is user specified (normal pump pressure, accidental pressure loads: shut-ins)
Note 2: Pipeline characteristics and steel material strengths are median values
Note 3: Shaded boxes represent user specified values

Figure B-3: Excel Spreadsheet to Calculate Probability of Failure of Corroded Pipeline, Lognormal Format

Probability of Failure
Dented-Gouged Pipelines

Pipeline Characteristics (median values)				Steel Material Strengths (median values)			
Diameter, D_{50}	$V_{D,1}$	Wall Thickness, t50	$V_{t,1}$	Yield Strength, YS_{50}	$V_{YS,1}$	Tensile Strength, TS_{50}	$V_{TS,1}$
Inches		Inches		PSI		PSI	
16	10%	0.332	12%	35000	8%	52000	8%

Pipeline Defect			
Dent	$V_{d,1}$	Gouge	$V_{H,1}$
Depth, H		Depth, d	
0.30	8%	0.02	8%

Reliability Parameters					
	Uncertainty Summary		Biases	Standard Deviation	
	Type I	Type II		$\sigma_{\ln S}$	$\sigma_{\ln R}$
Demands, S_{50}	0.12	0	1.0	0.120	0.241
Capacities, R_{50}	0.224	0.1	1.0		
Default Values	Type I	Type II	Biases	Standard Deviation	
Demands, S_{50}	15%	10%	1.0	$\sigma_{\ln S}$	$\sigma_{\ln R}$
Capacities, R_{50}	10%	10%	1.0	0.10	0.10

Distrubution Type: Lognormal
Correlation: $\rho_{rs} = 0$

Loading State			Probability of Failure		
Corroded Pipeline Capacity	Pipeline Demand	$V_{S,1}$			
R_{50}	S_{50}		β	$\Phi(\beta)$	P_f
5855.0	1000	12%	6.56	1.0000	0.000

Note 1: Pipeline demand is user specified (normal pump pressure, accidental pressure loads: shut-ins)
Note 2: Pipeline characteristics and steel material strengths are median values
Note 3: Shaded boxes represent user specified values

Figure B-4: Spreadsheet to Calculate Probability of Failure of Dented-Gouged Pipeline, Lognormal Format

Probability of Failure
New (Uncorroded) Pipeline

Pipeline Characteristics (median values)				Steel Material Strengths (median values)			
Diameter, D_{50}	$V_{D,I}$	Wall Thickness, t_{50}	$V_{t,I}$	Yield Strength, YS50	$V_{YS,I}$	Tensile Strength, TS_{50}	$V_{TS,I}$
Inches		Inches		PSI		PSI	
16	10%	0.332	12%	35000	8%	52000	8%

	Reliability Parameters						
	Uncertainty Summary		Biases	Standard Deviation		Distrubution Type	Correlation
	Type I	Type II		σ_{lnS}	σ_{lnR}	Normal	$\rho_{rs}=0$
Demands, S_{50}	30%	30%	1.0	0.407	0.346		
Capacities, R_{50}	19%	30%	1.2				

Default Values	Type I	Type II	Biases	Standard Deviation	
				σ_{lnS}	σ_{lnR}
Demands, S_{50}	15%	10%	1.0		
Capacities, R_{50}	10%	10%	1.0	0.10	0.10

Loading State			Probability of Failure		
Uncorroded Pipeline Capacity	Pipeline Demand	$V_{S,I}$			
R_{50}	S_{50}		β	$\Phi(\beta)$	P_f
2158	1700	30%	0.79	0.7849	21.5%

Note 1: Pipeline demand is user specified (normal pump pressure, accidental pressure loads: shut-ins)
Note 2: Pipeline characteristics and steel material strengths are median values
Note 3: Shaded boxes represent user specified values

Figure B-5: Excel Spreadsheet to Calculate Probability of Failure of New Pipeline, Normal Format

Probability of Failure
Corroded Pipeline

Pipeline Characteristics (median values)				Steel Material Strengths (median values)				Pipeline Defect	
Diameter, D_{50}	$V_{D,I}$	Wall Thickness, t_{50}	$V_{t,I}$	Yield Strength, YS_{50}	$V_{YS,I}$	Tensile Strength, TS_{50}	$V_{TS,I}$	Defect Type: Corrosion	
Inches		Inches		PSI		PSI		Depth, d	$V_{d,I}$
16	10%	0.332	12%	50000	8%	60000	8%	0.20	0.08

Reliability Parameters							
	Uncertainty Summary		Biases	Standard Deviation		Distribution Type	Correlation
	Type I	Type II		σ_{lnS}	σ_{lnR}	Normal	$\rho_s = 0$
Demands, S_{50}	12%	30%	1.0	0.315	0.430		
Capacities, R_{50}	21%	40%	1.0				

Default Values	Type I	Type II	Biases	Standard Deviation	
				σ_{lnS}	σ_{lnR}
Demands, S_{50}	15%	10%	1.0		
Capacities, R_{50}	10%	10%	1.0	0.10	0.10

Loading State			Probability of Failure		
Corroded Pipeline Capacity	Pipeline Demand	$V_{S,I}$			
R_{50}	S_{50}		β	$\Phi(\beta)$	P_f
2318.2	2300	12%	0.66	0.7439	25.6%

Note 1: Pipeline demand is user specified (normal pump pressure, accidental pressure loads: shut-ins)
Note 2: Pipeline characteristics and steel material strengths are median values
Note 3: Shaded boxes represent user specified values

Figure B-6: Excel Spreadsheet to Calculate Probability of Failure of Corroded Pipeline, Normal Format

Probability of Failure
Dented-Gouged Pipelines

Pipeline Characteristics (median values)				Steel Material Strengths (median values)			
Diameter, D_{50}	$V_{D,I}$	Wall Thickness, t_{50}	$V_{t,I}$	Yield Strength, YS_{50}	$V_{YS,I}$	Tensile Strength, TS_{50}	$V_{TS,I}$
Inches		Inches		PSI		PSI	
16	10%	0.332	12%	35000	8%	52000	8%

Pipeline Defect			
Dent	$V_{d,I}$	Gouge	$V_{H,I}$
Depth, H		Depth, h	
0.30	8%	0.1	8%

Correlation	Distribution Type
$\rho_{RS} = 0$	Normal

Reliability Parameters					
	Uncertainty Summary		Biases	Standard Deviation	
	Type I	Type II		σ_{lnS}	σ_{lnR}
Demands, S_{50}	0.12	0	1.0	0.120	0.241
Capacities, R_{50}	0.224	0.1	1.0		
Default Values	**Type I**	**Type II**	Biases	Standard Deviation	
Demands, S_{50}	15%	10%	1.0	σ_{lnS}	σ_{lnR}
Capacities, R_{50}	10%	10%	1.0	0.10	0.10

Loading State			Probability of Failure		
Corroded Pipeline Capacity	Pipeline Demand	$V_{S,I}$			
R_{50}	S_{50}		β	$\Phi(\beta)$	P_f
7435.3	6000	12%	2.83	0.9977	0.002

Note 1: Pipeline demand is user specified (normal pump pressure, accidental pressure loads: shut-ins)
Note 2: Pipeline characteristics and steel material strengths are median values
Note 3: Shaded boxes represent user specified values

Figure B-7: Excel Spreadsheet to Calculate Probability of Failure of Dented-Gouged Pipelines, Normal Format

Appendix C: Probability of Failure—Truncated Format

Uncorroded Pipeline Probability of Failure-Truncated Distributions

User Specified Inputs:

Input	Value	Uncertainties Type I	Uncertainties Type II
Pipeline Characteristics(Inches):		Type I	Type II
Diameter, D50:	8	10%	N/A
Wall Thickness, t50:	0.5	8%	N/A
Material Strength(PSI):			
SMYS:	42000	10%	N/A
SMTS:	50000	10%	N/A
Reliability Parameters:			
σ_{lnR}	1.01		
Total Uncertainty, $V_{I,II}$	0.16		
Pipeline Demand (PSI)			
Mean	2500		
Median	1442		
Standard Deviation, psi	750	*Uncertainties*	
Standard Deviation, Normalized	1.05	Type I	Type II
MOP/Pressure Relief Valve (upper bound)	3300	10%	N/A
Distribution Type			
Demands, S:	Lognormal		
Capacity, R:	Lognormal		
Pressure Increment(PSI):			
ΔS	110.0		
P_f	38.6%		

Note: Shaded Cells Represent User Specified Values

Pressure	(ln(P)/P) / St.Dev	P_P	β	$P_{f\|P}$	$P_{f\|P} * P_P * \Delta S$
3300	0.00000	0.50000	0.43797	0.33070	0.03474
3190	-0.03232	0.48711	0.46122	0.32232	0.03299
3080	-0.06578	0.47378	0.48529	0.31374	0.03123
2970	-0.10046	0.45999	0.51023	0.30495	0.02947
2860	-0.13644	0.44574	0.53611	0.29594	0.02771
2750	-0.17384	0.43100	0.56300	0.28672	0.02596
2640	-0.21276	0.41576	0.59100	0.27726	0.02422
2530	-0.25334	0.40000	0.62018	0.26757	0.02249
2420	-0.29572	0.38372	0.65067	0.25763	0.02077
2310	-0.34008	0.36690	0.68257	0.24744	0.01907
2200	-0.38660	0.34953	0.71603	0.23699	0.01740
2090	-0.43550	0.33160	0.75120	0.22627	0.01576
1980	-0.48705	0.31311	0.78828	0.21527	0.01416
1870	-0.54155	0.29406	0.82748	0.20398	0.01260
1760	-0.59935	0.27447	0.86905	0.19241	0.01110
1650	-0.66089	0.25434	0.91331	0.18054	0.00965
1540	-0.72667	0.23371	0.96062	0.16837	0.00827
1430	-0.79733	0.21263	1.01144	0.15590	0.00696
1320	-0.87365	0.19115	1.06634	0.14314	0.00575
1210	-0.95661	0.16938	1.12601	0.13008	0.00463
1100	-1.04749	0.14744	1.19137	0.11676	0.00362
990	-1.14794	0.12550	1.26362	0.10318	0.00272
880	-1.26024	0.10379	1.34439	0.08941	0.00195
770	-1.38756	0.08264	1.43596	0.07551	0.00131
660	-1.53454	0.06245	1.54167	0.06158	0.00081
550	-1.70838	0.04378	1.66670	0.04779	0.00044
440	-1.92113	0.02736	1.81973	0.03440	0.00020
330	-2.19543	0.01407	2.01701	0.02185	0.00006
220	-2.58202	0.00491	2.29507	0.01086	0.00001
110	-3.24291	0.00059	2.77041	0.00280	0.00000

Figure C-1: Excel Spreadsheet to Calculate Probability of Failure of New Pipeline, Truncated Distribution Format

Corroded Pipeline Probability of Failure-Truncated Distribution

User Specified Inputs:

		Uncertainties	
Pipeline Characteristics (Inches):		Type I	Type II
Diameter, D_{50}:	8	10%	N/A
Wall Thickness, t_{50}:	0.5	8%	N/A
Material Strength (PSI):			
SMYS:	42000	10%	N/A
SMTS:	50000	10%	N/A
Pipeline Defect (Inches):			
Depth of Corrosion, d:	0.08	d/t(%)	16%
Burst Pressure, P_b(PSI)	6236		
Reliability Parameters (Capacity):			
$\sigma_{\ln R}$	1.01		
Total Uncertainty, $V_{I,II}$	0.16		
Pipeline Demand (PSI)			
Mean	2500		
Median	1442		
Standard Deviation, psi	250		
Standard Deviation, Normalized	1.05	*Uncertainties*	
		Type I	Type II
MOP/Pressure Relief Valve (upper bound)	4900	10%	N/A
Distribution Type			
Demands, S:	Lognormal		
Capacity, R:	Lognormal		
Pressure Increment (PSI):			
ΔS	163.3		
P_f	52.9%		

Note: Shaded Cells Represent User Specified Values

Pressure	(ln(P)/P) / St.Dev	P_P	β	$P_{f\|p}$	$P_{f\|p} \cdot P_P \cdot \Delta S$
4900	0.00000	0.50000	0.16536	0.43433	0.04563
4737	-0.03232	0.48711	0.18861	0.42520	0.04352
4573	-0.06578	0.47378	0.21267	0.41579	0.04139
4410	-0.10046	0.45999	0.23761	0.40609	0.03925
4247	-0.13644	0.44574	0.26349	0.39609	0.03709
4083	-0.17384	0.43100	0.29039	0.38576	0.03493
3920	-0.21276	0.41576	0.31838	0.37510	0.03277
3757	-0.25334	0.40000	0.34757	0.36408	0.03060
3593	-0.29572	0.38372	0.37805	0.35270	0.02843
3430	-0.34008	0.36690	0.40995	0.34092	0.02628
3267	-0.38660	0.34953	0.44341	0.32873	0.02414
3103	-0.43550	0.33160	0.47859	0.31612	0.02202
2940	-0.48705	0.31311	0.51567	0.30304	0.01994
2777	-0.54155	0.29406	0.55486	0.28949	0.01789
2613	-0.59935	0.27447	0.59644	0.27544	0.01588
2450	-0.66089	0.25434	0.64070	0.26086	0.01394
2287	-0.72667	0.23371	0.68801	0.24572	0.01207
2123	-0.79733	0.21263	0.73883	0.23000	0.01028
1960	-0.87365	0.19115	0.79372	0.21368	0.00858
1797	-0.95661	0.16938	0.85339	0.19672	0.00700
1633	-1.04749	0.14744	0.91875	0.17911	0.00555
1470	-1.14794	0.12550	0.99100	0.16084	0.00424
1307	-1.26024	0.10379	1.07178	0.14191	0.00309
1143	-1.38756	0.08264	1.16335	0.12234	0.00212
980	-1.53454	0.06245	1.26906	0.10221	0.00134
817	-1.70838	0.04378	1.39409	0.08165	0.00075
653	-1.92113	0.02736	1.54711	0.06092	0.00035
490	-2.19543	0.01407	1.74440	0.04054	0.00012
327	-2.58202	0.00491	2.02245	0.02156	0.00002
163	-3.24291	0.00059	2.49779	0.00625	0.00000

Figure C-2: Excel Spreadsheet to Calculate Probability of Failure of Corroded Pipeline, Truncated Distribution Format

Dented-Gouged Pipeline Probability of Failure-Truncated Distributions

User Specified Inputs:

		Uncertainties	
Pipeline Characteristics (Inches):		Type I	Type II
Diameter, D_{50}:	8	10%	N/A
Wall Thickness, t_{50}:	0.5	8%	N/A
Material Strength(PSI):			
SMYS:	42000	10%	N/A
SMTS:	50000	10%	N/A
Pipeline Defect(Inches):			
Depth of Dent, H	4	10%	N/A
Depth of Gouge, d	0.10	10%	N/A
Dented-Gouged Burst Pressure, P_b(PSI)	2381		
Reliability Parameters(Capacity):			
$\sigma_{\ln R}$	1.01		
Total Uncertainty, $V_{I,II}$	0.16		
Pipeline Demand (PSI)			
Mean	2500		
Median	1442		
Standard Deviation, psi	250		
Standard Deviation, Normalized	1.05	*Uncertainties*	
		Type I	Type II
MOP/Pressure Relief Valve (upper bound)	2500	10%	N/A
Distribution Type			
Demands, S:	Lognormal		
Capacity, R:	Lognormal		
Pressure Increment(PSI):			
ΔS	83.3		
P_f	64.5%		

Note: Shaded Cells Represent User Specified Values

Pressure	(ln(P)/P) / St.Dev	Pp	β	$P_{f\|p}$	$P_{f\|p}*P_p*\Delta S$
2500	0.00000	0.50000	-0.03346	0.51335	0.05392
2417	-0.03232	0.48711	-0.01021	0.50407	0.05158
2333	-0.06578	0.47378	0.01385	0.49447	0.04921
2250	-0.10046	0.45999	0.03879	0.48453	0.04682
2167	-0.13644	0.44574	0.06468	0.47422	0.04440
2083	-0.17384	0.43100	0.09157	0.46352	0.04197
2000	-0.21276	0.41576	0.11957	0.45241	0.03951
1917	-0.25334	0.40000	0.14875	0.44087	0.03705
1833	-0.29572	0.38372	0.17924	0.42888	0.03457
1750	-0.34008	0.36690	0.21114	0.41639	0.03209
1667	-0.38660	0.34953	0.24460	0.40338	0.02962
1583	-0.43550	0.33160	0.27977	0.38983	0.02715
1500	-0.48705	0.31311	0.31685	0.37568	0.02471
1417	-0.54155	0.29406	0.35605	0.36090	0.02229
1333	-0.59935	0.27447	0.39762	0.34545	0.01992
1250	-0.66089	0.25434	0.44188	0.32929	0.01759
1167	-0.72667	0.23371	0.48919	0.31235	0.01534
1083	-0.79733	0.21263	0.54001	0.29459	0.01316
1000	-0.87365	0.19115	0.59490	0.27595	0.01108
917	-0.95661	0.16938	0.65457	0.25637	0.00912
833	-1.04749	0.14744	0.71993	0.23578	0.00730
750	-1.14794	0.12550	0.79219	0.21413	0.00564
667	-1.26024	0.10379	0.87296	0.19134	0.00417
583	-1.38756	0.08264	0.96453	0.16739	0.00291
500	-1.53454	0.06245	1.07024	0.14225	0.00187
417	-1.70838	0.04378	1.19527	0.11599	0.00107
333	-1.92113	0.02736	1.34830	0.08878	0.00051
250	-2.19543	0.01407	1.54558	0.06110	0.00018
167	-2.58202	0.00491	1.82364	0.03410	0.00004
83	-3.24291	0.00059	2.29898	0.01075	0.00000

Figure C-3: Excel Spreadsheet to Calculate Probability of Failure of Dented-Gouged Pipeline, Truncated Distribution Format

Appendix D: Probability of Failure—Undetected Defects

Burst Pressure Analysis: Corroded Pipe

For pipeline corrosion defects not detected by the pig during its run, the level of corrosion can be predicted using a corrosion prediction model. The internal loss of wall thickness due to corrosion was predicted, based on a corrosion prediction model:

Loss of pipeline wall thickness due to corrosion (Bea, et.al., OTC, 1998):

$$t_c = t_{ci} + t_{ce}$$

Where:

t_c = total loss of wall thickness
t_{ci} = internal corrosion
t_{ce} = external corrosion

$$tc_i = \alpha_i \cdot \nu_i \cdot (L_s - L_p)$$

t_{ci} = loss of wall thickness due to internal corrosion
α_i = effectiveness of the inhibitor or protection
ν_i = average corrosion rate
L_s = average service life of the pipeline
L_p = life of the initial protection provided to pipeline

Internal Inhibitor Efficiency, α_i	
Descriptor	Inhibitor Efficiency
Very Low	10
Low	8
Moderate	5
High	2
Very High	1

Table D-1: Internal Inhibitor Efficiency

Expected Life of Protective System (Lp), or Service Life of the Pipeline(Ls)	
Descriptor	Lp or Ls (years)
Very Short	1
Short	5
Moderate	10
Long	15
Very Long	>20

Table D-2: Expected Life of Initial Protective System, or Service Life of Pipeline

Corrosion Rates and Variabilities		
Descriptor	Corrosion Rate, v_t	Corrosion Rate Variability
Very Low	3.94E-5 in./year	10%
Low	3.94E-4 in./year	20%
Moderate	3.94E-3 in./year	30%
High	.0394 in./year	40%
Very High	.394 in./year	50%

Table D-3: Corrosion Rates and Variabilities (Bea, et.al., OTC, 1998)

Once the corrosion properties are known, for a given pipeline, they can be collected into a table, where the loss of wall thickness, t_c , can be calculated. The following table summarizes the corrosion characteristics for a given pipeline, and computes the loss of internal wall thickness, or depth of corrosion.

Pipeline Characteristics	
Wall Thickness, t (Inches)	0.322
Corrosion Characteristics	
Internal Inhibitor Effeciency, α_i	5
Expected Life of Protective System, Lp (Years)	10
Service Life of Pipeline, Ls (Years)	20
Corrosion Rate, v_t (Inches/Year)	0.00394
Total Loss of Internal Wall Thickness (Inches)	0.197
Depth of Corrosion, d (Inches)	0.197
Loss of Wall Thickness as a Percent of Initial Wall Thickness, (d/t)	61%

Table D-4: Excel Spreadsheet to Calculate Total Loss of Internal Wall Thickness

Appendix E: Pipeline Pressure Demands

Research conducted at U.C. Berkeley on pipeline internal pressure loading involves the recording and analysis of pressure data on a continuous basis. Oil companies monitor the pressure in pipelines; this data has been made available to pipeline researchers.

Several different types of pressure occur in pipelines, including:

- Pressure at one specific point in the pipeline.
- Inlet and outlet pressure.
- Pressure profile throughout the entire pipeline.
- Normal operating conditions.
- Accidental or emergency shut-in pressures.
- Maximum expected pressure in lifetime of the pipeline (Iversen, 2000)

Instituto Mexicano del Petroleo (IMP) conducted a study on pipeline operating pressures, for a collection of pipelines in the Bay of Campeche. Table E-1 summarizes the results of this study.

Service	Diameter (inches)	Wall thickness (inches)	Temperature °F	Operating pressures (psi)		
				Minimum	Normal	Maximum
Gas	8	0.312	68	782	1000	1100
Gas	8	0.312	68	782	1000	1100
Gas	20	0.500	68	782	1000	1100
Gas	8	0.312	68	782	1000	1100
Gas	8	0.375	68	782	1000	1100
Oil	36	0.625	147	227	470	500
Gas	36	0.875	130		924	1000
Gas	36	0.750	130		965	1000
Gas	36	0.750	68	800	1000	1200
Gas	24	0.562	170	85	100	
Gas	8	0.500	130	782	1000	1100
Gas	8	0.500	130	782	1000	1100
Gas	8	0.312	68	782	1000	1100
Oil	48	0.625	86	240	360	600
Oil	36	0.875	140	560	640	711
Oil-Gas	20	0.625	176/208/230	176	208	230
Oil-Gas	20	0.500	176/208/230	170	425	1000
Oil-Gas	36	0.750	176/208/230	170	425	1000
Oil	36	0.750	140	560	640	711
Gas	36	0.875	130/145		924	1000
Oil	36	0.750	140	5	25	711
Oil	24	0.688	165	426	500	570
Oil	36	0.875	140	560	640	711
Oil	36	0.625	140	560	640	711

Table E-1: Pipeline Pressures from IMP Study (Iversen, 2000)

For the IMP study, the mean operating pressure was 61% of the maximum design pressure with a coefficient of variation of 34%. The average ratio of maximum design pressures to hydrostatic pressures is approximately 15 to 16. The variations of the maximum operating pressures were reported to be approximately 10%. The maximum design pressure is not exceeded, in any of the examples (Iversen, 1999).

Appendix F: Hydrotesting of Pipelines: Truncation of Capacity Distribution

As mentioned previously, hydrotesting of a pipeline acts to 'flash-photo' a pipeline's capacity. That is, for a given instant in time, for a pipeline containing active corrosion defects, the pipeline's internal pressure loading capacity is validated. Hydrostatic testing of pipelines is used to verify pipeline integrity, as an alternative to the preferred method of pipeline inspection: in-line inspection. For new pipelines, where in-line inspection is not practical, hydrotesting becomes a favorable alternative for the purpose of validating new pipeline. As constructed, new linepipe may contain defects or imperfections from the pipeline manufacturing process, transit fatigue, or construction flaws. But, if such defects are not severe enough to fail in the hydrotest, they will remain in the pipeline and may become enlarged by pressure cycle induced fatigue. Furthermore, there exists debate over the subject of hydrotesting, for several reasons. For example, hydrotesting can leave behind defects that could be detected by in-line inspection. Therefore, hydrotesting demonstrates serviceability for only a short period of time (for growing corrosion defects). Another aspect of the hydrotesting debate revolves around the level of the specified minimum yield strength (SMYS) of the pipe material. Or should the pipeline be tested, based on a percent of its ultimate strength? The higher the ratio of test pressure to operating pressure, the more confidence one can have in the pipeline (Kiefner, 2000).

According to John Kiefner, in an article published in the Oil and Gas Journal, July 31, 2000, one needs to consider the practical upper limits of the pipeline that is being hydrotested. For example, in the case of a new pipeline, constructed of modern, high quality steel, the maximum test level can exceed 100% SMYS. Testing of an existing, in-service pipeline is a possible way to validate the serviceability of the pipeline. Testing of an in-service line does pose some practical difficulties, including economic considerations. For example, the pipeline operator must take the pipeline out of service and purge the pipeline of product. This downtime represents loss of revenue, and disruption of service to the customer. Next, the operator must obtain enough hydrotest fluid to fill the pipeline. A mile long, 16" diameter pipeline requires 1300 gallons of fill water. After the test, the water is considered a hazardous material because of being contaminated with the remaining product in the pipeline.

The issue of 'pressure reversal' presents another limitation to hydrotesting. A pressure reversal is the occurrence of a failure of a defect at a pressure level that is less than the pressure level that the defect has previously survived due to defect growth produced by the previously higher pressurization, and possible subsequent damage upon depressurization.

In conclusion, it should be noted that the test-pressure to operating pressure ratio measures the effectiveness of the test. Furthermore, in line (MFL) inspection is preferable to hydrostatic testing. Lastly, testing the pipeline to its yield strength is acceptable for modern materials. (Kiefner, 2000)

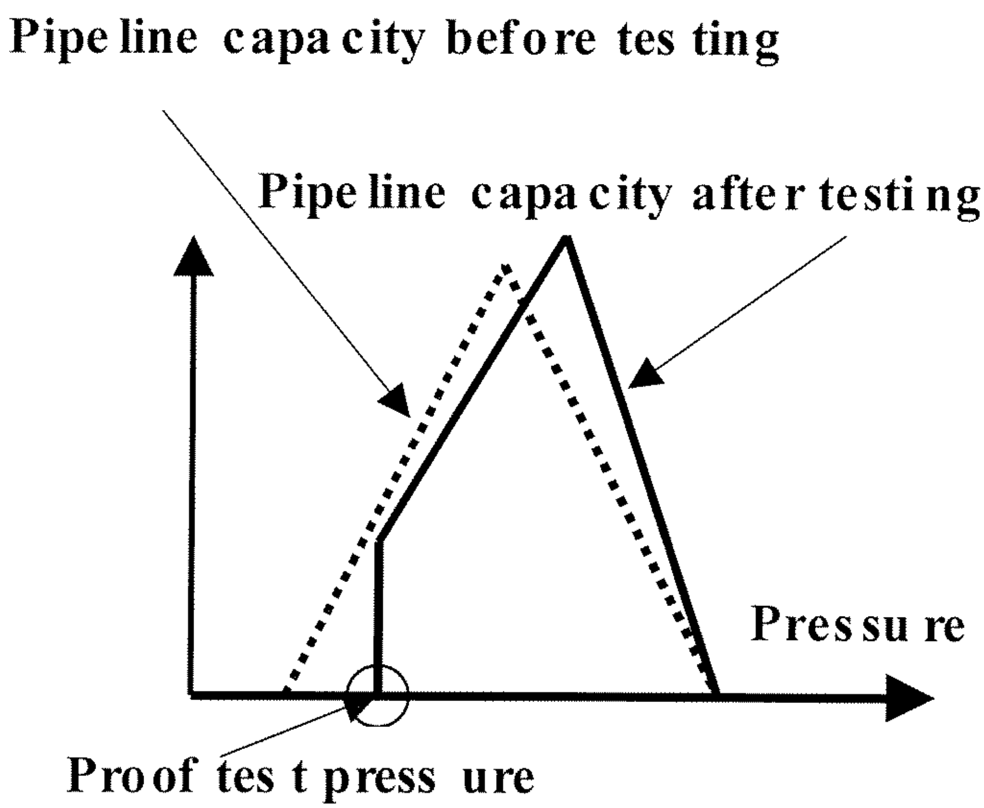

Figure F-1: Effects of Hydrotesting on Pipeline Capacity (Bea, 1999)

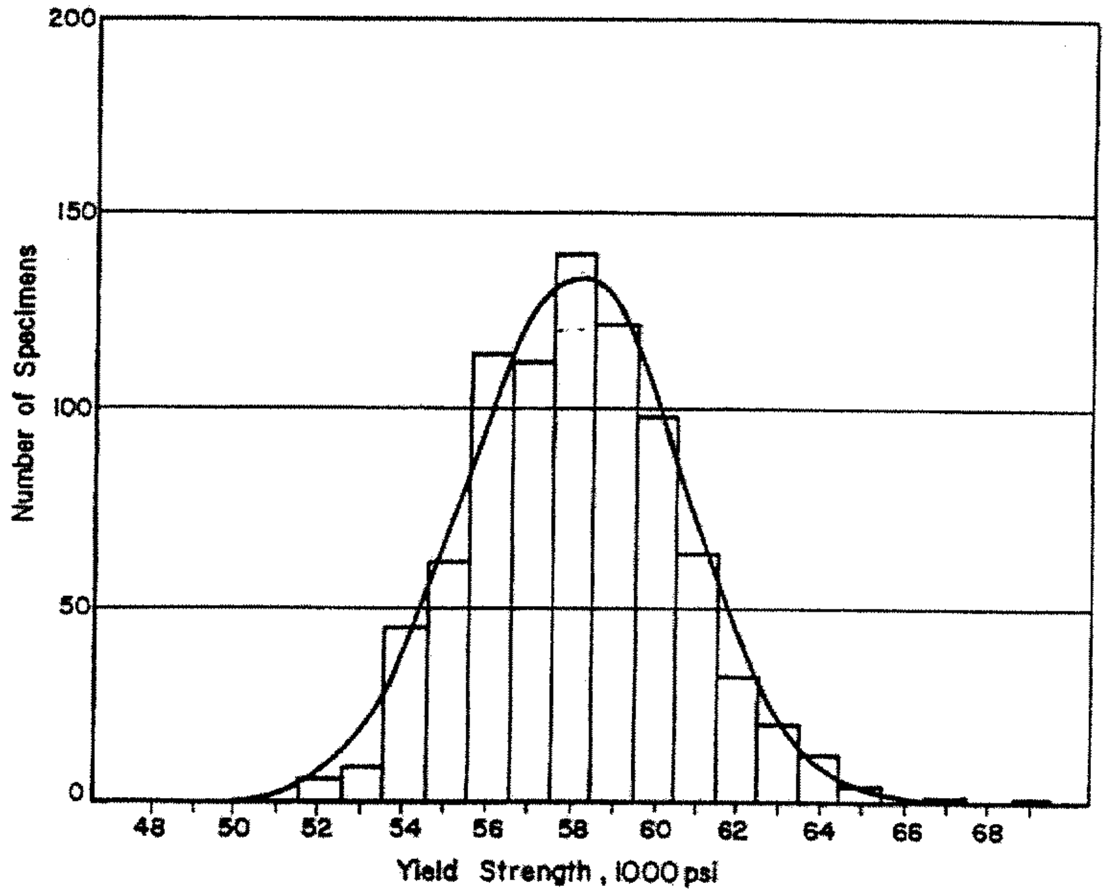

Figure F-2: Normal distribution curve fitted to Distribution of Yield Strength for X-52 pipe (Kiefner, 2000)

Appendix G: Sensitivity of Safety Index

In order to demonstrate the sensitivity of safety index, β, to common input parameters, such as standard deviation, bias, and the ratio of demand to capacity. It should be noted that the safety index is a direct measure of probability of failure. As an approximation $P_f = 10^{-\beta}$.

The results indicate that β, is most sensitive to biases of demand and capacity, and β is less sensitive to changes in the standard deviation.

Probability of Failure

The probability that a structural system will survive the demand is defined as the reliability:

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

Where Ps is the probability of success, or reliability. And P (R > S) is read as the probability that the capacity (R) exceeds the demand (S).

In analytical terms, the reliability can be computed from:

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

Where Φ is the standard normal distribution cumulative probability of the variable β. β is referred to as the safety index. Given lognormally distributed, independent demands (S) and capacities (R), the safety index, β, is computed as follows:

$$\beta = \frac{\ln\left(\dfrac{B_b \cdot \underline{R}}{B_o \cdot \underline{S}}\right)}{\sqrt{\sigma^2{}_{\ln b} + \sigma^2{}_{\ln o} - 2\rho\sigma_{\ln b}\sigma_{\ln o}}}$$

$\underline{R}$ = median capacity

$\underline{S}$ = median demand

$\sigma_{\ln S}$ = standard deviation of the demand

$\sigma_{\ln R}$ = standard deviation of the demand

ρ = correlation coefficient

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). Examples of Type I Uncertainties include annual maximum wave height, earthquake peak ground acceleration, or ice impact kinetic energy that will be experienced by a structure at a given location during a given period of time. Type I Uncertainties associated with capacities are the yield strength of steel, the tensile strength of aluminum, and the shear strength of a material. The second type of uncertainty, Type II Uncertainties, are identified as unnatural, cognitive, parameter, measurement, or modeling uncertainties. Type II Uncertainties apply to deterministic, but unknown value of parameters, to modeling uncertainty, and to the actual state of the system. Examples in loading uncertainties, Type II, include uncertainties in computed wind, wave, current, earthquake, and ice conditions and forces that are due to imperfections in analytical models. Examples of Type II Uncertainties in capacities is the difference between the nominal yield strength of steel and the median yield strength of steel. Type II Uncertainties are characterized by a measure of the bias, which is the ratio of the measured value to the nominal value (Bea, 1995).

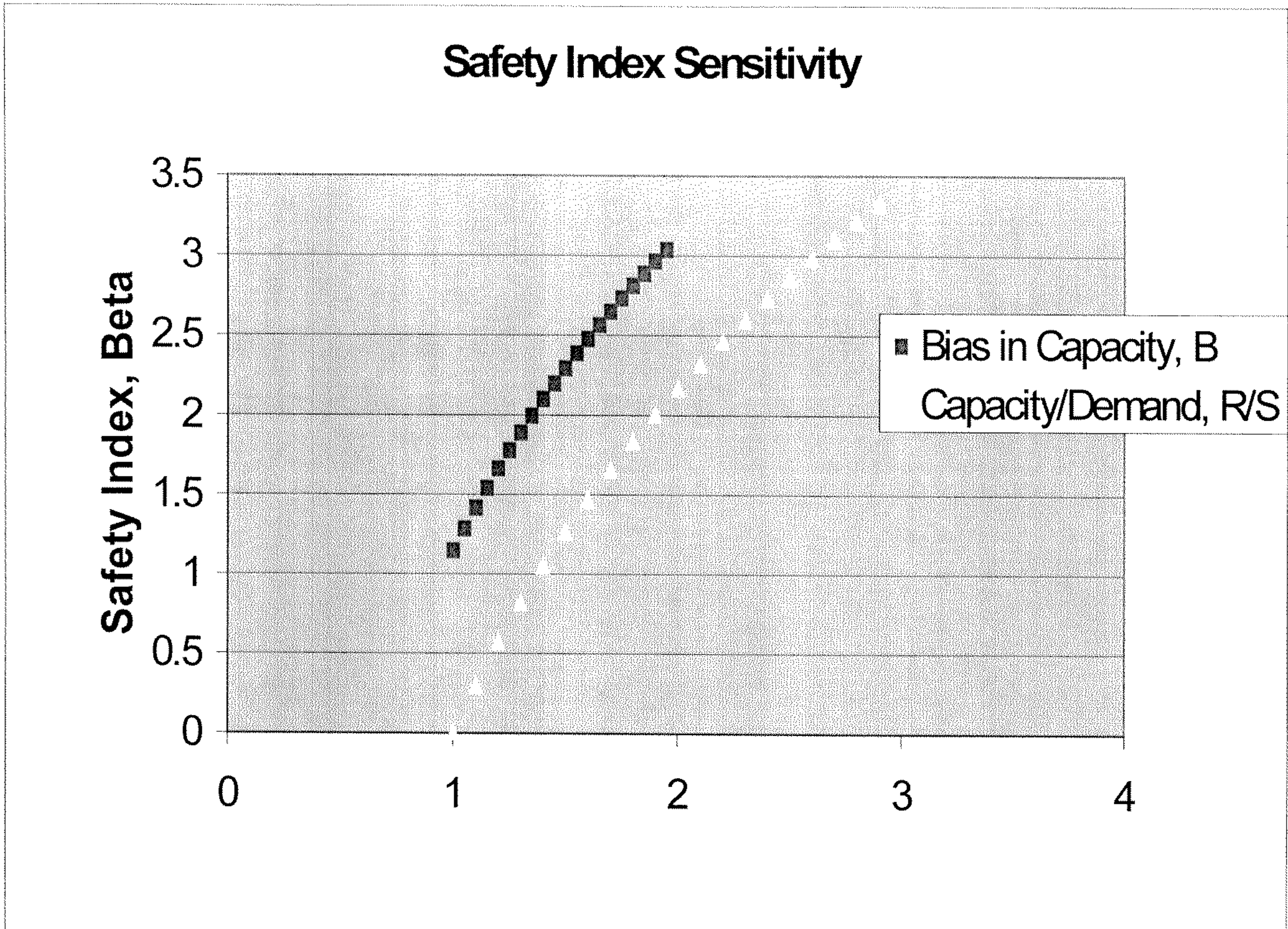

Figure G-1: Plot of Safety Index vs. Bias and Ratio of Capacity to Demand

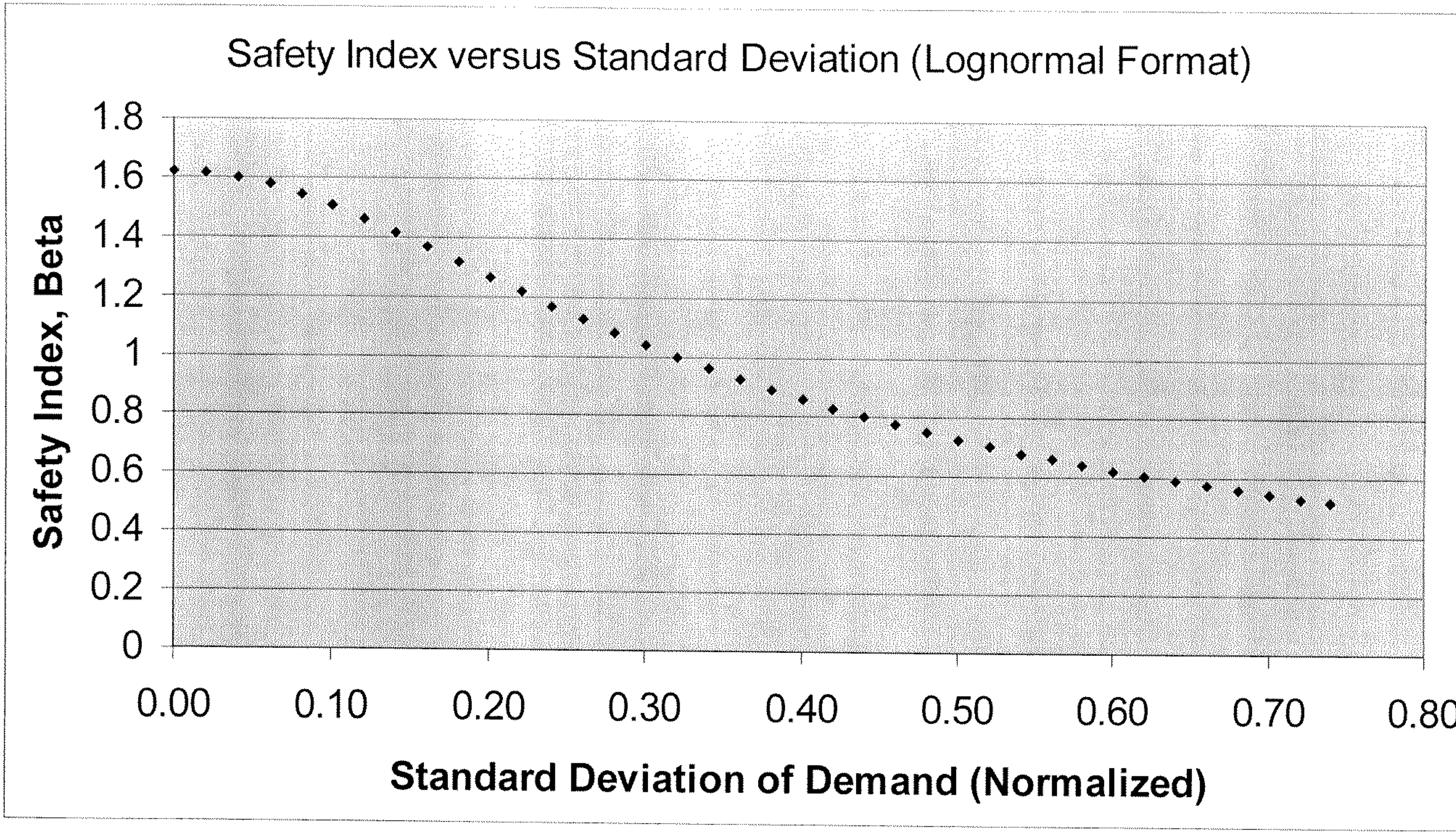

Figure G-2: Plot of Safety Index vs. Standard Deviation

Appendix H: Conversion of POF format to RAM Uncertainty

Confidence Interval of a Mean

The mean you calculate from a sample is not likely to be exactly equal to the population mean. The size of the discrepancy depends on the size and variability of the sample. If your sample is small and variable, the sample mean may be quite far from the population mean. If your sample is large with little scatter, the sample mean will probably be very close to the population mean. Statistical calculations combine sample size and variability (standard deviation) to generate a confidence interval (CI) for the population mean. Confidence intervals can be calculated for any desired degree of confidence, but 95% confidence intervals are most common. If you assume that your sample is randomly selected from some population (that follows a Gaussian distribution), you can be 95% sure that the confidence interval includes the population mean. More precisely, if you generate many 95% CI from many data sets, you expect the CI to include the true population mean in 95% of the cases and not to include the true mean value in the other 5%. Since you usually don't know the population mean, you'll never know when this happens.

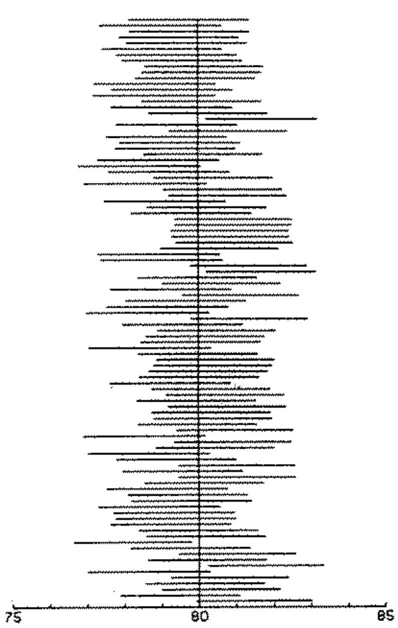

Figure H-1: A 95% Confidence Interval Is Shown For 100 different samples. For About 95% of the Samples, the Interval Covers the Population Percentage, Marked by a Vertical Line (Freedman et. al., 1980)

If a population random variable X has a mean, μ, whose value is unknown. From a random sample of size n, the value x^*, of the sample mean X^* , can be used to estimate μ at the 95 percent confidence level as follows:

$$P\left(\mu - E \leq X^* \leq \mu + E\right) = .95$$

Where the margin of error, E, is computed as:

$$E = \frac{z^* \cdot \sigma}{\sqrt{n}}$$

Where σ is the standard deviation, z^* is from the standard normal distribution table, and n is sample size (Freedman et. al., 1980)

Appendix I: Parametric Study of the Effects of Truncating Demand and Capacity Distributions

Introduction

A study was undertaken to compare the effects of truncating the demand distribution on the probability of failure. For this study, the lognormal distribution was assumed for both the demand (S) and capacity (R) distributions.

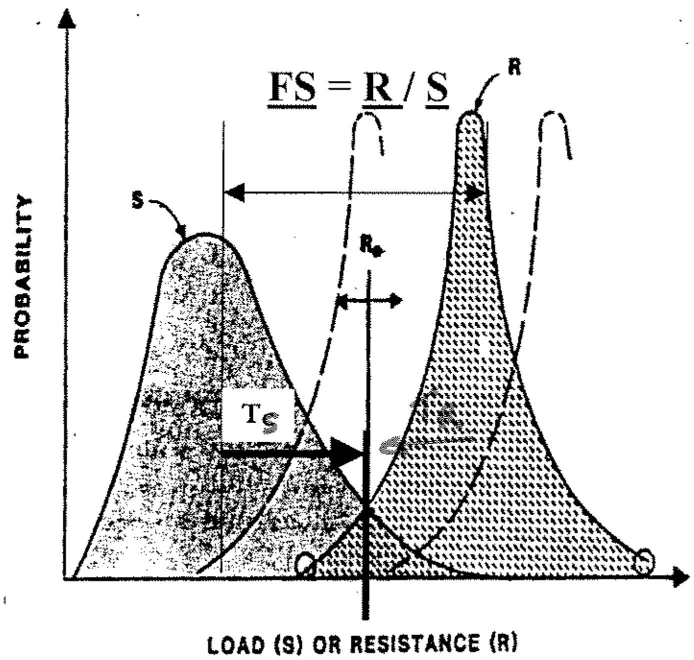

Figure I-1: Truncation of Demand and Capacity Distribution

Theory

For calculating the probability of failure, the first step is to determine the distribution type of the demand and capacity distributions. A lognormal distribution has been chosen for the demand (operating pressure), and capacity (burst pressure) distributions, consistent with previous probability of failure calculations. For lognormally distributed variables, the probability of failure can be calculated as:

$$P_f = 1 - \Phi(\beta)$$

β is the factor of safety, and Φ is the standard normal cumulative function. In the case of truncated distributions, which are used in this study, the probability of failure is represented by the following equation:

$$P_f = \sum P_f\big|_p \cdot P_P \cdot \Delta P$$

The equation may be read as " the probability of failure is equal to the probability of failure, given the occurrence of a pressure, times the probability of the pressure occurring, times the pressure increment, delta P." The applied reliability section, in the main body of the report, further describes theory involved in calculating the probability of failure, with truncated demand and capacity distributions.

Referring to Figure I-1, the variable T_C represents the extent of truncation of the distribution, where T_C is a multiple of the mean of the truncated (demand, S) distribution. For example, if the median pressure demand is 2500 psi, and T_C is chosen to be 1.5, then the truncation point would be 1.5*2500, or 3750 psi. That is, the distribution would extend only to 3750 psi, where it would abruptly end, due to truncation. FS_{50} is the 'factor of safety,' and is a direct measurement of the spread between the median capacity, $\underline{R}$, and the median demand, $\underline{S}$. The standard deviation of the demand and capacity, σ_{LNS} and σ_{LNR}, respectively, are held constant at 20%. P_f is the probability of failure of a corroded pipeline, given lognormally distributed distributions for both demand and capacity, and a truncated demand distribution (due to pressure relief valves, for example).

Results

Table I-1 presents the result of the study. In Case 1, the safety factor, FS_{50} , is held constant at 3.0. T_C is slowly increased from 1.0 to 2.5, in .5 step increments. The probability of failure, P_f , slowly increases, from 0% to 9.3%, as extent of the truncated distribution increases ('the tail grows').

In Case 2, the factor of safety, FS_{50} , is decreased to 2.0, moving the demand and capacity distributions closer together. T_C is again slowly increased from 1.0 to 2.5, in .5 step increments. As the tail of the truncated demand distribution increases, the probability of failure, P_f , shows greater sensitivity to T_C, increasing from .3% to 34.3%, as extent of the truncated distribution increases.

	FS_{50}	$\sigma_{\ln S}$	$\sigma_{\ln R}$	T_C	P_F
Case 1	3.0	0.2	0.2	1.0	**0.0%**
	3.0			1.5	**3.0%**
	3.0			2.0	**2.7%**
	3.0			2.5	**9.3%**
Case 2	2.0			1.0	**0.3%**
	2.0			1.5	**5.6%**
	2.0			2.0	**19.6%**
	2.0			2.5	**34.3%**

Table I-1: The Effects of Truncation on the Probability of Failure

Conclusion

Based on the results of this study, it has been shown that the probability of failure of a corroded pipeline is sensitive to the extent of truncation of the demand distribution. The study further proved that the factor of safety also affects the probability of failure calculation. In the case of a pipeline equipped with pressure relief valves, the pressure setting at which the pipeline relieves the internal pipeline pressure, relative to the capacity of the pipeline system, affects the probability of failure of the system.

Appendix J: March 2-4 Houston Meeting -- Presentation Notes

Real-Time RAM Project Meeting #1

Prof. Bob Bea and GSR Angus McLelland

Ocean Engineering Graduate Program

University of California at Berkeley

March 2-3, 2001

Houston, Texas

1

Project Sponsors

Many thanks for input and direction provided by Thomas Beuker and Robert Smith

2

Real-Time RAM Project Outline: Meeting Notes

- Project Goals and Objectives
- Project Tasks
- Project Plan
- Probability of Failure Analyses
- Project Summary

3

Project Goal

- **To develop, verify, and test procedures that can be used during in-line instrumentation of pipelines to characterize their reliability**
  - **reliability is defined as the likelihood that pipeline containment is maintained during a given time period**

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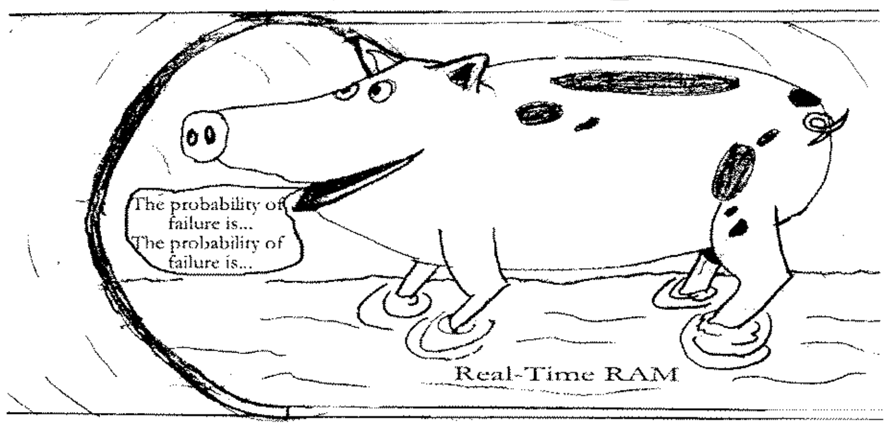
"Pipeline Pig"



Project Objectives

- Development of assessment methods to help manage pipeline integrity to provide acceptable serviceability and safety
- Definition of reliabilities based on data from in-line instrumentation of pipelines to provide acceptable safety and serviceability

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Project Objectives

- Development of assessment processes to evaluate characteristics of in-line instrumented pipelines,
- Evaluation of the effects of uncertainties associated with in-line instrumentation data, pipeline capacity, and operating conditions
- Formulation of analysis of pipeline reliability characteristics in current and future conditions

7

Project Objectives

- Validation of the formulations with data from hydro-testing of pipelines and risers provided by the Performance of Offshore Pipelines Project
- Definition of database software to collect in-line inspection data and evaluate the reliability of a pipeline

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Real-Time RAM Project Tasks

- Summarize formulations to determine pipeline capacities for corrosion, dents, gouges, and cracks
- Summarize formulations to determine pipeline demands for internal conditions (pressure, temperatures)
- Summarize formulations to evaluate data from in-line instrumentation

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Project Tasks

- Summarize formulations to characterize uncertainties associated with pipeline demands, capacities, and in-line instrumentation data
- Summarize formulations to analyze pipeline reliability characteristics in the current conditions
- Summarize formulations to determine the effects of future conditions on pipeline demands, capacities, and uncertainties

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Project Tasks

- Summarize formulations to analyze pipeline reliability characteristics in the future conditions
- Validate the formulations through applications to in-line instrumented pipelines
- Document the foregoing results in four project reports
- Transfer the results to project sponsors in five project meetings (first meeting March 2001)

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Real-Time RAM Project Plan

- **Graduate Student Researchers:**
  - Sang Kim: Summer 2000
  - Angus McLelland: Spring 2001 (January to May 2001)
- Project Plan:
  - Summer 2000: summarize background
  - Spring 2001:
    - Develop Excel spreadsheet program to perform calculations of burst pressures for intact pipelines, and pipelines with corrosion, and dented-gouged pipelines.
    - Program the calculation of pipeline probabilities of failure(Excel Spreadsheet):
      - Standard lognormal format
      - 'Truncated demand' format
    - Interfacing: Probability of detection and accuracy of measurements related to probability of failure

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Summer 2000: summarized & documented

- Probability of failure (Pf) formulations
- Damaged pipeline formulations (corroded, dented/gouged, cracked)
- Instrumentation performance specifications
- Results from Rosen Risk Assessment Workshop

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Pf formulations

- Conditional on specified characteristics
  - Does not include uncertainties associated with specification of characteristics
- Lognormal distributions (demand - S, capacity - R) format used for pipeline sections Pf's
- Probability based systems analysis used for convolution of Pf's to determine pipeline Pf

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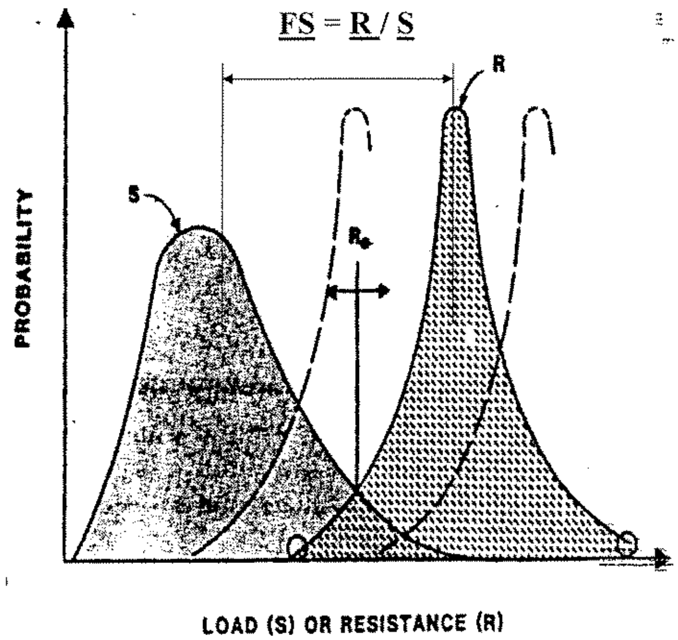
Probability of Failure



Probability of Failure

- Uncertainties associated with structural loadings and capacities:
  - Type I: natural or inherent randomness
    - E.g. Thickness of steel, yield strength of a material
  - Type II: measurement or modeling uncertainty
    - E.g. simplification of analytical models used in practice, wrong assumptions used in an analysis
- Uncertainty characterization: Coefficient of Variation(COV = standard deviation / mean value)

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Probability of Failure

- Reliability measure: Safety Index β
  - For Lognormally distributed, uncorrelated demands and capacities:

$$\beta = \frac{\ln\left(\frac{\underline{R}}{\underline{S}}\right)}{\sqrt{\sigma_{\ln R}^{2} + \sigma_{\ln S}^{2}}}$$

where:

$\underline{R}$ = median capacity

$\underline{S}$ = median demand

$\sigma_{\ln R}$ = standard deviation of capacity

$\sigma_{\ln S}$ = standard deviation of demand

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Probability of Failure

- Calculation of standard deviation:

$$\sigma_{\ln X} = \sqrt{\ln(1 + V_x^{2})}$$

V_x = coefficient of variation

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Probability of Failure

- Probability of Failure, P_f

$$P_f = 1 - \Phi(\beta)$$

$\Phi(\beta)$ = standard normal distribution cumulative probability of the variable, β

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Probability of Failure: *must specify*

- Pipeline operating internal pressure (stress, strain) conditions + external conditions (pipeline demands - stresses / strains - median values, uncertainties)
- Pipeline capacities (stresses / strains that produce loss of containment) of the pipeline (median values, uncertainties)

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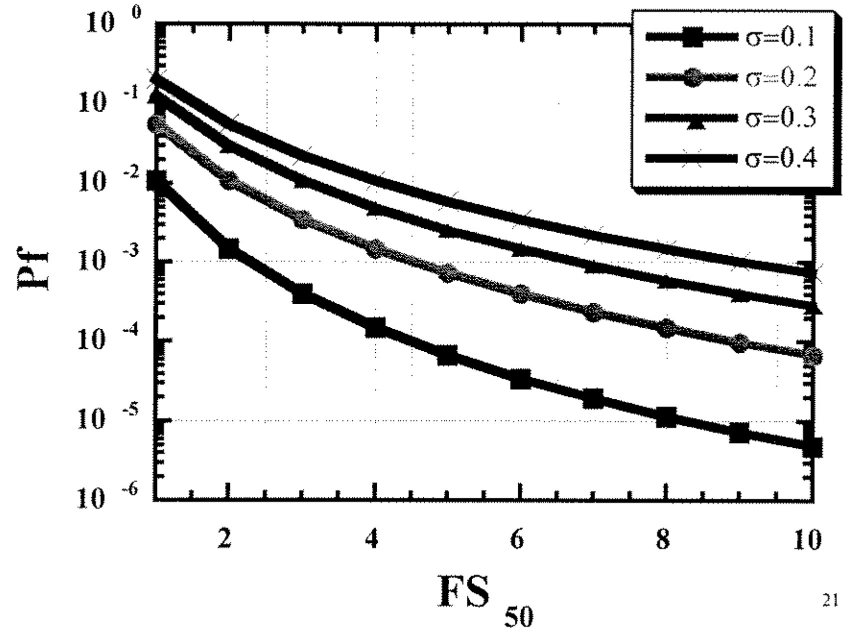

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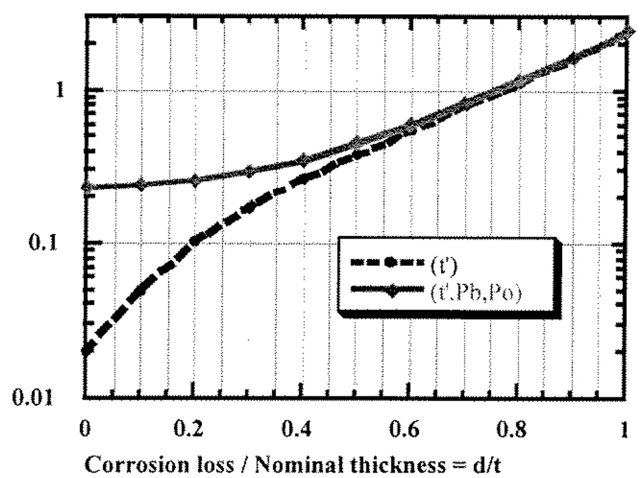
Pf - time effects



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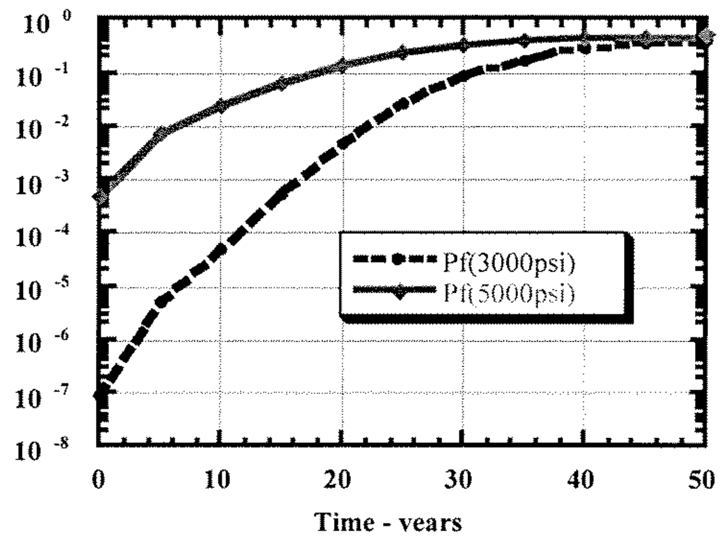
Example Pf results



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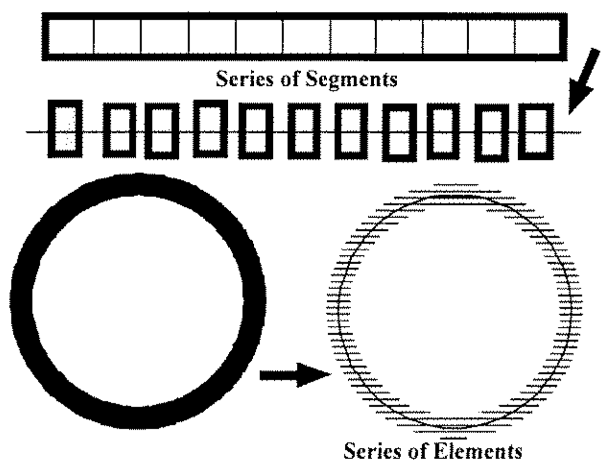
Pf's of pipeline sections relation to Pf of pipeline



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Pf from Pf's

- $Pf = 1 - \Pi (1-Pf_i)$
  - (if correlation of element capacities $\rho_{ij} = 0$)
- $Pf = Pf_{max}$
  - (if correlation of element capacities $\rho_{ij} = 1$)

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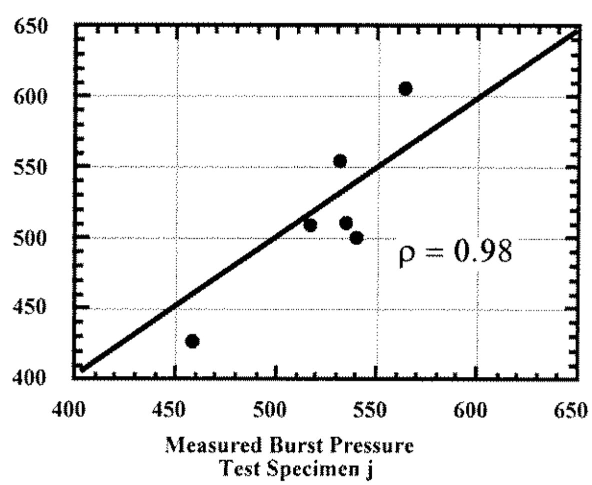
Correlation: burst pressure paired lab test results



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RAM PIPE capacity formulations

Loading States	Formulation	Formulation Factors
Pressure – Burst - Pb		
Corroded	$Pb_C = \dfrac{2.4 \bullet t \bullet SMTS}{(D-t) \bullet SCFc}$	$SCFc = 1 + 2\,(d/R)^{0.5}$
Dented	$Pb_D = \dfrac{2tSMTS}{(D-t) \bullet SCF_D}$	$SCF_D = 1 + 0.2\,(H/t)^3$
Gouged	$Pb_G = \dfrac{2tSMTS}{(D-t) \bullet SCF_G}$	$SCF_G = 1 + 2\,(h\,/\,r)^{0.5}$
Dented & Gouged	$Pb_{DG} = \dfrac{2tSMTS}{(D-t) \bullet SCF_{DG}}$	$SCF_{DG} = [1\text{-}d/t\text{-}(16H/D)(1\text{-}d/t)]^{-1}$
• Propagating-**Pp*** *evaluated with 10-year return period conditions	$Pp = 34 \bullet SMYS\left(\dfrac{t_{nom}}{D_0}\right)^{2.5}$	

RAM Pipe symbols

A_d	- effective cross sectional area of damaged (dent) section
A_0	- cross-sectional area of undamaged section
d	- damage depth
ΔY	- Primary out-of-straightness of a dented member
ΔY_0	- 0.001L
I_d	- Effective moment of inertia of undamaged cross-section
K_0	- Effective length factor of undamaged member
K	- Effective buckling length factor
λ_d	- Slenderness parameter of a dented member $= (P_{ud} / P_{ed})^{0.5}$
	- Ultimate moment capacity
M_{cr}	- Critical moment capacity (local buckling)
M_{ud}	- Ultimate negative moment capacity of dent section
M_-	- Negative moment of dent section
M_+	- Positive moment of dent section
M^*	- Neutral moment of dent section
P_{crd}	- Critical axial buckling capacity of a dented member ($\Delta / L > 0.001$)
P_{crd0}	- Critical axial buckling capacity of a dented member ($\Delta / L = 0.001$)
P_E	- Euler load of undamaged member
P_{crl}	- Axial local buckling capacity
P_{cr}	- Axial column buckling capacity
P_u	- Axial compression capacity
P_{ud}	- Axial compression capacity of a short dented member

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RAM PIPE Formulation: burst pressure, corroded

$$p_{bd} = \frac{3.2 \cdot t_{nom} \cdot SMYS}{D_o \cdot SCF}$$

p_{bd} = burst pressure of corroded pipeline

t_{nom} = pipe wall nominal thickness

D_o = mean pipeline diameter (D-t)

SMYS = Specified Minimum Yield Strength of pipeline material

SCF = Stress Concentration Factor = $SCF = 1 + 2 \cdot (d / R)^{.5}$

d = depth of corrosion, R = Do/2

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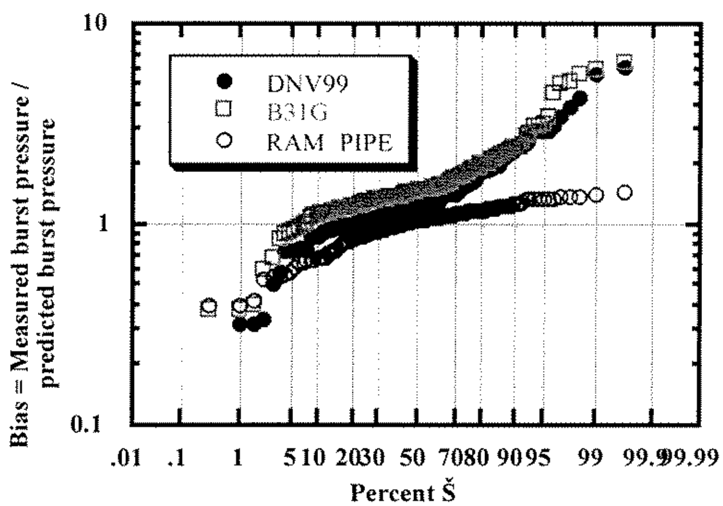
RAM PIPE Pbd Bias - *lab test data (natural corroded & machined)*



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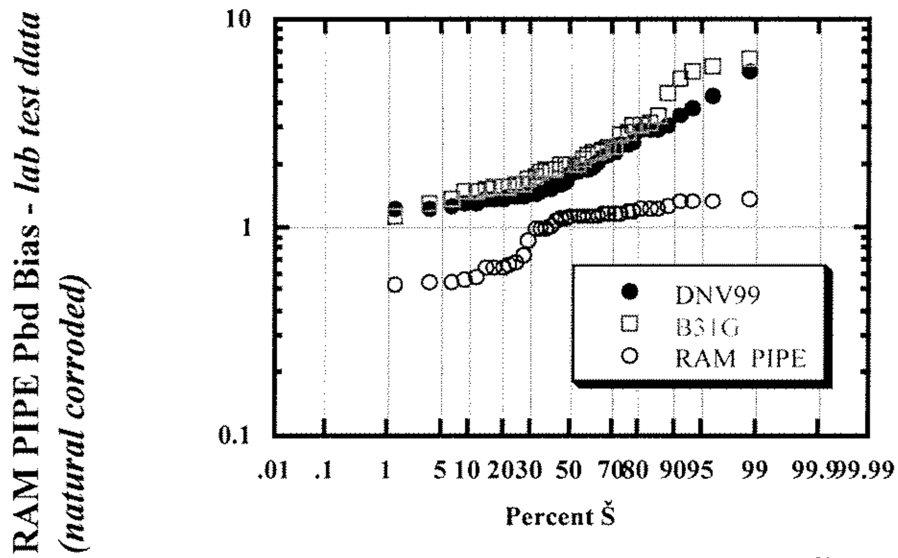

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Summary: P_{bd} Bias

Lab, natural & machined

Formulation	B mean	B_{50}	V_B %
DNV 99	1.46	1.22	56
B 31 G	1.71	1.48	54
Eq. 2	1.01	1.03	22

Lab, natural

Formulation	B mean	B_{50}	V_B %
DNV 99	2.10	1..83	46
B 31 G	2.51	2.01	52
Eq. 2	1.00	1.1	26

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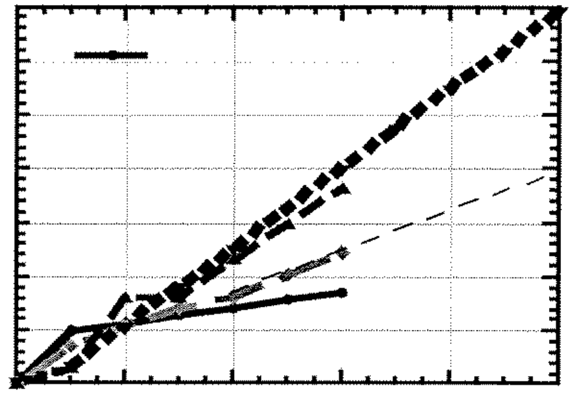
Dents & gouges

• Dent SCF's



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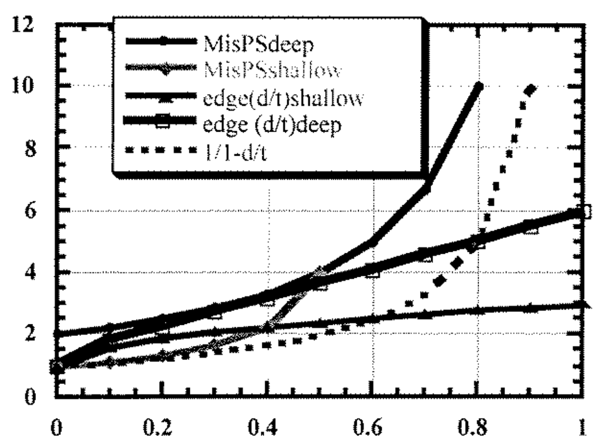
Dents & gouges

• Gouges SCF's



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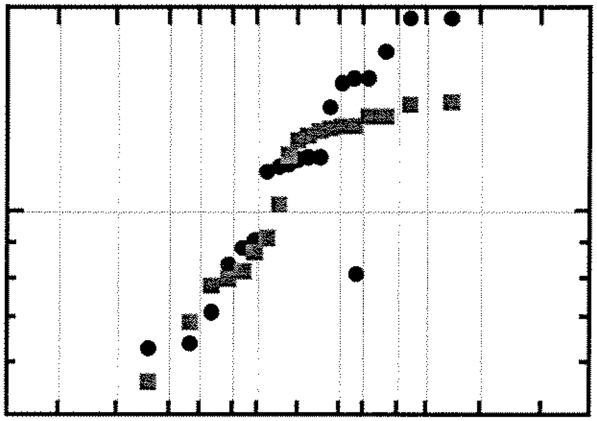
Dents & gouges: BG 30-in tests



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Summary: RAM PIPE formulations biases

Loading States (1)	Capacity Analysis Eq n. (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 -C ld	2	1.2	1.0	0.25
-Compression Global - C gd	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 -P b	12	2.5	1.0	0.25
C-Mu -P c*	13	2.6	1.0	0.25

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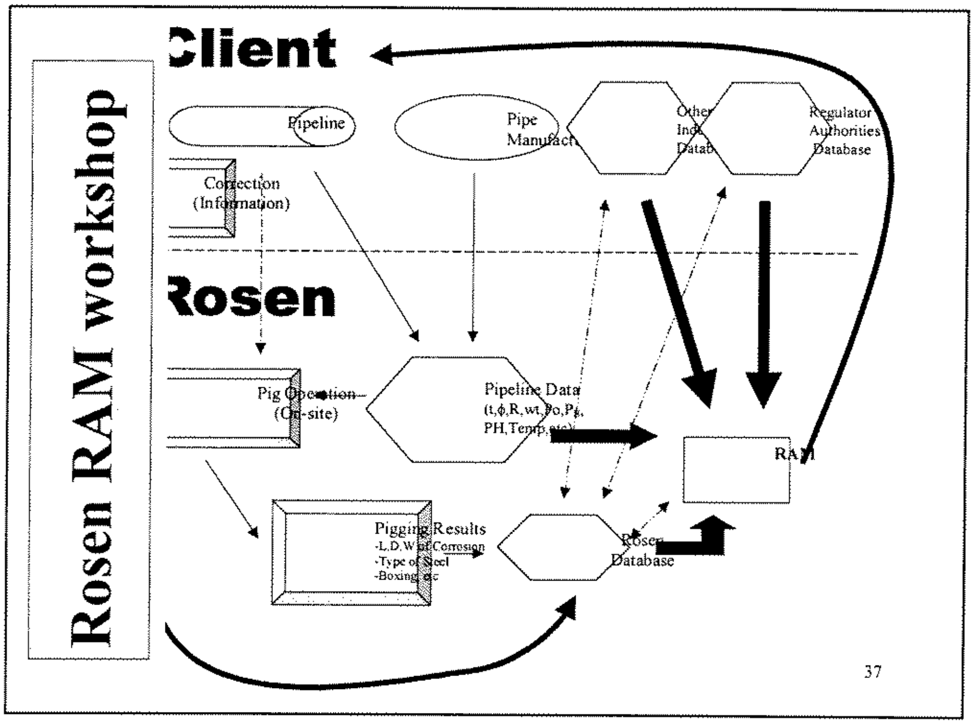

Real-Time RAM Analyses: Spring 2001

- Program analyses of pipeline burst pressures (intact, corroded, dented-gouged)
- Program analyses of pipeline probabilities of failure (intact, corroded, dented-gouged)
  - Lognormal
  - Truncated (proof testing effects on capacities, pressure relief values / systems on demands)
- Event tree analysis: instrument POD's & Biases
- Parametric analyses

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Pipeline Characteristics(median values)				Steel Material Strengths(median values)			
Diameter, D_{50}	$V_{D,1}$	Wall Thickness, t50	$V_{t,1}$	Yield Strength, YS_{50}	$V_{YS,1}$	Tensile Strength, TS_{50}	$V_{TS,1}$
Inches		Inches		PSI		PSI	
16	0.10	0.332	0.12	35000	0.08	52000	0.08

Excel Pf - corroded pipelines

	Reliability Parameters				
	Uncertainty Summary		Biases	Standard Deviation	
	Type I	Type II		$\sigma_{\ln S}$	$\sigma_{\ln R}$
Demands, S_{50}	0.12	0	1.0	0.120	0.229
Capacities, R_{50}	0.209	0.1	1.0		
Default Values					
Demands, S_{50}					
Capacities, R_{50}					

Distrubution Type: Lognormal
Correlation: $\rho_{rs} = 0$

Loading State			Probability of Failure		
Corroded Pipeline Capacity	Pipeline Demand	$V_{S,1}$			
R_{50}	S_{50}		β	$\Phi(\beta)$	P_f
2009.1	1000	0.12	2.71	0.9966	0.003

Note 1: Pipeline demand is user specified (normal pump pressure, accidental pressure loads: shut-ins)
Note 2: Pipeline characteristics and steel material strengths are median values
Note 3: Shaded boxes represent user specified values

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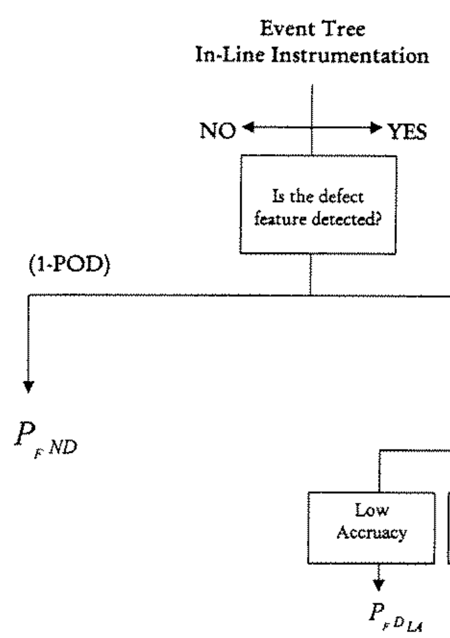
Analysis:Pf's given in-line instrumentation



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$$Pf = Pf_{ND} + Pf_D$$

- $Pf_{ND} = \Sigma[Pf|ND]\ [1-POD]$
- $Pf_D = \Sigma[Pf|D]\ [POD]$

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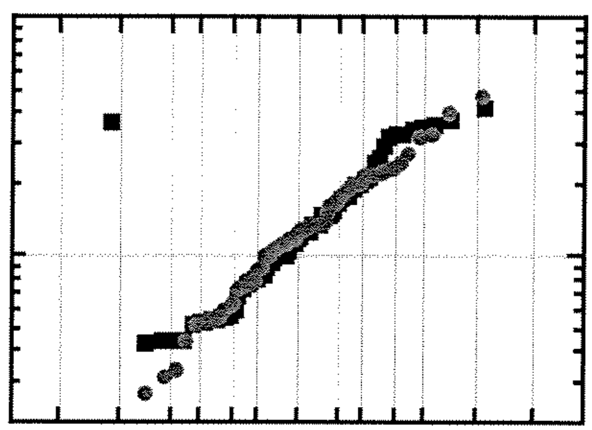
Pf_{ND} - corrosion rates from in-line instrumentation (example)



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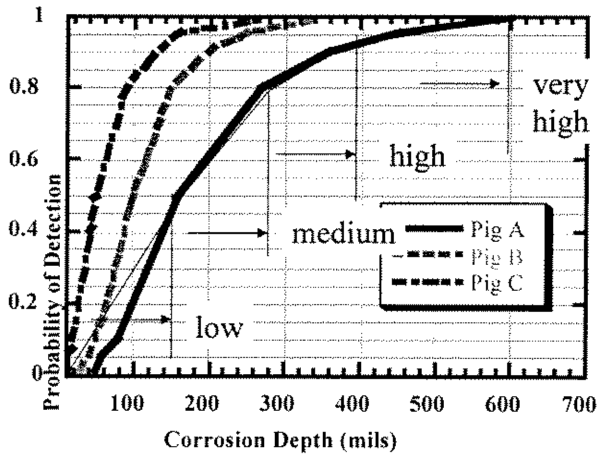
Example PODs: in-line MFL instruments



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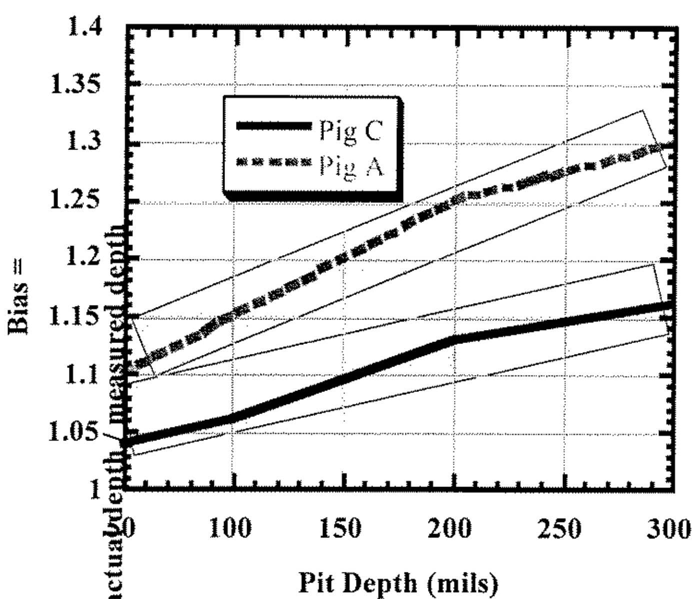
Example: in-line MFL measurement Biases (COV's = 25 % - 35 %



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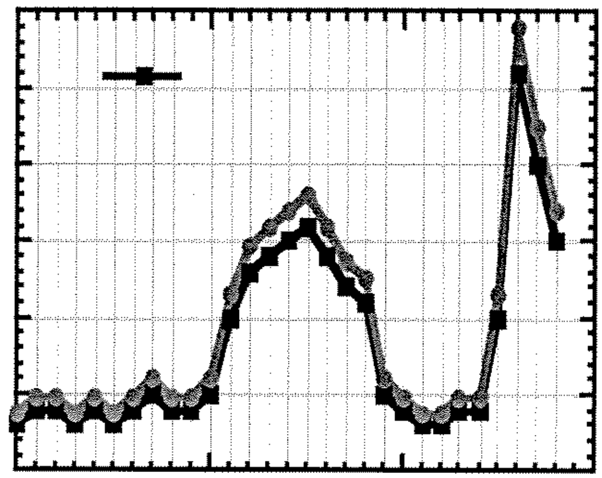
Example: measured & corrected



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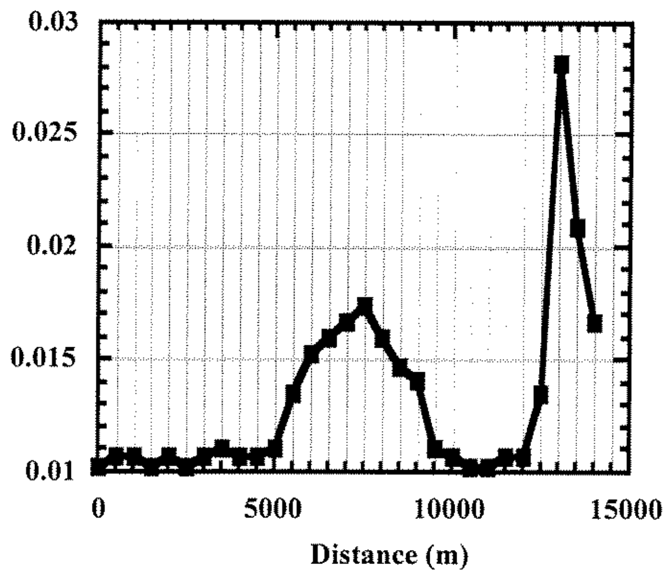
Example: $Pf_D + Pf_{ND}$



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Truncated distributions

- Capacity distributions truncated by hydro-testing
- Demand distributions truncated by pressure relief systems & flanges

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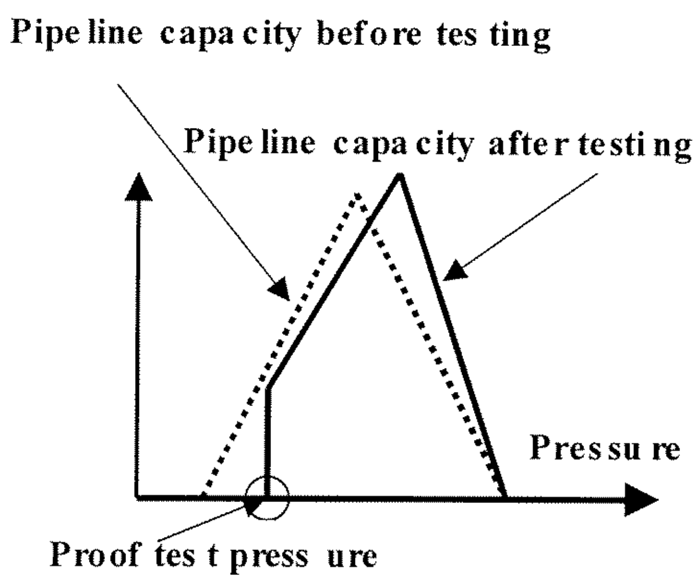
Capacity truncations - hydro-testing



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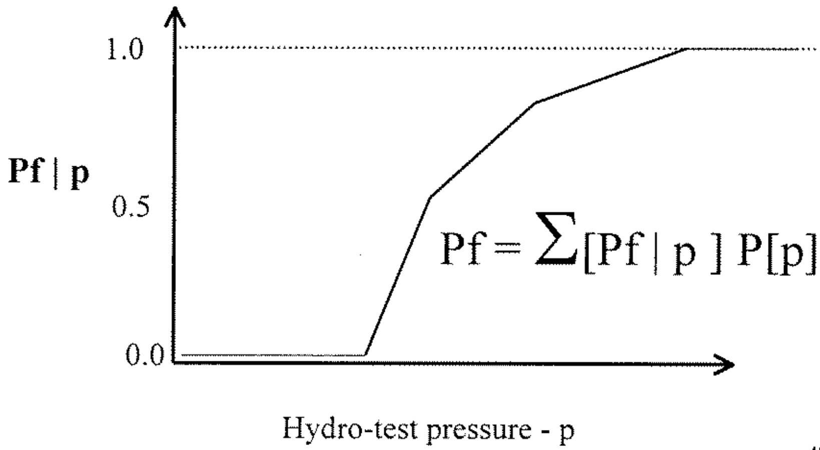
Truncated capacities: *fragility curve Pf formulation*



$$Pf = \sum [Pf \mid p\ ]\ P[p] \Delta p$$

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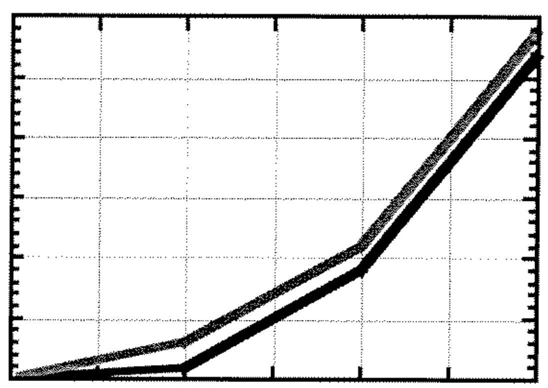
Proof testing effects (example)



$K = \ln (Xp / p_b) / \sigma_{lnpb}$

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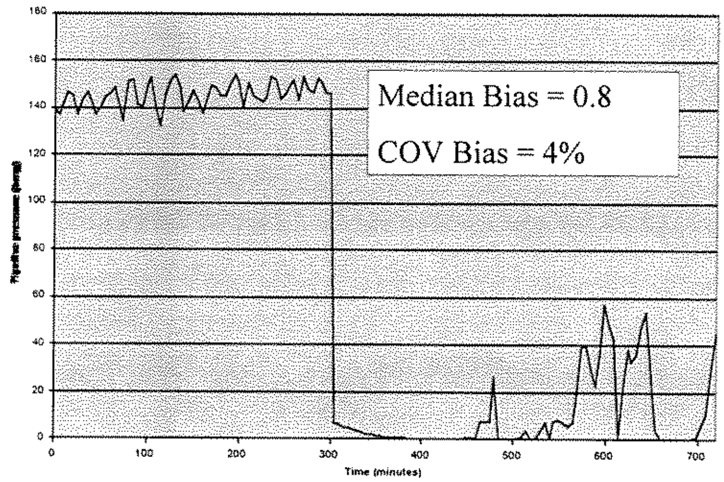
Oil and gas pipelines maximum pressure distributions: normal



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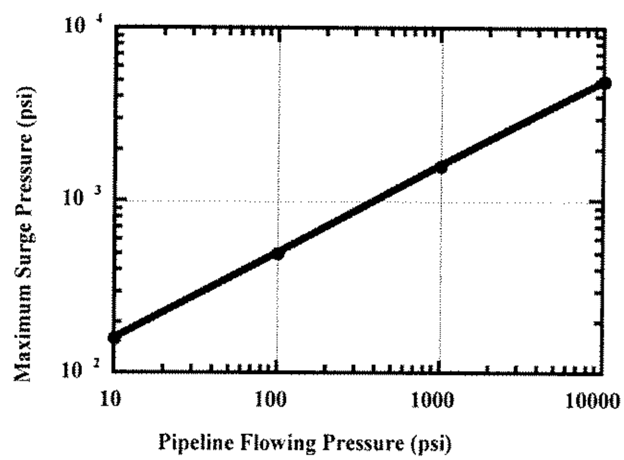
Oil & gas pipelines maximum pressure distributions: accidental



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Real-Time RAM Results/Conclusions

- Capacity formulations developed
- Demand formulations developed
- Capacity formulation biases developed
- Demand formulation biases developed
- Probabilities of failure formulations developed & programmed (conditional on given inputs, not truncated)

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Real-Time RAM Results/Conclusions

- Probabilities of failure formulations being developed (conditional on given inputs, truncated)
- Probabilities of failure formulations being developed (conditional on in-line instrumentation results)
- Parametric studies to be performed
- Document results (project report 2, May 2001)

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Real-Time RAM Schedule (funded for 2 years)

- Summer 2000 - Sang Kim
- Fall 2000 - no GSR
- Spring 2001 - Angus McLelland
- Summer 2001 - no GSR (Bob Bea?)
- Fall 2001 - new GSR
- Spring 2002 - new GSR
- Summer 2002 - new GSR

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Real-Time RAM Budget

- 1-year grant funding from Rosen
- 2-year sponsored project funding from MMS
- $60 k available direct cost funds per year
- Expended summer 2000 (25% year one)
- Expended spring 2001 (25% year one)
- Unexpended first year (50% year one)

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Real-time RAM project summary

- Technical developments behind plan for 1st year (estimate 75% completed)
- Budget - under-expended by 50%
- Schedule can be caught-up during summer 2001 (if Bea does GSR work)
- Developments and schedule for last year of project dependent on locating qualified and motivated GSR (two potential candidates)
- Given second grant from Rosen (1/2002), project can be completed within budget and by year end 2002

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Questions & discussion points

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Questions & discussion points

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