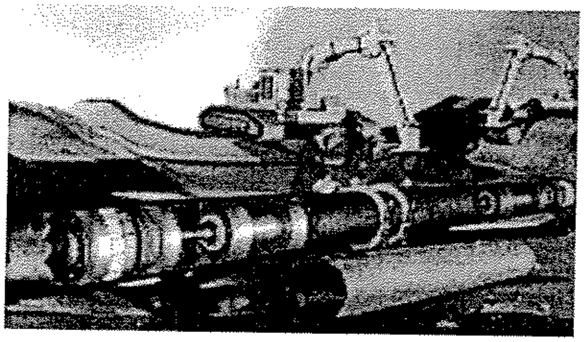
Real-Time Risk Assessment and Management of Pipelines Project



Sponsored by:

Rosen Engineering and the U.S. Minerals Management Service

Report Four

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January 22, 2002

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I) Introduction

1. Objective

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

2. Scope

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

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

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

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

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

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

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

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

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

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

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

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

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

3. Background

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

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

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

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

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

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

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

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

These works formed an important stating point for this project.

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

1) Serviceability and Safety Classifications (SSC) of pipelines and risers,
2) Guidelines for analysis of in-place pipelines loadings (demands) and capacities (resistances), and
3) Guidelines for analysis of on-bottom stability (hydrodynamic and geotechnical forces).
4) Guidelines for installation design of pipelines.

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

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

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

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

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

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

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

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

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

4. Approaches

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

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

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

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

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

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

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

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

4) Evaluate the variabilities, uncertainties, and Biases (different between nominal and true value) associated with the demands. This evaluation must be consistent

with the variabilities and uncertainties that were included in the decision process that determined the desirable and acceptable target reliabilities for the system,

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

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

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

5. The Project Premises

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

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

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

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

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

6. Project Tasks

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

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

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

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

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

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

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

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

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

9) Document the forgoing results in four project phase reports

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

7. Current research phase tasks.

1) Literature review on pipeline corrosion, inspection techniques, reliability methods, truncated distribution, and prediction models for evaluation of burst pressures.

2) Develop Excel spreadsheet to compute probability of failure for truncated Normal distribution of both demand and capacity.

3) Develop Excel spreadsheet to compute probability of failure for truncated lognormal distribution of both demand and capacity.

4) Running parametric study using the developed spreadsheets to understand the effect of separate demand and capacity parameters on the probability of failure of truncated Normal and Lognormal distributions for both demand and capacity.

5) Plotting the effect of every parameter studied versus the probability of failure.

6) The following parameters where analyzed:

   - The choice of the truncation on demand.
   - The choice of the truncation on capacity.
   - The variation of the demand coefficient of variation V%.
   - The variation of the capacity coefficient of variation V%.
   - The variation of the Mean (Median) capacity by varying mainly the Do/t ratio (diameter to thickness ratio).
   - The variation of the Mean (Median) demand.

7) Analyzing and reasoning on the effect of every parameter and recommendations on Truncated distribution studies on both demand and capacity.

II) Literature Review

1. Corrosion

1.1 Fundamentals

Corrosion is a major problem for the engineering industry, and the potential for savings that corrosion control can provide constantly on the rise. Corrosion is also a complex process involving a large number of variables that both vary in space and time. The key to understanding the corrosion problem is to be able to accurately predict the nature of the reaction taking place at the interface of the corroding material and the environment. Electrochemical corrosion of carbon steel will not occur unless these two requirements are met:

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

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

A threshold water cut is required for corrosion to begin.

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

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

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

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

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

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

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

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

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

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

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

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

1.2 Inspection

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

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

- Magnetic Flux Leakage
- Ultrasonic
- High Frequency Eddy Current
- Remote Field Eddy Current

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

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

1.3 Fundamentals of In-Line Instrumentation

1.3.1 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)

1.3.2 Pigging procedure

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.

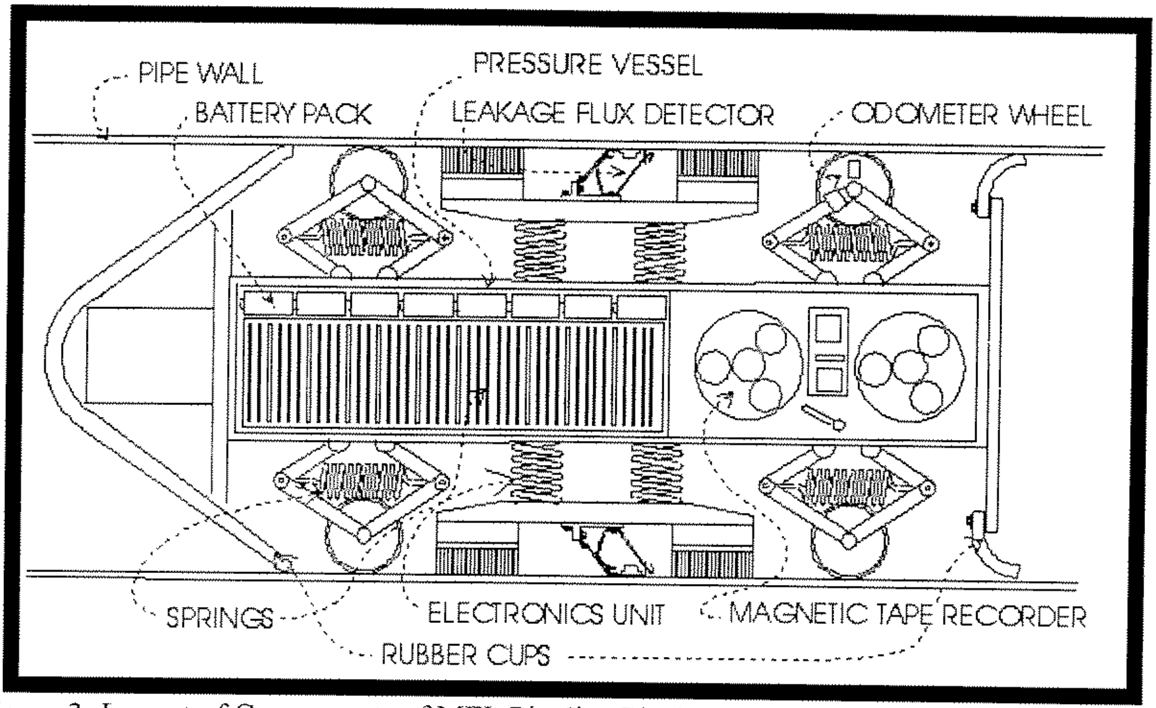


Figure 3: Layout of Components of MFL Pipeline Pig (www.phy.queensu.ca)

1.4 Performance Specifications for In-Line Instrumentation

1.4.1 Detection and Sizing Capabilities

1.4.1.1 Manual Analysis

(Applicable for detailed analyzed features)

POD = Probability of Detection

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

1.4.1.2 Automatic Analysis

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

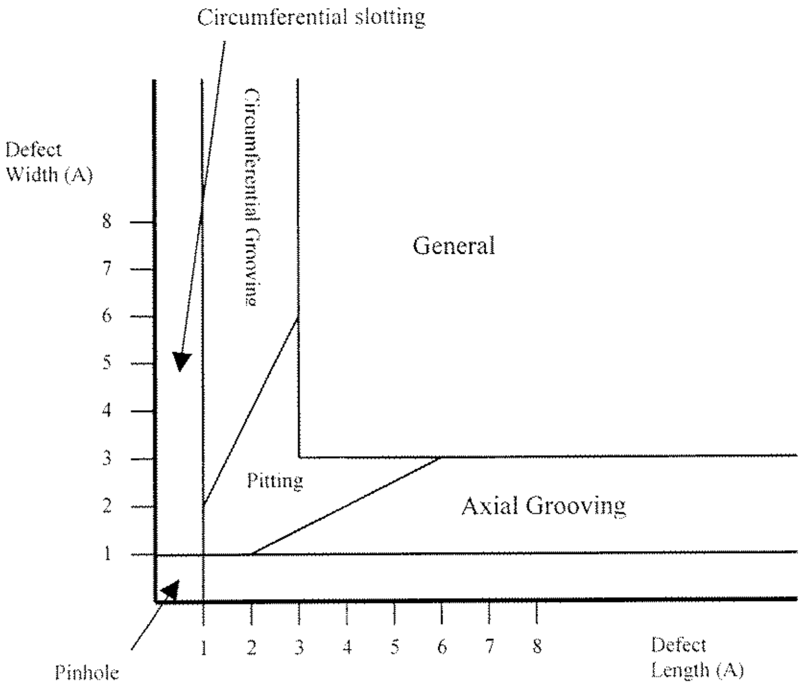
1.4.1.3 Wall Thickness Detection

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

1.4.2 Location and Orientation Capabilities

a. Axial position accuracy from reference marker: ± 1m
b. Axial position from closest weld: ± 0.1m
c. Circumferential position accuracy: ± 10^{0}

1.4.3 Defect Dimension Definition



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

1.4.4 Identification of Features

POI: Probability of Identification

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

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

2. Applied Reliability Theory

2.1 Principles

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 the probability of failure for any individual defect can be calculated by the use of the following Equation.

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

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 σ is the standard normal cumulative function. σ 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 assumed to be zero, and therefore the third term under the radical can be neglected.

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:

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

2.2 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:

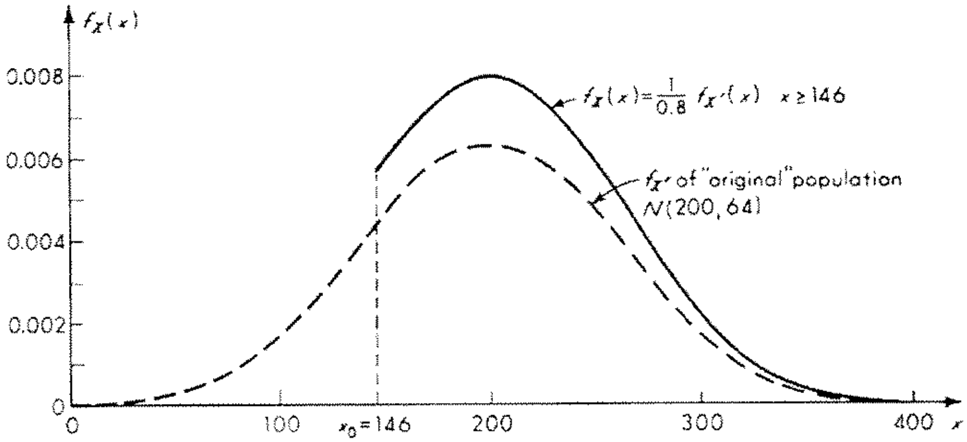


Figure 8: Truncated Distribution (Benjamin and Cornell, 1970)

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.

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 $x>x_o$.

$$f_Y(y) = \left| \begin{array}{l} 0 \quad for \quad y < x_o \\ \hline k \cdot f_x(y) \quad for \quad y \geq x_o \end{array} \right.$$

$where:$

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

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:

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

Where:

$\Phi = cumulative\ distribution\ function$
$of\ the\ normal\ distribution$

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

$$P_f = \sum [P_f\ |p] \cdot [P(p)] \cdot [\Delta P]$$

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.

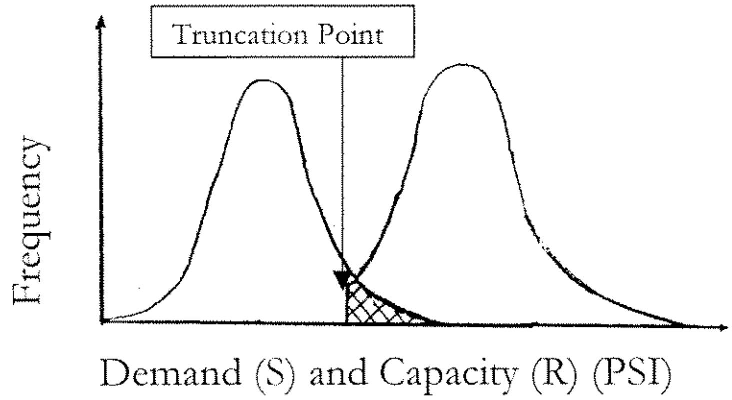


Figure 9: Demand and Capacity Distribution

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 $P_f \mid p = 1 - \Phi(\beta)$, 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

The extent to which the tail of the probability distribution is truncated directly affects the probability of failure of a corroded pipeline

3. Summary of Current Pipeline Requalification Practice

3.1 ASME B31-G, 1991

The ASME B31-G manual is to be used for the purpose of providing guideline information to the pipeline designer/owner/operator with regard to the remaining strength of corroded pipelines. As stated in the ASME B31-G operating manual, there are several limitations to ASME B31-G, including:

- The pipeline steels must be classified as carbon steels or high strength low alloy steels;
- The manual applies only to defects in the body of the pipeline which have smooth contours and cause low stress concentration;
- The procedure should not be used to evaluate the remaining strength of corroded girth or longitudinal welds or related heat affected zones, defects caused by mechanical damage, such as gouges and grooves, and defects introduced during pipe or plate manufacture;
- The criteria for corroded pipe to remain in-service are based on the ability of the pipe to maintain structural integrity under internal pressure; and
-

The 'safe' maximum pressure (P') for the corroded area is defined as:

$$P' = 1.1P\left[\frac{1-\frac{2}{3}\left(\frac{d}{t}\right)}{1-\frac{2}{3}\left(\frac{d}{t\sqrt{A^2+1}}\right)}\right] \qquad \text{for } A = .893\left(\frac{Lm}{\sqrt{Dt}}\right) \leq 4$$

Where:

Lm = measured longitudinal extent of the corroded area, inches

D = nominal outside diameter of the pipe, inches

t = nominal wall thickness of the pipe, inches

d = measured depth of the corroded area

P = the greater of either the established MAOP of P = SMYS*2t*F/D

(F is the design factor, usually equal to .72)

3.2 Det Norske Veritas (DNV) RP-F101, Corroded Pipelines, 1999

DNV RP-F101 provides recommended practice for assessing pipelines containing corrosion. Recommendations are given for assessing corrosion defects subjected to internal pressure loading and internal pressure loading combining with longitudinal compressive stresses.

$$\mathrm{Pf} = \frac{2 \cdot t \cdot \mathrm{UTS}\left(1-(d/t)\right)}{(D-t)\left(1-\dfrac{(d/t)}{Q}\right)}$$

Where Q is:

$$Q = \sqrt{1 + .31\left(\frac{1}{\sqrt{D \cdot t}}\right)^{2}}$$

Pf = failure pressure of the corroded pipe
t = uncorroded, measured, pipe wall thickness
d = depth of corroded region
D = nominal outside diameter
Q = length correction factor
UTS = ultimate tensile strength

Note: If the ultimate tensile strength is unknown, the specified minimum tensile strength can be substituted for the ultimate tensile strength. (DNV, 1999)

DNV RP-F101 has several defect assessment equations. The majority of the equations use partial safety factors that are based on code calibration and are defined for three different reliability levels. The partial safety factors account for uncertainties in pressure, material properties, quality, tolerances in the pipe manufacturing process and the sizing accuracy of the corrosion defect. The three reliability levels are: (1) safety class normal defined as oil and gas pipelines isolated from human activity; (2) safety class high defined as risers and parts of the pipelines close to platforms or in areas with frequent activity; and (3) safety class low defined as water pipelines.

There are several assessment equations that give an allowable corroded pipe pressure. Equation 3.2 gives P' for longitudinal corrosion defect, internal pressure only. Equation 3.3 gives P' for longitudinal corrosion defect, internal pressure and superimposed longitudinal compressive stresses. Equation 3.4 gives a P' for circumferential corrosion defects, internal pressure and superimposed longitudinal compressive stresses. Section Four of the manual provides assessments for interacting defects. Section Five assesses defects of complex shape.

It is important to note that the DNV RP-F101 guidelines are based on a database of more than seventy burst tests on pipes containing *machined* corrosion defects and a database of line pipe material properties. (DNV, 1999)

3.3 RAM PIPE Formulation (U.C. Berkeley)

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
SCF_C = Stress Concentration Factor for corrosion features, defined by:

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

The stress concentration factor is the ratio of maximum hoop stress over nominal hoop stress due to a notch of depth d in the pipeline cross section that has a mean radius R=(.5*D-.5*t)

(Bea, Xu, 1999)

III) POP Project work

The POP project work included the development, based on pig data, of predicted burst pressure vs length of the pipeline, the probability of failure vs length of pipeline as well as fragility curves of the pipeline using the RAM, the DNV and the B31G formulations. The third author was responsible of developing results using the B31G formula and using it with different variation (with/without biases, with/without factor of safety). The obtained predictions and results are shown below. The reason that the pressure appears deterministic values is that B31G mostly accounts for longitudinal and area corrosion. In other term, if longitudinal and area corrosion are small, the B31G treats the pipeline as intact despite some large d/t (wall thickness loss), and Pb is thus is predicted as the design pressure. This has typically occurred in the POP project.

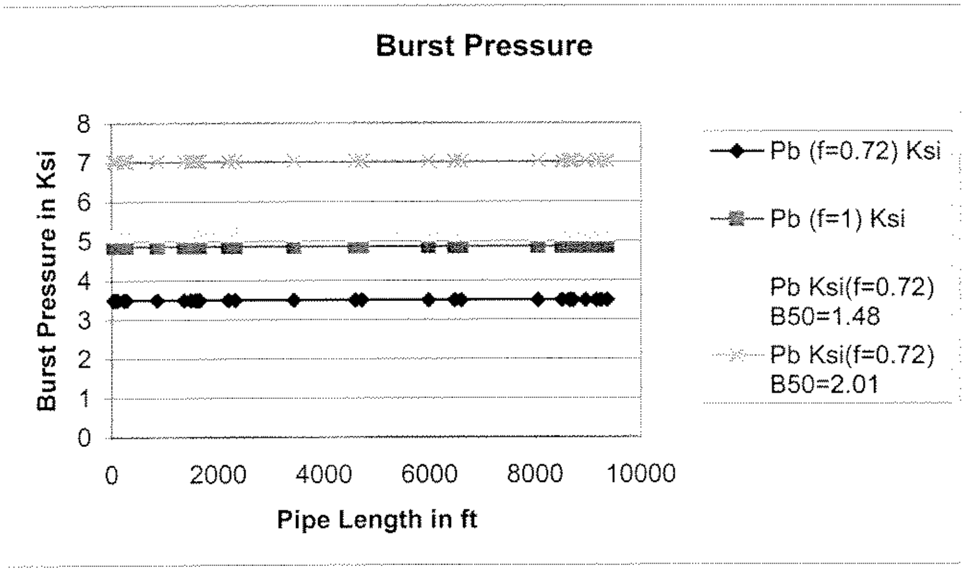


Fig 1: Predicted burst pressure over length of the pipeline

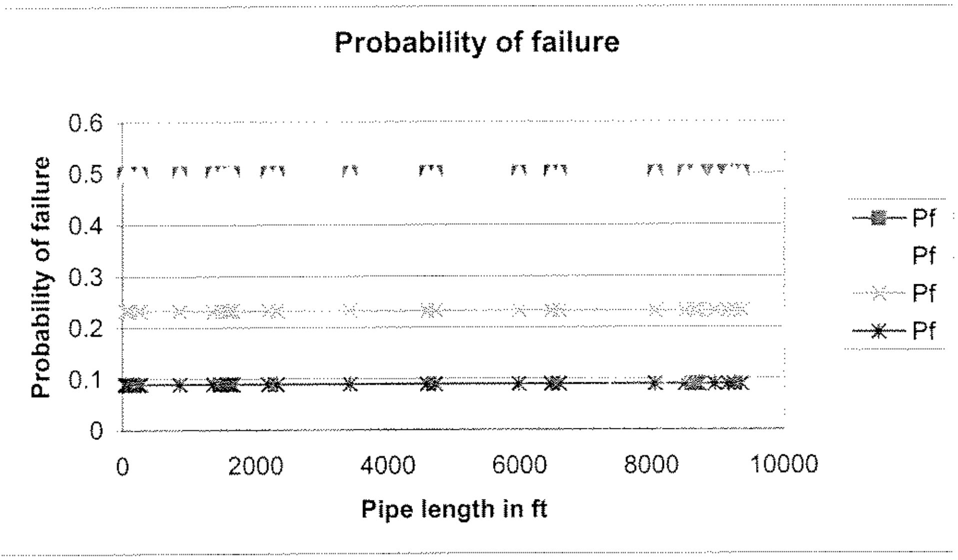


Fig 2: Predicted probability of failure of pipeline versus distance in feet.

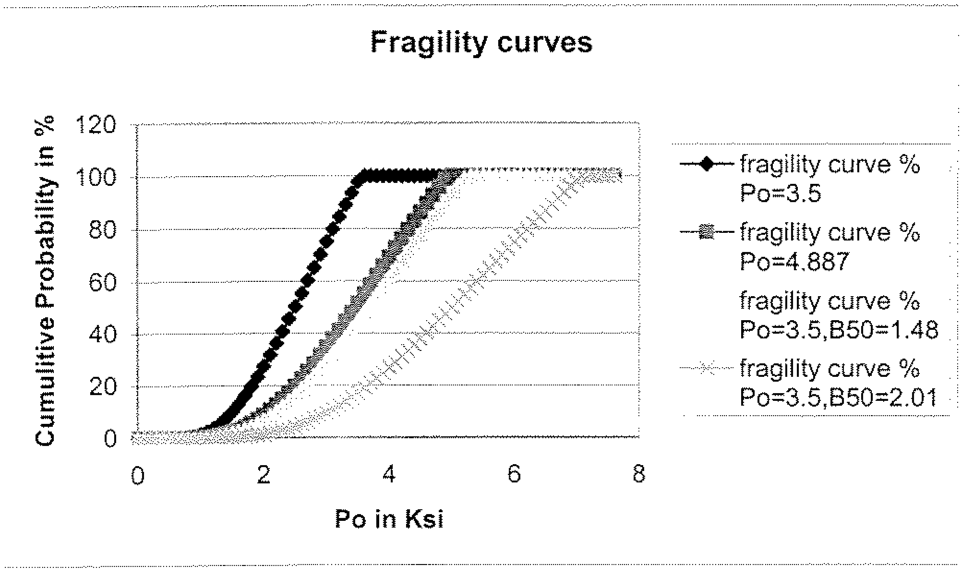


Fig 3: Fragility curves of the pipeline with different variations on biases and factors of safety

IV) Truncated Pipeline Demand and Capacity Distribution Effects

In this section, we will analyze the effect of truncations on both demand and capacity combined. Excel spreadsheets were developed for this purpose. These spreadsheets can be used to compute the probability of failure with and without truncations, as well as the probability of failure with truncations on demand alone, capacity alone, and both demand and capacity. Two spreadsheets were programmed to account for normal as well as lognormal distributions of both demand and capacity. (See Appendix A)

The user is required to input the following:

- The mean/median Diameter of the pipeline and its coefficient of variation.
- The mean/median thickness of the pipeline and its coefficient of variation.
- The SMYS and SMTS and their coefficient of variations (note: The SMYS was used in the calculations).
- The truncated capacity (due to hydrotest).
- The Mean/Median pressure and its variation.
- The relief pressure of the pressure relief valve.

Note:

-The calculations were done using the RAM pipe equation:

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

-The truncations on both demand and capacity were assumed deterministic values, i.e. with zero coefficients of variations.

- In the parametric study, mainly type one uncertainty on both capacity and demand were used.

-Use Spreadsheets Normal and Lognormal for all calculations except for the calculation of the non-truncated lognormal Pf with varying pressure use the lognormal-pressure spreadsheet.

- To use the spreadsheets for non-truncation calculations, enter −100000 psi or 1 psi for the hydrotest in the Normal case and 1 for hydrotest in the Lognormal case. For the pressure relief valves enter values as large as 40000 psi.

In the parametric study the following values of the parameter were set to be the base value, i.e. during the study, we fixed the parameter at the following base value while varying one parameter at a time to reveal its effect on the Pf.

Parameter	Base value	Variation V%
Diameter D50 (in)	8.63	10%
Wall thickness t50 (in)	0.67	8%
SMTS (psi)	50,000	10%
Truncated capacity (psi)	500	0%
Truncated demand (psi)	6,000	0%
Mean/Median capacity (psi)	10,100	16%
Mean/Median demand (psi)	5,000	16%

Table 1: Base parameters values.

Base parameters selection rational:

-The choice of demand and capacity was based mostly on the selection of the Mean/Median factor of safety since this is what affects the Pf, i.e. the relative ratio between median demand and median capacity. In this study, a factor of safety of 2 was chosen. In fact the factor of safety varies according to different safety classes, and different industries might use different factors of safety. I will list here the factors of safety listed by the Williams Gas Pipeline Safety for the different safety classes:

Class 1: 1.39

Class 2: 1.67

Class 3: 2

Class 4: 2.5

Where the classes are defined based on the cost of failures and potential causalities. In offshore application however, the design factor is usually set at 0.72 giving a factor of safety of 1.39. On onshore applications or close to residential areas (especially gas pipelines) the factor of safety might rise to 2.5. Moreover, although a design factor of 0.72 is specified for design offshore pipelines, the mean operating pressure tends to be lower than 0.72 of the mean capacity similar to the fact that the effective median loads on a building are much lower than the loads designed for.

One might argue that the specified median pressure is high (5,000 psi). It is true that in practical application such pressures are rarely used; however this will not affect the parametric study since the Pf is dependant on the Capacity to demand ratio or median factor of safety, and the capacity was also set high to have a median factor of safety of 2.

- The choice of the demand truncation was made with the following assumptions: The mean operating pressure was close to the MAOP (Mean operating pressure: 5,000 psi, MAOP: 5,500). It is specified in codes that the pipeline pressure shall not exceed the MAOP or at the worst case 10% of the MAOP. Based on this I have chosen the demand truncation value to be 6,000 psi.
- The choice of the Truncation on the capacity side was somehow confusing. In fact, the specified Hydrotest shall usually occur at 125% of the MAOP. However this will give a capacity truncation higher than the demand truncation with no overlap between the two distributions. The choice of the 500 psi for the capacity truncation was arbitrary for the purpose of the parametric study. After affecting the analysis and with the given coefficient of variations, I believe that given such coefficient of variation (16%), the

capacity truncation would be more effective for values of 3/10 to 1/2 of the mean capacity or 3/5 to 1 of the mean demand.

1. Effect of the hydrotest:

Looking at (Fig 1), the Pf is first insensitive to the truncation of capacity at low values (until 3000 psi) for the simple fact that the area under the curve for values less than 3000 is negligible especially that the mean is "far" (10,100 psi) and the standard deviation relatively small. After 3000 psi, and when the Truncation/Mean ratio exceeds 3/7, the truncation becomes effective and the overlap area between demand and capacity decreases resulting in the tremendous reduction in Pf.

For the lognormal distribution (Fig 2), the truncation becomes effective in around 4500 psi due to the fact that the specified coefficient of variation results in a more spread normal distribution than the lognormal distribution. The lognormal distribution starts at a probability of failure much lower than the normal distribution (fig 3) due to the nature of the lognormal distribution and its logarithmic scale. This fact, as well as that the curve is less spread, resulted in a steeper decreasing slope for the Pf for the lognormal distribution.

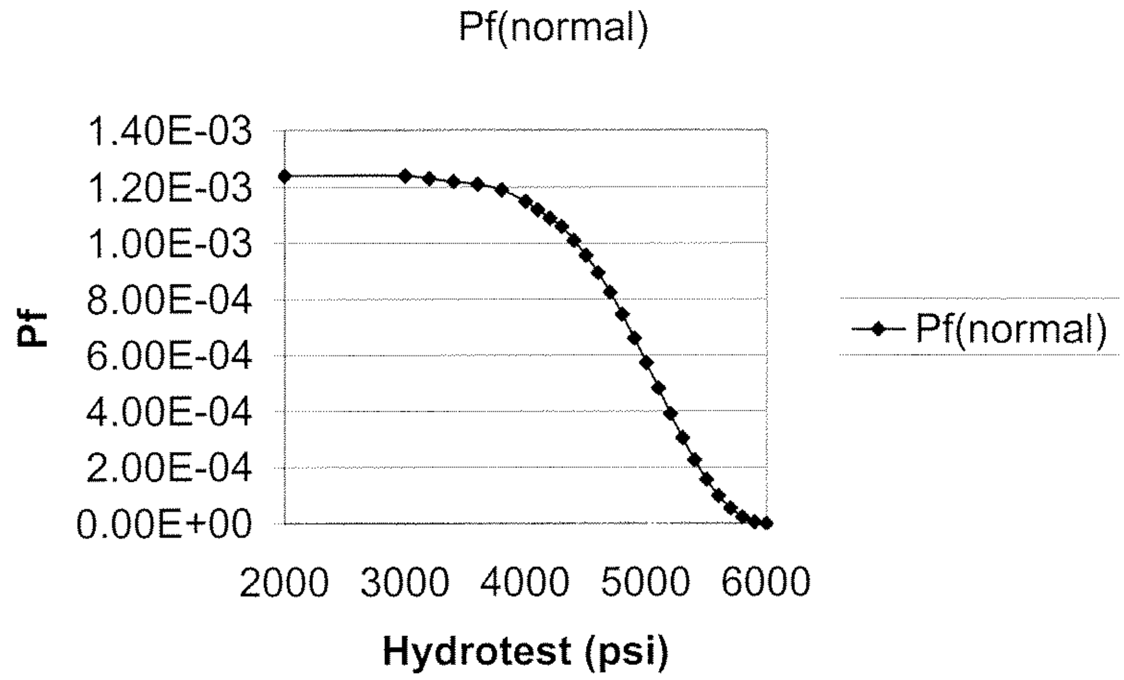


Fig 1: Effect of capacity truncation on Pf for a normal distribution

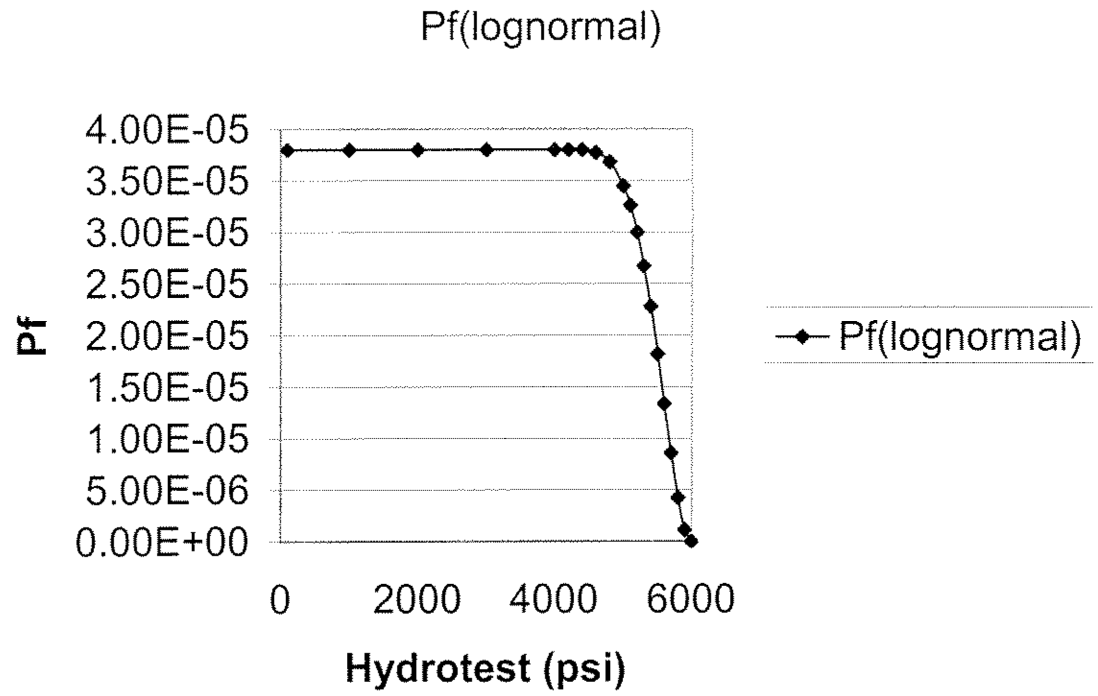


Fig 2: Effect of capacity truncation on Pf for a lognormal distribution

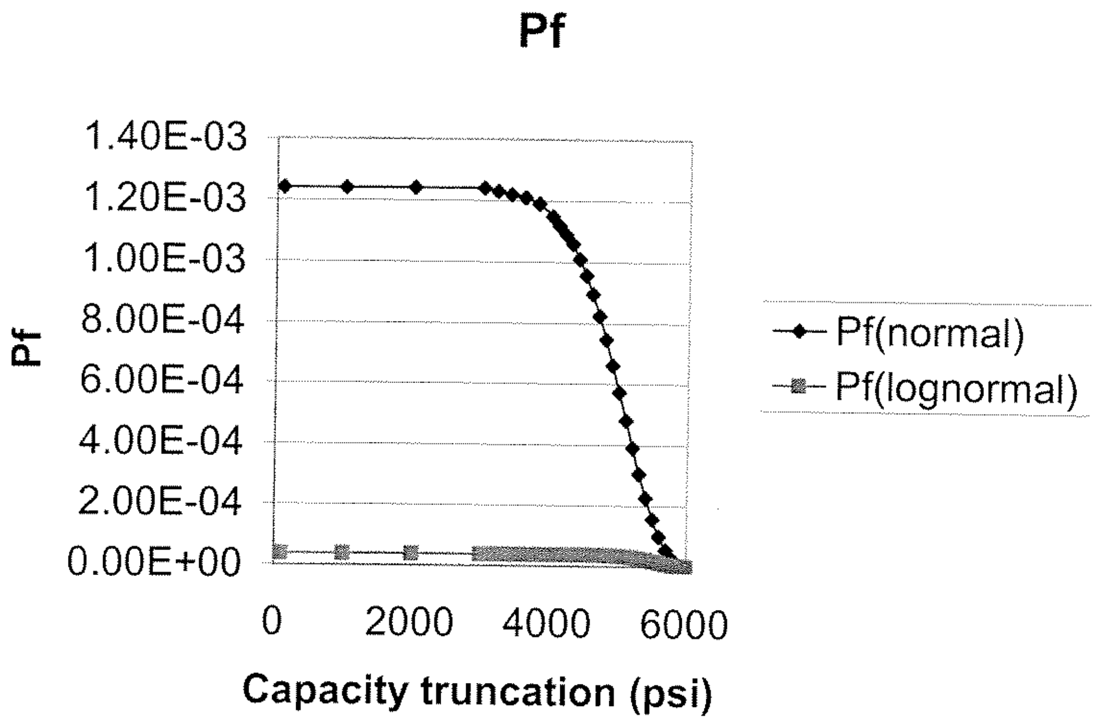


Fig 3: Effect of capacity truncation on Pf for both normal and lognormal distribution

2. Effect of capacity variations:

Note: When first reading the graphs, coefficients of variation as high as 1000% are plotted. This is certainly not a practical V, however it was plotted to give a further understanding of the effect of truncations. A closer and reasonable look on practical V between 0 and 100% are also given. (Fig: 7, 8, 9).

For relatively small variations the Pf tends to increase since the overlap area between capacity and demand is increasing. However, after a certain value, the spread of the capacity curve results in an important truncation of the area below the curve thus reducing the Pf. The larger the value of the truncation, the closer it is to the mean and the more important is the truncation: The maximum Pf gets lower and is reached for lower values of V (test at 500 and test at 3000). It should be noted however that for most of the practical applications with reasonable V (Fig 7,8 and 9), the Pf is increasing with V but is reduced relative to the non-truncated case. The combined effect of truncation and V is clearly important compare to the non-truncated curves (fig 6) since non-truncated curves tend to continuously increase the Pf (until a certain value beyond which little increase in the overlap area occurs with large increases in V), while the truncation reduces the value of the Pf and drastically modify its distribution. It is clear that the effect of the truncation is more important for the normal distribution especially for the values used in the analysis due to the fact that the lognormal distribution is less spread for the same V compare to the normal distribution, and large values for the truncation on capacity (>3000) are needed to start inducing considerable effects as can be seen from (Fig 5). In fact (fig 5) illustrates the relative effect of different capacity truncations and that of the coefficient of variation V on Pf. As expected, Pf considerably decrease higher hydrotest values.

Less values of Pf were registered for lognormal the distribution which is expected due to the logarithmic sensitivity of the distribution. It is remarkable however that the picks occur approximately for almost the same values (normal pick is reached first) for both normal and lognormal distributions.

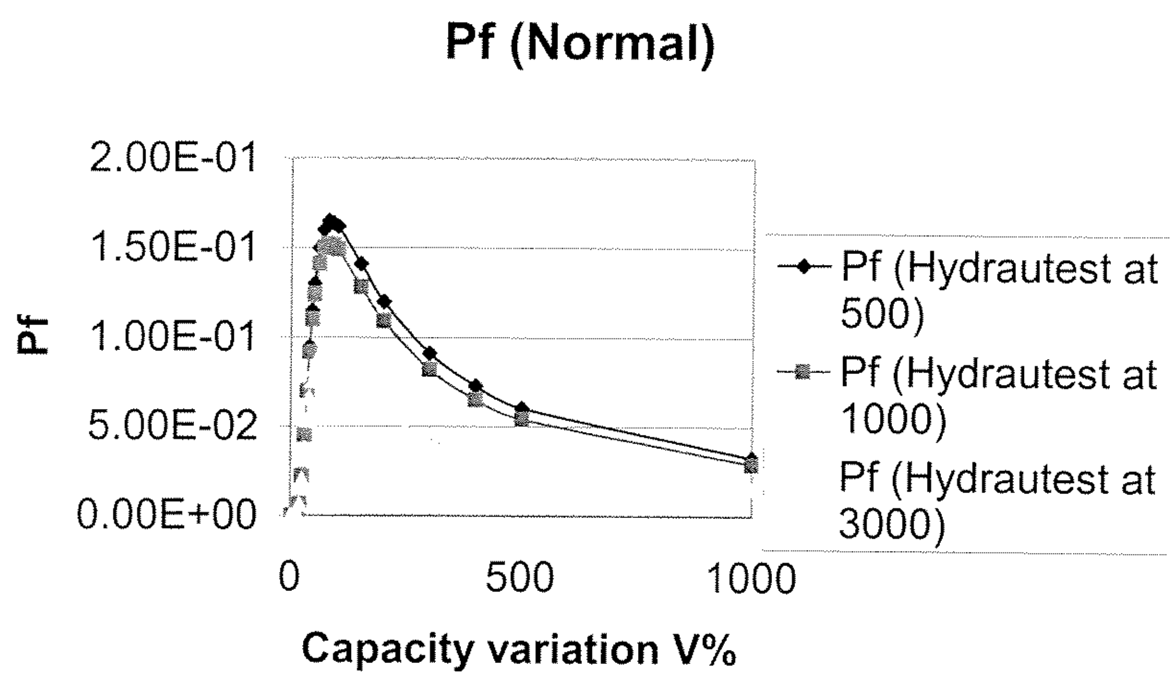


Fig 4: Effect of capacity variations on Pf for a normal distribution.

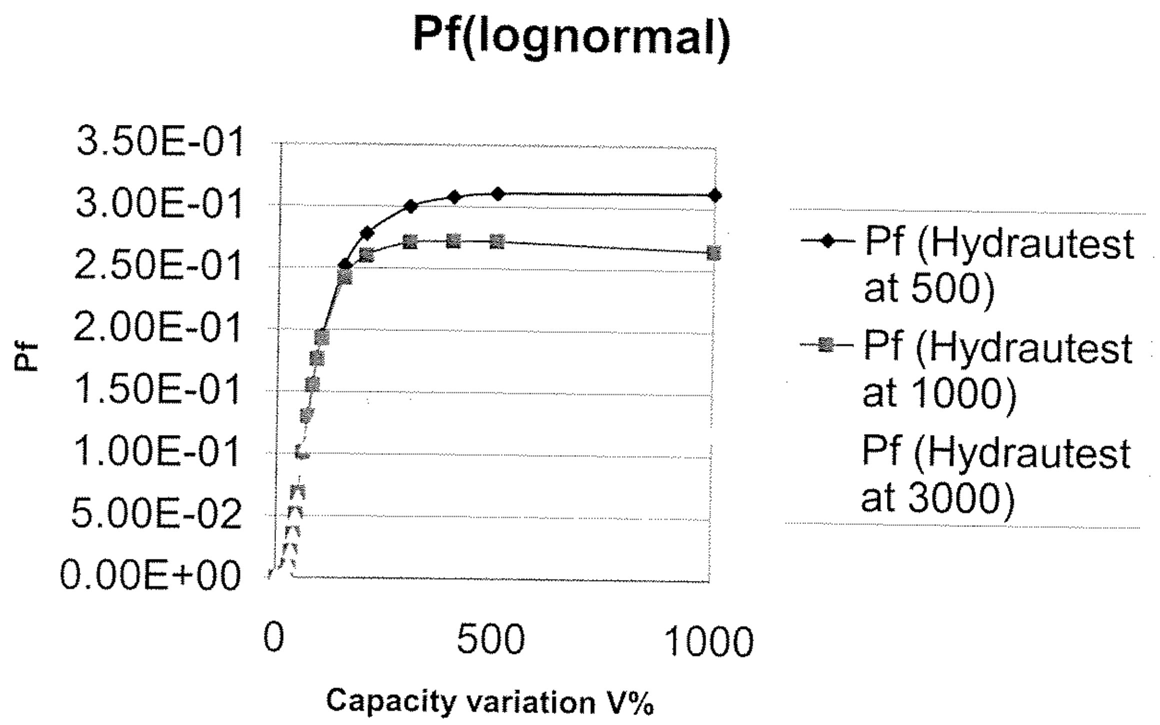


Fig 5: Effect of capacity variation on Pf for a lognormal distribution

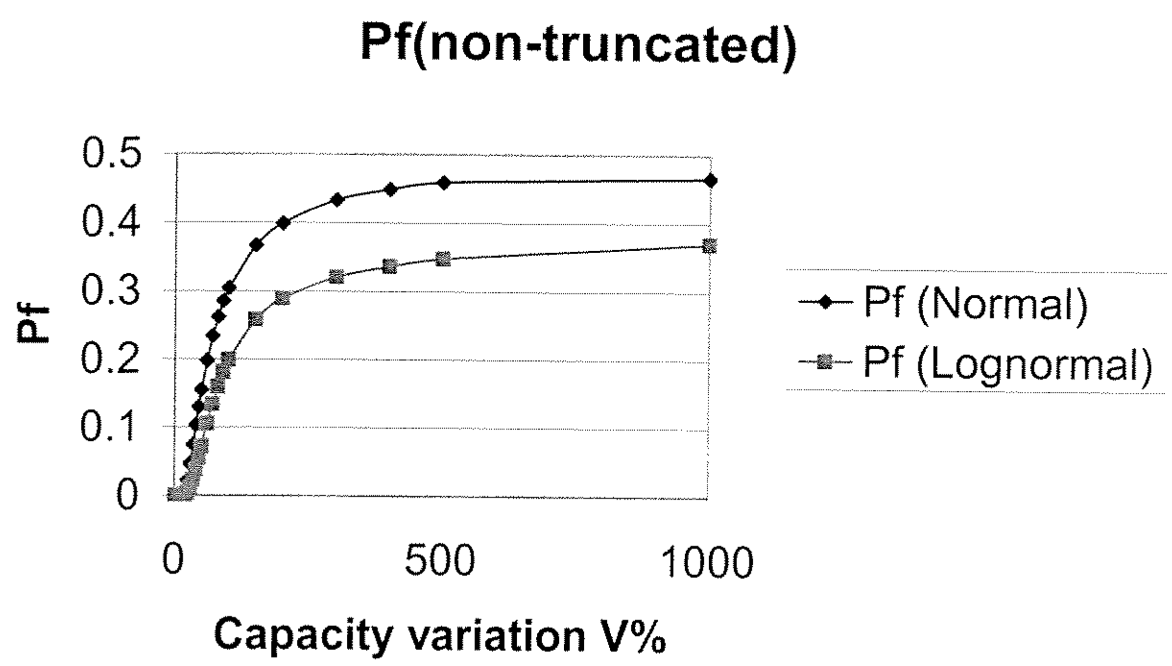


Fig 6: Effect of capacity variation on Pf for non-truncated normal and lognormal distributions

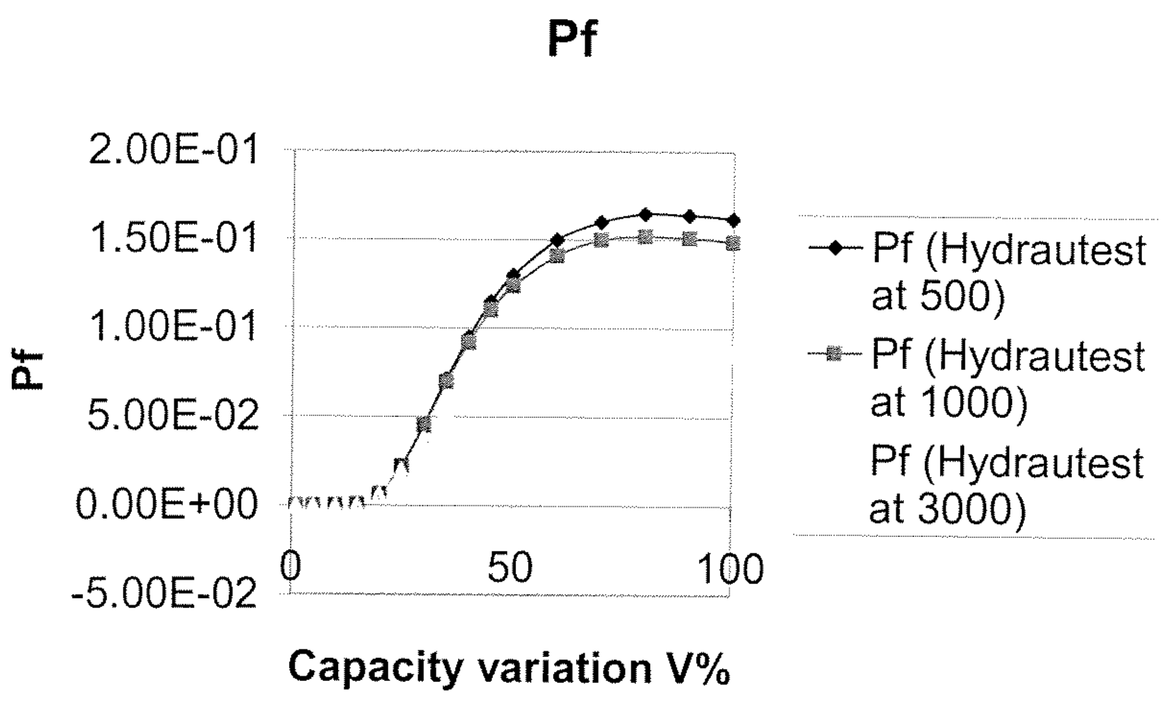


Fig 7: Closer look on the effect of capacity variations on Pf for a Normal distribution

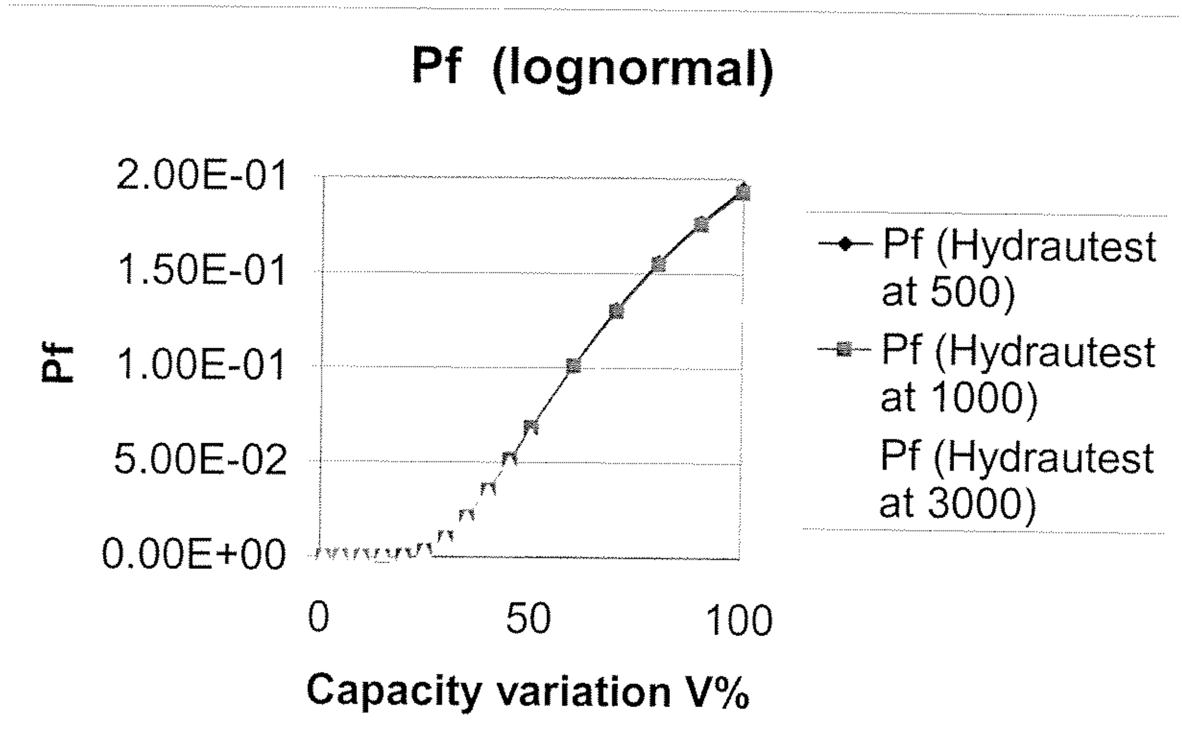


Fig 8: Closer look on the effect of capacity variations on Pf for a lognormal distribution

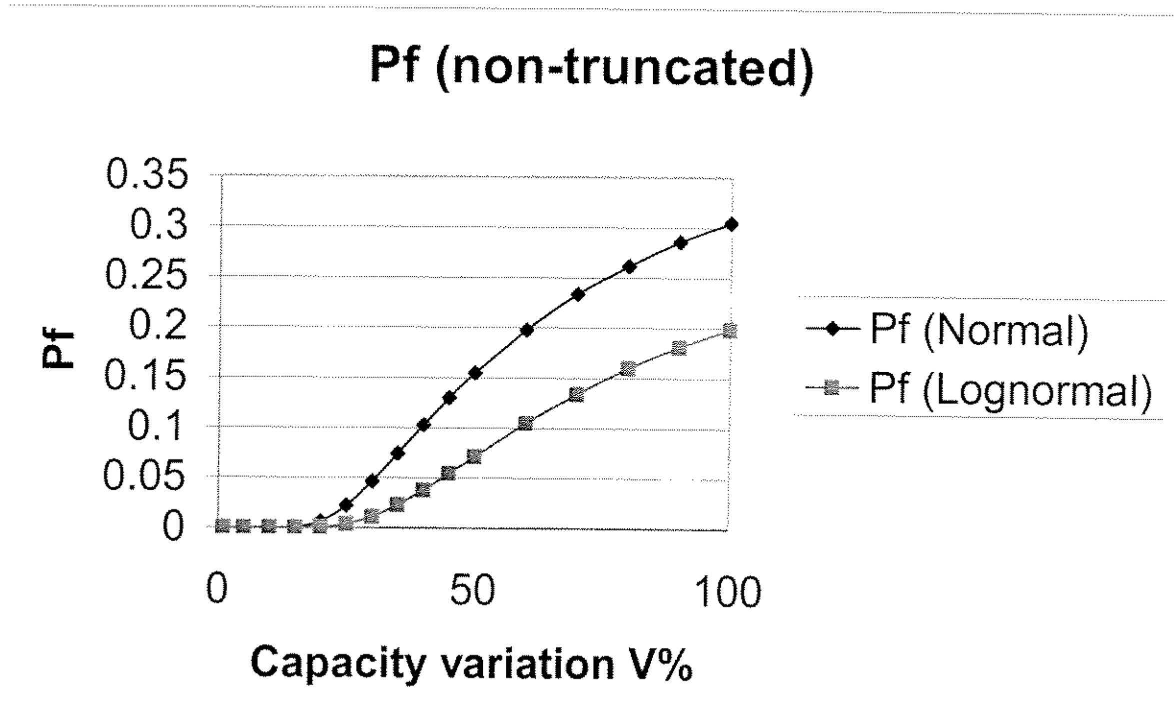


Fig 9: Closer look on the effect of capacity variations on Pf for non-truncated normal and lognormal distributions

3. Effect of demand variation:

The same logic discussed in the capacity variation part applies for the demand variation. However the effect of the variation is more important since the demand truncation is close to the mean/median and has a greater effect than in the previous analysis on the capacity. This is clearly shown in (Fig 10, 11, 12,13) where the maximum Pf is reached for low V values (around 30%) and then the Pf starts decreasing for both normal and lognormal.

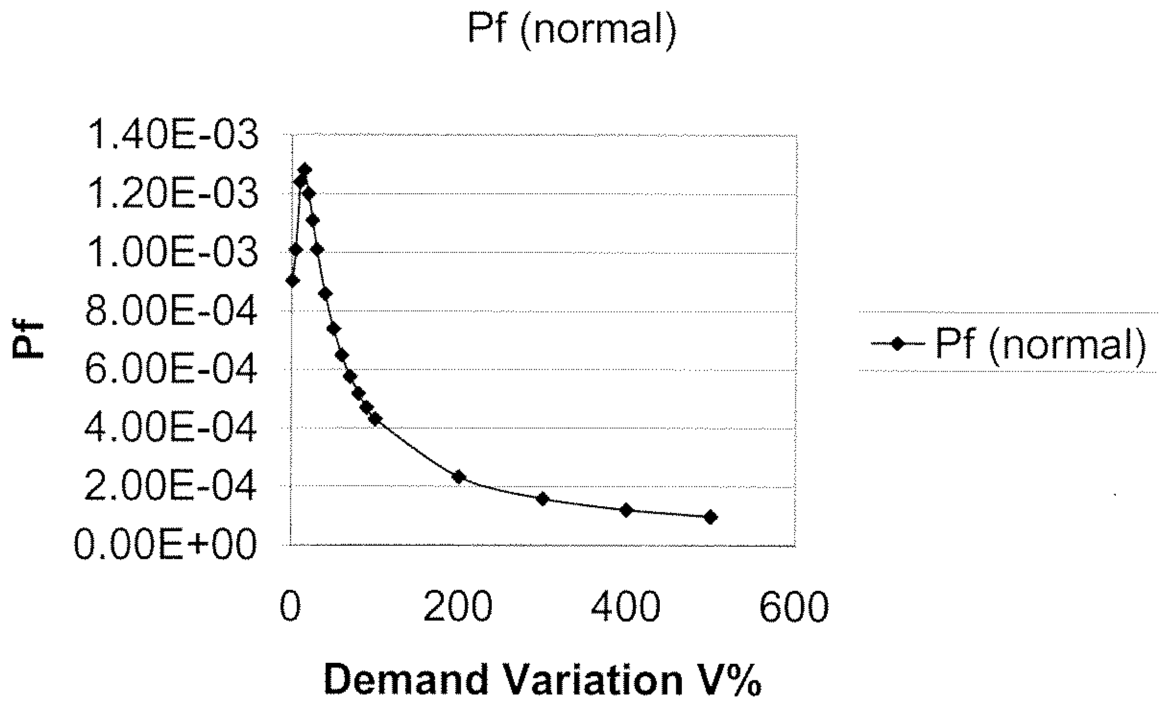


Fig 10: Effect of demand variations on Pf for a normal distribution

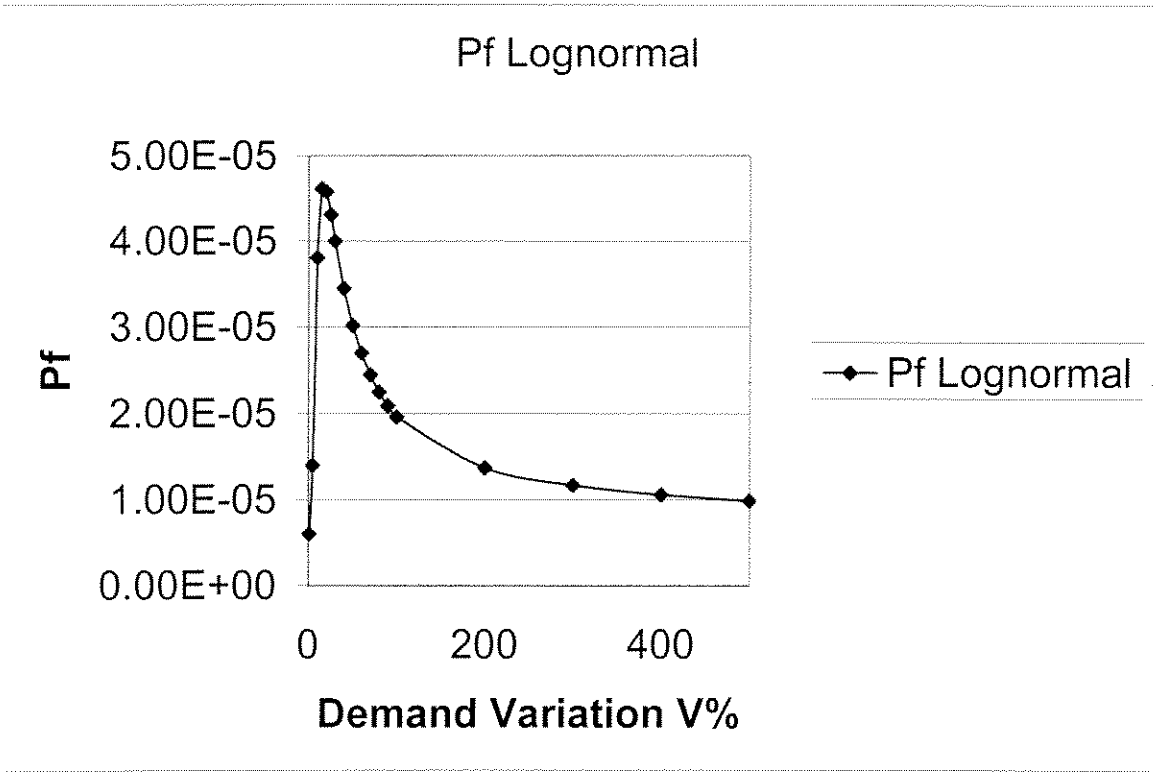


Fig 11: Effect of demand variations on Pf for a lognormal distribution

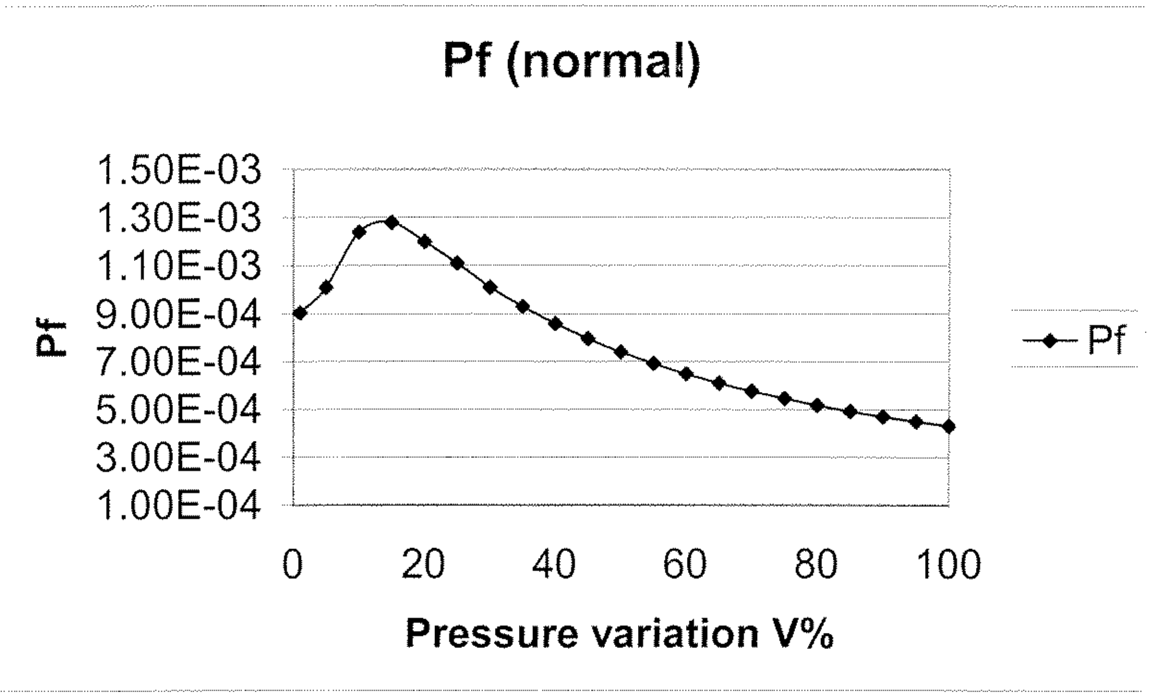


Fig 12: Closer look on the effect of demand variations on Pf for a lognormal distribution

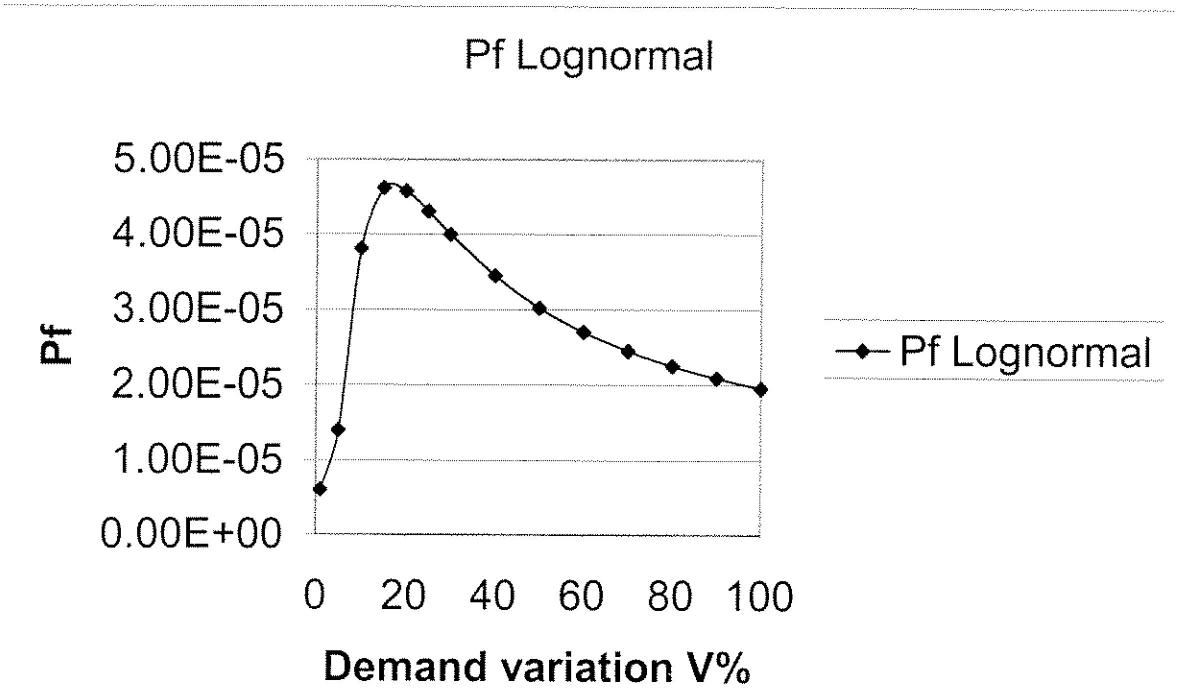


Fig 13: Closer look on the effect of demand variations on Pf for a lognormal distribution

4. Effect of Demand truncation:

The effect of the truncation on the demand side is almost the mirror of that on the capacity side: The demand curve and its truncation tend to reduce the overlap area, and thus the Pf, for low values of the truncation, while the capacity truncation tend to increase the overlap area, and thus the Pf, for low values of the truncation. The max Pf in both cases is almost similar which is approximately equal to the Pf with no truncation. It is also noticed that since the lognormal curve is less spread, the change occurs within a small range of the truncation value, but the curve is steeper within this range. Fig (14, 15)

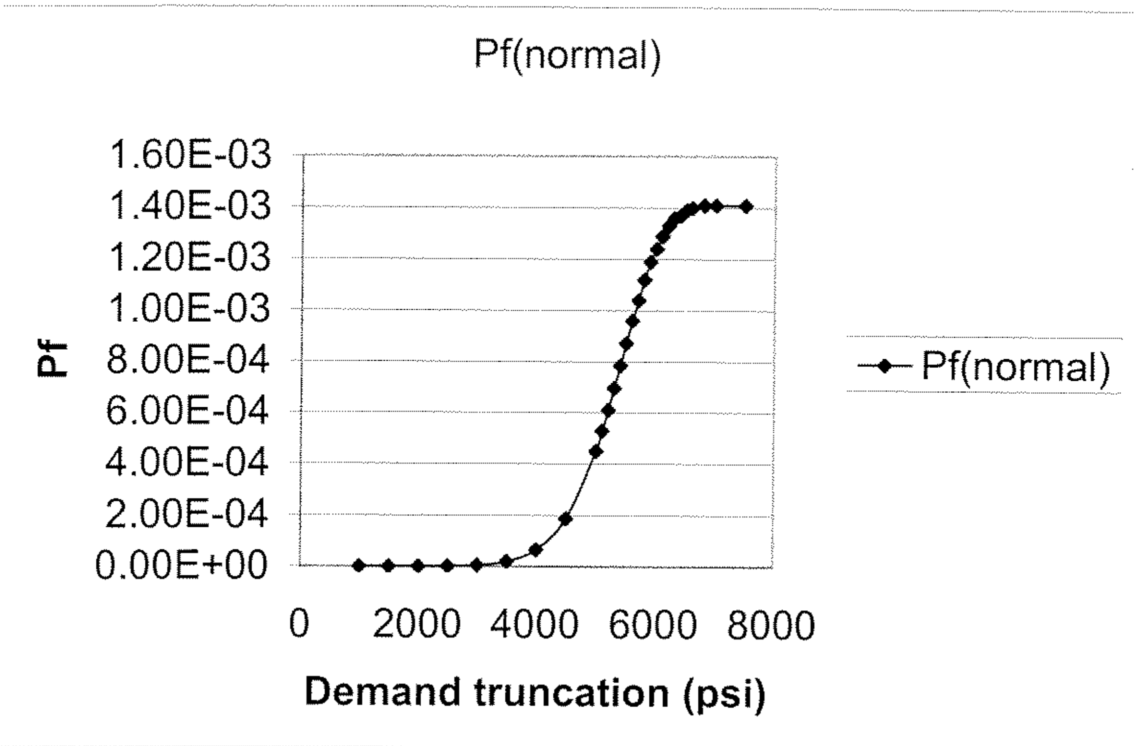


Fig 14: Effect of demand truncation on Pf for a normal distribution

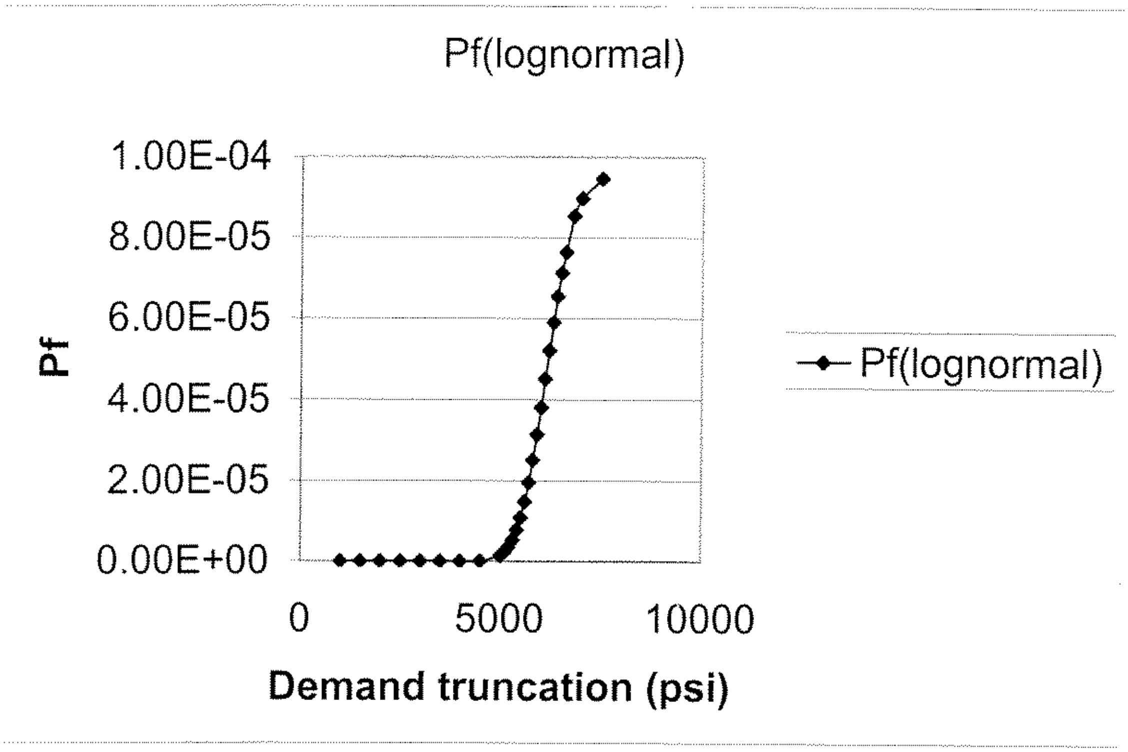


Fig 15: Effect of demand truncation on Pf for a lognormal distribution

5. Effect of the ratio of the diameter to thickness ratio; Do/t:

The effect of Do/t on Pf follows a traditional S curve with or without truncations due to the shift of the distribution (Mean/Median) closer to the demand side for higher Do/t. In fact, truncations on demand and capacities resulted in lower Pf for the same diameter to thickness ratio. This is expected due to reduction of the overlap area. The normal and the lognormal distributions have almost the same shape (the lognormal little steeper). (Fig 16,17)

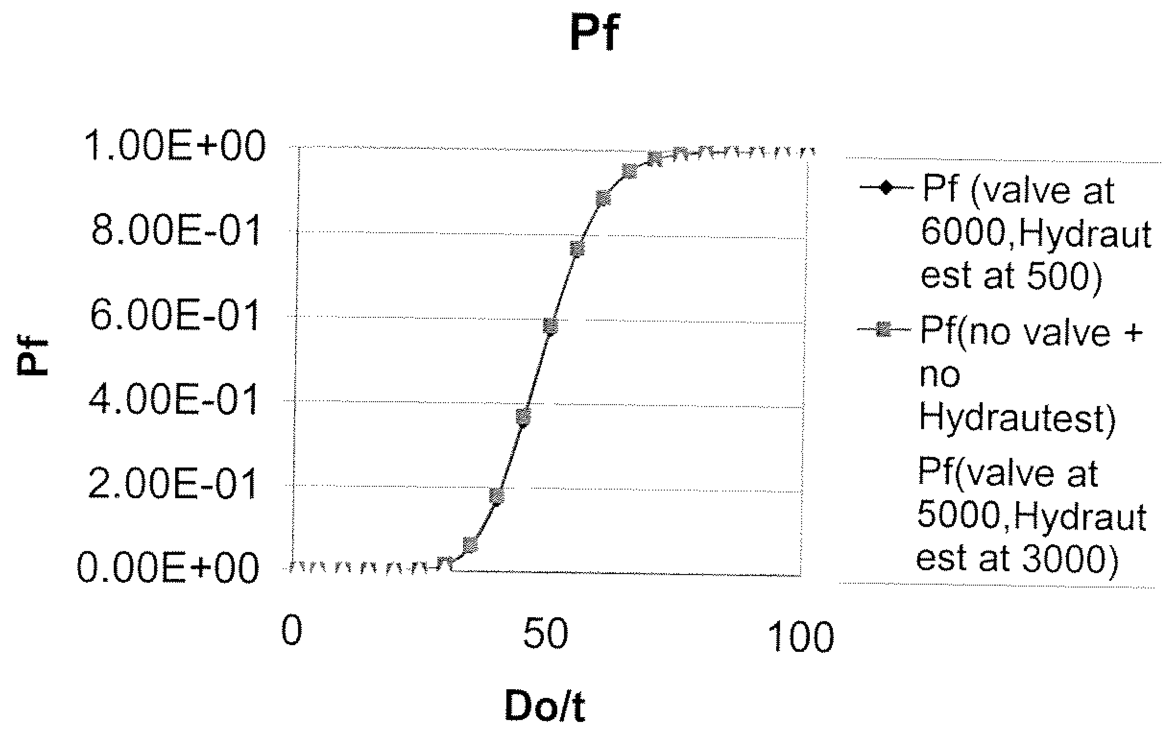


Fig 16: Effect of Do/t on Pf for a Normal distribution

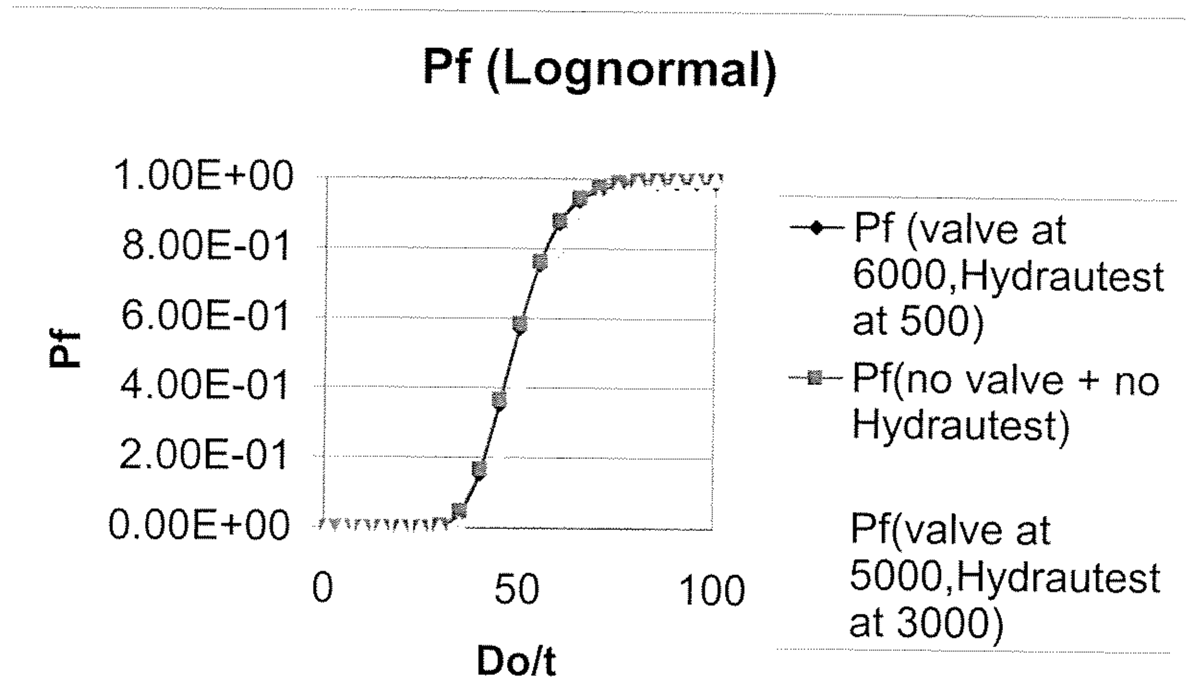


Fig 17: Effect of Do/t on Pf for a lognormal distribution

6. Effect of pressure:

The behavior of the varying pressure on the truncated distributions is really remarkable: For the normal case (Fig 19), the Pf rises very quickly while the mean pressure is moving closer to the mean capacity and the overlap area is increasing (but less values of Pf are recorded for the truncated distribution than that of the non-truncated distribution). At a certain point (around 10,000 psi), the demand curve becomes considerably far from the demand truncation, and the the probability of occurrence Pp of values smaller and equal to the truncation becomes very low despite the high redistribution coefficient K (K=1/F(x)). This causes the curve to reach a plateau first before starting to decrease drastically. The same happens also to the lognormal curve (around 13,000 psi the curve start decreasing).

One might wonder why the Do/t variation did not introduce the same change: The reason is that despite how small Do/t becomes, the mean capacity gets closer to the mean demand (thus the increase in Pf) and is always positive, thus relatively always close to the capacity truncation especially that the specified capacity truncation was low (500 psi), to the demand mean/median. One might argue that this might not be the real behavior in the field in term of that when we increase the mean pressure; the Pf must always increase despite the truncation. The answer is that the observed behavior on our study is based on the assumption of the type of the truncation effect: the truncated area is redistributed to all of the remaining points by a factor K=1/(1-F(Xo)). I suggest that we consider approaching the problem later with a truncation formulation that redistributes the lost area only around the truncation point especially for the demand side. In fact the demand side truncation is normally a pressure relief valve. When the pipeline pressure exceeds the valve pressure, the valve opens allowing the release of the all pressure higher than the valve pressure (within a certain range and variation depending on how sensitive is the valve. This range of uncertainty is mainly due to manufacturing error which normally tends to be relatively small and with a coefficient of variation of around 10%). Every pressure in the distribution exceeding the truncation will take the value of the truncation and thus the redistribution occurs only for pressures within the pressure relief valve error range.

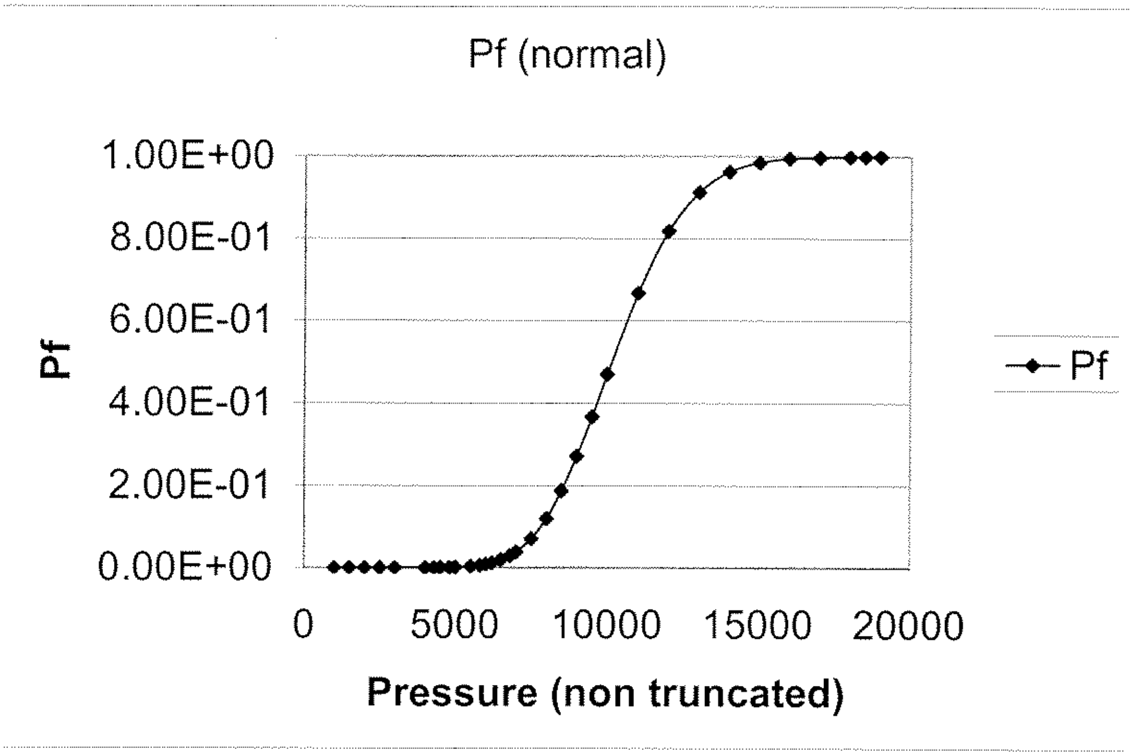


Fig 18: Effect of varying pressure on Pf for a non-truncated normal distribution

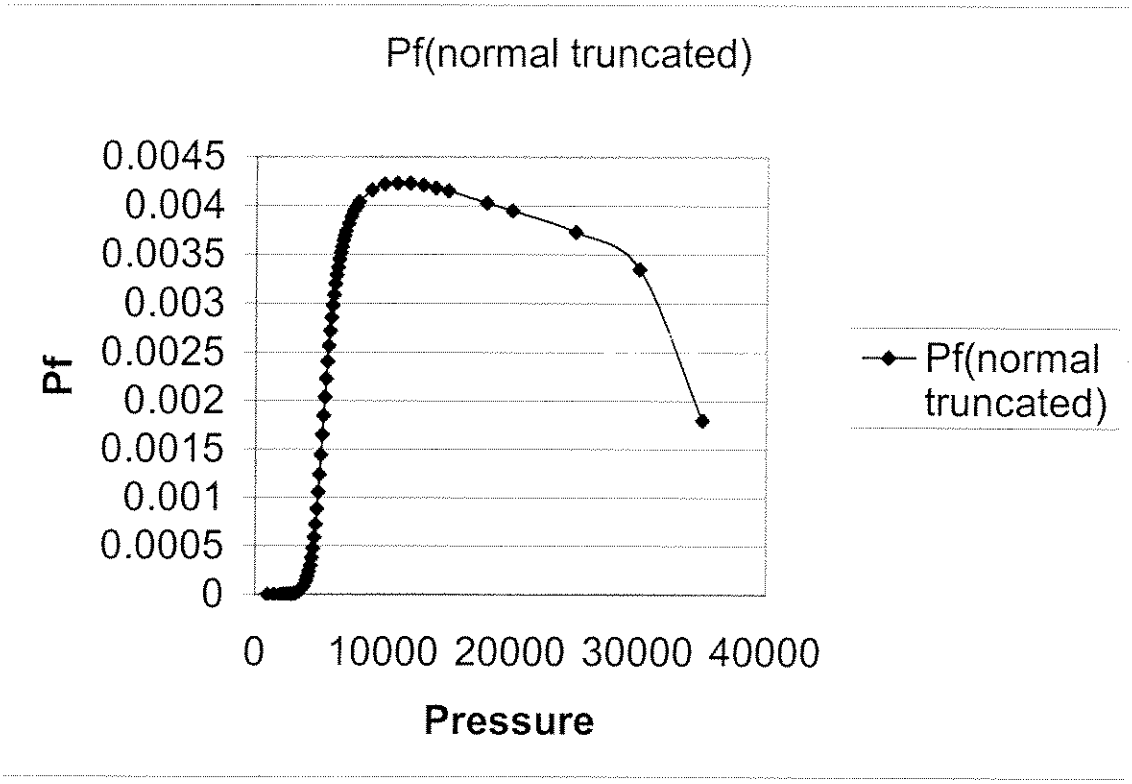


Fig 19: Effect of varying pressure on Pf for a normal truncated distribution

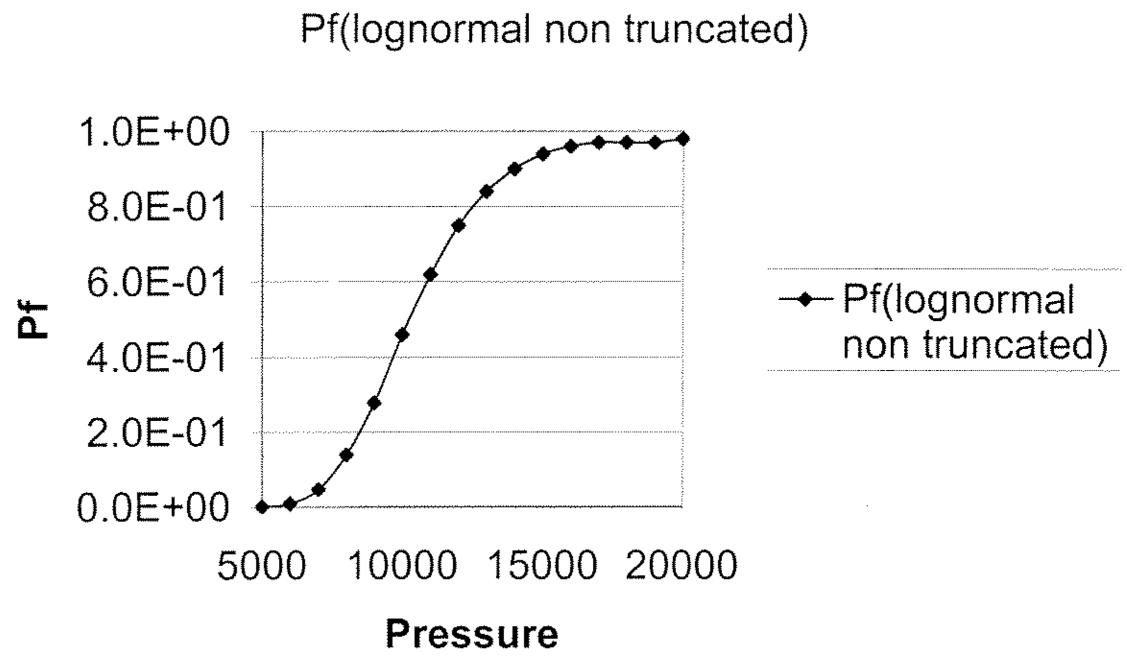


Fig 20: Effect of varying pressure on Pf for a non-truncated lognormal distribution

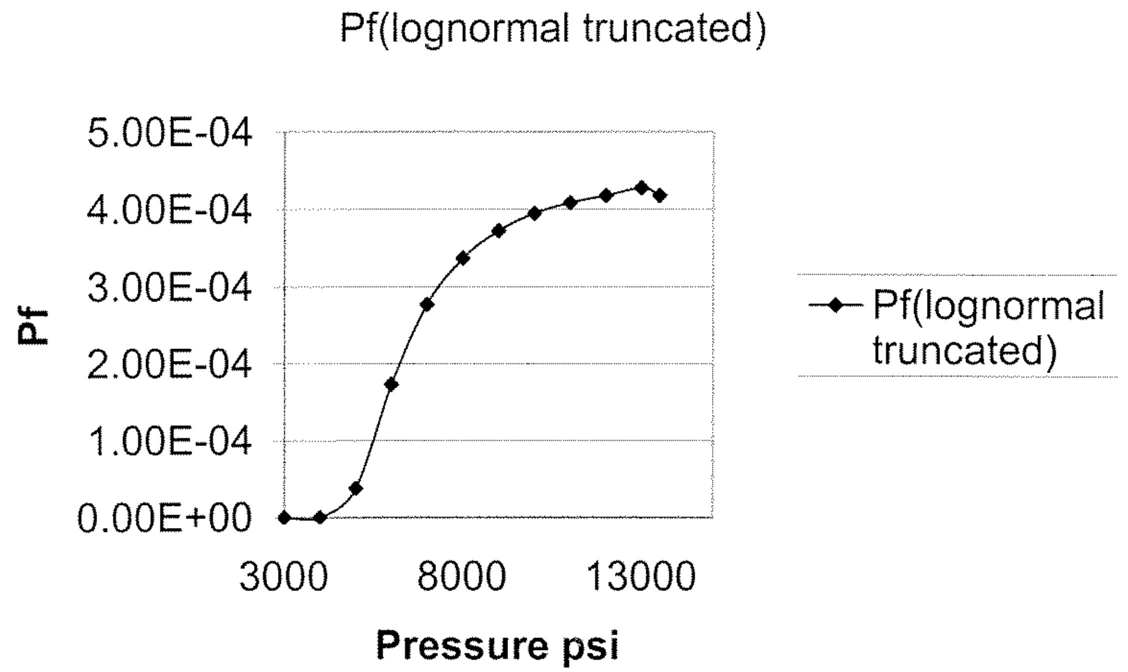


Fig 21: Effect of varying pressure on Pf for a lognormal truncated distribution

7. Remarks on the parametric study:

- There are two factors that that affect the Pf with truncated distribution. The truncation, which reduce the overlap area and limits it thus acting to decrease the Pf, and the redistribution of the truncated area, which tend to increase the Pf. In most, if not all our study, it was the first factor that governed and thus the effect of the truncation is to decrease the Pf.
- The decrease of the Pf due to truncation is remarkable and might reach a factor of 10 for every truncation alone and might result in a 3-degree of magnitudes difference or more for the combined effect of truncations on both demand and capacity. Thus considering the use of relief valves, and well as proper choice of hydrotesting has very important effects in reducing the Pf.
- The specified base truncation value on the capacity (500 psi) revealed to be small and not very effective. The Pf becomes really sensitive for large values around 3,000 psi and greater.
- The specified truncation value on the demand (6000 psi) was very effective on the parametric study.
- The most important effect of the truncation is that it resulted in much lower Pf.
- The choice of the truncation method is reasonable, but after this study I believe that an improvement on the truncation method must occur which will redistribute the truncated area around the truncation value only especially for the demand side.
- The parameters that affected the most the Pf in the truncated distribution were the choice of the truncation values for both demand and capacity, as well as the mean pressure and the variation on the pressure, probably because the truncation on the demand side in our study is more significant in term it was closer to the mean (demand: truncation/mean = 6/5, capacity: truncation/mean = 1/21) (and closer to the mean.

- In this study only type I uncertainties were used as inputs, however when using large values of V for both capacity and demand during the parametric study, this simulates the introduction of the variability part of type II uncertainties.

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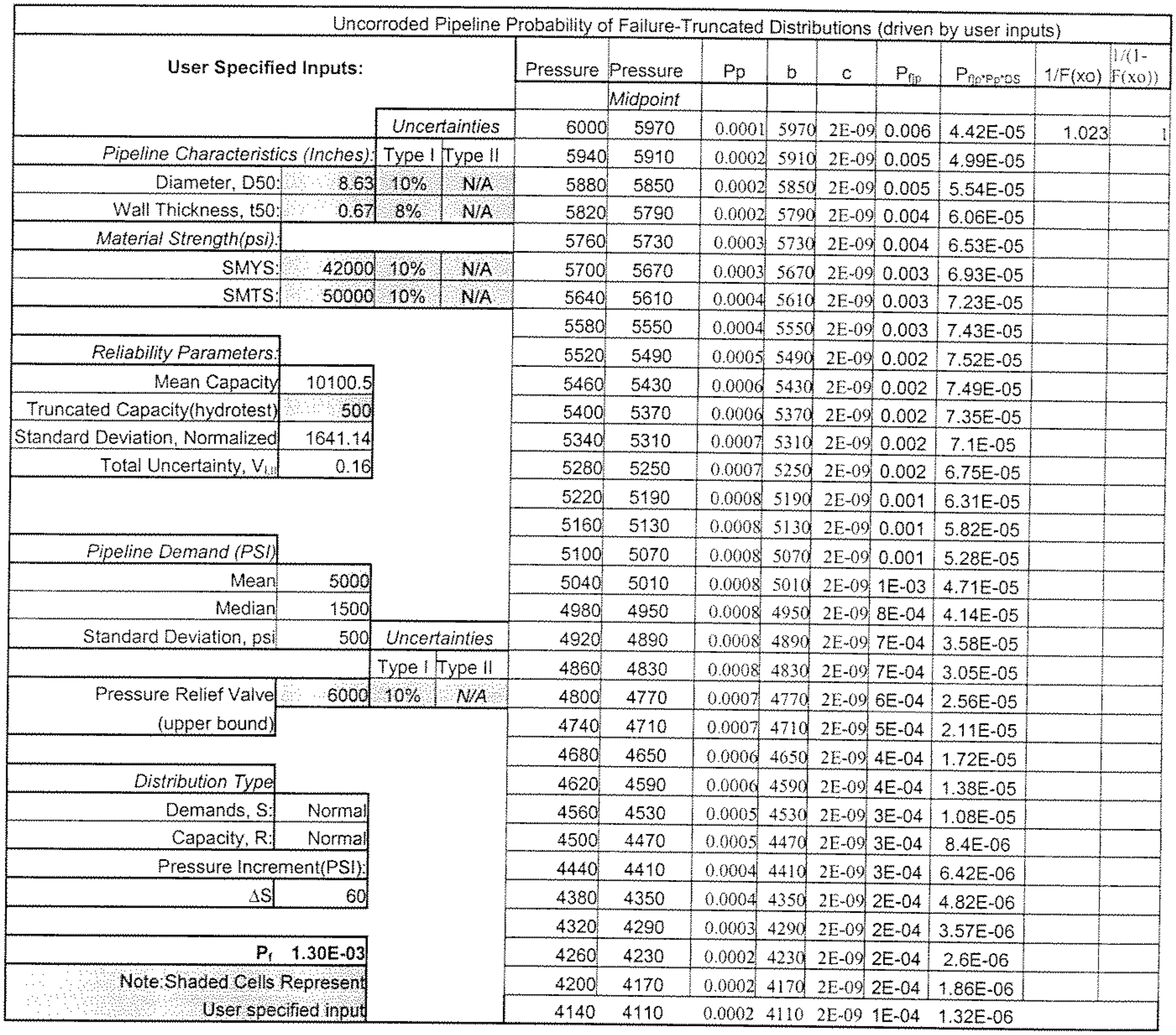
Appendix A

Excel Spreadsheets of the Parametric Study analysis



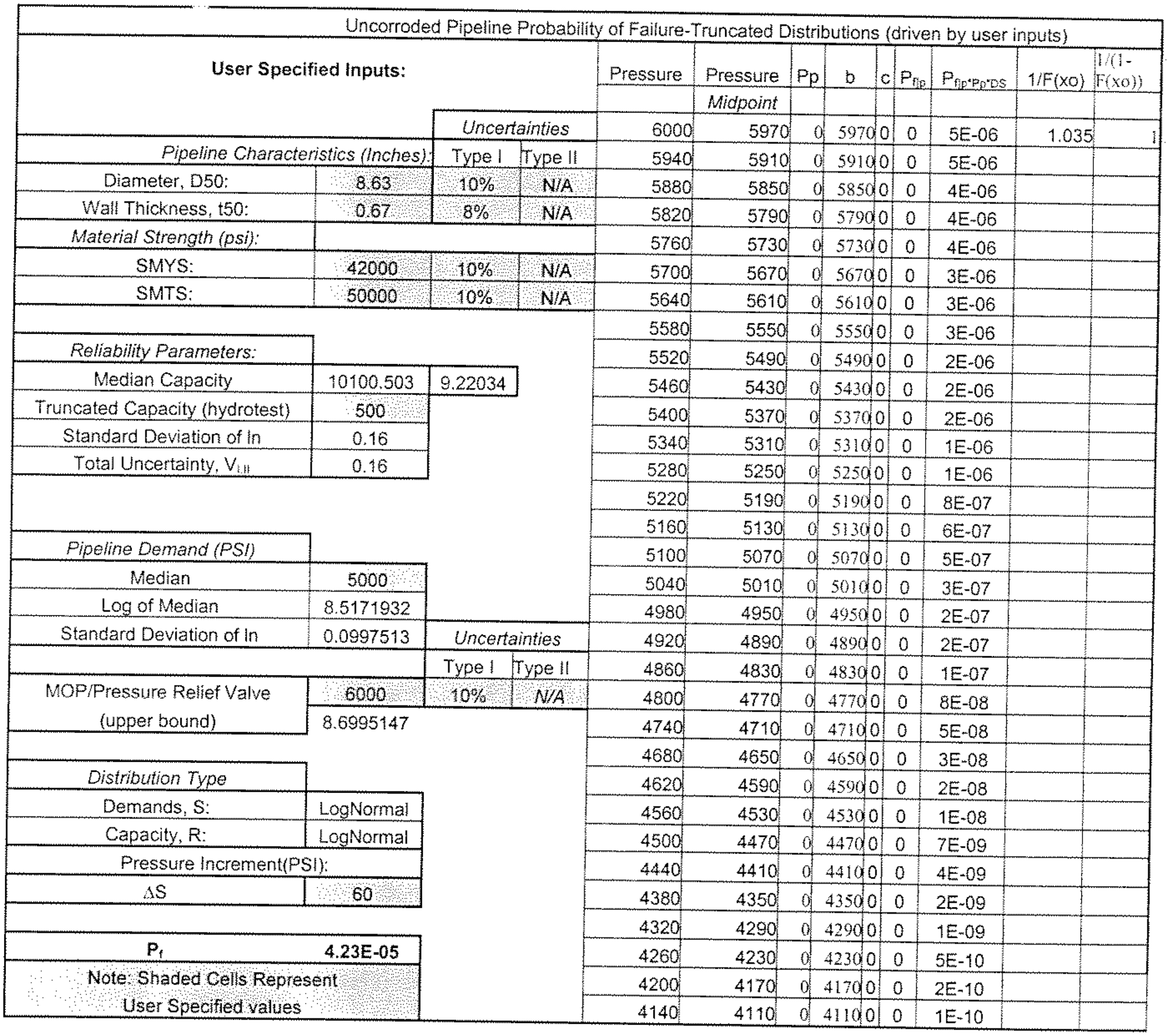
Uncorroded Pipeline Probability of Failure-Truncated Distributions (driven by user inputs)

User Specified Inputs:

		Uncertainties	
Pipeline Characteristics (Inches):		Type I	Type II
Diameter, D50:	8.63	10%	N/A
Wall Thickness, t50:	0.67	8%	N/A
Material Strength(psi):			
SMYS:	42000	10%	N/A
SMTS:	50000	10%	N/A
Reliability Parameters:			
Mean Capacity	10100.5		
Truncated Capacity(hydrotest)	500		
Standard Deviation, Normalized	1641.14		
Total Uncertainty, V_{LU}	0.16		
Pipeline Demand (PSI)			
Mean	5000		
Median	1500		
Standard Deviation, psi	500	*Uncertainties*	
		Type I	Type II
Pressure Relief Valve (upper bound)	6000	10%	*N/A*
Distribution Type			
Demands, S:	Normal		
Capacity, R:	Normal		
Pressure Increment(PSI):			
ΔS	60		
P_f	**1.30E-03**		
Note:Shaded Cells Represent User specified input			

Pressure	Pressure *Midpoint*	Pp	b	c	P_{fip}	$P_{fip*Pp*DS}$	1/F(xo)	1/(1-F(xo))
6000	5970	0.0001	5970	2E-09	0.006	4.42E-05	1.023	1
5940	5910	0.0002	5910	2E-09	0.005	4.99E-05		
5880	5850	0.0002	5850	2E-09	0.005	5.54E-05		
5820	5790	0.0002	5790	2E-09	0.004	6.06E-05		
5760	5730	0.0003	5730	2E-09	0.004	6.53E-05		
5700	5670	0.0003	5670	2E-09	0.003	6.93E-05		
5640	5610	0.0004	5610	2E-09	0.003	7.23E-05		
5580	5550	0.0004	5550	2E-09	0.003	7.43E-05		
5520	5490	0.0005	5490	2E-09	0.002	7.52E-05		
5460	5430	0.0006	5430	2E-09	0.002	7.49E-05		
5400	5370	0.0006	5370	2E-09	0.002	7.35E-05		
5340	5310	0.0007	5310	2E-09	0.002	7.1E-05		
5280	5250	0.0007	5250	2E-09	0.002	6.75E-05		
5220	5190	0.0008	5190	2E-09	0.001	6.31E-05		
5160	5130	0.0008	5130	2E-09	0.001	5.82E-05		
5100	5070	0.0008	5070	2E-09	0.001	5.28E-05		
5040	5010	0.0008	5010	2E-09	1E-03	4.71E-05		
4980	4950	0.0008	4950	2E-09	8E-04	4.14E-05		
4920	4890	0.0008	4890	2E-09	7E-04	3.58E-05		
4860	4830	0.0008	4830	2E-09	7E-04	3.05E-05		
4800	4770	0.0007	4770	2E-09	6E-04	2.56E-05		
4740	4710	0.0007	4710	2E-09	5E-04	2.11E-05		
4680	4650	0.0006	4650	2E-09	4E-04	1.72E-05		
4620	4590	0.0006	4590	2E-09	4E-04	1.38E-05		
4560	4530	0.0005	4530	2E-09	3E-04	1.08E-05		
4500	4470	0.0005	4470	2E-09	3E-04	8.4E-06		
4440	4410	0.0004	4410	2E-09	3E-04	6.42E-06		
4380	4350	0.0004	4350	2E-09	2E-04	4.82E-06		
4320	4290	0.0003	4290	2E-09	2E-04	3.57E-06		
4260	4230	0.0002	4230	2E-09	2E-04	2.6E-06		
4200	4170	0.0002	4170	2E-09	2E-04	1.86E-06		
4140	4110	0.0002	4110	2E-09	1E-04	1.32E-06		

Figure A-1: Excel Spreadsheet to Calculate Probability of Failure of a Pipeline with Normally distributed parameters and with truncations on both demand and capacity.

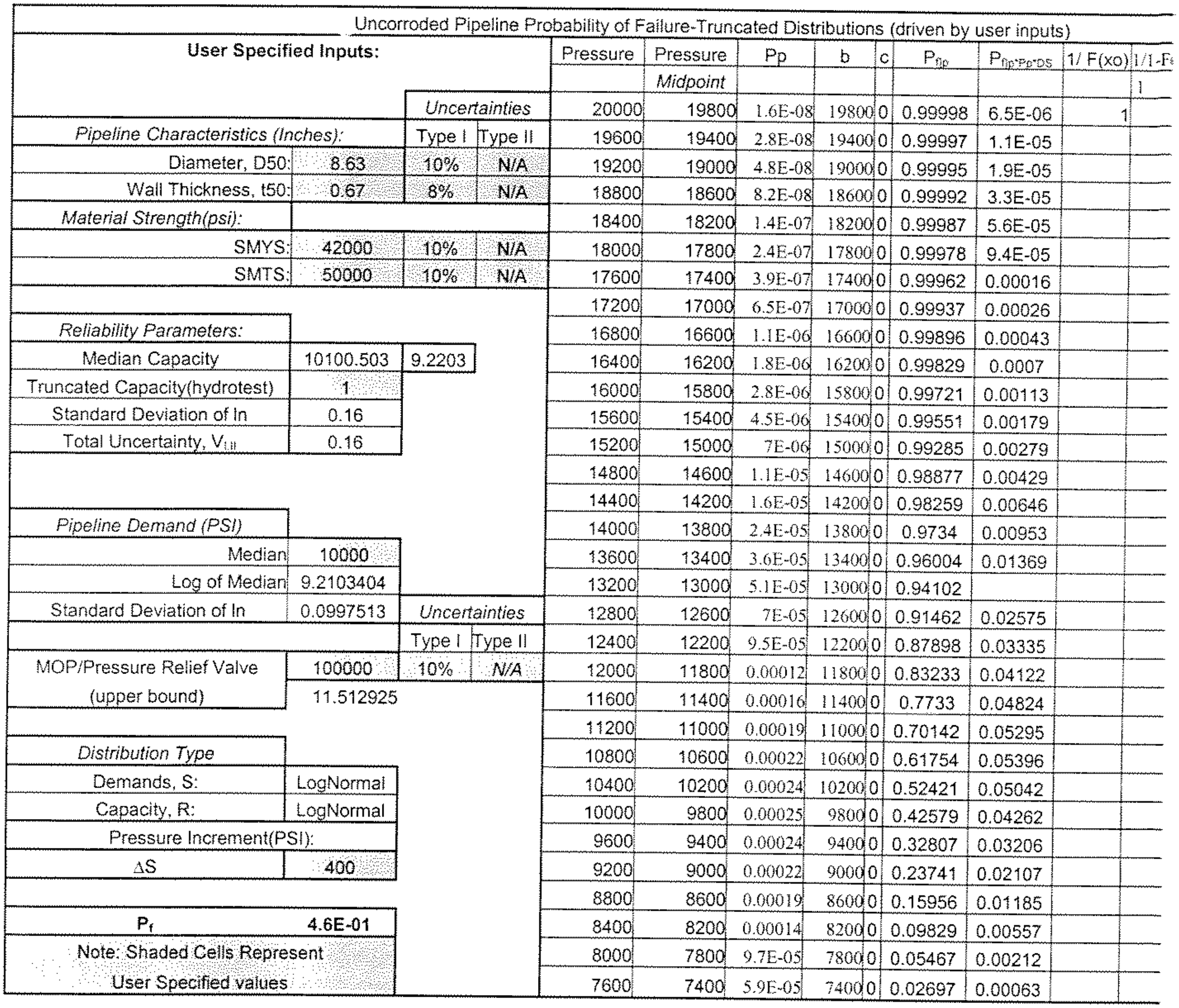


Uncorroded Pipeline Probability of Failure-Truncated Distributions (driven by user inputs)

User Specified Inputs:			
		Uncertainties	
Pipeline Characteristics (Inches):		Type I	Type II
Diameter, D50:	8.63	10%	N/A
Wall Thickness, t50:	0.67	8%	N/A
Material Strength (psi):			
SMYS:	42000	10%	N/A
SMTS:	50000	10%	N/A
Reliability Parameters:			
Median Capacity	10100.503	9.22034	
Truncated Capacity (hydrotest)	500		
Standard Deviation of ln	0.16		
Total Uncertainty, $V_{I,II}$	0.16		
Pipeline Demand (PSI)			
Median	5000		
Log of Median	8.5171932		
Standard Deviation of ln	0.0997513	*Uncertainties*	
		Type I	Type II
MOP/Pressure Relief Valve (upper bound)	6000 8.6995147	10%	*N/A*
Distribution Type			
Demands, S:	LogNormal		
Capacity, R:	LogNormal		
Pressure Increment(PSI):			
ΔS	60		
P_f	**4.23E-05**		
Note: Shaded Cells Represent User Specified values			

Pressure	Pressure *Midpoint*	Pp	b	c	P_{flp}	$P_{flp*Pp*DS}$	1/F(xo)	1/(1-F(xo))
6000	5970	0	5970	0	0	5E-06	1.035	1
5940	5910	0	5910	0	0	5E-06		
5880	5850	0	5850	0	0	4E-06		
5820	5790	0	5790	0	0	4E-06		
5760	5730	0	5730	0	0	4E-06		
5700	5670	0	5670	0	0	3E-06		
5640	5610	0	5610	0	0	3E-06		
5580	5550	0	5550	0	0	3E-06		
5520	5490	0	5490	0	0	2E-06		
5460	5430	0	5430	0	0	2E-06		
5400	5370	0	5370	0	0	2E-06		
5340	5310	0	5310	0	0	1E-06		
5280	5250	0	5250	0	0	1E-06		
5220	5190	0	5190	0	0	8E-07		
5160	5130	0	5130	0	0	6E-07		
5100	5070	0	5070	0	0	5E-07		
5040	5010	0	5010	0	0	3E-07		
4980	4950	0	4950	0	0	2E-07		
4920	4890	0	4890	0	0	2E-07		
4860	4830	0	4830	0	0	1E-07		
4800	4770	0	4770	0	0	8E-08		
4740	4710	0	4710	0	0	5E-08		
4680	4650	0	4650	0	0	3E-08		
4620	4590	0	4590	0	0	2E-08		
4560	4530	0	4530	0	0	1E-08		
4500	4470	0	4470	0	0	7E-09		
4440	4410	0	4410	0	0	4E-09		
4380	4350	0	4350	0	0	2E-09		
4320	4290	0	4290	0	0	1E-09		
4260	4230	0	4230	0	0	5E-10		
4200	4170	0	4170	0	0	2E-10		
4140	4110	0	4110	0	0	1E-10		

Figure A-2: Excel Spreadsheet to Calculate Probability of Failure of a Pipeline with Lognormally distributed parameters and with truncations on both demand and capacity.



Uncorroded Pipeline Probability of Failure-Truncated Distributions (driven by user inputs)

User Specified Inputs:

		Uncertainties	
Pipeline Characteristics (Inches):		Type I	Type II
Diameter, D50:	8.63	10%	N/A
Wall Thickness, t50:	0.67	8%	N/A
Material Strength(psi):			
SMYS:	42000	10%	N/A
SMTS:	50000	10%	N/A

Reliability Parameters:		
Median Capacity	10100.503	9.2203
Truncated Capacity(hydrotest)	1	
Standard Deviation of ln	0.16	
Total Uncertainty, $V_{I,II}$	0.16	

Pipeline Demand (PSI)			
Median	10000		
Log of Median	9.2103404		
Standard Deviation of ln	0.0997513	*Uncertainties*	
		Type I	Type II
MOP/Pressure Relief Valve (upper bound)	100000 11.512925	10%	*N/A*

Distribution Type	
Demands, S:	LogNormal
Capacity, R:	LogNormal
Pressure Increment(PSI):	
ΔS	400

P_f	**4.6E-01**

Note: Shaded Cells Represent User Specified values

Pressure	Pressure *Midpoint*	Pp	b	c	P_{fip}	$P_{fip*Pp*DS}$	1/ F(xo)	1/1-F
								1
20000	19800	1.6E-08	19800	0	0.99998	6.5E-06	1	
19600	19400	2.8E-08	19400	0	0.99997	1.1E-05		
19200	19000	4.8E-08	19000	0	0.99995	1.9E-05		
18800	18600	8.2E-08	18600	0	0.99992	3.3E-05		
18400	18200	1.4E-07	18200	0	0.99987	5.6E-05		
18000	17800	2.4E-07	17800	0	0.99978	9.4E-05		
17600	17400	3.9E-07	17400	0	0.99962	0.00016		
17200	17000	6.5E-07	17000	0	0.99937	0.00026		
16800	16600	1.1E-06	16600	0	0.99896	0.00043		
16400	16200	1.8E-06	16200	0	0.99829	0.0007		
16000	15800	2.8E-06	15800	0	0.99721	0.00113		
15600	15400	4.5E-06	15400	0	0.99551	0.00179		
15200	15000	7E-06	15000	0	0.99285	0.00279		
14800	14600	1.1E-05	14600	0	0.98877	0.00429		
14400	14200	1.6E-05	14200	0	0.98259	0.00646		
14000	13800	2.4E-05	13800	0	0.9734	0.00953		
13600	13400	3.6E-05	13400	0	0.96004	0.01369		
13200	13000	5.1E-05	13000	0	0.94102			
12800	12600	7E-05	12600	0	0.91462	0.02575		
12400	12200	9.5E-05	12200	0	0.87898	0.03335		
12000	11800	0.00012	11800	0	0.83233	0.04122		
11600	11400	0.00016	11400	0	0.7733	0.04824		
11200	11000	0.00019	11000	0	0.70142	0.05295		
10800	10600	0.00022	10600	0	0.61754	0.05396		
10400	10200	0.00024	10200	0	0.52421	0.05042		
10000	9800	0.00025	9800	0	0.42579	0.04262		
9600	9400	0.00024	9400	0	0.32807	0.03206		
9200	9000	0.00022	9000	0	0.23741	0.02107		
8800	8600	0.00019	8600	0	0.15956	0.01185		
8400	8200	0.00014	8200	0	0.09829	0.00557		
8000	7800	9.7E-05	7800	0	0.05467	0.00212		
7600	7400	5.9E-05	7400	0	0.02697	0.00063		

Figure A-3: Excel Spreadsheet to Calculate Probability of Failure of a Pipeline with Lognormally distributed parameters and with NO truncations on both demand and capacity.

Demand truncation	Pf(normal)	Pf(lognormal)
1000	8.87E-09	0.00E+00
1500	6.09E-08	0.00E+00
2000	3.06E-07	0.00E+00
2500	1.37E-06	0.00E+00
3000	5.52E-06	1.14E-14
3500	2.01E-05	1.02E-11
4000	6.54E-05	1.70E-09
4500	1.87E-04	8.13E-08
5000	4.50E-04	1.44E-06
5100	5.29E-04	2.31E-06
5200	6.10E-04	3.57E-06
5300	6.95E-04	5.35E-06
5400	7.84E-04	7.76E-06
5500	8.73E-04	1.09E-05
5600	9.60E-04	1.48E-05
5700	1.04E-03	1.96E-05
5800	1.12E-03	2.51E-05
5900	1.19E-03	3.14E-05
6000	1.24E-03	3.81E-05
6100	1.29E-03	4.51E-05
6200	1.33E-03	5.21E-05
6300	1.36E-03	5.90E-05
6400	1.37E-03	6.54E-05
6500	1.39E-03	7.13E-05
6600	1.40E-03	7.64E-05
6800	1.41E-03	8.54E-05
7000	1.41E-03	8.98E-05
7500	1.41E-03	9.47E-05

Table A-1: Data used for the calculation of the effect of demand truncation on Pf for Normal and Lognormal distributions. (Fig 14, 15)

Hydrotest	Pf(normal)	Pf(lognormal)
100	1.24E-03	3.80E-05
1000	1.24E-03	3.80E-05
2000	1.24E-03	3.80E-05
3000	1.24E-03	3.80E-05
3200	1.23E-03	3.80E-05
3400	1.22E-03	3.80E-05
3600	1.21E-03	3.80E-05
3800	1.19E-03	3.80E-05
4000	1.15E-03	3.80E-05
4100	1.12E-03	3.80E-05
4200	1.09E-03	3.80E-05
4300	1.06E-03	3.80E-05
4400	1.01E-03	3.80E-05
4500	9.57E-04	3.80E-05
4600	8.95E-04	3.77E-05
4700	8.25E-04	3.73E-05
4800	7.47E-04	3.68E-05
4900	6.62E-04	3.59E-05
5000	5.73E-04	3.45E-05
5100	4.82E-04	3.26E-05
5200	3.92E-04	3.00E-05
5300	3.06E-04	2.67E-05
5400	2.27E-04	2.28E-05
5500	1.57E-04	1.82E-05
5600	1.00E-04	1.34E-05
5700	5.57E-05	8.58E-06
5800	2.39E-05	4.26E-06
5900	5.70E-06	1.16E-06
6000	0.00E+00	0.00E+00

Table A-2: Data used for the calculation of the effect of capacity truncation on Pf for Normal and Lognormal distributions. (Fig 1, 2, 3)

Variation on capacity V%	Pf (Hydrotest at 500)	Pf (Hydrotest at 1000)	Pf (Hydrotest at 3000)
1	0.00E+00	0.00E+00	0.00E+00
5	8.28E-19	8.28E-19	8.28E-19
10	1.26E-06	1.26E-06	1.26E-06
15	5.61E-04	5.61E-04	5.59E-04
20	6.46E-03	6.46E-03	6.25E-03
25	2.24E-02	2.23E-02	2.01E-02
30	4.58E-02	4.52E-02	3.74E-02
35	7.13E-02	6.97E-02	5.34E-02
40	9.48E-02	9.17E-02	6.62E-02
45	1.15E-01	1.10E-01	7.55E-02
50	1.30E-01	1.24E-01	8.20E-02
60	1.50E-01	1.41E-01	8.89E-02
70	1.60E-01	1.50E-01	9.08E-02
80	1.65E-01	1.52E-01	9.00E-02
90	1.64E-01	1.51E-01	8.79E-02
100	1.62E-01	1.49E-01	8.51E-02
150	1.41E-01	1.28E-01	7.01E-02
200	1.20E-01	1.09E-01	5.81E-02
300	9.11E-02	8.19E-02	4.27E-02
400	7.28E-02	6.52E-02	3.36E-02
500	6.05E-02	5.41E-02	2.77E-02
1000	3.26E-02	2.91E-02	1.47E-02

Table A-3: Data used for the calculation of the effect of capacity variation on Pf for a Normal distribution. (Fig 4, 7)

Variation on capacity V%	Pf (Hydrotest at 500)	Pf (Hydrotest at 1000)	Pf (Hydrotest at 3000)
1	0.00E+00	0.00E+00	0.00E+00
5	0.00E+00	0.00E+00	0.00E+00
10	1.31E-09	1.34E-09	1.34E-09
15	1.17E-05	1.17E-05	1.17E-03
20	4.54E-04	4.54E-04	4.54E-04
25	3.11E-03	3.11E-03	3.11E-03
30	9.88E-03	9.80E-03	9.88E-03
35	2.10E-02	2.10E-02	2.08E-02
40	3.50E-02	3.53E-02	3.46E-02
45	5.15E-02	5.15E-02	4.94E-02
50	6.84E-02	6.84E-02	6.38E-02
60	1.01E-01	1.01E-01	8.86E-02
70	1.31E-01	1.30E-01	1.07E-01
80	1.56E-01	1.55E-01	1.20E-01
90	1.77E-01	1.76E-01	1.28E-01
100	1.95E-01	1.93E-01	1.30E-01
150	2.52E-01	2.42E-01	1.34E-01
200	2.78E-01	2.60E-01	1.43E-01
300	3.00E-01	2.71E-01	1.42E-01
400	3.08E-01	2.72E-01	1.36E-01
500	3.11E-01	2.72E-01	1.28E-01
1000	3.12E-01	2.65E-01	1.18E-01

Table A-4: Data used for the calculation of the effect of capacity variation on Pf for a lognormal distribution. (Fig 5, 8)

Variation on capacity V%	Pf (Normal)	Pf (Lognormal)
1	0	7.12E-13
5	0	1.14E-10
10	1.26E-06	2.65E-07
15	5.61E-04	4.03E-05
20	6.46E-03	7.10E-04
25	2.24E-02	3.87E-03
30	4.65E-02	1.12E-02
35	7.43E-02	2.29E-02
40	1.03E-01	3.77E-02
45	1.30E-01	5.43E-02
50	1.55E-01	7.14E-02
60	1.98E-01	1.05E-01
70	2.34E-01	1.34E-01
80	2.62E-01	1.60E-01
90	2.86E-01	1.81E-01
100	3.05E-01	1.99E-01
150	3.67E-01	2.58E-01
200	3.99E-01	2.89E-01
300	4.33E-01	3.21E-01
400	4.49E-01	3.37E-01
500	4.59E-01	3.48E-01
1000	4.66E-01	3.71E-01

Table A-5: Data used for the calculation of the effect of capacity variation on Pf for NON-truncated normal and lognormal distributions. (Fig 6, 9)

Pressure (psi)	Pf (lognormal non truncated)	Pf (normal non truncated)
1000	0.0E+00	1.29E-08
2000	0.0E+00	4.65E-07
3000	3.4E-08	1.00E-05
4000	2.2E-05	1.46E-04
5000	9.1E-04	1.41E-03
6000	9.6E-03	9.07E-03
7000	4.7E-02	3.95E-02
8000	1.4E-01	1.21E-01
9000	2.8E-01	2.71E-01
10000	4.6E-01	4.70E-01
11000	6.2E-01	6.67E-01
12000	7.5E-01	8.19E-01
13000	8.4E-01	9.13E-01
14000	9.0E-01	9.63E-01
15000	9.4E-01	9.85E-01
16000	9.6E-01	9.95E-01
17000	9.7E-01	9.98E-01
18000	9.7E-01	9.99E-01
19000	9.7E-01	1.00E+00
20000	9.8E-01	1.00E+00

Table A-6: Data used for the calculation of the effect of pressure on Pf for NON-truncated normal and lognormal distributions. (Fig 18, 20)

Pressure	Pf (lognormal truncated)	Pf (normal truncated)
1000	0.00E+00	1.29E-08
2000	0.00E+00	4.65E-07
3000	0.00E+00	1.00E-05
4000	4.44E-07	1.46E-04
5000	3.81E-05	1.24E-03
6000	1.73E-04	2.98E-03
7000	2.77E-04	3.74E-03
8000	3.37E-04	4.04E-03
9000	3.73E-04	4.16E-03
10000	3.95E-04	4.22E-03
11000	4.09E-04	4.23E-03
12000	4.18E-04	4.23E-03
13000	4.28E-04	4.21E-03
14000	N/A	4.18E-03
15000	N/A	4.15E-03
18000	N/A	4.03E-03
20000	N/A	3.95E-03
25000	N/A	3.73E-03
30000	N/A	3.35E-03
35000	N/A	1.80E-03

Table A-7: Data used for the calculation of the effect of pressure on Pf for truncated normal and lognormal distributions. (Fig 19, 21)

Pressure variation %	Pf (normal)	Pf Lognormal
1	9.05E-04	6.08E-06
5	1.01E-03	1.40E-05
10	1.24E-03	3.81E-05
15	1.28E-03	4.62E-05
20	1.20E-03	4.58E-05
25	1.11E-03	4.31E-05
30	1.01E-03	4.00E-05
40	8.59E-04	3.45E-05
50	7.40E-04	3.02E-05
60	6.49E-04	2.70E-05
70	5.76E-04	2.45E-05
80	5.18E-04	2.25E-05
90	4.70E-04	2.09E-05
100	4.31E-04	1.96E-05
200	2.33E-04	1.37E-05
300	1.59E-04	1.17E-05
400	1.21E-04	1.06E-05
500	9.76E-05	9.90E-06

Table A-8: Data used for the calculation of the effect of pressure variation on Pf for truncated normal and lognormal distributions. (Fig 10, 11, 12, 13)

Do/t	Pf (valve at 6000,Hydrotest at 500)	Pf(no valve + no Hydrotest)	Pf(valve at 5000,Hydrotest at 3000)
1	4.30E-10	8.44E-10	1.79E-10
5	1.77E-08	1.88E-08	9.49E-09
10	6.30E-07	6.70E-07	3.14E-07
15	1.47E-05	1.63E-05	6.23E-06
20	2.24E-04	2.53E-04	8.39E-05
25	2.20E-03	2.49E-03	7.88E-04
30	1.40E-02	1.56E-02	5.21E-03
35	5.92E-02	6.42E-02	2.46E-02
40	1.72E-01	1.81E-01	8.35E-02
45	3.59E-01	3.70E-01	2.10E-01
50	5.77E-01	5.85E-01	4.02E-01
55	7.63E-01	7.68E-01	6.14E-01
60	8.86E-01	8.89E-01	7.88E-01
65	9.52E-01	9.53E-01	8.98E-01
70	9.82E-01	9.82E-01	9.55E-01
75	9.94E-01	9.94E-01	9.81E-01
80	1.00E+00	9.98E-01	9.92E-01
85	1.00E+00	9.99E-01	9.96E-01
90	1.00E+00	1.00E+00	9.98E-01
95	1.00E+00	1.00E+00	9.99E-01
100	1.00E+00	1.00E+00	1.00E+00

Table A-9: Data used for the calculation of the effect of capacity on Pf for a normal distribution with different truncation values on both capacity and demand. (Fig 16)

Do/t	Pf (valve at 6000,Hydrotest at 500)	Pf(no valve + no Hydrotest)	Pf(valve at 5000,Hydrotest at 3000)
1	0.00E+00	0.00E+00	0.00E+00
5	0.00E+00	0.00E+00	0.00E+00
10	0.00E+00	6.88E-17	0.00E+00
15	1.92E-11	4.41E-10	4.79E-14
20	4.22E-07	1.98E-06	6.13E-09
25	1.36E-04	2.93E-04	6.97E-06
30	4.53E-03	6.63E-03	5.83E-04
35	3.98E-02	4.80E-02	1.00E-02
40	1.53E-01	1.68E-01	6.29E-02
45	3.51E-01	3.67E-01	2.02E-01
50	5.72E-01	5.85E-01	4.12E-01
55	7.54E-01	7.63E-01	6.27E-01
60	8.72E-01	8.80E-01	7.91E-01
65	9.37E-01	9.45E-01	8.91E-01
70	9.65E-01	9.77E-01	9.46E-01
75	9.82E-01	9.91E-01	9.73E-01
80	9.87E-01	9.96E-01	9.86E-01
85	9.89E-01	9.99E-01	9.93E-01
90	9.90E-01	1.00E+00	9.96E-01
95	9.90E-01	1.00E+00	9.98E-01
100	9.90E-01	1.00E+00	9.99E-01

Table A-10: Data used for the calculation of the effect of capacity on Pf for a Lognormal distribution with different truncation values on both capacity and demand. (Fig 17)