A Mechanistic Analysis Based Decision Support System for Scheduling Optimal Pipeline Replacement

By

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Failure of pipes in water distribution systems is a common occurrence especially in large cities. The failure of a pipe results in: loss of water; property damage; interruption of service; decreased system performance; and the financial cost of restoring the failed pipe. The cost of replacement and rehabilitation in the United States is estimated at 23 plus billion dollars. It is virtually impossible to replace all vulnerable pipes at the same time. As a result, there is a need for methods that can help in progressive system rehabilitation and replacement subject to budgetary constraints. If delaying is considered a good strategy due to the time value of money then, the timing of preventive maintenance becomes a crucial element for system maintenance and operation. The central underpinning element in the decision process for scheduling preventive maintenance is the deteriorating nature of a pipe under a given surrounding. By planning to replace pipes before they fail, proper planning can be put in place for securing of finances and labor force needed to rehabilitate the pipes. With this approach, service interruptions are minimized as the loss of service time is limited to the time used in replacing the pipe.

In this research, a mechanistic model for assessing the stage of deterioration of an underground pipe is developed. The developed model consists of three sub-models namely, the Pipe Load Model (PLM), the Pipe Deterioration Model (PDM), and the Pipe Break Model (PBM). The PLM simulates the loads and stresses exerted on a buried water main. These loads include the earth load, traffic load, internal pressure, expansive soil loads, thermal, and frost loads. The PDM simulates the deterioration of the pipe due to corrosion resulting from the physical characteristics of the pipe environment. The pipe deterioration effect is modeled in two stages. First, the thinning of the pipe wall is modeled using a corrosion model. Second, the localized pit growth is used to determine the residual strength of the pipe based on the fracture toughness and the initial design strength of the pipe.

The PBM assesses the vulnerability of a pipe at any time in terms of a critical safety factor. The safety factor is defined as the ratio of residual strength to applied stress. For a conservative estimate the multiplier effect due to thermal and frost loads are considered. For a chosen analysis period, say 50 years, the pipes with safety factors less than the critical safety factor are selected and ordered by their
rank. Aided by the prioritized list of failure prone pipes, utilities can organize a replacement schedule that minimizes cost over time.

Additionally a physically based regression model for determining the optimal replacement time of pipe is also presented. A methodology for assessing the consequences of accelerated and delayed replacement is also provided. The methodologies developed in this dissertation will enable utilities to formulate future budgetary needs compatible with the intended level of service. An application of the model and results are included in the dissertation.
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Chapter 1 - Introduction

1.1 Scope of the problem

Failure of pipes in water distribution systems (WDS) is a common occurrence especially in large cities. Pipe breakage results in: loss of water; property damage; interruption of service; decreased system performance; and the financial cost of restoring the failed pipe. The importance of water distribution systems cannot be over emphasized. These systems are designed to provide reliable source of contaminant-free water for domestic, industrial, and commercial purposes. The condition of a pipe in a water distribution system deteriorates over time. Presently many large cities such as Houston, Washington (D.C.), New York, and Philadelphia which have water distribution systems installed as far back as 1870 are experiencing frequent pipe failures which tend to be costly and pose a threat to the safety of the water (Habibian, 1994; Male et. al., 1990; and Walski and Pellicia, 1982 ).

Pipe failure is a situation that a water distribution system operator must be prepared for both in terms of the labor force and the financial resources needed to restore the pipe. Water utilities have a number of options in developing a policy for replacing or restoring of pipes. For any given pipe, at a given time, there are three possible alternatives, namely, do nothing, rehabilitate, or replace.

In the first option, pipes are allowed to fail and are then replaced. This option leads to inefficiency in terms of water quality issues related to old pipes such as degraded water quality; compensation for damaged property; and unanticipated disruptions in the service provided to customers. Pipe breaks in some cases may lead to property damage, the cost of which may have to be borne by the utility company. Proactive replacement of pipes overcomes these problems. Proper planning can be put in place for securing the finances and labor force needed to rehabilitate pipes before they fail. With this approach, service interruptions are minimized as the loss of service time is limited to the times used in replacing the pipe. In the case where pipes fail before they are replaced, loss of service includes the duration from pipe failure time to the time the failure is reported; time taken to locate the failed pipe; and time taken to repair the pipe. Water utilities have found from experience that “do nothing until a system component fails” is
not the best decision due to costly repairs, customer dissatisfaction and potential environmental problems. When pipes are replaced ahead of time, the number of unanticipated breaks or failures is minimized.

There is a need for methods that can help in progressive system rehabilitation and replacement subject to budgetary constraints. For example, many municipalities coordinate aged pipe replacement with the resurfacing of pavement schedule. If “delaying” is considered a good strategy due to the time value of money, the “timing” of preventive maintenance becomes a crucial element for system maintenance and operation.

Any decision to replace or rehabilitate must include a consideration of the impact of a particular pipe on the system as a whole. The central underpinning element in the decision process is the deteriorating nature of a pipe under the given surrounding. Although on-site inspection of a pipe is the best procedure to analyze its condition, this approach is extremely expensive and may be destructive because it requires the digging up of a pipe and the possible removal of a coating that might have been in good condition.

1.2 Why Do Pipes Fail?

Buried water mains are designed to withstand certain design loads. Generally, these loads include earth load, truck/live load, working pressure, and water hammer pressure. The pipe material and wall thickness are chosen to withstand these loads. Pipes located in regions prone to freezing temperatures sometimes experience an additional load (frost load) caused by frost heaving of surrounding soil. Similarly, wide and rapid temperature variations in the soil-pipe-water environment lead to additional thermal stresses on the pipe. Leakage in pipes and bad construction practices around the pipe lead to pipe bed disruption and thereby making it prone to breakage due to beam action.

In addition to the increased loads on the pipe, the pipe’s structural integrity is jeopardized temporally by corrosion at a rate dependent on the pipe material type; characteristics of the surrounding soil; and the hydraulic and chemical properties of the water flowing in the pipe. Corrosive soils accelerate the development of corrosion pits on the pipe outside surface. Corrosive water accelerates the graphitization and the eventual reduction in pipe wall thickness from the inside of the pipe. The quality of water also dictates the growth of tuberculation within the pipe and tends to reduce the effective diameter of the pipe as well as increase the pipe
roughness. The changing of these two hydraulic properties of the pipe leads to increased head loss in the pipe. To compensate for the increased head loss, the use of a pump may be needed. This increase in pressure can induce additional stresses.

It is a generally accepted notion that small diameter mains (150-200 mm [6-8 in.]) are susceptible to circumferential breaks whereas larger diameter pipes (≥ 250mm [≥ 10 in.]) are prone to longitudinal breaks (O’Day, 1982). Longitudinal breaks are attributed to ring failure or crushing whereas circular breaks are considered to be caused by beam failure (O’Day, 1982).

1.3 Costs and Consequences of Pipe Failure

According to Deb et. al (1995), 20 to 40 percent of processed water is unaccounted for in many large cities. Millette and Mavinic (1988) report that in 1983, the city of Toronto budgeted 5 million dollars for corrosion related water distribution system repair. The city of Winnipeg spent 7.7 million dollars. The United States annual corrosion costs for water supply topped 700 million dollars in 1979, without the consideration of costs incurred for the repair of private water systems (Millette and Mavinic, 1988).

When pipes fail, the consequences may include but are not limited to: service disruption, consumer dissatisfaction, property damage, and inefficient use of funds. Some of these consequences tend to be either interrelated or compliment each other leading to more expensive scenarios. For example, loss of water service to commercial sites that depend largely on water for servicing their customers would lead to business loss. In some cases, undetected failed water mains may create sinkholes by washing away the bedding underneath roads there by posing a hazard to both vehicular and pedestrian traffic. Flooding is also a likely consequence. Depending on the size and capacity of the failed pipe, the damage caused by flooding can be substantial.

1.4 Objectives

The primary objective of this research is to develop a methodology to identify failure prone pipes in a water distribution system for prioritized replacements. The specific objectives are as follows:

1. Develop models to quantify loads that are borne by a pipe.
2. Develop a corrosion model that will predict remaining wall thickness of a pipe at a given time.
3. Develop stress concentration model that accounts for increased stress surrounding a corrosion pit which accelerates pipe breakage.
4. Develop a safety factor model that accounts for the stresses and residual strength as the result of remaining wall thickness. Prioritize pipes for replacement that have a safety factor value near unity.
5. Derive the optimal replacement time for a pipe by linking the corrosion behavior to the most economic break rate for replacement.
6. Assess the penalty cost for accelerated/delayed replacement from the optimal replacement schedule.
7. Develop an interactive software that will facilitate data extraction, manipulation, analysis and, reporting of results for large databases maintained by water utilities.

1.5 Organization of dissertation

This dissertation is organized as follows. Chapter 1 gives an introduction of water distribution systems, the failure mechanisms, and the objectives of the research. Chapter 2 reviews literature relevant to water distribution system deterioration modeling and rehabilitation. Chapter 3 provides an overview of the proposed methodology. Data requirements and issues related to data acquisition and management are also discussed in chapter 3. Chapter 4 describes the formulation of the pipe deterioration model and the statistical correlation model; these models determine the deterioration of pipe through corrosion and the subsequent effect on the reduction of the pipe strength. In chapter 5, the pipe load models are formulated. Specific loads on the buried pipe and the determination of these loads and their imposed stresses on the pipe are considered. The residual strength of a main evaluated from the pipe deterioration model together with the stresses obtained from the pipe load model determine the time of failure for a particular pipe. Chapter 6 describes the application of the model to a test case water utility. The effect of the critical factors in the model in the form of sensitivity analysis is discussed. Chapter 7 contains an application of the model to data from a second water utility. In chapter 8, an economic criterion is included for optimal replacement time. The economically sustainable
replacement cost is compared with the pipe failure rate in terms of number of breaks per year. If the break rate exceeds economically sustainable rate, the pipe should be replaced. A methodology for estimating the penalties for replacing pipes at times other than the optimum time is presented in chapter 9. Finally, chapter 10 contains a summary of the content and results of the research; conclusions and limitations of the methodology developed in the research; and suggestions for future research. The Appendix presents the details for running the software.
Chapter 2 - Literature Review

2.1 Pipe Renewal and Prioritization Methodologies

A review of the literature identified several basic approaches for prioritizing pipes for replacement or rehabilitation within a distribution system. These may be grouped into the following four categories:

- Deterioration point assignment methods
- Break-even analyses
- Failure probability and regression methods
- Mechanistic models

2.1.1 Deterioration Point Assignment Method

In the deterioration point assignment (DPA) method, a set of factors associated with pipe failures is identified. These factors may include age of pipe, pipe material, pipe size, type of soil, location, water pressure, discoloration, and number of previous breaks. The numerical values for these factors are grouped into several class intervals. For each class interval a failure score is assigned. For any pipe a total failure score is obtained by summing the class interval failure scores for that pipe. If the total failure score exceeds a threshold value then the pipe is considered a candidate for replacement or rehabilitation. This approach cannot discriminate between competing pipes when funding is limited. That is, pipes receiving the same score cannot be further prioritized. Also, this assessment lacks the predictive power that is crucial for future course of actions.

An example of this type of system was described in Deb et al. (1995). The Louisville Water Company’s (LWC) Pipe Evaluation Model (PEM) includes a detailed scoring system that assigns points based upon 23 parameters. The 23 parameters encompass four broad categories, namely geographical, service quality, hydraulic and maintenance.
2.1.2 Break-Even Analysis

The break-even analysis is a cost based method and considers repair costs and replacement cost simultaneously. This method must be augmented with a predictive technique for pipe breaks. The predicted break occurrence times are utilized along with the replacement cost. The present value cost of replacing the pipe decreases over time. The present value of cumulative repair costs increases over that same time period. At any time, the total cost associated with the pipe is the sum of the present values of replacement and cumulative repair. The optimum economic time to replace the pipe is when the total present worth cost is at a minimum. Stacha (1978), Shamir and Howard (1979), Walski (1987a, 1987b) and Walski and Pellicia (1982) have addressed the break-even analysis in more detail.

In determining whether to replace or repair a failed pipe, Stacha (1978) compared the annual cost of replacing a pipe to the annual cost of repairing. A methodology for using historical record of failures and repairs to project the accumulated cost of repair within a specific time frame was presented. The accumulated cost was then compared with the replacement cost to make a repair decision. Stacha advised that use of the cost difference alone was inadequate. Other parameters such as water quality and flow capacity also needed to be taken into consideration.

Male et al. (1990) described an effective replacement policy in use by New York City. The authors showed that at that time the replacement policy of replacing all pipes with two or more breaks was the most cost effective system-wide policy. The analysis involved the consideration of five alternatives: (1) replace after one or more breaks, (2) replace after two or more breaks, (3) replace after three or more breaks, (4) replace after four or more breaks, and (5) do nothing. Alternative 2 also turned out to be the most proactive policy. The authors also showed that some cost improvements could be made if alternative replacement policies were used in some of the boroughs. Male et al. (1990) also indicated that the discount rate used in the calculation affected which alternative was selected. For example, a higher discount rate lead to a less proactive policy and vice versa.

Kleiner et al. (1998a, 1998b) considered repair costs in terms of improved flow capacity of a pipe achieved by relining. A reduced C-value would increase the head loss and reduce pressure. Kleiner et al. incorporated mass balance, energy, and head-loss with time varying C-
value and minimum pressure constraints in a rolling time horizon to find the optimal replacement
times as relining costs become non-optimal. The objective was to minimize total costs of relining
and associated replacement cycles in an infinite time horizon.

Su et al. (1987) and Wagner et al. (1988) addressed an alternative form of a reliability
constraint based on the probability of satisfying nodal demands and pressure head requirements
under various network failure configurations. Duan et al. (1990) considered the optimization and
reliability of pumping systems in a network. Similar studies were also presented by Lansey
(1989), Mays (1989), and Park and Liebman (1993). Although these models did not directly
address the causal mechanisms of failures in pipes, they provide a framework for further
economic analysis. Issues and methods related to pipe network optimization are fully covered by
Loganathan et al. (1990, 1995) and Sherali et al. (1998). For a comprehensive book on water
distribution systems, the reader is referred to Mays (2000).

In 1999, the St. Louis County Water Company (SLCWC) conducted an economic
evaluation of water mains in its distribution system. Grablutz and Hanneken (2000) described an
economic model that considered the total present worth cost of a pipe to be the sum of
cumulative projected future repair costs plus replacement cost. The optimum economic time to
replace a pipe was when the total cost was at a minimum. Figure 2.1 illustrates this basic
concept for a pipe segment of 2795 ft. The economic model was applied to those pipes in the
SLCWC system that had previously had 3 or more water main breaks. The resulting analysis
indicated that between 175 and 255 miles of pipe needed to be replaced over a five-year period
solely based on these economic factors. Non-economic factors also would certainly be
considered in the final replacement decision.
Figure 2.1 Example of economic break-even analysis conducted for SLCWC

2.1.3 Failure Probability and Regression Methods

The failure probability methods are related to the DPA method in that they build on the same deterioration factors but bring in a predictive capability by assessing the probability of a pipe’s survival. However, only a few of the failure probability models are well detailed. Comprehensive reviews of such models are given in Andreou et al. (1987) and O’Day et al. (1986). The two lumped parameter models of Shamir and Howard (1979) provided a rudimentary estimate for the number of breaks at a chosen time. In an attempt to account for the relative impacts of various exogenous agents, Clark et al. (1982) proposed certain multiple regression equations for the number of years from installation to the first repair. Another equation was also proposed for the number of repairs over a time period measured from the time
of the first break. These equations had coefficients of determination ($R^2$) of 0.23 and 0.47, respectively. Thus, while Clark et al.’s procedure was a significant improvement in predicting pipe breaks, it did raise some concerns because of the low values of the coefficients of determination. Following Clark et al.’s study, Andreou et al. (1987) suggested another approach to estimate the survival probability of an individual pipe with the aid of Cox’s regression model. In contrast to Clark et al.’s expected times of failures, Andreou et al. provided the probabilities of failure. Clark et al. made the following observations: only a subset of pipes have recurrent repairs; the time to first repair is relatively long (typically about fifteen years); the time between repairs becomes shorter as pipes get older; large diameter pipes tend to have fewer problems; and industrial development, in general, results in more repairs.

Goulter and Kazemi (1988, 1989) observed both spatial and temporal clustering of pipe failures for the city of Winnipeg. A non-homogeneous Poisson distribution model was proposed to predict the probability of subsequent breaks in a pipe (given that the first break had already occurred). Mavin (1996) provided a review of the failure models in the literature. Mavin also pointed out the need to filter the data before constructing a failure model. He suggested not to include breaks that occurred within three years from installation and six months from a previous break, because these types of failure were likely to be associated with construction faults and not with a structural failure of the pipe. Based on the filtered data, a set of regression equations was constructed for number of failures over a time period and time interval between breaks.

Deb et al. (1998) discussed a probabilistic model called KANEW to estimate miles of pipes to be replaced on annual basis. The primary objective of KANEW was to provide water utilities with a tool to develop their long-range pipe renewal strategies. Based on the historical inventory of water mains and the estimated life-span data, KANEW predicted miles of different categories of pipes to be rehabilitated and replaced on an annual basis. It was not, however, intended to provide location specific rehabilitation and replacement information. The model used the actual water main inventory, with the pipes categorized according to such basic characteristics as age, material, diameter, soil corrosivity, etc. For each category $100^{th}$, $50^{th}$ and $25^{th}$ percentile ages were obtained either by expert opinion or by analysis. These percentiles were utilized to obtain the three parameters of the Herz probability density function from which the survival probabilities were obtained. These survival probabilities were used to obtain the expected survivors or its complement of non-survivors per year, which were to be renewed.
Roy F. Weston Inc. and TerraStat Consulting Group (1996) developed the Pipe Evaluation System (PIPES) model for use by the Seattle Public Utilities to evaluate the rehabilitation needs of pipes in the system. The PIPES model consisted of three sub models: deterioration, vulnerability, and criticality. Input data to these models were provided by a GIS database to correlate pipes with layered spatial data. The deterioration model used statistical analysis to relate pipe break history data to pipe properties (type, size, etc.). This analysis relied on the Cox regression proportional hazards and the Wiebul distribution. The deterioration model provided the probability of failure of a specific pipe within the next ten years. The vulnerability model further refined the results obtained from the deterioration model. Typically, the vulnerability model provided an answer to such questions as: “Which pipes are most likely to fail in the future?” The criticality model identified critical pipes based on their failure costs and the kinds of facilities they served. Thus, this model combined aspects of failure probability and cost models.

Shamir and Howard (1979) used regression analysis on pipe break data to develop an exponential function that predicted the number of pipe breaks for any given year. The costs associated with pipe repairs over a chosen number of years were compared with the replacement cost and the optimal year of pipe replacement was determined.

Walski and Pellicia (1982) proposed a model based on the use of pipe break history to project the pipe failure rates. Their model closely resembled the one by Shamir and Howard (1979) but had some modifications. Walski and Pellicia provided a correction factor to be applied to pipes based on the size and type. The factor also accounted for the effect of breaks due to cold temperatures. This temperature correction factor was related to the average temperature of the coldest month. Walski and Pellicia warned that due to the difficulty in predicting the severity of a winter until after the fact, the use of the temperature correction factor in predicting future breaks could be erroneous. Walski (1987) improved on the previous research by introducing a cost model that accounted for the lost water due to leakage and broken valves.

Karaa et al. (1987) described an appropriate technique for time phased replacement of failure-prone pipes. In this procedure pipes that were to be rehabilitated, replaced, or to be constructed were grouped into so-called “bundles”, based upon similarities in characteristics and criticality measures. A failure model might be used to delineate such bundles, based upon their role in determining the reliability of the system. Furthermore, the optimal number of bundles to
be replaced was determined through the use of a linear program with annual budget constraints. Sensitivity analyses could be performed to assess the variations in proportions of pipes to be replaced/rehabilitated each year against budget changes. Such analyses also pointed to the budgetary requirements for various anticipated levels of system upgrades. This information was crucial for proper planning, and assisted in understanding the gravity of the problem. For example, this type of analysis could show that to ensure a reliable network by the year 2020, a water utility should rehabilitate or replace 11 miles of pipe annually. In the same vein, PPK Consultants (1993) provided a comprehensive assessment procedure considering water distribution system as a critical resource.

Lane and Buehring (1978) discussed Los Angeles Department of Water and Power (LADWP)’s use of a DBMS to formulate a “sound long-range” replacement program. The computer system used information on pipes (properties and service history); information on their surroundings (soil and water properties); and potential for liability to prioritize pipes for rehabilitation. The LADWP DBMS was used to identify pipes with high probabilities of failure and required engineering judgement to select a specific pipe for replacement.

Another failure probability study is the development of UtilNets by the Computer Technology Institute (CTI) and funded by the European Union (CTI 1997). UtilNets was a decision-support system (DSS) for rehabilitation planning and optimization of water distribution networks, and uses expert system (ES), DBMS, and GIS tools. The DSS performed reliability-based life predictions of pipes and determined the consequences of maintenance and neglect over time in order to optimize rehabilitation policy. The prototype of UtilNets was implemented for gray cast iron water pipes, but could be extended to other pipe materials. Since complete information about the state of the pipe network was generally not available, UtilNets was designed to yield reliable forecasts even when data were incomplete. It included the following (CTI 1997):

“Probabilistic models that give a measurement of the likelihood of structural and hydraulic failure of pipe segments over the next several years
Assessment of the effects that pipe condition can exert on water quality
Assessment of both the quantifiable and qualitative consequences of various rehabilitation options and neglect over time
Selection of the optimal rehabilitation policy for each failed pipe segment
An aggregate structural, hydraulic, water quality and service profile of the network
together with an assessment of the required rehabilitation expenditures
An assessment of network reliability in terms of demand point connectivity and flow adequacy”

2.1.4 Mechanistic Models

Several mechanistic models or approaches have been used to model corrosion (Romanoff 1957, Rossum 1969, Kumar et al. (1984, 1986, 1987), and Basalo 1992). For modeling the change in pit depth with time, soil environment and age, Rossum (1969) developed a set of equations. Rossum’s equation for the pit depth had the form:

\[ p = f(\text{soil parameters}) \times \text{time} \times \left[ \frac{(10-\text{pH})}{\text{soil resistivity}} \right]^N \]  \hspace{1cm} (2.1)

where \( p = \text{pit depth} \)
\( N = \text{parameter} \)

His equations are partly based on the extensive data collection effort by the National Bureau of Standards (NBS) (Romanoff 1957). The NBS buried 36,500 specimens representing 333 varieties of materials in 47 soils starting in 1922. An analysis by NBS led to an equation of the form:

\[ p = k(T)^n \]  \hspace{1cm} (2.2)

where \( p = \text{depth of the deepest pit at time, } T \)
\( k, n = \text{parameters} \)

The values of the parameters \( k \) and \( n \) were provided for the 47 different soil groups with the fit being considered poor for only four. Later, Rossum (1968) took advantage of these results in developing his equations.
These mechanistic models can be categorized by the major stress considered in the model. Various models have been developed for temperature-induced stresses (U.S. Pipe and Foundry Co. 1962, Wedge 1990, and Habibian 1994), frost load (Cohen and Fielding 1979, Fielding and Cohen 1988, Rajani and Zahn 1996) and other failure processes using the underlying physical principles.

Philadelphia Water Department (PWD) (1985) provided a detailed account of the various structural failure modes for a water main.


Kumar et al. (1984) provided a methodology for assessing corrosion growth in terms of a Corrosion Status Index (CSI) over time. The CSI depends on pipe coating, liquid carried, buried depth, soil resistivity, soil chlorides, soil sulfides, soil pH, soil moisture, pipe material, cathodic protection, and pipe diameter. The CSI is given by:

\[ \text{CSI} = 100 - 100 \left[ \frac{P_{av}}{t} \right] \]

(2.3)

where CSI = Corrosion Status Index
\( P_{av} \) = average pit depth of a 1 m section of pipe
\( t \) = wall thickness of pipe

The pit depth, \( P_{av} \) and CSI enable one to predict the loss of useful pipe thickness over time which in turn is related to the residual strength of a pipe. If the loss in thickness is denoted as \( d \), the design thickness as \( t \), and failure thickness as \( t_f \), then \( P[t-d<t_f] \) indicates the probability of failure for the pipe of interest. By relating the current thickness (t-d) to its residual strength, \( S_y \), from laboratory tests a comparison can be made against the anticipated applied stress, \( S_{act} \). The risk can also be evaluated as the probability that the strength, \( S_y \), is less than the applied stress, \( S_{act} \), denoted by \( P[S_y < S_{act}] \). Another measure is the safety factor defined as the ratio of residual strength, \( S_y \), to the applied stress, \( S_{act} \).

Besides external corrosion, water mains are also prone to deteriorative mechanisms occurring internally. Through experiments Millette and Mavinic (1988) showed that the internal pipe deterioration through corrosion is dependent upon certain water quality parameters. These
include pH, water velocity (or pressure), hardness, and dissolved oxygen content. Millette and Mavinic reported the following findings: cast iron corroded twice as fast in a pressurized system as opposed to in a gravity system and iron levels found in tap water exceeded levels found in raw water indicating the presence of corrosion and iron uptake by the water in the distribution system.

Wedge (1990) showed that the excess pressure developed in a piping system could amount to as much as 200 psi for a 10° F change in temperature. Wedge’s methodology basically converted the strain due to thermal expansion into to a corresponding pressure. Pipe break data analysis of the Washington Suburban Sanitary Commission (WSSC), MD, water distribution system showed a trend in increased pipe breakage rate due to temperature changes (Habibian 1994). Specifically, the data showed that temperature drop was a significant factor in increased pipe break rate. Each time the temperature reached a new low, a surge was noted in the number of breaks. Such a trend indicated that the temperature change alone was inadequate to correlate increased number of pipe breaks. Possibly, the actual initial and final temperatures had to be considered.

Temperature also affects the pipe in the form of increased loads that results from frost heaving of the soil. Monie and Clark (1974) were among the first to show experimentally the increased load exerted on pipes by frost heaving. In an experiment conducted in Portland, Maine, Monie and Clark found that the load on the buried pipe doubled due to frost heave. Also, frost conditions seemed to transmit live loads to the pipes from farther distances from the buried pipe. Though the authors attributed increased number of breaks in pipes to frost loads, they also speculated that the cold water had the potential for increased stresses in the pipe thus leading to more failures.

Cohen and Fielding (1979) provided a simplified formula for the determination of the frost depth in a soil as a function of the freezing index. Fielding and Cohen (1988) further developed a modified Boussinesq equation relating the expected frost load with the frost depth. The results obtained from the modified Boussinesq equation compared very well with field measurements.

In frost load assessment Rajani and Zahn (1996) suggested computing frost heave using two paths due to a) freezing of the in situ pore water, and b) water arriving at the freezing front.
From elsewhere. With the aid of a vertical one-dimensional force equilibrium analysis, the frost heave was converted into incremental frost pressure at the freezing front.

While these mechanistic models help to understand the failure processes, the predictive capability must be considered either through a correlation analysis or through a probabilistic analysis by considering the parameters/variables to be random. As described in Chapter 4, in this study the mechanistic methods provide strength estimates as a function of failure causing factors. The mechanistic methods are incorporated within a probabilistic scheme for assessing the stage of deterioration of an underground pipe. The stage of deterioration has to be inferred from the environmental factors and repair history of a pipe. The background deterioration is attributed to corrosion. However, this failure rate can be accelerated by unintended traffic load, frost load, and temperature effects. The accelerated failure rate is accommodated by shifting between curves or by raising the failure thickness. The net result is that it is possible to obtain the residual strength for a pipe at a given time. It is precisely this information needed for making replacement and rehabilitation decisions.

2.2 Gas Utility Practices

Gas and water utilities face similar challenges in conveying a product to the customers of the system. The obvious difference is the material that is conveyed through the pipe. Due to its explosive nature, gas pipes are managed and monitored more closely to avoid failures and their resulting consequences. Similarly, the operation and maintenance of gas distribution systems is more regulated than water distribution systems. High priority is given to public safety and customer service in gas distribution system where federal regulations are in place for all aspects of operation and maintenance. Some of the major operation and maintenance features of a gas distribution system that may be applicable to water distribution systems include (Deb et al. 1995):

Unaccounted-for product (comparable to unaccounted-for water) in the gas industry is closely monitored and is generally less than 5 percent. Regulations require gas utilities to conduct leakage surveys on a regular basis. The frequency of the surveys depends on the service district and consequences of leaks on public safety. Annual surveys are required for downtown and high value districts. Every time a gas pipe is exposed, its condition must be assessed and
recorded. As a result, a gas utility typically has extensive data on the condition of pipe in its system.

All gas utilities are required by regulation to submit operations and maintenance (O&M) plans. Gas utilities classify leaks on the basis of consequence and location. A leak that poses high risk for public safety is classified as a Grade 1 leak and must be repaired immediately. A leak that does not represent a safety risk is a Grade 2 leak that must be monitored regularly until a repair is completed.

Unlike water utilities, the documentation requirements for a leak incident in a gas utility are well established. A leak report for a gas utility would as a minimum include the following: work order #; street address’ plat #; condition of pipe (excellent, good, fair, poor - immediate notification is required if pit depth is about 70% of wall thickness and should be clamped.); graphitization; repair description; number and size of openings; tax district; town code; leak grade; pipe size; pipe material; cause of leak; type of coating; condition of coating; anodes; installed; time; date; and type of pavement removed.

A leak record card process flow chart as followed by a southern New Jersey gas company is shown in Figure 2.2. After completion of a leak repair, information from the leak record cards is used to prepare leak maps. As a minimum leak maps contain the following information: repaired leaks; documentation of leaks; and information on main replacement and improvements. The leak maps are kept up to date as part of the normal leak record documentation. The leak maps are also used in conjunction with main replacement evaluations that are used to prioritize infrastructure renewal.
Figure 2.2 Sample leak record card process flow chart for a gas company
Gas utilities often apply the concepts of risk management in optimizing maintenance activities and in developing infrastructure renewal programs. Risk management is used in a variety of fields to achieve an acceptable level of operational safety at an affordable price. In a manufacturing setting, the processes, manufactured components, and other factors that contribute to malfunctions are controllable in a way that detailed cost/benefit analyses can be performed to optimize the process and minimize risk. For the gas industry, risk management involves balancing the consequences of a gas main or pipeline failure against the costs of inspecting, maintaining, rehabilitating, or replacing the pipe(s) in question. Research is being conducted by the Gas Research Institute (GRI) to develop formalized procedures for assigning probabilities of risk. Until the formalized procedures are available, the industry has been using a “ranking” system based on “relative” risk to prioritize maintenance.

Kiefner and Morris (1997) describe a Risk Management Tool (RMT) that consists of an algorithm which calculates a total risk number ($R_{tot}$). $R_{tot}$ is the product of $P_{tot}$ and $C_{tot}$ where:

$$P_{tot} = \text{sum of the probabilities of failure from all postulated causes},$$

$$C_{tot} = \text{consequence of failure comprised of consequences to life and property, to throughput, and to the environment}.$$

The consequences of a gas main or pipeline failure can be more severe than a water main break. However, many of the concepts used in estimating the probability of gas main failure are applicable to pipes in a water distribution system. The following components are considered in estimating the probability of failure for a gas main:

*External corrosion* – The probability of failure due to external corrosion is a function of wall thickness, corrosion rate factor, stress (pressure) level, history of previous incidents, temperature, stray current, coating type, coating condition, microbiological influence in surrounding soils, and mitigating influence of inspections or testing. For external corrosion and many of the other components that follow, the probability of a failure is assumed to be reduced as a result of inspections or testing of the pipe.

*Internal corrosion* – Many of the same factors that influence the probability of external corrosion causing a failure apply to internal corrosion. These include wall thickness, stress (pressure) level, history of previous incidents, and mitigating influence of inspections and testing. In addition, gas composition, biological activity within the
product, inhibitor effectiveness, and seam orientation (certain weld types promote internal corrosion) must also be accounted for in considering internal corrosion.

3rd party damage – The probability of failure due to 3rd party damage is dependent on pipe geometry (wall thickness and diameter), pipe material strength, class location, depth of burial, history of prior encroachments, and preventative response factors. Class location refers to the land use and population density in the vicinity of the gas main, and is defined uniformly across the gas industry. Preventative response refers to the effectiveness of “one call” systems, patrolling of the right of way, and permanently marking or identifying right of ways.

Stress-corrosion cracking (SCC) – SCC is characterized as an environmentally-stimulated, stress-driven form of longitudinally-oriented cracking. It occurs only in pipes subjected to very high hoop stresses, and is very temperature dependent. Factors considered in estimating the probability of failure due to SCC include stress (pressure) level, mitigating influence of testing, distance from compressor station (which impacts pressure and temperature), stress corrosion indicator, coating type, coating condition, history of prior SCC incidents, and temperature.

Material factors – The probability of failure due to material factors (i.e., pipe manufacturing defects) is a function of the ratio of initial hydrostatic testing pressure to operating pressure, seam type, age of material, girth weld quality, history of prior material incidents, and mitigating influence of retesting.

Construction factors – Construction defects might include weld defects, dents, gouges, and poor bedding or installation. Most construction factors are accounted for in other probability equations (for example, 3rd party and material factors), and thus there is no formal accounting for construction factors unless prior history has shown a problem associated with a particular construction technique or company.

Outside sources – This factor accounts for the probability of failure due to natural forces in locations such as water crossings, landslide or subsidence areas. Specific factors
include amount of crossing with shallow burial, amount of crossing with extremely shallow burial, amount of span subject to undermining, scouring potential, and amount of unsupported span.

*Electrical disturbances* – Some pipelines may be at risk from various kinds of electrical disturbances such as lightning strikes, electrical induction in areas with high voltage power lines, or mining areas where ground return might be used for dc equipment. Like the construction factors situation, some of the probability of failure due to electrical disturbance is accounted for in other probability equations, and is not considered separately.

All of these factors used in the gas industry are also applicable to pipes in a water distribution system. As a result, a similar approach of assigning probability of failure to water pipes could be developed as a first step in planning future maintenance activities and ultimately for prioritizing water main renewal programs.

The need to protect public safety has resulted in a greater degree of regulation in the gas industry. The types of data being collected by gas companies related to the condition of pipes is not significantly different than the data generally being collected by water utilities. The major difference between the two industries is that a typical gas utility has consistently collected a uniform and comprehensive set of data related to the condition of its piping infrastructure. This allows them to anticipate failures and plan future renewal programs more effectively.

This review of current information identified current practices related to water main break data collection. It also highlighted uses of these main break data, primarily in terms of developing water main renewal programs.

The WATER:STATS database does not contain detailed data on water main breaks. The database does show that almost half of the distribution system pipe in the US and Canada is cast iron. It also provides the number of water main breaks that occurred annually. In 1995 the 702 utilities that responded to the question experienced 90,952 main breaks, or approximately 23 breaks/100 mi/yr.

The utility questionnaire gathered data on current water main break data collection practices in North America and Europe. The survey found that break rates are generally higher in Europe (50 breaks/100 mi/yr) than in North America (22 breaks/100 mi/yr). The higher break
rates may explain why 80% of European utilities reported that they have formal programs in place to control water main breaks, compared to less than half of North American utilities. About 11% of the North American utilities surveyed do not have water main inventories. This hinders the development of water main renewal programs in these systems since data on existing water mains is not easily accessible. On the other hand, 85% of European and 70% of North American utilities reported that they had water main break data in some form of computer database. This is an important first step in putting the data to use in the development of water main renewal programs.

The questionnaire also examined the types of water main break data that are collected. Basic information such as date, location, and type of break is recorded almost universally by those utilities that collect water main break data. Few utilities in North America or Europe record air, water, or soil temperature. This is somewhat surprising because temperature is often cited as one of the major factors influencing main breaks.

Actual water main break databases were collected from six utilities. These databases showed a wide range of detail, and are typical of water main break databases in the industry. A review of the databases showed that much of the detailed data needed to conduct a systematic analysis of main break trends is often not collected by utilities.

The literature review identified numerous methodologies for prioritizing water main renewal programs, many of which relied to some extent on the availability of water main break data. The DPA systems use a scoring methodology to rank pipes for renewal. The number of previous main breaks is typically an important scoring factor. Economic models compare the costs of renewal to ongoing repair costs for a pipe. Water main break data must be available to apply such models, including detailed cost information. Failure probability and regression models require very detailed water main break data in order to effectively analyze and identify the underlying causes of main breaks. A large data set is also valuable in order to improve the validity of the analyses. Mechanistic models make the most use of water main break data, and also require the most detailed data. These models attempt to predict water main breaks by considering the characteristics of the pipe and its environment, and simulating the loads the pipe experiences. Thus, the water main break data must include related information such as soil characteristics, temperatures, pressures, etc.
Finally, gas utility practices relative to pipe failures were examined. The more regulated environment of the gas industry has led to a more standardized approach to collecting information when a pipe fails. The types of information collected when a gas main fails are not substantially different from what a water utility might collect. However, because these standardized rules have been in place for some time, gas utilities typically have a larger database at their disposal. This facilitates the analysis of the data and provides a more comprehensive picture of the condition of the distribution system pipe.
Chapter 3 - Methodology and Data Issues

3.1 Introduction

The residual life of a pipe is a crucial factor in establishing the water main renewal priorities. Buried water mains are designed to withstand certain design loads. Generally, these loads include earth load, truck/live load, working pressure, and water hammer pressure. The pipe material and thickness are designed and selected to withstand these loads by considering internal and external stresses resulting from the loads.

Pipes located in regions prone to freezing temperatures sometimes experience an additional load (frost load) caused by frost heaving of surrounding soil. Similarly, wide and rapid temperature variations in the soil-pipe-water environment lead to additional thermal stresses on the pipe. Pipe leakage and bad construction practices around the pipe sometimes lead to the pipe bed disruption thereby making it prone to breakage due to beam action. In addition to the increased loads on the pipe, the pipe’s structural integrity deteriorates by corrosion at a rate dependent on the pipe material type, protection type, characteristics of the surrounding soil, and the hydraulic and chemical properties of the water flowing in the pipe. Corrosive soils accelerate the development of corrosion pits on the pipe outside surface and the decrease of the pipe thickness. Corrosive waters flowing in the pipe also accelerate the corrosion and the eventual reduction in pipe wall thickness. The quality of water inside an unlined pipe also dictates the growth of tuberculation within the pipe that tends to reduce the effective diameter of the pipe as well as increase the pipe roughness. To compensate for the increased head loss, the excessive use of a pump may be needed to maintain the working pressure.

In this study, design modules to assess the residual strength of a pipe were developed. The ratio of residual strength to working stress is considered the factor of safety. When the factor of safety falls below an acceptable level, the pipe becomes a candidate for replacement.

The next section describes an overview of the development of a mechanistic model of the corrosion process and loss of strength of the pipe. The data requirements for the model are also described.
3.2 Modeling Approach

The modeling approach incorporates several modules or calculation routines that are grouped by function. The loads to which the pipe is subjected and the resulting material stresses are calculated and described by the pipe load model (PLM). The corrosion process and the resulting loss of residual strength and thickness of the pipe is calculated by the pipe deterioration model (PDM). The statistical correlation model (SCM) is used to generate a modified corrosion model based on actual pipe corrosion data. The resulting corrosion model is then used in the PDM. The pipe break model (PBM) predicts the likelihood that a pipe will break by calculating a safety factor. This safety factor is the residual strength of the pipe (calculated by the PDM), divided by the maximum stress on the pipe (calculated by the PLM). The replacement of water mains can be prioritized by ordering the pipes in order of increasing safety factor, as calculated by the PBM.

The model is currently limited to cast iron pipes with diameters ranging from 4 inches to 12 inches (small diameter pipes). Internal corrosion is not considered in the model hence it is appropriate to apply the model to unlined pipes or pipes which do not have significant internal corrosion.

The diagram in Figure 3.1 illustrates the interactions between the modules of the modeling system to determine which pipes need to be replaced and the order they should be replaced.
Figure 3.1 Flow chart of pipe failure analysis

The steps by which water utility personnel would apply the model are as follows:

The user will select a main. The main ideally would be a pipe of continuous length having segments of uniform size, uniform type, and were all installed in the same year. The analysis procedure requires that any pipe being analyzed must be in a uniform environment. For example, a pipe being analyzed cannot have parts both in corrosive and non-corrosive soils. In order to avoid such a situation, the selected pipe will be divided into sections based on what types of soils they pass through. A generalized approach currently used by some utilities is to divide the area in which the water distribution system exists into grids. Each grid has its own soil and pertinent properties assigned to it. The portion of each pipe passing through a grid will be referred to as a section of that pipe.

The user needs to specify desired critical factor of safety as a criterion for renewal. This value is used to determine when a particular pipe section is near failure. Pipe break analysis then proceeds as follows:
Step i: Determine the following external and internal loads on pipe from PLM:
   Earth load
   Traffic load
   Expansive soil load
   Frost load
   Internal pressure (working pressure)
   Internal pressure (water hammer)
   Internal pressure (pressure increase due to thermal contraction of pipe)

Step ii: Determine the following stresses on pipe from external and internal loads using PLM:
   Ring stress from ring crushing loads (frost, expansive soil, earth, and traffic)
   Longitudinal stress from internal pressures
   Hoop stress from internal pressures
   Thermal stresses (longitudinal and ring)
   Flexural stress from beam action from external loads (frost, expansive soil, earth, and traffic)

Step iii: Estimate the following structural conditions of the pipe using PDM:
   Wall thickness reduction due to corrosion of pipe overtime
   Reduction in modulus of rupture for both beam action and ring deflection
   Stress concentration and susceptibility to fracture due to pit growth

Step iv: Calculate the reduction in residual strength due to corrosion pit growth. Confirm prediction of pit depth and residual strength with materials testing lab data if available.

Step v: Compute residual safety factors by comparing loads on pipe with the pipe’s structural condition. This will be accomplished using PBM. The safety factors will be computed and evaluated for the following stress components:
   Hoop stress
   Ring stress
   Longitudinal stress
Flexural (beam action) stress
Combined hoop and ring stress
Combined flexural and longitudinal stress

**Step vi:** Calibrate the model results:

Calculate safety factors for failed pipes by applying model to a break database
Confirm critical safety factor for pipe failure and failure mode

**Step vii:** Compare residual safety factors with critical safety factor for each item listed in item 3 above. This results in a list of the pipes where the calculated safety factor is less than the user-specified critical safety factor. The predicted failure mode of the pipe, such as beam stress or ring failure, is predicted by the stress component with the lowest safety factor.

Develop prioritized renewal program

Apply model to pipe inventory and calculate safety factors
List pipes with computed safety factors less than the critical safety factor
Order pipes in increasing order of safety factor. This is a prioritized list of water mains for replacement prioritized by their potential for failure.

3.3 Importance of Definition of a Pipe

Analysis of breakage patterns in water distribution mains requires the definition of what is being referred to as a ‘pipe’ or ‘main’ in the particular analysis. No matter what the definition of the ‘main’ is, often several segments are laid end to end constitute what is referred to as a main of a pipe. A pipe segment is defined as the smallest complete unit of pipe. The nominal length for a pipe segment is 18 feet. Changes in manufacturing practices over the years has led to a change over the years of both pipe joint design and material composition. An example pipe type is the super bell-tite push-on joint with one end of the pipe having a bell and the other end
having a spigot. This bell and spigot design allows the spigot of one pipe segment to fit into the bell of the other successively to form main.

Often main failures are quantified by breakage per distance per period (example 50 breaks/mile/year). This approach conveniently lumps together all pipes in the system irrespective of size, type or location. Sometimes in, more detailed analysis, the lumping is further categorized by type, size, or location. The definition of a ‘main’ in a water distribution system does not always stay the same. It is usually dependent on the utility and what type of analysis the utility is trying to perform.

In the analysis of pipe main failures, the definition of main will vary depending on the method of analysis being used. For methods that depend on a statistical modeling based on the pipe failure history in the system as a whole, the definition of pipe need to be very clear. Such methods usually lump pipes in to groups based on type, size, location, and time of installation. Information on the breakage is expressed in terms of breaks per mile per year.

When the actual physical conditions related to the pipe are to be used for mechanistically based failure analysis, the definition of a ‘pipe’ or ‘main’ becomes more critical. Since mechanistic analysis depend on the pipe material type and its deterioration with time, the definition of the pipe must take these into account if an accurate failure analysis is to be made. The strengths and deteriorative factors for different pipe materials tend to differ. As an illustration, consider a pipe with half of the length of the pipe as cast iron and the other half as ductile iron. It is known that ductile iron pipe is more resilient to beam action due to disruption of pipe bed material than cast iron. This implies that if the pipe is subjected to the same beam stresses, the cast iron section would experience a failure before the ductile iron section. If in the analysis the whole length is considered as a single pipe, the results become confusing as it would be hard to determine which part of the pipe the result applies to.

Also, soil environment plays an important role in determining the deterioration rate of an unprotected buried main. Again, if we assume main of uniform material type passing through soils of varying corrosivity, the portion in the higher corrosivity soil would experience a failure earlier the portion in the lower corrosivity soil (assuming the pipe failure is due to deterioration).

Other variables of importance in the definition of a pipe form mechanistic analysis include: pipe pressure, size, surface loading (traffic load and frequency), frost susceptibility, and age.
The accuracy of any mechanistic model is closely linked to how uniquely the pipe is defined with the characteristics. The major setback for such a unique definition of a pipe for mechanistic analysis is the lack of availability of information on the pipe. The type of system that is able to provide such a detailed definition of a pipe would be a well designed GIS system. Unfortunately, these are hard to come by. Many utilities are just now investing in the use of GIS to keep track of water distribution system inventory. Certain information pertaining to the soil however will, for a while, remain hard to come by. With time, as agencies and utilities accurately map soils and update their GISs the strength of mechanistic models will increase.

Until these are reached, reasonable generalizations must be made in defining pipes for mechanistic analysis. Pipes must be of unique size, type and installation year. For soil environment, pipes must be identified as passing through the environment of worst corrosivity for conservative purposes. Overburden loads for pipes laid under streets must also be applied to the entire pipe for worst case scenario analysis. The result of such a generalized definition of a pipe is that, the mechanistic model produces a worst case scenario for pipe failure or in practical terms, time of first failure. This first failure will actually occur at the section of the pipe actually experiencing the conditions used to define the attributes used in modeling the pipe condition. Subsequent failures are will occur progressively at points with less severe loads and deteriorative conditions.

3.4 Utility Main Break Databases

Most water utilities maintain a record of water main breaks in one form or another. These records may simply be paper forms filled out by office personnel and field crews in responding to main breaks. However, currently a more common approach is to create and maintain computerized databases of main breaks. These databases are often maintained and updated by the distribution department for their own use. Typically, older main breaks, i.e. those that occurred prior to the creation of the database, are not entered into the database even though the paper records may still exist. In some cases, the main break data is compiled as part of an overall work management system (WMS). The WMS may include information from the initial call to customer service, to the generation of a work order directing a crew to respond, to the recording
of crew times for payroll purposes. A sophisticated system may include links to a GIS to provide spatial capabilities.

The availability of a main break database is critical for evaluating the causes of main breaks and for planning future distribution system renewal programs. The contents of the database will vary from utility to utility, but certain key fields of data are necessary to successfully utilize the database for planning purposes.

Based on questionnaire responses from six water utilities in North America, it was determined that water main break databases were being maintained by all six in some form. These utilities were Philadelphia Water Department (PWD), Ft. Worth Water Department (FWWD), St. Louis County Water Company (SLCWC), Philadelphia Suburban Water Company (PSWC), Regional Municipality of Ottawa-Carleton (RMOC), and United Water New Jersey (UWNJ). These databases provide actual data for use in developing and calibrating the predictive main break models. Each of the utilities uses different database management software, and each provided the data in different formats but could all be imported to a standard environment such as MS Access.

PWD maintains a mainframe database of main breaks. Electronic data are available dating back to 1964, and the database contains approximately 29,000 records. FWWD provided approximately 60,000 records dating to 1971. SLCWC has an electronic database dating to 1983, and also has paper records of main breaks dating to the early 1960’s. The PSWC database has approximately 18,000 records dating back to 1960. RMOC’s database includes approximately 6,500 records of water main breaks from 1972 through the present. UWNJ maintains separate databases for water main leaks and breaks. The leak database contains approximately 3,000 records dating to 1968, while the break database contains approximately 4,000 records from 1963 through the present. Both databases share the same general format and content.

The following general categories of data are typical types of data maintained in a main break database:

Background data – date, time, address, etc.
Field observations – specific location, condition of pipe, cause of break, etc.
Pipe history – installation date, work order or other pipe identifier, etc.
Cost data – labor, material, and equipment, etc.
Testing results – soil testing and pipe testing
Table 3.1 summarizes the general data available in the main break databases provided by the six utilities.

<table>
<thead>
<tr>
<th></th>
<th>Background data</th>
<th>Field observations</th>
<th>Pipe history</th>
<th>Cost data</th>
<th>Testing results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philadelphia Water</td>
<td>Date, location (address, plate #, census</td>
<td>Detailed location (distance from curb, etc.), pipe material, pipe diameter,</td>
<td>Installation year, replacement contract</td>
<td>Repair time, main out of</td>
<td>Sample ID (link to separate test result database)</td>
</tr>
<tr>
<td>Department (PWD)</td>
<td>tract, etc.)</td>
<td>break type, joint material, pipe condition (corrosion, tuberculation, wall</td>
<td>#</td>
<td>service time, property</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>thickness, etc.), soil condition, frost depth, pavement condition, repair type</td>
<td></td>
<td>damage, number of</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>services affected</td>
<td></td>
</tr>
<tr>
<td>Fort Worth Water</td>
<td>Break ID, date, address</td>
<td>Pipe material, pipe diameter, break type, repair type</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Department (FWWD)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ticket #, date, address, map information</td>
<td>Break type, indication of corrosion, pipe diameter, pipe material, joint type,</td>
<td>Work order, installation year, length</td>
<td>Repair time, material</td>
<td>None</td>
</tr>
<tr>
<td>St. Louis County Water</td>
<td>(grid)</td>
<td>ground surface (paved, grass, etc.), detailed location (distance from</td>
<td>installed</td>
<td>used</td>
<td></td>
</tr>
<tr>
<td>Company (SLCWC)</td>
<td></td>
<td>intersection, etc.), depth of pipe, number of anodes installed, frost depth,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>other utilities, chlorine checked</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Background data</td>
<td>Field observations</td>
<td>Pipe history</td>
<td>Cost data</td>
<td>Testing results</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------------------</td>
<td>--------------------------------------------------------</td>
<td>------------------------------</td>
<td>----------------------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>PSWC</td>
<td>Date, location (division, municipality)</td>
<td>Detailed location, pipe material, pipe diameter, leak type, repair type, depth, apparent pipe condition</td>
<td>Extension number</td>
<td>Repair time, capital cost, damage caused, shut down duration, customers affected, number of valves closed</td>
<td>None</td>
</tr>
<tr>
<td>Regional Municipality of Ottawa-Carleton (RMOC)</td>
<td>Date, location (district, map #), township, pressure zone</td>
<td>Pipe material, pipe diameter, break type, pipe depth, frost depth, bedding, pipe condition, soil type</td>
<td>Pipe ID, length, installation year, C-factor</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>United Water of New Jersey (UWNJ)</td>
<td>Date, location (municipality, map #, etc.), pressure zone</td>
<td>Detailed location, pipe material, pipe diameter, type of break, cause of break, pavement type, soil type, depth, traffic conditions</td>
<td>Extension number, installation year</td>
<td>Time required, materials used</td>
<td>None</td>
</tr>
</tbody>
</table>
Review of these databases provides a view of current water utility practices in managing water main break data. It is interesting to note that of the six utilities only PWD has historically incorporated materials testing in main break analysis. This was part of a special study and is no longer routinely performed. Most of the utilities track time and materials as part of the main break database, providing an opportunity to directly track the “costs” of main breaks. In most cases, detailed cost information is tracked separately from the main break information, making it difficult to determine the costs of a specific main break incident.

These databases provided raw data for use in developing and calibrating the predictive models. They also served as a check that the data requirements for modeling were practical and within the ability of water utilities to produce.

3.5 Water Main Break Data Collection

Water main breaks are burdens for all water utilities. They represent a drain on limited maintenance budgets, create water quality and pressure problems, inconvenience customers, and can cause considerable property damage. However, they can also provide insight into the condition of the distribution system, and the information gained as a result of these main breaks can help a utility effectively plan infrastructure renewal programs. In order to take advantage of these opportunities, a utility must recognize the types of data that should be collected and maintained every time a water main fails. This chapter describes the basic types of information that a main break yields, discusses how to best collect and maintain that information, and presents the results of the field work that was done to test these procedures.

3.5.1 Data Collection Opportunities

Various types of useful data can be collected every time a water main fails. The first type of data is field data and includes the primary information about the failed pipe and its surroundings. This includes such basic physical information as diameter, material, depth, type and cause of break, water temperature, soil conditions, etc. The second basic type of data is referred to as office data. This includes background information about the pipe that cannot be observed in the field. This type of data includes installation date and previous break history for
the pipe. A third type is laboratory and field test data of pipes and soils. It may not be practical or affordable to test all pipes that fail and the soil surrounding them. But representative sampling of pipe and soils can yield valuable information for planning renewal programs. The final data type involves the costs of water main breaks. Cost data includes both direct and indirect costs associated with repairing the water main. Direct costs such as labor and material costs are commonly tracked for all maintenance activities. Other costs associated with water main breaks such as damage claims and overhead time associated with data management should also be captured. Ideally, these data would also include indirect costs such as customer inconvenience, traffic disruption, etc. These intangible costs are difficult to quantify, but should be considered in the decision making process when developing a water main renewal program. All of these types of data are necessary for the utility to take full advantage of main break data in planning for the future of the system.

Each utility should design its own specific data collection program. The design should consider the goal of the data collection program (i.e., What is the data going to be used for?), the resources available (i.e., Will field crews have the time to fill out forms? Are office staff available to research and record background information?), and existing data collection practices and available databases within the utility. This last consideration is important because a great deal of information needed to effectively analyze the causes and impacts of water main breaks is often already being collected within a water utility. The challenge is to identify the location of the data, how to access it, and how to link it to specific water main break events.

It is important to define what is and what is not considered a water main break relative to this study. In many utilities one group is responsible for investigating and repairing “leak” and “break” incidents in the distribution system. Therefore, the collection and management of information related to these incidents are often performed concurrently. For this study, a water main break was defined as a structural failure of the pipe. Pipe failures at a joint were considered water main breaks under this definition, but leakage at a joint did not qualify as a main break. Breaks or leaks in service lines or fire hydrant laterals also were not included. However, many of the basic data collection and management concepts also apply to distribution system leaks service line and fire hydrant lateral breaks or leaks.

Before discussing the specific data that should be collected, it is illustrative to consider the typical sequence of events that are associated with the identification, investigation, repair,
and follow-up of a water main break. Each step in this process generates information or data that should be recorded and maintained for later use. The availability of information, and the practicality of collecting it, must be considered by each utility in deciding which part of its organization is best suited for gathering the data.

The specific activities associated with each step are likely to differ among utilities. The following basic steps are typical of water utility’s response to a main break situation:

Identification of problem – A call from a customer of the system or an observation by a utility employee are typical examples of how a distribution system problem is first noted. Investigation of the problem will be initiated immediately or scheduled for the future depending on the perceived severity of the event.

Investigation of problem – An experienced utility employee is dispatched to investigate the problem. The employee identifies the nature of the problem (i.e., water main break causing property damage, service line leak, damaged hydrant, etc.), and initiates remedial action based on the severity of the incident.

Remedial action – The solution to the problem may involve a temporary repair, a permanent repair or replacement, or notification of third party (for example, for service line repair outside the utility’s responsibility).

Follow-up – Follow-up steps may include recording crew times and other information related to the costs associated with the event, updating maintenance histories, alerting customers to the status, etc. At this time it is also important to collect and record other data related to the water main break, but not available from the field crews. Examples of these types of data include the age of the water main involved, the maintenance history for that water main, etc.

As noted earlier, each of these steps in the process generates data. Figure 3.2 illustrates this concept and indicates the types of data that can be expected.
Figure 3.2 Data generated at each main break response step
3.6 Recommended Data Collection

Most water utilities already have procedures and forms in place for recording basic information related to main breaks. In some cases, these forms are used exclusively by crews to compile field data. In other cases, the forms are more comprehensive, and both field and office data are compiled on the same form. Some utilities in older cities have mains as old as 150 years or more. The conditions under which these mains were installed are most often unknown and can only be inferred from estimated design practices and available technology at the time.

An issue regarding the failure data is that the data is discarded by some utilities when pipes are actually replaced. The data on the replaced pipe, if kept could be used for predicting the conditions of similar pipes in the same utility or a similar pipe in a different utility. Figure 3.3 and Figure 3.4 provide a comprehensive form to capture the field and office water main break data identified as most useful for water utilities to use in developing water main renewal programs. A description of each data item requested is provided in Table 3.2. Note that some items may not be applicable to every water utility.
## WATER MAIN BREAK DATA COLLECTION FORM

1. Date of excavation: ____________________ 3. Address: ____________________
2. Employee name: ____________________ 4. Nearest cross street: ____________________
5. Distance (ft) from cross street: ____________________

### 6. Pipe Material
- [ ] Unlined Cast Iron
- [ ] Cement Lined Cast Iron
- [ ] Ductile Iron
- [ ] Other (__________)

### 7. Pipe Diameter
- [ ] 6-inch
- [ ] 8-inch
- [ ] 10-inch
- [ ] 12-inch
- [ ] Other (__________)

### 8. Pipe Protection
- [ ] None seen
- [ ] Cathodic
- [ ] Wrapped
- [ ] Other (__________)

### 9. Joint Type
- [ ] Rigid (lead, leadite, etc.)
- [ ] Flexible
- [ ] Unknown

### 10. Condition of Pipe Exterior
   - Extent of Corrosion
     - [ ] None
     - [ ] Local (no pattern, distinct points)
     - [ ] Uniform (over entire area)
     - [ ] Severe (80% or more)
   - Degree of Corrosion
     - [ ] Negligible (0% - 20%)
     - [ ] Light (20% - 50%)
     - [ ] Moderate (50% - 80%)
     - [ ] Severe (80% or more)

### 11. Condition of Pipe Interior (unlined pipe)
   - Extent of Corrosion
     - [ ] None
     - [ ] Local (no pattern, distinct points)
     - [ ] Uniform (over entire area)
     - [ ] Not observed
   - Degree of Corrosion
     - [ ] Negligible (0% - 20%)
     - [ ] Light (20% - 50%)
     - [ ] Moderate (50% - 80%)
     - [ ] Severe (80% or more)

### 12. Condition of Pipe Interior (cement lined pipe)
   - Liner intact and in good condition
   - Liner cracked or missing
   - Not observed

### 13. Surface and Traffic
- [ ] Uphill
- [ ] Sidewalk
- [ ] Basement - no traffic
- [ ] Roadway - light (residential) traffic
- [ ] Roadway - medium (mixed) traffic
- [ ] Roadway - heavy (commercial) traffic

### 14. Bedding (make observations at face of excavation is undisturbed areas)
   - Type
     - [ ] Granular
     - [ ] Sand
     - [ ] Native soil
   - Condition
     - [ ] Obvious voids or washout
     - [ ] Appears uniform

### 15. Depth of Pipe (surface to top of pipe) _______ feet
### 16. Frost Depth (from ground surface) _______ inches

### 17. Type of failure
- [ ] Blow out
- [ ] Circumferential break
- [ ] Longitudinal split along pipe
- [ ] Split belljoint
- [ ] Corrosion hole
- [ ] Other (__________)

### 18. Show location of the failure

### 19. Probable cause of the failure:
- [ ] Settlement
- [ ] Pipe/rock contact
- [ ] Bedding erosion
- [ ] Frost heave
- [ ] Traffic load
- [ ] High pressure
- [ ] Water temperature change
- [ ] Third party
- [ ] Corrosion
- [ ] Unknown
- [ ] Did corrosion protection fail?
   - [ ] Yes
   - [ ] No
   - [ ] Unknown

### 20. For pipe failures caused by bedding erosion, estimate the unsupported span length: _______ feet

---

Figure 3.3 Main break Data Collection Form (Page 1)
### Physical Testing Data

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>21) Soil Category</td>
<td></td>
</tr>
<tr>
<td>- Sand</td>
<td></td>
</tr>
<tr>
<td>- Silt</td>
<td></td>
</tr>
<tr>
<td>- Clay</td>
<td></td>
</tr>
<tr>
<td>- Rock</td>
<td></td>
</tr>
<tr>
<td>- Other (__________)</td>
<td></td>
</tr>
<tr>
<td>22) Soil Temperature</td>
<td></td>
</tr>
<tr>
<td>23) Soil pH</td>
<td></td>
</tr>
<tr>
<td>24) Soil Moisture Content</td>
<td></td>
</tr>
<tr>
<td>25) Soil Resistivity</td>
<td></td>
</tr>
<tr>
<td>26) Pipe wall thickness</td>
<td></td>
</tr>
<tr>
<td>27) Pipe modulus of rupture</td>
<td></td>
</tr>
<tr>
<td>28) Pipe fracture toughness</td>
<td></td>
</tr>
</tbody>
</table>

### Water Main Break History and System Information

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>29) Employee Name (completing this portion of the form)</td>
<td></td>
</tr>
<tr>
<td>30) Water Main Break ID</td>
<td></td>
</tr>
<tr>
<td>31) Water Main ID</td>
<td></td>
</tr>
<tr>
<td>32) Installation Year</td>
<td></td>
</tr>
<tr>
<td>33) Length</td>
<td></td>
</tr>
<tr>
<td>34) Dates of prior breaks on the same water main ID</td>
<td></td>
</tr>
<tr>
<td>35) Typical Pressure in Area of Break</td>
<td></td>
</tr>
<tr>
<td>- 20-40 psi</td>
<td></td>
</tr>
<tr>
<td>- 40-80 psi</td>
<td></td>
</tr>
<tr>
<td>- 80-100 psi</td>
<td></td>
</tr>
<tr>
<td>- 100 psi</td>
<td></td>
</tr>
<tr>
<td>36) Typical Flow in Area of Break</td>
<td></td>
</tr>
<tr>
<td>- 0-100 gpm</td>
<td></td>
</tr>
<tr>
<td>- 100-500 gpm</td>
<td></td>
</tr>
<tr>
<td>- 500-1,000 gpm</td>
<td></td>
</tr>
<tr>
<td>- 1,000 gpm</td>
<td></td>
</tr>
<tr>
<td>Note any unusual changes in pressure in the 24 hours prior to the break.</td>
<td></td>
</tr>
<tr>
<td>Note any unusual changes in flow in the 24 hours prior to the break.</td>
<td></td>
</tr>
<tr>
<td>37) Water Temperature (**°F or **°C)</td>
<td></td>
</tr>
<tr>
<td>38) Air Temperature (**°F or **°C)</td>
<td></td>
</tr>
<tr>
<td>39) # of consecutive days below 32 °F (0 °C)</td>
<td></td>
</tr>
</tbody>
</table>

### Water Main Break Cost Data

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>40) Crew size</td>
<td></td>
</tr>
<tr>
<td>41) Time on site</td>
<td></td>
</tr>
<tr>
<td>42) Was water service to customers interrupted?</td>
<td></td>
</tr>
<tr>
<td>- Yes</td>
<td></td>
</tr>
<tr>
<td>- No</td>
<td></td>
</tr>
<tr>
<td>43) Estimated number of customers whose service was interrupted</td>
<td></td>
</tr>
<tr>
<td>- residential</td>
<td></td>
</tr>
<tr>
<td>- commercial</td>
<td></td>
</tr>
<tr>
<td>- industrial</td>
<td></td>
</tr>
<tr>
<td>- schools</td>
<td></td>
</tr>
<tr>
<td>- hospitals</td>
<td></td>
</tr>
<tr>
<td>- other</td>
<td></td>
</tr>
<tr>
<td>44) Estimated time without service (hours)</td>
<td></td>
</tr>
<tr>
<td>45) Property damage</td>
<td></td>
</tr>
<tr>
<td>- Yes</td>
<td></td>
</tr>
<tr>
<td>- No</td>
<td></td>
</tr>
</tbody>
</table>

---

Figure 3.4 Main break Data Collection Form (Page 2)
<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Date of excavation</td>
<td>The date on which the water main was exposed to repair the main break</td>
<td>Temporal analyses of main break trends</td>
</tr>
<tr>
<td>2) Employee name</td>
<td>The name of the utility employee who provided the field data</td>
<td>Follow up of questions</td>
</tr>
<tr>
<td>3) Address</td>
<td>The nearest address to the location of the break</td>
<td>Spatial analysis of main breaks</td>
</tr>
<tr>
<td>4) Nearest cross street</td>
<td>The cross street closest to the main break.</td>
<td>Accurate location of main breaks where street address is not applicable</td>
</tr>
<tr>
<td>5) Distance (ft) from cross street</td>
<td>The distance from the main break to the nearest cross street</td>
<td>Accurate location of main breaks where street address is not applicable</td>
</tr>
<tr>
<td>6) Pipe material</td>
<td>The material of the pipe</td>
<td>Trend analyses of main breaks by pipe material</td>
</tr>
<tr>
<td>7) Pipe diameter</td>
<td>The nominal diameter of the pipe</td>
<td>Trend analyses of main breaks by pipe diameter</td>
</tr>
<tr>
<td>8) Pipe protection</td>
<td>This is an indication of the corrosion protection characteristics of the pipe. Ductile iron pipe may be wrapped or unwrapped depending on when it was installed and local soil conditions. Other cathodic protection measures (anodes, etc.) should be noted.</td>
<td>Evaluation of corrosion protection programs</td>
</tr>
<tr>
<td>9) Joint type</td>
<td>The type of joint connecting pipe segments</td>
<td>Trend analyses of main breaks by joint type</td>
</tr>
<tr>
<td>10) Condition of pipe exterior</td>
<td>The extent and degree of external corrosion on the pipe, based on a visual inspection,</td>
<td>Provides a qualitative assessment of external corrosion. Can be used to identify problematic soil areas in the distribution system.</td>
</tr>
<tr>
<td>11) Condition of pipe interior (unlined pipe)</td>
<td>The extent and degree of internal corrosion of the unlined pipe, based on a visual inspection, check the boxes that best describe it. If the pipe interior was not observed (for example, if a pipe clamp was applied) select “Not observed”</td>
<td>Provides a qualitative assessment of internal corrosion. Can be used to assess the need for cleaning and lining.</td>
</tr>
<tr>
<td>12) Condition of pipe interior (cement lined pipe)</td>
<td>The condition of the cement lining, based on a visual inspection. If the pipe interior was not observed (for example, if a pipe clamp was applied) select “Not observed”.</td>
<td>Provides a qualitative assessment of cement lining. Can be used to assess the need for relining or replacement.</td>
</tr>
<tr>
<td>13) Surface and traffic</td>
<td>Describes the surface under which the pipe is laid in order to estimate the traffic load the pipe experiences. “Roadway heavy (commercial) traffic” refers, for example, to a roadway that carries both a high volume of traffic, as well as a large number of trucks. “Roadway medium (mixed) traffic” would be indicative of a commercial shopping district where traffic volume might be high, but it consists primarily of automobiles. “Roadway light (residential) traffic” refers to a residential area where the traffic is almost exclusively automobile.</td>
<td>Helps to determine the cause of the main break. Can be used to examine trends in main breaks. May help in designing future water main installations. Data can be used in mechanistic models for predicting future main breaks.</td>
</tr>
<tr>
<td>14) Bedding</td>
<td>The “Type” and “Condition” of the bedding, based on a visual observation. It is recognized that the break itself is likely to disturb the bedding, and thus it is difficult to make observations about the bedding condition. Nevertheless, by examining the walls of the excavation in areas that are undisturbed, valuable information may be obtained.</td>
<td>Helps to determine the cause of the main break. May help in designing future water main installations.</td>
</tr>
</tbody>
</table>
Recommended water main break data collection (Continued)

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>15) Depth of pipe (surface to top of pipe)</td>
<td>The distance from the ground surface to the top of the pipe.</td>
<td>Helps to determine the cause of the main break. Can be used to examine trends in main breaks. May help in designing future water main installations. Data can be used in mechanistic models for predicting future main breaks.</td>
</tr>
<tr>
<td>16) Frost depth (from ground surface)</td>
<td>The depth of frost penetration from the ground surface at the time of the excavation</td>
<td>Helps to determine the cause of the main break. Can be used to examine trends in main breaks. May help in designing future water main installations. Data can be used in mechanistic models for predicting future main breaks.</td>
</tr>
<tr>
<td>17) Type of failure</td>
<td>The type of water main break, based on visual observation</td>
<td>Allows for analyses of main break trends.</td>
</tr>
<tr>
<td>18) Show location of the failure</td>
<td>Illustration of where the failure occurred</td>
<td>Helps to determine the cause of the main break.</td>
</tr>
<tr>
<td>19) Probable cause of the failure</td>
<td>The most likely cause of the main break, based on a visual observation</td>
<td>Can be used to examine trends in main breaks. May help in designing future water main installations.</td>
</tr>
<tr>
<td>20) For pipe failures caused by bedding erosion, estimate the unsupported span length</td>
<td>An estimate of the length of pipe that was unsupported as a result of the erosion of the bedding under the pipe prior to the break. This should only be provided when the most likely cause of the break was beam failure. It is recognized that the bedding will likely have eroded further as a result of water flowing from the broken pipe, so field judgment will be required to estimate the initial unsupported length (i.e., prior to the break).</td>
<td>Helps to determine the cause of the main break. Used in mechanistic model to calculate loads on the pipe.</td>
</tr>
<tr>
<td>21) Soil category</td>
<td>The type of soil surrounding the pipe</td>
<td>Useful for analyses of main break trends. Helps to define characteristics of soil surrounding the pipe, which are needed for mechanistic modeling.</td>
</tr>
<tr>
<td>22) Soil temperature</td>
<td>The temperature of the soil at the depth of the pipe</td>
<td>Useful for analyses of main break trends. Helps to define soil characteristics surrounding the pipe, which are needed for mechanistic modeling.</td>
</tr>
<tr>
<td>23) Soil pH</td>
<td>The pH of the soil in the vicinity of the main break</td>
<td>Useful for analyses of main break trends. Helps to define soil characteristics surrounding the pipe, which are needed for mechanistic modeling.</td>
</tr>
<tr>
<td>24) Soil moisture content</td>
<td>The moisture content of the soil in the vicinity of the main break</td>
<td>Useful for analyses of main break trends. Helps to define soil characteristics surrounding the pipe, which are needed for mechanistic modeling.</td>
</tr>
<tr>
<td>25) Soil resistivity</td>
<td>The resistivity of the soil in the vicinity of the main break</td>
<td>Useful for analyses of main break trends. Helps to define soil characteristics surrounding the pipe, which are needed for mechanistic modeling.</td>
</tr>
<tr>
<td>26) Pipe wall thickness</td>
<td>Thickness of the pipe wall, typically from a laboratory measurement.</td>
<td>Helps to determine the cause of the main break. Used in mechanistic model to calculate strength of the pipe.</td>
</tr>
<tr>
<td>27) Pipe modulus of rupture</td>
<td>Modulus of rupture of a pipe sample taken from the site of the main break. Laboratory measurement.</td>
<td>Used in mechanistic model to calculate strength of the pipe.</td>
</tr>
<tr>
<td>28) Pipe fracture toughness</td>
<td>Fracture toughness of a pipe sample taken from the site of the main break. Laboratory measurement.</td>
<td>Used in mechanistic model to calculate strength of the pipe.</td>
</tr>
<tr>
<td>Field</td>
<td>Description</td>
<td>Purpose</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>29) Employee name</td>
<td>The name of the employee researching the pipe history and system information</td>
<td>Follow up questions</td>
</tr>
<tr>
<td>30) Water main break ID</td>
<td>A unique identifier assigned by the utility to track the incident and related data</td>
<td>Provides a common identifier for data analyses.</td>
</tr>
<tr>
<td>31) Water main ID</td>
<td>A unique identifier to track the pipe on which the break occurred. If the utility has a water main</td>
<td>Provides a common identifier for data analyses.</td>
</tr>
<tr>
<td></td>
<td>inventory, this is simply the water main ID from that inventory. If no such database exists, the utility could consider other applicable identifiers such as Main Extension Number or Project Number.</td>
<td></td>
</tr>
<tr>
<td>32) Installation year</td>
<td>The year in which the pipe that failed was installed</td>
<td>Useful for analyses of main break trends.</td>
</tr>
<tr>
<td>33) Length</td>
<td>The length of the pipe ID that failed. This length refers to the length recorded in a water main inventory.</td>
<td>Needed for developing pipe specific replacement program.</td>
</tr>
<tr>
<td>34) Dates of previous breaks on the same water main ID</td>
<td>Research existing main break databases and paper records to determine other water main breaks which occurred on the same “pipe”. In this case “pipe” refers to the length of pipe identified by the Water Main ID requested previously.</td>
<td>Frequency of and duration between breaks are key modeling parameters.</td>
</tr>
<tr>
<td>35) Typical pressure in area of break</td>
<td>Describes the typical pressure in the pipe that failed. Note any unusual pressure fluctuations prior to the discovery of the main break</td>
<td>Useful for analyses of main break trends. Also used in mechanistic model for estimating load on the pipe.</td>
</tr>
<tr>
<td>36) Typical flow in area of break</td>
<td>Describes the typical flows in the pipe that failed. Note any unusual flow changes (fire flows, etc.) prior to the discovery of the main break</td>
<td>Used to estimate the labor cost.</td>
</tr>
<tr>
<td>37) Water temperature</td>
<td>The water temperature at the time the main break was discovered. Treatment plant temperature is adequate for this purpose.</td>
<td>Useful for analyses of main break trends. Also used in mechanistic model for estimating load on the pipe.</td>
</tr>
<tr>
<td>38) Air temperature</td>
<td>The air temperature at the time the main break was discovered.</td>
<td></td>
</tr>
<tr>
<td>39) # of consecutive days below 32°F</td>
<td>Indicate the number of consecutive days that the air temperature was below 32°F prior to the discovery of the main break.</td>
<td>Used in mechanistic model for estimating load on the pipe.</td>
</tr>
<tr>
<td>40) Crew size</td>
<td>The number of employees responding to the main break</td>
<td>Used to estimate the labor cost.</td>
</tr>
<tr>
<td>41) Time on site</td>
<td>The duration of time needed to respond to the main break</td>
<td>Used to estimate the labor cost.</td>
</tr>
<tr>
<td>42) Was water service to customers interrupted?</td>
<td>Yes/no response to indicate if customers were without water as a result of the main break and subsequent repair activities</td>
<td>Used to estimate indirect cost of main break to customers.</td>
</tr>
<tr>
<td>43) Estimated number of customers whose service was interrupted</td>
<td>Estimated number of various types of customers that were without water as a result of the main break and subsequent repair activities</td>
<td>Used to estimate indirect cost of main break to customers.</td>
</tr>
<tr>
<td>44) Estimated time without service (hours)</td>
<td>Estimated length of time that various types of customers were without water</td>
<td>Used to estimate indirect cost of main break to customers.</td>
</tr>
<tr>
<td>45) Property damage</td>
<td>Yes/no response to indicate if any property damage occurred as a result of the main break</td>
<td>Used to estimate the total costs of the main break.</td>
</tr>
</tbody>
</table>
3.6.1 Field Data

Field data refers to information that can only be collected at the site of the water main break. This includes all visual observations of the failed water main, its environment, and the steps taken to repair it. Some of the requested information is obvious, and only requires that the field crews record it on the form. Other requested information requires some subjective judgment on the part of the field crew to assess the condition of the water main and the potential cause of the main break.

Field crews responsible for responding to water main breaks should receive training on completing the data collection form. The training should include a description of data requests that require subjective judgment on the part of the field crew. For example, item 10 on Figure 3.3 requests an assessment of the exterior condition of the pipe. Each utility should develop its own criteria for assessing the pipe, and examples of pipe sections fitting each criterion should be shown in the training as examples. Providing examples like this helps to ensure that the data that is collected is consistent even though multiple crews may be collecting the data. Finally, the training should stress the importance of the data collection effort. The data collection should be presented as a critical component of the utility’s overall infrastructure renewal program.

3.6.2 Office Data

Office data includes information related to the water main that has failed that cannot be observed in the field. This includes operational parameters (pressure and flow), environmental conditions (air and water temperatures), and a history of the pipe that failed. These requested data may or may not be available to the field crews that complete the field data portion of Figure 3.3.

An important example of office data is the identification of the specific pipe that failed. Field crews can provide the location of the main break in terms of street address or by referencing cross streets. However, in order to thoroughly analyze main break trends it is important to have the installation and maintenance history of the pipe available. Once the field data for a main break event has been submitted, the associated pipe ID should be identified and recorded. Ideally, it would then be possible to investigate the history of the pipe.
This highlights the need for a system to specifically identify a pipe section. Some utilities use the installation record of a pipe as its identifier. For example, all pipe installed under a single contract number would share the same pipe ID. This allows the utility to reference pipe installation information, but if the length of pipe represented by the pipe ID is too long, it may be difficult to isolate specific problems. Other utilities assign pipe IDs using combinations of map or drawing sheet number, street, and even block along a street. This provides a unique identifier for a reasonable length of pipe, but considerable work may be required to then link these pipe IDs back to pipe installation and maintenance histories. A GIS provides the most powerful method of managing, retrieving, and analyzing pipe specific information.

3.6.3 Physical Testing Data

In addition to the field and office information that should be collected every time a water main breaks, there are other more detailed physical data that can prove valuable. Testing of pipe and surrounding soils can provide critical information for a utility in developing a water main renewal program. For example, a utility experiencing reduced flows and water quality problems related to the tuberculation of cast iron water mains may consider cleaning and cement mortar lining as a solution. However, if the existing cast iron pipe is not structurally sound, replacing the pipe may be a more appropriate solution. Testing of soils is critical in the development of corrosion protection programs to prolong the life of pipe. A water main renewal program that does not adequately address soil corrosivity may not achieve the desired results. Lack of data regarding soil conditions could lead to premature aging of water mains installed as part of the renewal program.

3.6.4 Pipe Testing

The physical testing described here is appropriate for cast iron pipes. All structural testing of pipe should be performed following the specifications of the American Society for Testing and Materials (ASTM) for overall methodology, and following American Water Works Association (AWWA) standards for water pipe specific requirements. The governing standards for cast iron pipe are AWWA C106/ANSI A21.6 for metal mold manufacturing and AWWA
C108/ANSI A21.8 for sand mold manufacturing. For ductile iron pipe the governing standard is AWWA C151/ANSI A21.51.

The following tests could provide valuable information about the condition of a pipe:

Pipe wall thickness (remaining) – Remaining wall thickness is a measure of loss of metal due to corrosion, and provides an indication of remaining structural strength. Determination of wall thickness is by an ultrasonic thickness gauge according to ASTM E-797. Alternatively, a micrometer can be used to take representative measurements around the circumference of the pipe.

Tensile strength – The general testing methodology is specified in ASTM E-8 for both cast and ductile iron. Preparation of sample coupons differs for cast and ductile iron, and the appropriate AWWA/ANSI specifications should be followed.

Hardness – Rockwell hardness is specified only for metal mold cast iron, and sample preparation and test methodology is provided in ASTM E-18.

Modulus of Rupture - The modulus of rupture test should be done in accordance with AWWA C106/108, which also specifies the number of samples and sample preparation.

Carbon Percentage – The percent carbon in the sample is a measure of the extent of graphitization of the pipe. Graphitization is essentially the leaching of iron from the pipe, resulting in reduced pipe strength. Determination of the carbon percentage in the pipe can be done using the Leco Carbon and Sulfur Analyzer.

Fracture toughness – This test is a measure of the remaining pipe strength resulting from the weakening produced by corrosion pits.

The costs of conducting all of these tests on every pipe sample could be prohibitive. Some of these tests have been determined to be critical in the use of mechanistic models of main failures, while others are useful but not critical. In order to minimize costs, only the following critical tests are recommended:

Wall thickness
Modulus of rupture
Fracture toughness.
It is not physically or economically practical to take a pipe sample for material testing from every water main break. For example, many utilities rely on pipe clamps to repair circumferential breaks, and therefore, do not remove a piece of the pipe. Ideally, the samples that are collected would be equally representative of the type of pipe in the system. That is, samples should be collected from different groupings of pipe materials, diameters, and ages.

A minimum pipe length of four feet should be collected. For a circumferential break, this should include two foot on either side of the break. This will provide sufficient pipe material to test the physical properties of the pipe, including a portion that did not fail. For a longitudinal break, the pipe sample should be selected from a “typical” segment of the failed pipe, but should at least include some portion that did not fail.

Few water utilities have the in-house facilities to perform these tests; thus outside laboratories must usually be used. Some savings in cost could be achieved if the utility prepares the required specimens. Details of specimen preparation are provided in the appropriate ASTM, AWWA, or ANSI specifications. However, it should be noted that the specimen preparation is very exacting, and requires a skilled machinist with the appropriate equipment. Preparation of cast iron specimens is particularly difficult due to the brittle nature of cast iron. Therefore, it is recommended that the laboratory prepare the test specimens from pipe samples sent by utilities. Samples sent to the laboratory should be labeled carefully so that the results can be matched to the water main break documentation previously described. The laboratory should be consulted for the appropriate chain of custody (COC) procedures. Each pipe should be identified using two methods so that it can be positively identified later. First, spray paint or other indelible marker should be used to directly label the pipe. Second, a tag should be attached to the pipe sample with wire. The painted label and tag should include the following information as a minimum:

Utility name
Main break ID (from the data collection form)
Date of main break
If the laboratory COC procedures require additional information, it should be provided. Finally, the pipe should be marked to indicate its orientation in the ground. The top of the pipe should be indicated with paint, and the bell and spigot ends should also be marked.

3.6.5 Soil Testing

Soil characteristics can impact the condition of cast iron and ductile iron water mains. In particular, corrosive soils can greatly reduce the life span of these pipes unless precautions are taken. Encasement of ductile iron pipe in a polyethylene wrap has become standard practice for many utilities in order to protect against corrosive soil. ANSI/AWWA C105/A21.5-82 defines the standards for polyethylene encasement of ductile iron pipe. This same standard also describes soil-testing procedures to determine if polyethylene encasement is needed to protect against corrosive soil. Thus, ANSI/AWWA C105/A21.5-82 is a good guide to assist utilities in developing soil-testing programs.

The following eight parameters are suggested for evaluating polyethylene encasement requirements according to Appendix A of ANSI/AWWA C105/A21.5-82:

Earth (soil) resistivity – Three methods for determining earth (soil) resistivity include four-pin, single-probe, and soil box. Resistivity is highly dependent on soil moisture content and temperature. Therefore, it is recommended that interpretation of results be based on the lowest reading obtained.

pH – A direct reading of soil pH is made, accounting for soil pH.

Moisture content – Soil moisture content is accounted for to some extent under earth resistivity, but is so important to overall corrosion that it also needs to be addressed separately. Conditions typically vary widely over the course of the year. Therefore, a general description of the moisture content can be provided as 1) poor drainage, continuously wet, 2) fair drainage, generally moist, or 3) good drainage, generally dry.

Soil description (category) – Several basic soil types should be noted, including sand, loam, silt, or clay. Unusual soils such as peat should also be noted. More detailed soil testing, such as particle size, plasticity, friability, and uniformity, can also be performed.
Oxidation-reduction (redox) potential – Redox potential is significant because the most common sulfate-reducing bacteria live only under anaerobic conditions. Soil samples can undergo a change in redox potential on exposure to air, and thus should be tested immediately.

Sulfides – A positive sulfide reaction indicates a potential problem due to sulfate reducing bacteria.

Potential stray direct current – The proximity of potential sources of stray current to the pipe in question should be noted. Potential sources include other utility’s cathodic protection systems, electric railways, and industrial equipment (including welding).

Experience with existing installations in the area – Possibly the most important indication of soil corrosivity is past experience in the area. This again highlights the need to collect and maintain information related to main breaks that would indicate external corrosion. Discussions with other utilities, particularly gas utilities, can also provide useful information regarding potential corrosion problems.

The first six parameters require testing of the soil. These tests are preferably performed in the field, as changes in soil characteristics can occur during transport to a laboratory. The remaining two parameters do not require testing, but should be noted each time a water main break is investigated. Eventually, a database of soil characteristics based on actual experience can be developed, providing important information for evaluating the existing condition of water mains and planning for future distribution system renewal.

An additional soil characteristic determined to be critical to the modeling of main breaks is soil temperature. Soil temperature is needed to calculate the thermal stresses experienced by the pipe prior to failure. Correlations between ambient air temperature and soil temperature have been investigated, but found to be dependent on too many other factors to be practically applied. Therefore, it is recommended that soil temperatures be collected at the time of the break excavation.

In summary, the following soil characteristics were identified as critical in this project and were included in Figure 3.3 and Figure 3.4:

1) Soil category
2) Soil temperature
3) Soil pH
4) Soil moisture content
5) Soil resistivity

All of these soil characteristics can be measured in the field. Soil categories can be broad and field personnel can be trained to recognize and record them. Soil temperature can be measured using a thermometer placed into the wall of the excavation at the depth of the pipe. It is recognized that the reading may be subject to ambient air temperatures, but it is believed that a valid reading can be made. Inexpensive instruments are commercially available for measuring soil pH and soil moisture content.

Soil resistivity measurements are more complicated than the others, but there are water utilities that have collected resistivity readings. Both the City of Calgary and the RMOC have collected soil resistivity data in the field using utility personnel.

If soil measurements cannot be made in the field, then the following soil testing procedure developed by the National Research Council (NRC) Canada can be used (Rajani 1998).

Before taking soil samples from the trenches, a utility soil engineer should become familiar with Appendix A of ANSI/AWWA C105/A21.5-88. Soil samples should be taken at four selected sites of longitudinal split and circular main breaks. All relevant soil data indicated in Figure 3.3 and Figure 3.4 should be completed.

Two soil samples from every trench, one from the bell end and one from the spigot end of the trench, should be collected. The samples should be taken from the sides of the trench as close to the pipe as possible in undisturbed soil. Soil samples can be damp or moist but must not be waterlogged or saturated. If the soil closest to the pipe is too wet, the closest good sample should be taken.

Each soil sample from the trench should be placed in its own polyethylene bag. A clean shovel should be used to collect the samples. Each sample should weigh at least 3 to 5 kg (6 to 10 lb). The sample bags should be securely sealed, and as much air as possible should be removed. Air may cause unreliable soil test results. Each soil sample should be clearly and securely labeled. Laboratory COC guidelines should be followed, but as a minimum the label should indicate the following:
Utility name
Date of sample
Time of sample
Address
Water main break ID

One soil sample bag from each trench should be sent to the soil laboratory for soil classification, index and soil resistivity measurements (soil-box).

3.6.6 Cost Data

Cost data should capture the true costs of responding to and repairing a water main break. The direct costs, including labor and materials, are straightforward and usually recorded by some group within the water utility. Other information related to the indirect costs of water main breaks is not typically recorded by utilities. Utilities should begin to collect these data, and ultimately use them in developing water main renewal programs.

3.6.7 Field Test

The data collection recommendations described in Table 3.2 were used by four participating utilities to record water main break events over an approximately 6-month long period. The implementation of these recommendations highlighted several important points for a utility to consider when designing its own data collection program. These include:

Field crew input is vital to the success of the effort. The primary function of the field crew when there is a water main break is to get the pipe back into service as soon as possible. This may involve a simple repair or a partial pipe replacement. In any event, the field crew may be reluctant to collect and record data that is viewed to be extraneous to this basic function. The utility staff that is requesting the data (engineering, management, etc.) must work with the field crews to explain the importance of the data collection effort. They should stress that the goal of such a program is to ultimately reduce the number of main breaks that the crew must deal with. Data collection forms must be customized for each utility. The form shown in Figure 3.3 and Figure 3.4 provides an example of how data collection forms could be organized. However,
each utility has unique terminology that utility personnel are accustomed to using. Every effort should be made to use utility-specific terminology.

The data collection form should be kept as simple as possible. Check boxes and yes/no type responses should be used whenever possible. This makes it easier and quicker for the field crews to complete the form. This should increase the number of forms that are completed and returned, thus improving the thoroughness of the data collection. Standardizing responses through the use of check boxes also facilitates data analysis. For example, lengthy descriptions of the causes of a water main break would be difficult to evaluate.

Handling of soil and pipe samples must be considered before the samples are collected. Soil and pipe samples are likely to be collected only from selected main break locations. Procedures must be in place to properly label, record, and deliver the samples to the appropriate laboratory before the sampling takes place. Otherwise, samples could be lost or rendered unusable. For example, in this project problems arose at the pipe-testing laboratory because several pipe samples were not adequately labeled. This made it difficult in several instances to coordinate laboratory results with main break locations.

The coordination of data collection must be assigned to a specific individual. In this project, two of the utilities used university students to compile the main break data. Assigning the responsibility of water main break data collection and management to a single person (or group) ensures that the task will receive the attention needed.

In this project, the collection of water main break data began in January 1999. Ultimately, PSWC, PWB, RMOC, and UWNJ provided data. Table 3.3 summarizes the data collection effort. Laboratory results for the pipe and soils testing are provided in Table 3.4.
Table 3.3 Summary of water main break data collection effort

<table>
<thead>
<tr>
<th>Utility</th>
<th>Number of water main breaks</th>
<th>Number of pipe and soil samples collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSWC</td>
<td>101</td>
<td>14</td>
</tr>
<tr>
<td>PWB</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>RMOC</td>
<td>Not available</td>
<td>19</td>
</tr>
<tr>
<td>UWNJ</td>
<td>227</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 3.4 Summary of laboratory testing results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Material</th>
<th>Diameter</th>
<th>Installation Year</th>
<th>Pressure (psi)</th>
<th>Wall thickness (in)</th>
<th>Modulus of rupture (psi)</th>
<th>Fracture toughness (Mpa*m1/2)</th>
<th>pH</th>
<th>Resistivity (ohm-cm)</th>
<th>Moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMOC 1</td>
<td>Lined cast iron</td>
<td>6&quot;</td>
<td>1961</td>
<td>75</td>
<td>0.466</td>
<td>32,045</td>
<td>11.4</td>
<td>5.7</td>
<td>1,193</td>
<td>32%</td>
</tr>
<tr>
<td>RMOC 2</td>
<td>Lined cast iron</td>
<td>8&quot;</td>
<td>1962</td>
<td>62</td>
<td>0.451</td>
<td>47,705</td>
<td>11.8</td>
<td>7.1</td>
<td>2,987</td>
<td>39%</td>
</tr>
<tr>
<td>RMOC 3</td>
<td>Unlined cast iron</td>
<td>4&quot;</td>
<td>1950</td>
<td>71</td>
<td>0.295</td>
<td>41,905</td>
<td>-</td>
<td>7.2</td>
<td>4,040</td>
<td>17%</td>
</tr>
<tr>
<td>RMOC 4</td>
<td>Unlined cast iron</td>
<td>16&quot;</td>
<td>1954</td>
<td>42</td>
<td>0.747</td>
<td>48,302</td>
<td>12.0</td>
<td>7.2</td>
<td>179</td>
<td>68%</td>
</tr>
<tr>
<td>RMOC 5</td>
<td>Unlined cast iron</td>
<td>6&quot;</td>
<td>1954</td>
<td>65</td>
<td>0.446</td>
<td>34,475</td>
<td>11.1</td>
<td>7.0</td>
<td>2,025</td>
<td>16%</td>
</tr>
<tr>
<td>RMOC 6</td>
<td>Unlined cast iron</td>
<td>8&quot;</td>
<td>1960</td>
<td>62</td>
<td>0.559</td>
<td>51,932</td>
<td>12.2</td>
<td>7.3</td>
<td>882</td>
<td>35%</td>
</tr>
<tr>
<td>RMOC 7</td>
<td>Lined ductile iron</td>
<td>8&quot;</td>
<td>1974</td>
<td>85</td>
<td>0.344</td>
<td>76,828</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RMOC 8</td>
<td>Unlined cast iron</td>
<td>8&quot;</td>
<td>1960</td>
<td>63</td>
<td>0.491</td>
<td>13,943</td>
<td>12.2</td>
<td>6.9</td>
<td>819</td>
<td>46%</td>
</tr>
<tr>
<td>RMOC 9</td>
<td>Unlined cast iron</td>
<td>6&quot;</td>
<td>1977</td>
<td>58</td>
<td>0.407</td>
<td>48,430</td>
<td>13.0</td>
<td>5.8</td>
<td>216</td>
<td>29%</td>
</tr>
<tr>
<td>RMOC 10</td>
<td>Lined cast iron</td>
<td>8&quot;</td>
<td>1971</td>
<td>57</td>
<td>0.433</td>
<td>53,070</td>
<td>13.8</td>
<td>5.4</td>
<td>1,119</td>
<td>38%</td>
</tr>
<tr>
<td>RMOC 11</td>
<td>Lined ductile iron</td>
<td>6&quot;</td>
<td>1974</td>
<td>64</td>
<td>0.293</td>
<td>74,095</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RMOC 12</td>
<td>Lined ductile iron</td>
<td>6&quot;</td>
<td>1972</td>
<td>80</td>
<td>0.287</td>
<td>77,575</td>
<td>-</td>
<td>6.0</td>
<td>2,749</td>
<td>35%</td>
</tr>
<tr>
<td>RMOC 13</td>
<td>Lined ductile iron</td>
<td>12&quot;</td>
<td>1977</td>
<td>68</td>
<td>0.267</td>
<td>78,880</td>
<td>-</td>
<td>7.3</td>
<td>321</td>
<td>26%</td>
</tr>
<tr>
<td>RMOC 14</td>
<td>Lined ductile iron</td>
<td>8&quot;</td>
<td>1973</td>
<td>83</td>
<td>0.221</td>
<td>123,540</td>
<td>-</td>
<td>7.1</td>
<td>709</td>
<td>36%</td>
</tr>
<tr>
<td>RMOC 15</td>
<td>Unlined cast iron</td>
<td>6&quot;</td>
<td>1958</td>
<td>70</td>
<td>0.325</td>
<td>50,895</td>
<td>14.2</td>
<td>7.4</td>
<td>2,172</td>
<td>32%</td>
</tr>
<tr>
<td>RMOC 16</td>
<td>Unlined cast iron</td>
<td>6&quot;</td>
<td>1961</td>
<td>62</td>
<td>0.436</td>
<td>47,850</td>
<td>11.9</td>
<td>7.4</td>
<td>990</td>
<td>35%</td>
</tr>
<tr>
<td>RMOC 17</td>
<td>Unlined cast iron</td>
<td>6&quot;</td>
<td>1961</td>
<td>62</td>
<td>0.508</td>
<td>41,905</td>
<td>11.2</td>
<td>6.3</td>
<td>861</td>
<td>35%</td>
</tr>
<tr>
<td>RMOC 18</td>
<td>Unlined cast iron</td>
<td>6&quot;</td>
<td>1955</td>
<td>59</td>
<td>0.440</td>
<td>55,245</td>
<td>13.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RMOC 19</td>
<td>Lined cast iron</td>
<td>6&quot;</td>
<td>1963</td>
<td>48</td>
<td>0.330</td>
<td>-</td>
<td>11.9</td>
<td>7.1</td>
<td>1,583</td>
<td>59%</td>
</tr>
<tr>
<td>Portland 1</td>
<td>Lined cast iron</td>
<td>6&quot;</td>
<td>1960</td>
<td>40-80</td>
<td>0.350</td>
<td>20,485</td>
<td>90.3</td>
<td>6.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Portland 2</td>
<td>Lined cast iron</td>
<td>6&quot;</td>
<td>1960</td>
<td>40-80</td>
<td>0.388</td>
<td>17,332</td>
<td>-</td>
<td>6.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Portland 3</td>
<td>Lined cast iron</td>
<td>4&quot;</td>
<td>80-100</td>
<td>0.405</td>
<td>9,662</td>
<td>-</td>
<td>83.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>40-80</td>
<td>0.514</td>
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<td>-</td>
<td>87.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>Portland 5</td>
<td>Unlined cast iron</td>
<td>8&quot;</td>
<td>1953</td>
<td>80-100</td>
<td>0.449</td>
<td>21,324</td>
<td>99.9</td>
<td>5.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PSWC 1</td>
<td>Unlined cast iron</td>
<td>6&quot;</td>
<td>1948</td>
<td>&gt; 100</td>
<td>0.437</td>
<td>23,589</td>
<td>100.5</td>
<td>7.7</td>
<td>10,780</td>
<td>18.4%</td>
</tr>
<tr>
<td>PSWC 2</td>
<td>Lined cast iron</td>
<td>6&quot;</td>
<td>1950</td>
<td>&gt; 100</td>
<td>0.416</td>
<td>9,815</td>
<td>-</td>
<td>8.0</td>
<td>3,590</td>
<td>30.6%</td>
</tr>
</tbody>
</table>
Sample | Material       | Diameter | Installation Year | Pressure (psi) | Wall thickness (in) | Modulus of rupture (psi) | Fracture toughness (Mpa*m1/2) | pH | Resistivity (ohm-cm) | Moisture content (%) |
-------|----------------|----------|-------------------|----------------|---------------------|--------------------------|----------------------------|----|----------------------|---------------------|
PSWC 3 | Lined cast iron | 6"       | 1923              | -              | 0.464               | 11,415                   | 77.1                       | 8.0 | 4,180                | 32.1                |
PSWC 4 | Unlined cast iron | 8"      | 1951              | > 100          | 0.424               | 18,618                   | -                          | 7.2 | 3,080                | 31.1                |
UWNJ 1 | Unlined cast iron | 8"      | 1921              | 80-100         | 0.467               | -                        | 6.6                       | 1,860 | 35.9%                |
UWNJ 2 | Unlined cast iron | 6"      | -                 | 80-100         | 0.396               | -                        | 8.2                       | 2,770 | 27.5%                |
UWNJ 3 | Unlined cast iron | 6"      | -                 | 80-100         | 0.461               | 8,221                    | -                          | 8.2 | 4,230                | 27.3%               |
UWNJ 4 | Unlined cast iron | 6"      | -                 | 80-100         | 0.365               | -                        | 7.9                       | 1,170 | 22.1%                |
UWNJ 5 | Unlined cast iron | 6"      | -                 | 80-100         | 0.408               | 6,768                    | 17.8                      | 7.1  | 1,870                | 17.2%               |
UWNJ 6 | Unlined cast iron | 8"      | 1921              | 80-100         | 0.466               | 8,503                    | 61.4                      | 6.6  | 1,860                | 35.9%               |
UWNJ 7 | cast iron        | 6"      | -                 | 80-100         | 0.395               | 10,119                   | -                         | 7.9  | 1,170                | 22.1%               |
UWNJ 8 | cast iron        | 6"      | -                 | 80-100         | 0.303               | 8,538                    | -                         | 7.6  | 2,200                | 27.7%               |
UWNJ 9 | cast iron        | 6"      | -                 | 80-100         | 0.442               | 9,123                    | -                         | 8.2  | 4,230                | 27.3%               |
UWNJ 10| cast iron        | 6"      | 1961              | 80-100         | 0.393               | 19,776                   | -                         | 6.8  | 1,370                | 26.8%               |

3.6.8 Data Management

Collecting the appropriate water main break data is only the first step in the use of these data to develop water main renewal programs. Some utilities have been collecting water main break data for many years. Although these data might often have only basic information, due to the long span of time covered by the data, valuable input to the decision-making process might be provided. However, if the data is only available in paper records and not organized in a useful fashion, then the utility of the data might be limited.

Utilities should plan for management of the water main break data as carefully as they plan for its collection. In the simplest form, a computer database of water main breaks should be created. This database should include fields for all of the data that a utility is or will collect. Ideally, the database would be linked to a computerized water main inventory. One of the recommended (see Figure 3.3 and Figure 3.4) “Office Data” fields is Pipe ID. Using the same Pipe ID in both the water main break database and the water main inventory facilitates data analysis.

More sophisticated data management systems would link customer service information systems, water main inventories, break databases, and work management systems (WMS) to provide a comprehensive data set for analysis. The customer information system would capture
the initial identification of the problem, the water main inventory and break databases would provide the specific information related to the pipe and the break events, and the WMS would provide detailed cost information.
Chapter 4 - Pipe Deterioration (PDM) and Statistical Correlation Models (SCM)

4.1 Introduction

The formulation of the two models used for assessing the pipe’s strength at any time is discussed in this chapter. These are the pipe deterioration and statistical correlation models. The ultimate goal of the pipe deterioration model is to determine the reduction the pipe’s strength or load bearing capacity over time. The load capacity of the pipe is dependent on the wall thickness and the material strength. This model can be used to relate the factors that promote the deterioration of a pipe over time to the growth of pits in the pit wall. The model addresses only external corrosion due to corrosive soil conditions, as indicated by soil pH, resistivity, and soil aeration. In the Statistical Correlation Model (SCM), data collected on pipe conditions over time are be used to develop an adjustment factor that relates the computed deterioration (corrosion) with expected measured values. The formulation of the two models is discussed as an integral process. These two models focus on the external corrosion of the pipe. This research did not involve modeling internal corrosion. Figure 4.1 illustrates the steps involved in the formulation of the pipe deterioration model. Pipe material properties are used in conjunction with surrounding soil properties to determine the growth of corrosion pits on the external walls over time. These pits are the used in conjunction with the strength properties (Fracture toughness and material strength) to determine the failure stress for the pipe as a result of the corrosion pit.

Corrosion pits, created by corrosion of the ferrous material, cause the strength of the material to be reduced. The pits also have the effect of concentrating stresses around the vicinity of the corrosion pits. Figure 4.2 shows the general location of corrosion pits on a deteriorating pipe. It is assumed that the actual material strength does not change with time but the pipe’s structural integrity is compromised over time as a result of the exacerbation of flaws within the material by corrosion and imposed stresses.
Correlate pipe properties with soil properties and time to determine pit depth

External, pit depth:

\[ p_e = f(\text{Soil, Pipe Properties, time}) \]

Soil Sample

Pipe Sample

Field and Lab Tests

Soil Property: pH, Moisture, Resistivity, Aeration

Pipe Property: pit depth, areal extent, diameter, length, age, corrosion protection

Material Properties: Design Strength, Fracture Toughness

Failure Stress/Residual Strength

Figure 4.1 Pipe deterioration model

LEGEND

- \( a \) = effective thickness
- \( b \) = internal corrosion
- \( c \) = external corrosion
- \( d \) = tuberculation
- \( e \) = disrupted bedding
Figure 4.2 Illustration of reduced pipe wall thickness and loss of bedding support for a buried pipe

The growth of corrosion pits can be modeled by analyzing the electrochemical reaction that occurs between the pipe and the surrounding media. Consider the total mass, m (grams) corroded at time, t, given by Faraday’s law

\[ m = \left( \frac{It}{nF} \right) M \]  

(4.1)

\[ F = 1 \text{ faraday} = \text{electric charge contained in 1 mole electrons} = 96500 \text{ coulombs/mol} \]

\[ M = \text{molar mass of oxidizing agent in grams} \]

\[ t = \text{time in seconds} \]

\[ I = \text{current in Amperes (coulombs/sec)} \]

\[ n = \text{number of moles of electrons transferred from the reducing agent to oxidize 1 mol of the oxidizing agent in the overall redox equation.} \]

For example consider the half cell reactions for the electrolytic cell containing molten CaCl₂

**Anode:** \[ 2\text{Cl}^- \rightarrow \text{Cl}_2(g) + 2e^- \]  

(4.2)

**Cathode:** \[ \text{Ca}^{2+} + 2e^- \rightarrow \text{Ca}(l) \]  

(4.3)

\[ \text{Ca}^{2+} + 2\text{Cl}^- \rightarrow \text{Ca}(l) + \text{Cl}_2(g) \]  

(4.4)

The quantities of Ca metal and Cl₂ gas formed depend on the number of electrons that pass through the electrolytic cell which in turn depends on the current I, and time duration t or the total charge C. The cathode reaction tells that 2F charge carried by the electrons is required to reduce one mol of Ca²⁺ ions.
Therefore the term within parentheses in Eq. (4.1) accounts for number of moles of the oxidizing agent obtained as the ratio of total charge, $I t$, and the charge, $nF$, required to oxidize one mol of the cation.

The ratio $M/n$ is also known as the equivalent mass. Eq. (4.1) is the Faraday’s law. From Eq. (4.1), we can obtain corrosion mass rate, $r_m$ (g/cm²·sec) per unit surface area as

$$r_m = \frac{m}{A t} = \frac{i M}{n F}$$  \hspace{1cm} (4.5)

in which: $i = I/A$ (Amperes/cm²) = current density, $A =$ surface area. We can convert corrosion mass rate, $r_m$ to corrosion rate, $r$, in depth units by dividing $r_m$ by the density of the metal, $\rho_m$ and therefore

$$r = \frac{r_m}{\rho_m} = \frac{i M}{n F \rho_m}$$  \hspace{1cm} (4.6)

If we assume a hemispherical shape for a corrosion pit and further assume only one such pit is being formed, we may write Eq (4.1) as

$$\frac{2 \pi r^3 \rho_m}{3} = \left( \frac{I t}{F} \right) \left( \frac{M}{n} \right)$$  \hspace{1cm} (4.7)

and

$$r^3 = \frac{3 \left( \frac{M}{n} \right) \left( \frac{I t}{\rho_m F} \right)}{2 \pi}$$  \hspace{1cm} (4.8)

in which: $r =$ radius of the pit. Rossum (1969) exploited Eq (4.8) to obtain semi-empirical equations for pitting rates in ferrous metals as dictated by soil parameters.

Clearly, the current I is the most troublesome quantity to estimate Eq.(4.8). The current is related by the potential difference, $E$ and resistivity, $R$. The potential difference for a cell can be obtained from the Nernst equation given by
\[ E = E^o - \frac{2.303RT}{nF} \log_{10} Q \]  

(4.9)

in which: \( E^o \) = standard potential difference, \( R = \) universal gas constant = 8.314J/K.mol, 
\( n = \) number of moles of electrons, \( F = 96500 \) coulombs/mole, 
\[ Q = \frac{[C]^c[D]^d}{[A]^e[B]^f} \] = reaction quotient 
and \( aA + bB \rightleftharpoons cC + dD \), \( Q \) is computed at a point other than the equilibrium point, the \([.]\) quantity is the concentration and the exponent is the stoichiometric coefficient. Note that when hydrogen ions are involved \( \log_{10} Q \) leads to \( \text{pH} \). Therefore, Rossum formulated an equation for the pit depth, \( p \) as

\[ p = K_n K_a \left( \frac{10 - pH}{\omega} \right)^a T^n A^a f^a \]  

(4.10)

in which:
\( p \) = pit depth, mils
\( K_n \) and \( n \) = constants dependent on the soil aeration
\( pH \) = soil \( \text{pH} \)
\( \omega \) = the soil resistivity, ohm/cm
\( A \) = the area of pipe exposed to the soil, ft\(^2\)
\( K_a \) and \( a \) = constants dependent on the pipe material
\( f \) = fraction of pipe exposed to corrosion
\( T \) = the time of exposure, years

Revie (2000) provides a comprehensive review. The corrosion estimation is in general obtained from regression equations and charts. Because of its theoretical basis and the use of the long term observed data (Romanoff, 1957), in this dissertation a modified form of the Rossum’s equation is developed with the aid of regression analysis.

The Rossum model was initially used in its original form to model the growth of corrosion pits in the pipe wall. The resulting effects of these pits indicated that a majority of the pipe’s strength was being lost just within the first year. This observation led to a closer
examination of the Rossum model. It was determined that according to the Rossum model, the amount of yearly pit growth is maximum in the first year and then the decreases in the subsequent years. Figure 4.3 illustrates the differences in the yearly incremental pit depth for pipe id ED-2. From the figure, it seen that the incremental pit depth for year 1 is about 3 times that of year 2. This large difference can be partly explained by the nature of the Rossum corrosion model. The model assumes that the pit growth in a hemispherical shape hence for the same yearly volume of material corroded, the incremental pit depth would decrease over time. The effect of this large pit growth is magnified when the pit depth is used to determine the residual strength of the pipe. In order to calibrate the Rossum model, a comparison was made between computed pit depth from the Rossum model and pit depths observed from pipe samples from the field. A modified version of the Rossum equation was therefore developed and used to model the pit growth. With data collected from actual pipe samples and soil samples, it was possible to determine how well the Rossum model was able to predict actual pit growth on pipes. Table 4.1 contains pipe corrosion pits measured from pipe samples and the corresponding soil parameters. The soil parameters were used in the Rossum model to compute the corrosion pit and the resulting values were compared with the actual measured pit depths.
4.2 Statistical Correlation Model (SCM)

The goal of the statistical correlation model (SCM) is to determine how well the Rossum model approximates the corrosion pit growth and to determine and adjustment factor or determine a modified form of the model more appropriate for modeling the corrosion of the pipes. In this analysis, the pipes were all assumed to be of an 18 foot length and the fraction exposed was assumed to be 1. Figure 4.4 shows a flow chart of fitting the statistical correlation model.

Based on the effect of the year 1 incremental pit depth, two formulations were used to determine the adjustment factor. These are:

Formulation 1:

\[
\text{MAPD} = \alpha \times \text{RPDt}
\]  

(4.11)

Where:

\(\text{MAPD} = \) measured average pit depth of pipe sample, in
RPDt = pit depth computed using Rossum model at year t, in
\( \alpha \) = constant of proportionality

Formulation 2:

\[
MAPD = \beta \ast (RPDt \ominus RPD1)
\]  \hspace{1cm} (4.12)

Where:

\( \beta \) = constant of proportionality

RPD1 = pit depth computed using Rossum model at year 1, in.

Figure 4.5 and Figure 4.6 show the regression for both formulations. The \( r^2 \) for both indicates a lack of correlation between either MAPD and RPDt or MAPD and (RPDt \ominus RPD1). A filtration criterion was then used to attempt eliminate possible outliers. For each of the samples, the parameter \((RPDt \ominus RPD1)/MAPD = 1/\beta \) was computed (see Table 4.2). The average and standard deviation of \( 1/\beta \) were determined as 2.15 and 1.31 respectively. The regression was then performed on data fitting three different categories:

- within 1 standard deviation of the average
- within 0.9 standard deviation of the average
- within 0.8 standard deviation of the average

The resulting regression fits are shown in Figure 4.7 through Figure 4.12. There is no reasonable correlation for both formulation 1 and formulation 2 when data within 1 standard deviation is considered (see Figure 4.7 and Figure 4.8). An improvement is seen for data within 0.9 standard deviation but a better correlation is obtained when data within 0.8 standard deviation are considered (see Figure 4.11 and Figure 4.12). This results in an \( r^2 \) of 0.4069 and a \( \beta \) value of 0.6183.
### Table 4.1 Soil and Pipe Sample Data

<table>
<thead>
<tr>
<th>SampleID</th>
<th>Pipe Age (yrs)</th>
<th>Pipe Type</th>
<th>Pipe Size (mm)</th>
<th>pH</th>
<th>Aeration</th>
<th>In Situ Resistivity (ohm-cm)</th>
<th>Average Pit Depth (mm)</th>
<th>Average Pit Depth (in)</th>
<th>Rpdt (in)</th>
<th>Rpdt (in)</th>
<th>Rpdt-Rpdt (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MN-4</td>
<td>49</td>
<td>spun cast</td>
<td>175</td>
<td>6.90</td>
<td>poor</td>
<td>5967</td>
<td>3.35</td>
<td>0.132</td>
<td>0.024</td>
<td>0.171</td>
<td>0.146</td>
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<tr>
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<td>spun cast</td>
<td>175</td>
<td>6.70</td>
<td>poor</td>
<td>8350</td>
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<td>0.021</td>
<td>0.131</td>
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<td>spun cast</td>
<td>175</td>
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<td>poor</td>
<td>1300</td>
<td>1.41</td>
<td>0.056</td>
<td>0.046</td>
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<tr>
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<td>poor</td>
<td>6700</td>
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<td>0.156</td>
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<td>75</td>
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<td>225</td>
<td>6.00</td>
<td>good</td>
<td>240</td>
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<td>0.091</td>
<td>0.270</td>
<td>0.558</td>
<td>0.268</td>
</tr>
<tr>
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<td>spun cast</td>
<td>175</td>
<td>7.00</td>
<td>fair</td>
<td>410</td>
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<td>0.201</td>
<td>0.132</td>
<td>0.366</td>
<td>0.234</td>
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<tr>
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<td>spun cast</td>
<td>175</td>
<td>7.70</td>
<td>poor</td>
<td>515</td>
<td>5.50</td>
<td>0.216</td>
<td>0.071</td>
<td>0.410</td>
<td>0.339</td>
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<td>ED-3</td>
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<td>poor</td>
<td>470</td>
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<td>fair</td>
<td>1100</td>
<td>1.33</td>
<td>0.052</td>
<td>0.091</td>
<td>0.307</td>
<td>0.216</td>
</tr>
<tr>
<td>MN-2</td>
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<td>spun cast</td>
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<td>poor</td>
<td>634</td>
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<td>0.233</td>
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<td>7.10</td>
<td>fair</td>
<td>422</td>
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<td>0.123</td>
<td>0.129</td>
<td>0.410</td>
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<td>spun cast</td>
<td>175</td>
<td>7.90</td>
<td>fair</td>
<td>1260</td>
<td>2.97</td>
<td>0.117</td>
<td>0.081</td>
<td>0.262</td>
<td>0.181</td>
</tr>
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<td>pit cast</td>
<td>175</td>
<td>7.90</td>
<td>good</td>
<td>11000</td>
<td>1.77</td>
<td>0.069</td>
<td>0.130</td>
<td>0.275</td>
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</tr>
<tr>
<td>TO-2</td>
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<td>pit cast</td>
<td>175</td>
<td>8.20</td>
<td>good</td>
<td>1900</td>
<td>4.45</td>
<td>0.175</td>
<td>0.168</td>
<td>0.328</td>
<td>0.160</td>
</tr>
<tr>
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<td>pit cast</td>
<td>175</td>
<td>7.90</td>
<td>good</td>
<td>5589</td>
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<td>0.095</td>
<td>0.145</td>
<td>0.307</td>
<td>0.162</td>
</tr>
<tr>
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<td>175</td>
<td>5.80</td>
<td>good</td>
<td>1575</td>
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<td>0.049</td>
<td>0.198</td>
<td>0.355</td>
<td>0.157</td>
</tr>
<tr>
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<td>spun cast</td>
<td>175</td>
<td>5.00</td>
<td>good</td>
<td>1560</td>
<td>1.10</td>
<td>0.043</td>
<td>0.204</td>
<td>0.381</td>
<td>0.176</td>
</tr>
<tr>
<td>BS-3</td>
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<td>pit cast</td>
<td>225</td>
<td>6.10</td>
<td>good</td>
<td>2455</td>
<td>3.14</td>
<td>0.124</td>
<td>0.193</td>
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Table 4.2 Computed and Measured Pit Depths (Filtered and Non-Filtered)

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<th>Rpd (in)</th>
<th>Rpdt (in)</th>
<th>Rpdt-Rpd1 (in)</th>
<th>(Rpdt-Rpd1) / avgpitd</th>
<th>Average Pit Depth (in) within 100% Stdev</th>
<th>Rpdt-Rpd1 (in) within 90% stdev</th>
<th>Rpdt-Rpd1 (in) within 80% stdev</th>
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<td>(Rpdt-Rpd1) / avgpitd</td>
<td>Average Pit Depth (in) within 100% Stdev</td>
<td>Rpdt-Rpd1 (in) within 90% Stdev</td>
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<td>7.68</td>
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</table>

Average: 2.15
St. Dev: 1.31
Figure 4.5 Formulation 1 (Non Filtered)

Figure 4.6 Formulation 2 (Non Filtered)
Average Pit Depth vs Pit Depth at year t - Filtered (Within 1 stdev)

\[ y = 0.3443x \]

\[ R^2 = -0.2436 \]

Figure 4.7 Formulation 1 (Filtered within 1 Standard Deviation)
Figure 4.8 Formulation 2 (Filtered within 1 Standard Deviation)

Figure 4.9 Formulation 1 (Filtered within 0.9 Standard Deviation)
Average Pit Depth vs Pit Depth at year t minus Pit Depth at year 1 - Filtered (With 0.9 Stdev)

\[ y = 0.5688x \]

\[ R^2 = 0.1054 \]

Figure 4.10 Formulation 2 (Filtered within 0.9 Standard Deviation)

Average Pit Depth vs Pit Depth at year t - Filtered (Within 0.8 stdev)

\[ y = 0.3933x \]

\[ R^2 = 0.1206 \]
Figure 4.11 Formulation 1 (Filtered within 0.8 Standard Deviation)

\[ y = 0.6183x \]
\[ R^2 = 0.4069 \]

Figure 4.12 Formulation 2 (Filtered within 0.8 Standard Deviation)

The Rossum model is modified to better fit the data trend as follows:

\[ p = 0.6183 f^n A^a K_n K_a \left[ \frac{(10 - pH)}{\omega} \right]^n (T^n - 1^n) \]  
(4.13)

The generalized form of the modified equation can be written as

\[ p = \Phi A^a f^n K_n K_a \left[ \frac{(10 - pH)}{\omega} \right]^n (T^n - \Theta^n) \]  
(4.14)

where \( \Phi = 0.6183 \) and \( \Theta = 1 \)
The values of \( n \) and \( K_a \) in the Rossum equation are determined from the following Table 4.3:

Table 4.3 Soil aeration constants for use in Rossum corrosion pit growth equation

<table>
<thead>
<tr>
<th>Soil Aeration</th>
<th>( n )</th>
<th>( Kn )</th>
</tr>
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<tr>
<td>Good</td>
<td>0.16</td>
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</tr>
<tr>
<td>Fair</td>
<td>0.33</td>
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</tr>
<tr>
<td>Poor</td>
<td>0.50</td>
<td>355</td>
</tr>
</tbody>
</table>

Source: Rossum 1969.

For cast iron \( K_a = 1.40, \ a=0.22 \)

4.3 Determination of Fraction Exposed:

A critical parameter that is difficult to determine in the Rossum equation is the fraction of the pipe surface area exposed to the corrosive condition. This section describes a simple method to estimate the fraction of the pipe exposed.

The regression analysis produced the modified Rossum equation of the form

\[
p = \Phi A^a f^a K_n K_a \left[ \frac{(10 - pH)}{\omega} \right]^n (T^n - \Theta^n) \tag{4.15}
\]

where \( \Phi \) is the regression coefficient and \( \Theta = 1 \).

If it is assumed that at the time of first failure, \( T_{fi} \), the failure occurred at the worst segment of the pipe, then the fraction of pipe exposed could be determined by solving for \( f \) from equation (4.15). Thus,

\[
f = \left[ \frac{p}{\Phi A^a K_n K_a \left[ \frac{(10 - pH)}{\omega} \right]^n (T^n - \Theta^n)} \right]^{1/a} \tag{4.16}
\]
4.4 Determination of Residual Pipe Wall thickness

At any time, the remaining pipe wall thickness can be determined as a function of the pit depth and the design wall thickness. Therefore, if the $T_a$ is the time of analysis, the thickness at time $T_a$ is defined as:

$$t_a = D_i - \Phi A^a f^n K_n K_a \left[ \frac{(10 - \rho H)^n}{\omega} \right] (T_a^n - \Theta^n) \quad (4.17)$$

where $D_i$ is the design thickness and $t_a$ is the thickness at time of analysis.

4.5 Failure Stress/Residual Strength

4.5.1 Fracture Toughness

The discussion related to fracture toughness closely follows Flinn and Trojan (1990). Failures occur in many components even when the operating stress is well below the yield stress. Generally such failures are due to stresses in particular regions that have been amplified by the presence of holes, cracks, and other discontinuities around which the stress exceed the strength. The capacity of a particular flaw to cause failure depends on the material property called fracture toughness. However, the stress concentration at the edge of the flaw depends on the geometry of the flaw and the geometry of the component but not on the properties of the material. An equation that relates the fracture stress and the fracture toughness is:

$$\sigma = \frac{K_{IC}}{Y \sqrt{\pi a}} \quad (4.18)$$

where

$K_{IC}$ = Fracture toughness , psi$\sqrt{\text{in}}$

$\sigma$ = nominal stress at fracture, psi

$a$ = a measure of crack length, in
Y = a dimensionless correction factor that accounts for the geometry of the component containing the flaw

Equation (4.18) specifies a threshold stress level as well as provides a flaw size towards failure (i.e., the residual strength of the pipe). In the corrosion of buried pipes, a corrosion pit present on the pipe can be considered as a notch in the pipe wall. If the corrosion pit is assumed to have a hemispherical shape, then the reduction in the pipe strength can be accounted for by modifying a methodology developed by Smith (1977) to determine the effect of a notch on the strength of a material. In the article, Smith showed that the relationship between the fracture toughness, material plain fatigue strength, and notch depth can be represented by:

\[
2 - 1 + 4 \frac{y}{r_n} = \frac{4}{\pi r_n} \left( \frac{K_0}{1.12 \sigma_{nom}} \right)^2
\]

(4.19)

where 

- \( y \) = the depth of the notch, in
- \( r_n \) is the radius of the root of the notch, in
- \( \sigma_0 \) is the plain fatigue strength of the material, psi
- \( \sigma_{nom} \) is the smallest stress level to cause complete failure, psi
- \( K_0 \) is the fracture toughness of the material, psi√in

For the use of this equation in the current model, some assumptions must be made. The radius of the notch root is assumed to be equal to the notch depth (\( y = r_n \)). This reduces equation (4.19) to:

\[
\left( 1 + 2 \sqrt{\frac{y}{r_n}} \right) \frac{\sigma_{nom}}{\sigma_0} - 1 + 4 \left( \frac{y}{r_n} \right) = \frac{4}{\pi r_n} \left( \frac{K_0}{1.12 \sigma_{nom}} \right)^2
\]

(4.20)

\[
3 \left( \frac{\sigma_{nom}}{\sigma_0} \right)^2 + 3 = \frac{4}{\pi r_n} \left( \frac{K_0}{1.12 \sigma_{nom}} \right)^2
\]

(4.21)
Multiplying through by $\sigma^2$ leads to:

$$\sigma_{\text{nom}}^4 \left( \frac{3}{\sigma_0} \right)^2 + 3 \sigma_{\text{nom}}^2 - \frac{4}{\pi r_n} \left( \frac{K_0}{1.12} \right)^2 = 0$$

(4.22)

This is a quadratic equation of the form:

$$ax^2 + bx + c = 0$$

(4.23)

$$x = \sigma_{\text{nom}}^2$$

(4.24)

$$a = \left( \frac{3}{\sigma_0} \right)^2$$

(4.25)

$$b = 3$$

(4.26)

$$c = -\frac{4}{\pi r_n} \left( \frac{K_0}{1.12} \right)^2$$

(4.27)

From the preceding equation, $\sigma_{\text{nom}}^2$ can be determined as:

$$\sigma_{\text{nom}}^2 = \frac{-3 \pm \sqrt{9 + 4 \left( \frac{3}{\sigma_0} \right)^2 \frac{4}{\pi r_n} \left( \frac{K_0}{1.12} \right)^2}}{2 \left( \frac{3}{\sigma_0} \right)^2}$$

(4.28)

$$\sigma_{\text{nom}}^2 = \frac{-3 \pm \sqrt{9 + 4 \left( \frac{1}{\sigma_0} \right)^2 \frac{4}{\pi r_n} \left( \frac{K_0}{1.12} \right)^2}}{2 \cdot 3^2 \left( \frac{1}{\sigma_0} \right)^2}$$

(4.29)
\[ \sigma_{\text{nom}} = \frac{-\beta \pm \sqrt{1 + 4 \left( \frac{1}{\sigma_0} \right)^2 \left( \frac{4}{\pi r_n} \frac{K_0}{1.12} \right)^2}}{2 \cdot 3 \left( \frac{1}{\sigma_0} \right)^2} \]  

(4.30)

\[ \sigma_{\text{nom}} = \frac{-1 \pm \sqrt{1 + 4 \left( \frac{1}{\sigma_0} \right)^2 \left( \frac{4}{\pi r_n} \frac{K_0}{1.12} \right)^2}}{6 \frac{6}{\sigma_0^2}} \]  

(4.31)

\[ \sigma_{\text{nom}} = \frac{\sigma_0^2}{6} \left( -1 + \sqrt{1 + \frac{12.75}{\pi r_n} \left( \frac{K_0}{\sigma_0} \right)^2} \right) \]  

(4.32)

Taking the positive value of the equation since \( \sigma_{\text{nom}} \) cannot be negative,

The resulting equation represents the smallest stress required to cause a failure in the pipe. This stress is taken as the residual strength of the pipe as a result of corrosion pits occurring in the walls.

\[ \sigma_{\text{nom}} = \frac{\sigma_0^2}{6} \left( -1 + \sqrt{1 + \frac{12.75}{\pi r_n} \left( \frac{K_0}{\sigma_0} \right)^2} \right) \]  

(4.33)

A pipe’s vulnerability is assumed to be controlled by the ratio of each of four major strength parameters to the stresses on the pipe. These strength parameters are tensile strength, bursting tensile strength, modulus of rupture, and ring modulus. For each of these strengths, the above equation is used to compute the residual strength. The residual strength is then used in PBM to determine the pipe’s vulnerability. Equation (4.33) shows how the design \( \sigma_0 \) reduces to \( \sigma_{\text{nom}} \) as the design thickness is reduced by the corrosion pit depth, \( r_n \).
5.1 Introduction

The PLM model accounts for all the loads acting on a buried pipe. These loads fall into two main categories: external (traffic or live load, earth load, and frost load, expansive soil load, temperature induced expansion/contraction load) and internal (working pressure, surge pressure, and thermally induced pressure change). Though the expansion and contraction load has been classified as external load, it may be induced by the change in temperature of the water flowing through the pipe.

There are also other events which lead to failure rather quickly but do not follow a well defined pattern. These events include: (1) higher truck and overburden loads, (2) bedding disruption leading to beam action, (3) frost load, and (4) temperature induced stresses. Frost load leads to two phenomena, (1) an efficient transfer of over burden load to the pipe and increased load from the ice, and (2) the anomalous expansion of liquid pore water within the soil leading to an increase in load stemming from the volumetric strain. The increased load from the second effect is considered more significant than the first one. The efficient transfer of superimposed loads by the ice lenses can be modeled by the Boussinesq equation (Fielding and Cohen, 1988).

A significant number of failures are attributed to poor bedding condition. When bedding is disrupted the pipe is subject to beam action which might not have been accounted for in the original design. While a design might be based a particular type of bedding, under disturbed conditions that assumption is violated. Also, the bedding disturbance can vary the support length due to the erosion of bed material which is a crucial factor. According to DIPRA, interviews with water utility managers and pipe line repair crews indicate that the failures from frost loads occur as a combination of bedding disruption causing the pipe to act as beam and frost load exceeding the pipe beam strength.

The temperature related effects are due to significant temperature fluctuations. There is also evidence that more breaks occur when the first encounter with freezing temperature occurs. A stress-strain calculation yields a tensile stress of about 1371 psi for a temperature drop from
39°F to 32°F. This increased stress coupled with the loss of strength due to corrosion and the nature of the joints and poor bedding can all accelerate the failure. A large number of utilities attribute their pipe failures to the temperature effects (Wedge1996).

5.2 Sources and Computation of Loads on Buried Pipes

The loads related to pipe failure and their interaction are shown in Figure 5.1 and Figure 5.2 respectively.

Figure 5.1 Illustration of external and internal loads on a buried pipe

<table>
<thead>
<tr>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{\text{earth}} ) = Earth Load</td>
</tr>
<tr>
<td>( L_{\text{frost}} ) = Frost Load</td>
</tr>
<tr>
<td>( L_{\text{traffic}} ) = Traffic Load</td>
</tr>
<tr>
<td>( L_{\exp} ) = Expansive Soil Load</td>
</tr>
<tr>
<td>( P_w ) = Working Pressure</td>
</tr>
<tr>
<td>( P_s ) = Surge Pressure</td>
</tr>
<tr>
<td>( P_{\text{therm}} ) = Thermally Induced Pressure</td>
</tr>
</tbody>
</table>
5.2.1 Earth load.

The computation of earth loads on a pipe is dependent on the type of installation or ditch condition used. For ditch condition, the pipe laid is relatively narrow trench backfilled to original ground surface (CIPRA 1978). Trench width at the top of the pipe determines the earth load. The trench width may be widened for installation without increasing the load on pipe. For the model, the bedding type was chosen as type A. Under bedding type A, the pipe is laid on flat bottom trench, backfill not tamped.

The calculations are based on the recommended procedure outlined by ANSI/AWWA C101 as described in the Cast Iron Pipe Research Association Handbook (CIPRA). The general earth load per lineal foot is given by:
\[ W_e = C_d \rho B_d^2 \]  \hspace{1cm} (5.1)

where  \( W_e \) = earth load, lb/linear ft
\( C_d \) = a calculation coefficient
\( \rho \) = soil density, lb/ft\(^3\)
\( B_d \) = the trench width, ft

The actual values of \( C_d \) and \( B_d \) depend on the depth of cover, earth pressure, soil friction, and the type of ditch condition used.

\[ C_d = \frac{1 - e^{-\frac{(2K_r\mu'H)}{B_d}}}{2K_r\mu'} \]  \hspace{1cm} (5.2)

where
\( K_r \) = ratio of active horizontal pressure at any point in the fill to the vertical pressure which causes the active horizontal pressure.
\( \mu' \) = coefficient of sliding friction between fill materials and sides of trench
\( K_r\mu' = 0.130 \) for standard calculations
\( H \) = depth of cover to top of pipe

5.2.2 Traffic load (\( W_t \)).

The ANSI/AWWA C101 also describes the calculation of expected loads due to trucks depending on the following conditions: pavement type (unpaved, flexible, or rigid pavement); one or two passing trucks; wheel load; and impact factor. For unpaved or flexible pavement, the equation used is:

\[ W_t = CRPF \]  \hspace{1cm} (5.3)

and for rigid pavement,
\[ W_t = KDPF \]  \hspace{1cm} (5.4)

where

- \( W_t \) = truck superload (lb/lin ft)
- \( C \) = surface load factor for unpaved of flexible pavement. C values can be obtained from the CIPRA Handbook (Tables 1-11 and 1-12)
- \( R \) = reduction factor, accounting for the part of the pipe directly below the wheels (See Table 1-13 in CIPRA Handbook)
- \( P \) = wheel load (lb) (Standard, \( P = 9,000 \) lb)
- \( F \) = Impact factor (Standard, \( F = 1.50 \))
- \( K \) = surface load factor for rigid pavement (see Table 1-14 in CIPRA Handbook)
- \( D \) = outside diameter of pipe (ft) (see Table 1-15 in CIPRA Handbook)

5.2.3 Expansive Soil Load

Expansive soil load estimation. Issa (1997) derived the following set of equations through experimentation to help predict the swelling pressure based on the moisture content of a soil.

\[ P_{sw} = \alpha_1 (w_L - 46) \text{ when } 9.4\% \leq w_0 \leq 16.2\%; \]  \hspace{1cm} (5.5)

\[ P_{sw} = \alpha_2 (w_L - 56) \text{ when } 21.4\% \leq w_0 \leq 27.5\%; \]  \hspace{1cm} (5.6)

\[ P_{sw} = \alpha_3 (w_L - 77) \text{ when } 32.5\% \leq w_0 \leq 33.1\%; \]  \hspace{1cm} (5.7)

where

- \( \alpha_1 = 0.0300 \text{ MPa (626 psf)} \)
- \( \alpha_2 = \alpha_3 = 0.0245 \text{ MPa (511 psf).} \)
- \( W_L \) = the limiting soil moisture content, % by volume
- \( W_0 \) = the initial soil moisture content, % by volume
- \( P_{sw} \) = the swelling pressure, MPa
The soil moisture content will have to be measured from the field and the soil swelling pressure will be estimated using Issa’s equations. The discontinuity of the soil moisture range in the Issa’s work is compromised by extending the range of the equation through half way of the discontinuous part. For example, Eq. (5.5) will be valid up to 18.6% as opposed to the original 16.2%; and Eq. (5.6) will be valid from 18.601% instead of the original 21.4%.

In this research, it was discovered that the actual soil loads obtained from the Issa model produced relatively large loads. In a sample calculation for a 6 inch pipe buried at 5ft depth in a soil of liquid limit 70% and initial moisture content of 25%, the Issa model produced a load of 3600 lb/ft whereas the earth load and traffic load were 657lb/ft and 189lb/ft respectively. Though the value obtained from the Issa model seemed to be relatively large compared to the earth and traffic loads, lateral pressure values reported by Katti (1994) range from 2 kg/cm² (4096lb/ft² or 2048lb/ft) to about 7.9kg/cm² (16179.2lb/ft² or 8089lb/ft). These values were obtained from odeometer tests in the lab. According to Katti, swelling pressures from soils with clay content less than 30% was found to be zero. Also the ratio between the lateral and vertical pressures was found to be close to one. In light of these values, it is recommended that the incorporation of expansive soils in the mechanistic model should be done with care as the computed loads from expansive soils alone could dictate the estimation of the condition of the pipe.

5.2.4 Frost load estimation

The PLM accounts for frost loads in three ways. Based on Monie and Clark (1974), DIPRA (1986), and Fielding and Cohen (1988) the frost load is taken to be twice the earth load; or an explicit frost load magnitude; or, the frost load calculation due to Rajani and Zhan (1996). A summary of the Rajani and Zahn’s model is presented in Appendix C.

The frost load computed from Rajani and Zahn is adjusted as follows:

\[
W_{adj} = \frac{F_{d, max}}{F_{d, c}} * W_{frz}
\]

where

\[W_{adj} = \text{the adjusted frost load, lb/ft}\]
\[W_{frz} = \text{the frost load computed from the Rajani and Zahn equation, lb/ft}\]
Fd_{max} = the maximum frost depth supplied by the user, in
Fd_c = the frost depth computed from the Rajani and Zahn equation, in
Besides computing the frost load, the model also provides the user with an option to specify a known frost load that may be used in the pipe analysis.

5.2.5 Internal Pressure Loads

This is the actual working pressure of the pipe defined by the ultimate demand the pipe is designed to meet. The longitudinal and hoop stresses resulting from working pressure are calculated below.

5.2.6 Water hammer pressure.

Water hammer pressure results from sudden stopping of flow in the pipe. Its effect depends on how quickly a valve is opened or closed. In the design of pipes the CIPRA manual (1978) recommends a standard allowance for water hammer pressure based on the pipe size. These allowances are given in Table 5.1.
Table 5.1 Allowances for surge pressure for cast iron pipe design

<table>
<thead>
<tr>
<th>Pipe size (in)</th>
<th>Surge pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-10</td>
<td>120</td>
</tr>
<tr>
<td>12-14</td>
<td>110</td>
</tr>
<tr>
<td>16-18</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td>24</td>
<td>85</td>
</tr>
<tr>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>36</td>
<td>75</td>
</tr>
<tr>
<td>42-60</td>
<td>70</td>
</tr>
</tbody>
</table>

Source: CIPRA 1978

The surge pressure resulting from a rapid change in water velocity can be calculated from the following water hammer equations:

\[ a = \frac{4660}{\sqrt{1 + \frac{kd}{Et}}} \]  \hspace{1cm} (5.9)

and

\[ p = \frac{aV}{2.31g} \]  \hspace{1cm} (5.10)

where

- \( a \) = velocity of pressure wave, ft/sec
- \( k \) = fluid bulk modulus, 300,000 psi for water
- \( d \) = pipe diameter, in.
When exposed to a temperature differential, materials tend to expand or contract. In water distribution mains, the expansion or contraction of both the pipe material and the water contained within are of concern. The degree of expansion of water due to temperature change is greater than that of the pipe material volume. Within the pipe, expansion of water leads to extra internal pressure whereas the expansion in the pipe metal leads to the creation of additional stresses in the pipe. The change in pressure due to a rapid change in temperature is given by (Wedge 1996):

\[
\frac{dP}{dT} = \frac{C_{v_e} - 2\alpha(1+\nu)}{1 + \frac{d_i}{k} \frac{1}{tE} (1-\nu^2)}
\]

(5.11)

where \( \alpha = \) Coefficient of linear thermal expansion of pipe wall material
\( C_{v_e} = \) Coefficient of volume thermal expansion of liquid, \( dV/(VdT) \)
\( d_i = \) Original inside diameter of pipe, in.
\( E = \) modulus of elasticity of the pipe, 1,500,000 psi for cast iron
\( k = \) Bulk modulus of liquid, \( -dP/(dV/V) \), psi
\( P = \) Internal pressure in pipe wall; \( S_x \), axial stress, psi;  \( S_y \), hoop stress, psi
\( T = \) Temperature of pipe/liquid system, \( ^\circ F \)
\( t = \) Wall thickness of pipe material, in.
\( \nu = \) Poisson’s ratio of the pipe wall material
In this approach, Wedge assumes a closed pipe system. The assumption for a closed pipe system may not be directly applicable to a water distribution network but the pressure estimates from Wedge’s approach will provide the most conservative values for estimating pressure increases due the water temperature changes. Also, at night when there is the least use of the system, water flow is relatively minimal in the system. The stress induced by a rapid drop in water temperature is transient and resolves when the pipe wall reaches equilibrium with the lower water temperature. A discussion of the Wedge model can be found in Appendix C.

The stresses induced in the pipe wall due to thermal contraction of the pipe material are calculated based upon the assumption that the water distribution system is a rigid grid system that constrains the pipes from contracting when the temperature drops. It is assumed that the pipe grid is in a non-stressed condition at some equilibrium temperature (e.g., the temperature of the pipe at installation). The thermal induced contraction stress remains as long as the pipe temperature is lower than the equilibrium temperature.

The long-term thermal contraction stress is calculated as:

$$\sigma_{1,T} = E \alpha \Delta T$$

where $\sigma_{1,T}$ = longitudinal stress due to thermal contraction, psi 
$E$ = modulus of elasticity of the pipe, 1,500,000 psi for cast iron 
$\alpha$ = coefficient of thermal contraction, 6.26E-6 ft/ft/°F 
$\Delta T$ = temperature change, °F 

5.3 Load-Induced Stresses on Pipes

External loads, internal loads, and temperature changes create various components of stress on the pipe wall, including ring stress, hoop stress, longitudinal stress, and flexural (bending) stress. These stresses are illustrated in Figure 5.3. Methods for calculating the various stresses are described in the following sections.
5.3.1 Ring Stresses

5.3.1.1 Ring stresses due to external loads:

This is the stress that is induced circumferentially in the pipe wall. For any thickness and external load, this stress can be computed by:

\[ \sigma_\theta = \frac{0.0795w(d + t)}{t^2} \]  \hspace{1cm} (5.13)
where:
\[ \sigma_0 = \text{ring stress in the pipe wall, psi} \]
\[ t = \text{net thickness, in.} \]
\[ d = \text{nominal inside pipe diameter, in.} \]
\[ w = \text{external load on the pipe without internal pressure, lb/linear ft} \]

Equation (5.13) is derived by considering the pipe ring as a circular beam of unit width. For a maximum bending moment of \( M_{bending} \) due to load \( w \) and radius \( R \), and the area moment of inertia of \( I_m \). \( M_{bending} \), \( R \), and \( I_m \) are defined respectively in equations (5.16), (5.17), and (5.18). By applying the beam equation:

\[
\sigma = \frac{M_{bending} c}{I_m}
\]  
(5.14)

where

\[
c = \frac{t}{2}
\]  
(5.15)

t is the pipe wall thickness, in

\[
M_{bending} = \frac{wR}{\pi}
\]  
(5.16)

\[
R = \frac{d + t}{2}
\]  
(5.17)

d is the internal diameter, in

\[
I_m = \frac{bt^3}{12}
\]  
(5.18)

b is the width of the circular ring, equals 1, in
5.3.1.2 Ring stresses due to temperature.

According to Timoshenko and Goodier (1987), ring stress in pipe due to temperature change, $\sigma_{t,\theta}$

$$
\sigma_{r,\theta} = \frac{\alpha ET_i}{2(1-\nu) \log(b/a)} \left[ 1 - \log \frac{b}{r} - \frac{a^2}{(b^2-a^2)} \left( 1 + \frac{b^2}{r^2} \right) \log \frac{b}{a} \right]
$$

(5.19)

where

- $a =$ distance from center to inner wall, in
- $b =$ distance from center to outer wall, in
- $\nu =$ Poisson ratio
- $r =$ distance of any point from the center, in
- $\alpha =$ linear expansion coefficient of pipe, ft/ft
- $E =$ modulus of elasticity of the pipe, 1,500,000 psi for cast iron
- $T =$ temperature change, °F

Equation (5.19) is derived by considering the force equilibrium along with the strain relationship. The stress related strain is take to be total strain minus the thermal strain and is used in the equation of equilibrium.

5.3.1.3 Total Ring Stress

The total ring stress is the sum of the ring stress due to external loads and the ring stress due to thermal contraction.

$$
\sigma_{\theta,\text{total}} = \sigma_{\theta} + \sigma_{t,\theta}
$$

(5.20)
5.3.2 Beam Stress:

Beam stress represent a bending (flexural) stress on a beam simply supported at the ends with the central span of the beam unsupported. Deterioration of pipe bedding conditions can result in the uneven support of the pipe, causing it to be only supported at certain points along the pipe length. When such a situation arises, the pipe acts as a beam. The flexural stress or modulus of rupture in the pipe can be determined by:

\[ \sigma_f = \frac{(15.28)w(D)L^2}{(D^4 - d^4)} \]  

(5.21)

where \( \sigma_f \) = flexural stress at extreme fiber, psi
w = effective vertical load distributed along the unsupported pipe length, lb/linear foot
L = length of unsupported span, ft
D = outside diameter of the pipe, in.
d = inside diameter of the pipe, in.

Equation (5.21) is obtained for a hollow cylinder of length, L between supports carrying a load uniformly distributed load, w. For the maximum bending moment of wL²/8, the moment of inertia of \( \pi(D^4 - d^4)/64 \) and extreme fiber distance of D/2. With appropriate unit conversion equation (5.21) is obtained from the beam equation.

The pipe thickness necessary to withstand the load under beam action is contained in the term \( D^4 - d^4 \). The effective vertical load distributed along the unsupported pipe length, w is the sum of the traffic load, earth load, frost load and expansive soil load. Using the w value, the total flexural stress resulting from these loads can be computed.

5.3.3 Hoop Stress

The pipe needs a certain minimum thickness to withstand the hoop stress when the pipe has no over burden load. This stress is computed for two cases: working pressure with water hammer
pressure and then working pressure without water hammer pressure. The hoop stress is computed as:

\[ \sigma_h = \frac{Pd}{2t} \]  

(5.22)

where \( \sigma_h \) = hoop stress, psi

t = net thickness, in.

d = nominal inside pipe diameter, in.
P = water pressure, psi

Total hoop stress is calculated from the total water pressure. The individual components of hoop stress can be calculated separately by substituting working pressure, surge pressure, or pressure increase due to temperature changes for \( P \) in Equation (5.11).

5.3.4 Combined hoop and ring stress.

Crushing failure of pipe under external load is buckling caused by ring flexural stress in the pipe wall beneath the zone of load application. The critical flexural stress occurs at the inner surface of the pipe wall, which is where the critical hoop stress can develop under large internal pressures. To account for the pipe failure under the effect of both external loads and internal pressure, the following loading formula is provided by CIPRA (1978):

\[ \frac{w^2}{W^2} = \frac{(P - p)}{P} \]  

(5.23)

where \( p \) = internal pressure, psi

\( w \) = external load, lb/linear ft

\( P \) = ultimate bursting pressure for the pipe, psi

\( W \) = ultimate crushing load, lb/linear ft
The variables p and w are any combination of internal pressure and external load respectively that will cause failure of the pipe. In using this equation, it is necessary to compute the W and P values first. Both W and P can be estimated from modulus of rupture, R (psi) calculated by the PDM. P can be computed as:

\[ P = \frac{2Rt}{d} \]  \hspace{1cm} (5.24)

Similarly, W can be computed as:

\[ W = \frac{Rt^2}{0.0795(d + t)} \]  \hspace{1cm} (5.25)

5.3.5 Longitudinal pressure stress

In addition to internal pressure and ring loads, pipes are also subjected to longitudinal pressure stress resulting from hydrostatic conditions and changes in magnitude or direction of internal flow velocities. The longitudinal stress due to such pressures has a magnitude half as large as the hoop stress and can be defined as:

\[ \sigma_l = \frac{pd}{4t} \]  \hspace{1cm} (5.26)

where \( \sigma_l \) = the uniformly distributed longitudinal tensile stress due to internal pressure, psi

5.3.6 Longitudinal thermal stress.
According to Timoshenko and Goodier (1987), longitudinal stress in pipe due to a sudden temperature change, $\sigma_t$

$$\sigma_t = \frac{\alpha E T_i}{2(1-\nu)\log(b/a)} \left[1 \frac{2a^2}{(b^2-a^2)} \log \frac{b}{a} \right]$$

(5.27)

where  

$a = \text{distance from center to inner wall, in}$ 

$b = \text{distance from center to outer wall, in}$ 

$\nu = \text{Poisson’s ratio}$ 

$r = \text{distance of any point from the center, in}$ 

$\alpha = \text{linear expansive coefficient of the pipe material, ft/ft/}^\circ\text{F}$ 

$E = \text{modulus of elasticity of the pipe, 1,500,000 psi for cast iron}$ 

$T = \text{temperature change, } ^\circ\text{F}$

5.3.7 Longitudinal stress component of hoop stress.

Hoop stress creates a component of longitudinal stress as a characteristic of the internal matrix of the pipe material. The ratio of the longitudinal component of hoop stress to hoop stress is the Poisson’s ratio. The longitudinal component of hoop stress is calculated as:

$$\sigma_v = \nu(\sigma_{\theta,\text{total}} + \sigma_h)$$

(5.28)

where  

$\sigma_v = \text{longitudinal component of hoop stress, psi}$ 

$\sigma_{\theta,\text{total}} = \text{total ring stress, psi}$ 

$\sigma_h = \text{total hoop stress, psi}$ 

$\nu = \text{Poisson’s ratio}$

5.3.8 Total longitudinal stress.
In order to determine the combined effect of the longitudinal stress sources, the computed flexural stress is added to the longitudinal pressure stress and the longitudinal stress in pipe wall resulting from temperature change in water. The resulting value is the total expected longitudinal stress, \(\sigma_{l,T}\).

\[
\sigma_{l,T} = \sigma_l + \sigma_t + \sigma_v
\]  

(5.29)

5.3.9 Combined longitudinal and bending stress.

Longitudinal and bending stresses act in the same direction at the extreme fiber at the bottom (outside) of the pipe and therefore may exceed the failure stress of the pipe at that location. The total longitudinal and bending stresses, \(\sigma_{\text{flexlong}}\) are simply added to evaluate this condition.

\[
\sigma_{\text{flexlong}} = \sigma_f + \sigma_{l,T}
\]  

(5.30)

5.4 Pipe Break Model (PBM)

The PBM calculates a safety factor for each of the major stress components as the ratio of the residual strength of the pipe divided by the maximum expected stress. As the pipe ages and corrosion pits reduce the pipe wall thickness and concentrate stresses, the safety factor is reduced. Theoretically, the pipe will fail at a safety factor of 1 or less. In addition to the principal components of stress (ring, hoop, longitudinal, and beam stress) safety factors are computed for combined ring and hoop stress and for combined longitudinal and beam stress. After a certain time dictated by the particular pipe’s deterioration curve, the pipe thickness will reach failure thickness, that is the point at which the curve intersects the failure boundary (see Figure 5.4).
Figure 5.4  Pipe Strength and Load Interaction

Figure 5.5 shows the interaction of all the models leading to pipe condition assessment and replacement prioritization.

Pipe Residual Strength,  
[PDM, SCM]

PBM

Failure Prediction:
Pipes to fail; Time to fail; Factor of Safety (SF)
\( \sigma_{\text{Lab}} / \sigma_{\text{Field}} \leq SF, \Rightarrow \text{Fails} \)

Field Stresses in pipe (PLM)

Prioritize pipes for replacement
Generally, the safety factors are obtained by considering the six stress types: ring, flexural, tensile, hoop, combined hoop and ring, and combined flexural and longitudinal. In order to determine the safety factor of a pipe, the residual strength is estimated for the four strength categories (ring modulus, tensile strength, bursting tensile strength and modulus of rupture) by the equation (derived in Chapter 4):

\[
\sigma_{\text{res}} = \frac{\sigma_n^2}{6} \left( -1 + \sqrt{1 + \frac{12.75}{\pi r_n} \left( \frac{K_0}{\sigma_0} \right)^2} \right)
\]  

(5.31)

where \( r_n \) = the depth of the corrosion pit, in
\( \sigma_0 \) = is the plain fatigue strength of the material, psi
\( \sigma_{\text{res}} \) = the residual strength for each of strength category (ring modulus, tensile strength, bursting tensile strength, and modulus of rupture), psi
\( K_0 \) = the fracture toughness of the material, psi\( \sqrt{\text{in}} \)

5.5 Computation of Safety Factors

Using the residual strengths and the stresses computed from the pipe load model, the safety factors can be computed as follows:

5.5.1 Flexural (bending) safety factor.

This is the safety factor resulting from bending (flexural) stresses. It represents the ratio of the residual modulus of rupture to the bending stresses. It is defined as:
\[ SF_f = \frac{\sigma_{\text{res}(mr)}}{\sigma_f} \]  \hspace{1cm} (5.32)

where \( SF_f \) = safety factor due to flexural stresses

\( \sigma_{\text{res}(mr)} \) = residual modulus of rupture, psi.

\( \sigma_f \) = sum of flexural stresses, psi.

5.5.2 Ring safety factor.

It represents the ratio of the residual ring modulus to the ring stresses. It is defined as:

\[ SF_\theta = \frac{\sigma_{\text{res}(rm)}}{\sigma_\theta} \]  \hspace{1cm} (5.33)

where \( SF_\theta \) = safety factor due to ring stresses

\( \sigma_{\text{res}(rm)} \) = residual ring modulus of rupture, psi.

\( \sigma_\theta \) = sum of ring stresses, psi.

5.5.3 Hoop safety factor.

It represents the ratio of the residual bursting tensile strength to the hoop stresses. It is defined as:

\[ SF_h = \frac{\sigma_{\text{res}(bts)}}{\sigma_h} \]  \hspace{1cm} (5.34)

where \( SF_h \) = safety factor due to hoop stresses

\( \sigma_{\text{res}(bts)} \) = residual bursting tensile strength, psi.

\( \sigma_h \) = sum of hoop stresses, psi.
5.5.4 Longitudinal safety factor.

It represents the ratio of the residual tensile strength to the longitudinal stresses. It is defined as:

\[ SF_l = \frac{\sigma_{res(ts)}}{\sigma_l} \quad (5.35) \]

where \( SF_l = \) safety factor due to longitudinal stresses
\( \sigma_{res(ts)} = \) residual tensile strength, psi.
\( \sigma_l = \) sum of longitudinal stresses, psi.

5.5.5 Flexural Plus Longitudinal Safety Factor.

This safety factor represents the ratio of the residual modulus of rupture to the sum of flexural and longitudinal stresses. It is defined as:

\[ SF_{flexlong} = \frac{\sigma_{res(ts)}}{\sigma_{flexlong}} \quad (5.36) \]

where \( SF_{flexlong} = \) safety factor due to flexural plus longitudinal stresses
\( \sigma_{res(ts)} = \) residual tensile strength, psi.
\( \sigma_{flexlong} = \) sum of flexural and longitudinal stresses, psi.

5.5.6 Ring Plus Hoop Safety Factor.

The combined Hoop pressure and ring stress acting on a pipe can be represented by the following equation:
\[ w = W \sqrt{\frac{P - p}{P}} \]  

(5.37)

where

\( w = \) external load, lb/ft  
\( W = \) Crushing load, lb/ft  
\( p = \) internal pressure, psi  
\( P = \) bursting pressure, psi

If \( F \) is the safety factor, then

\[ Fw = W \sqrt{\frac{P - Fp}{P}} \]  

(5.38)

\[ F^2 \left( \frac{w}{W} \right)^2 = \frac{P - Fp}{P} \]  

(5.39)

\[ F^2 \left( \frac{w}{W} \right)^2 = 1 - \frac{Fp}{P} \]  

(5.40)

Let \( x = \frac{w}{W} \) and \( y = \frac{P}{P} \) then

\[ F^2 x^2 = 1 - Fy \]  

(5.41)

\[ F^2 x^2 + Fy - 1 = 0 \]  

(5.42)

This is a quadratic equation with coefficients \( x^2 \), \( y \) and \(-1\). The safety factor \( F \) can therefore be solved as
\[ F = \frac{-y \pm \sqrt{y^2 - 4(x^2)(-1)}}{2x^2} \]  

(5.43)

Taking the positive value of the two possible solutions,

\[ F = \frac{-y + \sqrt{y^2 + 4x^2}}{2x^2} \]  

(5.44)

Resubstituting \( x \) and \( y \) into the equation results in,

\[ F = \frac{-\left( \frac{p}{P} \right) + \sqrt{\left( \frac{p}{P} \right)^2 + 4 \left( \frac{w}{W} \right)^2}}{2 \left( \frac{w}{W} \right)^2} \]  

(5.45)

5.6 Pipe Vulnerability

Of all the six safety factors computed, the least safety factor dictates the vulnerability of the pipe. The combined longitudinal and flexural safety factor and combined hoop and ring safety factor usually tend to be the least of the six. By sorting the pipes according to the safety factors from the least to the greatest, a prioritized list of the order in which pipes should be replaced can be generated.
Chapter 6 - Application to the Ottawa System

6.1 Introduction

The mechanistic models were tested with an actual water utility data to test the applicability of the models. The RMOC water main inventory database was used to test the model. The following sections describe the modeling process and the final results.

6.2 Input Data

The various data inputs for the models were gathered from both the RMOC water main inventory and the RMOC main break database. Assumptions were made when the required data were not available. The complete RMOC inventory database contained 22,780 records and the break database consisted of 6703 records. Pipes were selected from the break database for analysis according to the following criteria:

- year installed not blank or zero
- soil class not blank
- diameter less than 310 mm (~12 in)
- material type (CI or UCI)
- pipe depth greater than 0
- Pipes with 3 or more breaks

The resulting data contained 999 records and 235 unique pipe ids. The break times ranged from 1972 to 1998. 924 of the breaks were circumferential and 75 were longitudinal. The installation year ranged from 1874 to 1970. The data fields extracted from the break database were:

- pipeid
- size (diameter)
- length
soil class
material type
year installed
pipe depth

The pipeid field provides a unique identifier for the pipe, and also provides the link to data in the main break database. The units of the pipe size were converted from millimeters to inches and the lengths were converted from meters to feet. The soil class is a designation used by RMOC to describe the soil environment of the pipe. Only cast iron pipes from the database were used for the analysis. These are designated in the database as CI (cement lined cast iron) and UCI (unlined cast iron). Pipes installed prior to and in 1929 were assumed to be pit cast and those after 1929 as spun cast. Since the inventory records had no associated pipe depth of cover, the depth of cover was obtained from pipes in the break database that had an associated depth of cover recorded. The “AnalysisYear” was chosen as 2000. In other words, the model simulates the aging of all pipes from the time of installation year until year 2000. The “TrafficType” for all the pipes was assumed to be heavy and the “PavementType” as paved. “WorkingPressure” was assumed to be 100 psi. The “BeamSpan” was assumed to be 4 ft for the purposes of calculating bending stress on the pipes. An analysis was perform to determine the effect of estimated beam span on the break prediction accuracy. This analysis is discussed later in this document.
Table 6.1 summarizes the various data inputs and from where the data were obtained. Table 6.2 provides the assumed values used where required data were not available. Table 6.3 lists the soil properties associated with each RMOC soil class. The soil types 1 through 5 show a progressive increase in corrosivity, with soil type 5 (organic clays) being the most corrosive. For soil type 8 (unclassified) the properties of soil type 5 were assigned.
<table>
<thead>
<tr>
<th>Input</th>
<th>Purpose/description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe ID</td>
<td>Identify individual pipes</td>
<td>Main break database</td>
</tr>
<tr>
<td>Region ID</td>
<td>Characterize certain weather related characteristics</td>
<td>Characteristics were assumed (see Figure 6.2)</td>
</tr>
<tr>
<td>Soil class</td>
<td>Assign corrosion characteristics for the soil surrounding the pipe</td>
<td>Main break database</td>
</tr>
<tr>
<td>Analysis year</td>
<td>The year in which the main break occurred representing the end point of the pipe deterioration</td>
<td>Main break database</td>
</tr>
<tr>
<td>Pipe type</td>
<td>The material of the pipe that failed</td>
<td>Main break database (either CI for cement lined cast iron or UCI for unlined cast iron)</td>
</tr>
<tr>
<td>Pipe diameter</td>
<td>The diameter of the pipe (in inches)</td>
<td>Main break database</td>
</tr>
<tr>
<td>Pipe year installed</td>
<td>The installation year of the pipe</td>
<td>Main break database</td>
</tr>
<tr>
<td>Pipe length</td>
<td>The length of the pipe in feet</td>
<td>Main break database</td>
</tr>
<tr>
<td>Traffic type</td>
<td>Assign live loading characteristics</td>
<td>Assumed (see Figure 6.2)</td>
</tr>
<tr>
<td>Working pressure</td>
<td>Compute loads due to water pressure</td>
<td>Main break database</td>
</tr>
<tr>
<td>Pipe depth</td>
<td>Compute soil load on pipe</td>
<td>Water main inventory</td>
</tr>
<tr>
<td>Pavement type</td>
<td>Compute dead load on pipe</td>
<td>Water main inventory</td>
</tr>
<tr>
<td>Beam span</td>
<td>Compute bending load on pipe</td>
<td>Assumed (see Figure 6.2)</td>
</tr>
</tbody>
</table>
Table 6.2 Assumptions used in RMOC test case of the model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumed input value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region ID characteristics</td>
<td></td>
</tr>
<tr>
<td>Minimum yearly temperature</td>
<td>-20 °F</td>
</tr>
<tr>
<td>Maximum yearly temperature</td>
<td>85 °F</td>
</tr>
<tr>
<td>Maximum frost depth</td>
<td>50 in</td>
</tr>
<tr>
<td>Maximum sudden water temperature change</td>
<td>6 °F</td>
</tr>
<tr>
<td>Maximum freeze days</td>
<td>60 days</td>
</tr>
<tr>
<td>Minimum water temperature</td>
<td>32 °F</td>
</tr>
<tr>
<td>Maximum water temperature</td>
<td>60 °F</td>
</tr>
<tr>
<td>Water velocity change</td>
<td>2 ft/s</td>
</tr>
<tr>
<td>Soil characteristics</td>
<td>See Table 6.3</td>
</tr>
<tr>
<td>Traffic type</td>
<td>heavy traffic</td>
</tr>
<tr>
<td>Beam span</td>
<td>4 ft</td>
</tr>
</tbody>
</table>
Table 6.3 RMOC modeling test case soil characteristic assumptions

<table>
<thead>
<tr>
<th>Soil class</th>
<th>Soil description</th>
<th>pH</th>
<th>Soil resistivity ohm-cm</th>
<th>Soil aeratation</th>
<th>Soil moisture %</th>
<th>Soil liquid limit</th>
<th>Soil density lb/ft³</th>
<th>Soil porosity %</th>
<th>Soil expansivity</th>
<th>Soil frost susceptible</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coarse: gravels, sands, loamy sands</td>
<td>8</td>
<td>1500</td>
<td>good</td>
<td>15</td>
<td>21</td>
<td>135</td>
<td>35</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>2</td>
<td>Moderately coarse: sandy loam, loam, silt loam</td>
<td>7</td>
<td>1200</td>
<td>good</td>
<td>20</td>
<td>32</td>
<td>130</td>
<td>45</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>3</td>
<td>Moderately fine: sandy clay loam, silt, silty clay loam, clay loam</td>
<td>6</td>
<td>1000</td>
<td>fair</td>
<td>20</td>
<td>32</td>
<td>120</td>
<td>45</td>
<td>y</td>
<td>y</td>
</tr>
<tr>
<td>4</td>
<td>Fine: sandy clay, silty clay, clay, heavy clay</td>
<td>6</td>
<td>1000</td>
<td>fair</td>
<td>20</td>
<td>26</td>
<td>120</td>
<td>40</td>
<td>y</td>
<td>y</td>
</tr>
<tr>
<td>5</td>
<td>Organic</td>
<td>5</td>
<td>700</td>
<td>poor</td>
<td>25</td>
<td>59</td>
<td>100</td>
<td>60</td>
<td>y</td>
<td>y</td>
</tr>
<tr>
<td>6</td>
<td>Bedrock</td>
<td>8</td>
<td>2000</td>
<td>good</td>
<td>15</td>
<td>39</td>
<td>135</td>
<td>50</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>7</td>
<td>Unclassified</td>
<td>5</td>
<td>700</td>
<td>poor</td>
<td>15</td>
<td>21</td>
<td>100</td>
<td>35</td>
<td>y</td>
<td>y</td>
</tr>
</tbody>
</table>
Note that although category 8 is “Unclassified”, it was assigned fairly corrosive soil characteristics to represent a worst case deterioration scenario.

6.3 Model Results

The results of applying the model to the RMOC main break database and water main inventory were evaluated in order to determine the effectiveness and applicability of the model for use by utilities in prioritizing main replacement programs. In evaluating the model, the SF for the combination of hoop and ring stresses (SF_{h,r}) and flexural and longitudinal stresses (SF_{f,l}) were considered. These SF represent the worst case combination of stresses and strengths for the pipe, and are, thus, most appropriate for analyzing past failures and probabilities of future failures.

6.3.1 Effective Beam Span

The beam span length is one of the most elusive input parameters needed for the model. In order to get an estimation of the beam span appropriate for the analysis. Generally, a 4 ft span is assumed in the model. An analysis was performed to determine how the accuracy of the model is affected by the beam span used. Four cases were considered:

- Case 1: Beam span = 2 ft
- Case 2: Beam span = 4 ft
- Case 3: Beam span = 8 ft
- Case 4: Beam span based on pipe age (See Table 6.4):
Table 6.4 Estimated Beam Span Versus Pipe Age

<table>
<thead>
<tr>
<th>Pipe Age (yrs)</th>
<th>Beam Span (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>2</td>
</tr>
<tr>
<td>10-19</td>
<td>3</td>
</tr>
<tr>
<td>20-29</td>
<td>4</td>
</tr>
<tr>
<td>30-39</td>
<td>5</td>
</tr>
<tr>
<td>40-49</td>
<td>6</td>
</tr>
<tr>
<td>50-59</td>
<td>7</td>
</tr>
<tr>
<td>60-69</td>
<td>8</td>
</tr>
<tr>
<td>70-79</td>
<td>9</td>
</tr>
<tr>
<td>80-89</td>
<td>10</td>
</tr>
<tr>
<td>&gt;90</td>
<td>12</td>
</tr>
</tbody>
</table>

For each of the 4 cases, the safety factors was computed and the predict failure mode was compared with the observed failure mode. The predicted failure mode was obtained from comparing the combined flexural and longitudinal safety factor with the combined hoop and ring stress safety factor. The safety factor with the minimum of the two is chosen as the predicting safety factor. That is if the combined flexural and longitudinal safety factor is minimum then the predicted failure mode would be circumferential break and if the combined hoop and ring stress safety factor is minimum then the predicted failure mode would be longitudinal break. The observed break modes were obtained from the break database for each pipe break. The results are summarized in Table 6.5.

Table 6.5 Prediction Accuracy versus Estimated Beam Span

<table>
<thead>
<tr>
<th>Overall(#)</th>
<th>Longitudinal(#)</th>
<th>Circumferential(#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-ft</td>
<td>11.0</td>
<td>96.0</td>
</tr>
<tr>
<td>4-ft</td>
<td>42.2</td>
<td>54.7</td>
</tr>
<tr>
<td>8-ft</td>
<td>83.0</td>
<td>17.3</td>
</tr>
<tr>
<td>AgeBased</td>
<td>44.7</td>
<td>50.6</td>
</tr>
</tbody>
</table>
For each of the 4 cases, the percentage of correctly classified breaks are determined in three categories: overall, longitudinal, and circumferential. The overall refers to what percentage of all the breaks were correctly predicted. Circumferential refers to what percentage of the known circumferential breaks were correctly predicted. Longitudinal refers to what percentage of the known longitudinal breaks were correctly predicted. Figure 6.1 shows a plot of the various accuracies and corresponding beam span and category.

![Prediction of Break Types](image)

**Figure 6.1 Break Prediction Accuracies**

When the beam span is set at 4 ft, the overall prediction is 42.2% and the longitudinal break prediction is 54.7% and the circumferential break prediction is 41.2%. If an 8 ft beam span is used the overall prediction increases to 83%. The circumferential break prediction accuracy also increased to 88.4%. On the other hand, the longitudinal break prediction accuracy dropped drastically to 17.3%. This can be explained by the fact that, a majority of the breaks were circumferential breaks. These circumferential breaks are controlled by the beam span.
Decreasing the beam span to 2 ft increases the longitudinal break prediction to 96%, the circumferential to 4% and the overall to 11%. It can be seen the setting the beam span at 4ft seem to provide a better accuracy for three categories (overall, longitudinal, and circumferential). In the last case, the overall accuracy and the circumferential break accuracy both increased over the case of 4ft beam span. The longitudinal break accuracy decreased from 54.7% to 50.6%. It can be said that compared the 4 ft beam span, the age based beam span estimation provided reasonable results.

Determination of the effective beam span for the pipe is a complex and almost impossible task. This is due to the fact that the pipe bedding deterioration depends on a number of different factors namely:

* **Deterioration due to erosion:** this results from the leaking of pipe joints of corroded pipes.

* **Deterioration due to disruption by other utilities:** often, utilities share the same space for burying their pipes underground. For example, a gravity sewer pipe may be buried underneath a water distribution pipe. When there is a need for repair of the gravity sewer pipe. There may be a need for digging around the water distribution pipe. When the repair is completed, the bedding of the water distribution pipe may not be restored to its original state.

* **Faulty repairs:** sometimes, when failed pipes are repaired, the bedding may be not be restored to the proper state. Repairs especially, those under freezing condition are most prone to this situation. Frozen soil coupled with freezing water may lead improper compactions of the bedding and the backfill. For example, the existence of bits of ice and frozen clumps of soil causes the structure of the bedding be changed when the soil temperature warms up and the bedding material resettles.
6.3.2 Effect of Pit Depth on strength degradation

The various strengths degrade at a rapid rate at the initial stages and then decrease gradually as time progresses and the pit depth increases. Figure 6.2 shows the degradation of the various strengths. Also it is seen that the ring modulus, the highest of all four strengths is the most affected by the pit growth. This phenomenon explains the rapid drop in the ring safety factor (see Figure 6.3).

![Figure 6.2 Pit Depth versus Pipe Strength](image)

6.3.3 Effect of pit depth on safety factors

Figure 6.3 shows the plots of the different pit depth extents versus the safety factors. The flexural, ring, and ring plus hoop safety factors are initially the among the highest but decrease rapidly with increasing pit depth. Beyond a pit depth of 0.15 inch, the degradation rate
decreases. Relatively, the hoop safety factor decreases the least with increasing pit depth. The relative decrease in hoop safety factor is due to the fact that the effect of the pit depth on the reduction of the bursting tensile strength is not significant as the other strengths (See Figure 6.2).

Figure 6.3 Pit depth versus Safety Factor
6.3.4 Effect of Soil Parameters on Pit Depth

The prediction of the pipe strength and consequently the safety factor relies on the corrosion pit. The effect of the various soil parameter relevant to the pit growth was analyzed by considering a 50 year old pipe from the database.

6.3.4.1 Effect of pH

Figure 6.4 shows the effect of pH change on the pit depth. The relationship seems to be almost linear. It also shows that for a difference of 1 in the pH, the corresponding change in the pit depth is about 0.005 inch of over the 50 year period. From Figure 6.2 and Figure 6.3, such a change in pit depth does not significantly affect the predicted strength and safety factors.

![Pit Depth vs pH](image)

**Figure 6.4** Pit Depth versus pH
6.3.4.2 Resistivity

The pit depth seems to be very responsive to the resistivity within a certain range. For resistivity less than 5000 ohm-cm, the corresponding change in the pit depth versus change in the resistivity is magnified (See Figure 6.5). This implies that for resistivities greater than 5000, the corrosion model is less sensitive to changes in the resistivity.

![Pit Depth Vs Resistivity](image)

Figure 6.5  Pit Depth versus Resistivity

6.3.4.3 Soil Aeration

The soil aeration, like the pH seems to have an almost linear relationship with the predicted pit depth. Between each aeration type and the subsequent aeration type, the change in
the pit depth is about 0.075 inch. From Figure 6.2 and Figure 6.3, this change can cause a substantial change in the predicted strength and safety factor.

![Pit Depth vs Soil Aeration](image)

**Figure 6.6  Pit Depth versus Aeration**

6.3.4.4 Effect of Soil Class on Pit Depth

Relatively, the most corrosive soils are the soil classes 5 and 8 (See Figure 6.7). Soil classes 3 and 4 are mildly corrosive and soils 1,2, and 7 are the least corrosive
6.3.4.5 Effect of Soil Class On Safety Factors

The relationship between the safety factors and soil class was analyzed. The analysis was performed on a 50 year old pipe in the database. It was expected that the safety factors would vary based upon soil category. More corrosive soils should have generally lower safety factors than non-corrosive soils. Figure 6.8 shows the safety factors estimated by the model for the selected pipe within each soil category. As expected, the less corrosive soils (categories 1, 2, and 7) have generally higher SF than do the corrosive soils (categories 5 and 8). The safety factors for the soil classes 5 and 8 are virtually down to zero.
The effect of pipe age on the safety factors was also examined. The model assumes that the strength of a pipe decreases over time as a result of loss of wall thickness due to external corrosion and the loss of strength due to the corrosion pits. Therefore, the SF should decrease over time since the loads are assumed to remain the same. Figure 6.9 and Figure 6.10 show the combined flexural and longitudinal safety factors and combined ring and hoop safety factors respectively, plotted against installation year of each pipe. As expected, safety factors are generally lowest for the oldest pipes in the inventory. In Figure 6.9 the combined flexural and longitudinal safety factors clearly increases as the installation year approaches the present day. The combined ring and hoop safety factors shown in Figure 6.10 exhibit much more scatter than shown by the flexural and longitudinal safety factors in Figure 6.10. The combined ring and hoop safety factors do show patterns similar to the combined flexural and longitudinal safety factors in that they are generally lower for the oldest pipe, and are grouped by soil category.
Figure 6.9 Combined flexural and longitudinal safety factors by installation year
Figure 6.10 Combined ring and hoop safety factors by installation year

Figure 6.9, and to a lesser extent Figure 6.10, also illustrates an interesting point related to pipe manufacturing standards. The safety factors for pipes installed between 1939 and 1951 are considerably lower than expected. A closer look at the design standards for pipes explains why this occurs. Table 6.6 summarizes pipe wall thicknesses for 6- and 8-inch cast iron pipes manufactured until 1966. Wall thicknesses were generally and gradually being reduced as manufacturing techniques improved. However, they were dramatically reduced between 1939 and 1951, amounting to about a one-third reduction in wall thickness. It is unknown if this was due to anticipated manufacturing improvements or related to material shortages during the war. After 1951 the wall thicknesses were increased, although not quite to pre-1939 values.
Table 6.6 Cast iron pipe wall thicknesses over time

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.47</td>
<td>0.44</td>
<td>0.43</td>
<td>0.28</td>
<td>0.38</td>
</tr>
<tr>
<td>8</td>
<td>0.47</td>
<td>0.44</td>
<td>0.46</td>
<td>0.32</td>
<td>0.41</td>
</tr>
</tbody>
</table>

6.4 Prioritization of Pipe for replacement

The 235 pipes were analyzed for replacement prioritization. A summary of the results in safety factors is shown in Table 6.7. For each pipe the analysis year was set as 2000. Meaning that the desire is to determine the most vulnerable pipes as at the year 2000. This is determined by picking the lowest safety factor from the six categories of safety factors for each pipe. The pipes are then sorted based on the minimum safety factor. Pipes with minimum safety factors less than 1.00 are identified as the vulnerable pipes. An excerpt from the list of the sorted pipes is shown in Table 6.8. Of the 235 pipes, 127 (54%) had minimum safety factors less than 1.00. It should be cautioned that this does not mean that 54% of the pipes in the utility’s inventory need to be replaced. As noted earlier on, the data used for this analysis is only a fraction of the total inventory of the utility.

Table 6.7 Summary of Safety Factors for Pipe Prioritization

<table>
<thead>
<tr>
<th>Flexural Ring</th>
<th>Hoop</th>
<th>Longitudinal</th>
<th>FlexuralLong</th>
<th>RingHoop</th>
<th>MinSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg</td>
<td>3.84</td>
<td>1.54</td>
<td>2.82</td>
<td>1.96</td>
<td>1.28</td>
</tr>
<tr>
<td>Min</td>
<td>8.86E-05</td>
<td>1.69E-09</td>
<td>1.89E-04</td>
<td>3.02E-04</td>
<td>6.74E-05</td>
</tr>
<tr>
<td>Max</td>
<td>12.87</td>
<td>5.44</td>
<td>4.24</td>
<td>2.69</td>
<td>1.88</td>
</tr>
<tr>
<td>Stdev</td>
<td>1.65</td>
<td>0.87</td>
<td>1.05</td>
<td>0.56</td>
<td>0.40</td>
</tr>
</tbody>
</table>
### Table 6.8 Sample List of Prioritized Pipe Replacement Scheme

<table>
<thead>
<tr>
<th>PipeID</th>
<th>Flex</th>
<th>Ring</th>
<th>Hoop</th>
<th>Long</th>
<th>FlexLong</th>
<th>RingHoop</th>
<th>MinSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>6831040-95</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>6832242-95</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>5619167-98</td>
<td>0.47</td>
<td>0.18</td>
<td>1.04</td>
<td>1.03</td>
<td>0.33</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>5619146-96</td>
<td>1.34</td>
<td>0.20</td>
<td>1.00</td>
<td>1.00</td>
<td>0.58</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>8036046-95</td>
<td>2.18</td>
<td>0.20</td>
<td>1.01</td>
<td>1.00</td>
<td>0.69</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>5819010-95</td>
<td>1.41</td>
<td>0.21</td>
<td>1.00</td>
<td>1.00</td>
<td>0.59</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>6215010-94</td>
<td>1.41</td>
<td>0.21</td>
<td>1.04</td>
<td>1.02</td>
<td>0.60</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>5619152-95</td>
<td>0.55</td>
<td>0.21</td>
<td>1.04</td>
<td>1.03</td>
<td>0.36</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>6624039-97</td>
<td>0.70</td>
<td>0.22</td>
<td>1.22</td>
<td>1.11</td>
<td>0.40</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>6631182-96</td>
<td>0.22</td>
<td>0.74</td>
<td>1.50</td>
<td>1.15</td>
<td>0.18</td>
<td>0.53</td>
<td>0.18</td>
</tr>
<tr>
<td>8034091-98</td>
<td>2.44</td>
<td>0.24</td>
<td>1.08</td>
<td>1.05</td>
<td>0.74</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>6215006-95</td>
<td>0.77</td>
<td>0.25</td>
<td>1.23</td>
<td>1.15</td>
<td>0.47</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>7632019-96</td>
<td>1.54</td>
<td>0.26</td>
<td>1.16</td>
<td>1.11</td>
<td>0.65</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>5619145-97</td>
<td>0.86</td>
<td>0.26</td>
<td>1.18</td>
<td>1.12</td>
<td>0.49</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>6624027-97</td>
<td>0.45</td>
<td>0.27</td>
<td>1.29</td>
<td>1.16</td>
<td>0.30</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>5819019-95</td>
<td>0.88</td>
<td>0.27</td>
<td>1.18</td>
<td>1.12</td>
<td>0.50</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>6830191-96</td>
<td>0.97</td>
<td>0.27</td>
<td>1.09</td>
<td>1.06</td>
<td>0.51</td>
<td>0.21</td>
<td>0.21</td>
</tr>
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<td>5819022-95</td>
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<td>0.28</td>
<td>1.18</td>
<td>1.12</td>
<td>0.51</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>6624030-97</td>
<td>0.47</td>
<td>0.28</td>
<td>1.29</td>
<td>1.16</td>
<td>0.31</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>5620011-97</td>
<td>0.95</td>
<td>0.29</td>
<td>1.18</td>
<td>1.12</td>
<td>0.52</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>8037081-94</td>
<td>1.83</td>
<td>0.30</td>
<td>1.12</td>
<td>1.08</td>
<td>0.68</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>5217090-97</td>
<td>0.93</td>
<td>0.30</td>
<td>1.23</td>
<td>1.15</td>
<td>0.52</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>6624031-95</td>
<td>0.50</td>
<td>0.30</td>
<td>1.29</td>
<td>1.16</td>
<td>0.33</td>
<td>0.23</td>
<td>0.23</td>
</tr>
</tbody>
</table>
Chapter 7 - Application to the St. Louis System

7.1 Introduction

The mechanistic model was also applied to data obtained from the St. Louis County Water Company (SLCWC). In this case the expected failure times for each of the pipes were determined. The results were then compared with results obtained from an earlier work by Park (2000). The primary purpose for application the model to the St. Louis County Water Company’s (SLCWC) system was to determine how the results of this mechanistic model would compare with results obtained by Park (2000) using the general break regression model (GBRM). In the general break regression model, Park used a weighting factor with both a linear and exponential model to obtain a combined model that better fits the nature of pipe break occurrences over time. A comparison of the results of the two models and the appropriateness of the comparison will be discussed at the end of this chapter.

7.2 SLCWC Distribution System Overview:

The total length of the pipes in the system was about 4,000 miles as of 1997. Figure 7.1 shows the composition of the system by pipe material. As shown in Figure 7.1, the current system is predominantly spun cast iron (66.5%), including pipe with rigid joints and flexible joints. Combined with the older pit cast iron pipe and the newer ductile iron pipe these four categories account for over 95% of the pipe in the system.

Figure 7.2 breaks down the pipe inventory by diameter, and shows that 79% of the system (approximately 3,160 miles) is either 6- or 8-inch. Pipe that is 4-inch or smaller accounts for a little more than 2% of the total. This means that there is over 80 miles of this generally small pipe in the system. Large diameter transmission mains (>=16-inch) account for 9.4% of the system, or about 376 miles.

Figure 7.3 examines the system in terms of pipe vintage. It shows that the majority of the system (63%) is less than 40 years old. On the other hand, 17% or 680 miles is greater than 60 years old.
Figure 7.1 Distribution System Composition By Pipe Material

Figure 7.1 Distribution System Composition By Pipe Material
7.3 Pipe Material History

Various pipe materials have been used at different times over the history of the system. The Company provided a general timeline for when various materials were in use. Figure 7.4 provides an overview of this history. In general, pit cast iron is the oldest pipe in the system. Because of the manufacturing process used, this pipe had very thick walls compared to the spun cast pipe that followed. Spun cast iron pipe was used into the 1970’s, but two distinctive types of joints were used over that time. Initially rigid joints were employed that prevented the pipe from “flexing” under stress. These rigid joints, in combination with the thinner walls compared to pit cast iron pipe, are believed to contribute to greater break frequencies for this type of pipe. Later, flexible joints were introduced that allowed the pipe to flex under stress. Most recently, ductile iron pipe was introduced to the system, and is now used almost exclusively by the Company.
Wrapping of the ductile iron pipe with a polyethylene sheet helps to protect the pipe from potentially corrosive soil conditions. This practice became standard within the Company in 1977.

**Figure 7.4 Timeline for Pipe Installation**

7.4 Data Requirements For Mechanistic Model:

The data required for the mechanistic model can be classified into three main categories – pipe attribute data, soil data, and regional data. A fourth category, break times data, is also discussed in this chapter but are used in the next chapter to determine the relationship between the actual break times and the predictions from a physically based model. In order to obtain the complete set of data required, data from several sources were used. These sources include Soil Survey Geographic Database (SSURGO), available literature, and best judgement for parameters that were unavailable. The following subsections discuss how the various data were obtained and processed for use with the mechanistic model.
7.4.1 Pipe Attribute Data

Ideally, a utility would keep both a pipe inventory database and a break database. The inventory database would contain information comprised mainly of non-changing attributes for each pipe in the system. Examples of these attributes are size, installation year, length, material type, and depth of burial. Unfortunately, because the systems in most cities such as St. Louis are so old, it is often difficult to find such data for the pipes. It is especially difficult for older pipes in the system. Though several utilities are beginning to utilize geographic information systems (GIS) to inventory and manage the pipes in their systems, most are far from achieving the goal of having a complete inventory database. In the case of SLCWC, the inventory database was unavailable. The inventory had to be generated from the available break database. SLCWC, over the years has developed one of the most comprehensive break databases the author has seen to date. Before proceeding, it is important to define one data feature that was integral to all evaluations and modeling. Much of the distribution system pipe information that the SLCWC maintains is in terms of “Work Order”. The Work Order for a pipe refers to the original project under which the water main was installed. Work Orders vary considerably in length, from less than 100 feet to more than 10,000 feet. The identification of pipes by work order number has a few setbacks.

A work order may have pipes located on differing streets. In many cases, it was noted that the pipes on the same work order number located in different streets had different footage values. Some work order numbers had pipes that had different installation dates, sizes, and lengths. If the work order number was to be used to define a pipe, it would result in cases where a ‘pipe’ would have a different material type, length, size, or installation year along various segments. Such a scenario would create problems for the mechanistic modeling procedure as the pipes are modeled by considering their unique physical attributes and environment.

A procedure of creating unique ‘pipe-ids’ was therefore implemented to differentiate between pipes of the same work order number. Key fields used in the modeling are described in Table 7.1. Actual dBase IV field names are provided in parentheses.
Table 7.1 SLCWC Leak Database Key Fields

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work Order (WORKORD)</td>
<td>The work order identifies the project under which the pipe was installed. This identifier was used to distinguish individual “pipes”.</td>
</tr>
<tr>
<td>Footage (FOOTAGE)</td>
<td>The length of the work order, in feet.</td>
</tr>
<tr>
<td>Replaced (REPLACED)</td>
<td>A logical field that indicates if a pipe, or a portion thereof, was replaced as a result of a main break. This field is updated for older records when a replacement occurs on a portion of pipe that has experienced previous breaks.</td>
</tr>
<tr>
<td>Year Acquired (YEARACQ)</td>
<td>The year in which the pipe was installed (or in some cases acquired from another system).</td>
</tr>
<tr>
<td>Date (LKDATE)</td>
<td>The date on which the break was reported.</td>
</tr>
<tr>
<td>Subgrid (GRID)</td>
<td>The location of the break in terms of the five digit county subgrid number.</td>
</tr>
<tr>
<td>Diameter (SIZM)</td>
<td>The diameter of the pipe, in inches.</td>
</tr>
<tr>
<td>Material (TYPM)</td>
<td>The material of the pipe.</td>
</tr>
<tr>
<td>Break Type (LEAKCODE)</td>
<td>A descriptive code assigned by the Maintenance Supervisor after reviewing the failure. It is used to identify the type of the break (circumferential, longitudinal, broken hydrant, etc.).</td>
</tr>
</tbody>
</table>
The SLCWC break database comprised of data collected between January of 1983 and December of 1997 and consisted of over 32,000 incidences of water main break repair. These records represent only the data in digital format. The company also had break records on paper dating back as far as the early 1960’s. From the break records, the oldest pipe in the system was installed in 1874. The original format of the database is dBase IV. For the analysis, the database was converted in the Microsoft Excel format for pre-processing.

However, not all of these records were applicable to the needs of this project. Some of the records in the database related to hydrant leaks, breaks caused by third parties, valve leaks, etc. Others involved galvanized iron, concrete, asbestos cement, or plastic pipes that were not the focus of this study since they account for only a minor percentage of the pipe in the system. Between 1965 and 1982 the Company maintained paper records of main breaks. Approximately 8,500 main failures occurred during this 18-year period, or an average of approximately 472 main breaks per year. This is considerably lower than the 32,242 recorded failures since 1983, or about 2,150 per year. Unfortunately, the paper records cannot be accessed as easily as the computerized records. However, the Company did investigate specific Work Orders in an attempt to produce a more complete break history for selected pipes. These data were compiled in the same format as the electronic database. A total of 318 additional main break records were added to the electronic data set in this fashion.

Steps were taken to preprocess the leak database for use in the modeling. The preprocessing included deleting records that were not applicable to this analysis, deleting records with inconsistencies, assigning Pipe IDs to each record, creating the final pipe inventory, and computing the time from installation to each break for every pipe.

Data Preprocessing Procedure

The Leak Database dBase IV file was imported into Microsoft Excel. The data was preprocessed using a set of Visual Basic for Application (VBA) macros that were developed specifically for the Company. The macros are Microsoft Excel based. The main steps involved in the preprocessing analysis include:

- Data cleanup
Assignment of Pipe ID
· Creation of Pipe Inventory
· Generation of Year to Breaks (YTBs)

Data Cleanup

A small percentage of records in the Leak Database had inconsistencies that dictated their removal from the data set prior to analysis. A macro was developed to identify and remove records from the data set according to the following parameters:

· Zero FOOTAGE – Records with a length equal to zero were removed.
· Blank WORKORD values – Records where the Work Order was not noted were removed from consideration.
· Specified SIZM – Records where the pipe diameter was zero were removed.
· Pipes of type AC, ST, GV, and PL – Records for pipes other than cast iron or ductile iron were removed.
· Blank ONDATE – Records where the date of the incident was not provided were removed.
· Blank YEARACQ – Records where the date of installation was not provided were removed.
· ONDATE earlier than YEARACQ – Records where the date of the incident was earlier than the date of installation were removed.
· GRID name inconsistent with the county GRID system – Records where the subgrid designation did not fit into the county’s grid system were removed.

The records were removed from the data set and copied to a new worksheet within the Excel file. In this way, the “bad” data can be examined, corrected, and included in future model applications. Records were also removed based on the type of leak code. Only records with selected break codes were retained. The selected break codes include circumferential breaks (LEAKCODE = “CB**”), longitudinal breaks (“LB**”), and corrosion holes (“CH**”). Records associated with any other type of leak were deleted. These include records of incidents
such as hydrant leaks (LEAKCODE = “HL***”), struck hydrants (“HS***”), damage by others ("BR**), flush valve leaks (“FV**”), joint leaks (“JL**”), and miscellaneous leaks (“MS***”).

*Creation of Unique PipeIDs*

The original idea was to use the Work Order (WORKORD) of a pipe to distinguish individual pipe segments. However, inconsistencies occurring with records having the same WORKORD values necessitated the creation and use of Pipe IDs. These inconsistencies included:

· Pipes of the same WORKORD but having different year acquired (YEARACQ) values
· Pipes of the same WORKORD but having different diameters (SIZM) values
· Pipes of the same WORKORD but having different material (TYPM) values

If pipes were to be analyzed solely based on WORKORD values, pipes of different types, sizes, year installed could be analyzed as one, thereby leading to erroneous results. In order to resolve these inconsistencies, pipes were identified by Pipe IDs. The Pipe IDs were based on a concatenation of WORKORD, YEARACQ, TYPM, and SIZM. For example, a pipe with WORKORD = “12738B”; YEARACQ = “1951”; TYPM = “CI”; and SIZM = “16” would have a PIPEID = “12738B-1951-CI-16”. Such a notation of the PipeID differentiates this pipe from another pipe of size 12 inches installed under the same work order number and same year. In the latter case, the pipe id would be “12738B-1951-CI-12”.

*Creation of Pipe Inventory*

In order to determine all the unique Pipe IDs in the break database, the following steps were followed:

1. Using the break database, the records are sorted by Pipe ID then by pipe length (FOOTAGE) in descending order. This groups the pipes by their unique Pipe IDs. The purpose of sorting by FOOTAGE is to get the maximum FOOTAGE for each particular Pipe ID. Ideally, all records associated with each Pipe ID should have the same FOOTAGE. However, this was not always true. For example, in some cases the FOOTAGE entered was the ‘as built’ length whereas in others, the length entered was the ‘as designed’ value. Typographical errors also created some differences.
2. All unique Pipe IDs were extracted and stored in a separate Excel worksheet. For each Pipe ID, the following attributes were extracted from the records.

- Pipe ID – the identifier for the pipe segment as described previously.
- WORKORD – the Work Order associated with the pipe installation.
- Category – the pipe category defined for the KANEW modeling (see Section 4).
- TYPM – the pipe material.
- SIZM – the pipe diameter.
- YEARACQ – the year the pipe was installed (or acquired).
- FOOTAGE – the length of the pipe in feet.
- GRID – the St. Louis County subgrid designation
- NumBrk – the total number of breaks a Pipe ID has experienced.
- InstCostPerFt – the cost of pipe installation. Costs were assigned according to pipe diameter.
- DirRepairCost – the direct cost of pipe repair. Costs were assigned according to pipe diameter.
- IndRepairCost – the indirect cost of pipe repair. This field was not used for this model application, but indirect costs could be assigned here in the future according to pipe diameter, subgrid, number of customers affected, etc.
- RepCostPerBrk – the sum of the direct and indirect repair costs.

Note that field names from the Company’s Leak Database are indicated with all capital letters, and fields created for this project are in lower case.

*Generation of Break History For Each Pipe*

Years to break (YTB) is simply the number of years occurring before each pipe experienced a failure in the break database. In order to generate the YTB for each Pipe ID, the records for each Pipe ID were sorted by date (ONDATE) in an ascending order. Each YTB was then determined by subtracting the YEARACQ (installation year) from the ONDATE (data of break occurrence). For example, if a pipe with YEARACQ = 1950 having 3 records in the database with ONDATEs 11/04/84, 08/06/90, and 07/09/95, then the YTB would be as follows: 34, 40, and 45. The YTB values are also referred to as actual break times
7.4.2 Spatial/Soil Data

As previously discussed, the mechanistic model also requires data related to the spatial or soil environment of the pipe. Specifically, this data includes the physical properties of the soil in which the pipe is buried. Most accurate data could be obtained from actual field surveys. For this research, due to lack of available soil data from the water utility, most of the relevant soil information was acquired from the Soil Survey Geographic (SSURGO) soils database.

**Brief Description of the Soil Survey Geographic (SSURGO) database**

The SSURGO database contains digital geographic data developed from detailed soil survey maps, generally at scales of 1:15,840; 1:20,000; and 1:24,000. SSURGO consists of spatial data (digital soil survey maps compiled on control base to agency standards) and attribute data (data on map unit composition, soil properties, and interpretations from the National Cooperative Soil Survey database). SSURGO is the most detailed level of soil mapping done by the Natural Resources Conservation Service (NRCS). SSURGO digitizing duplicates the original soil survey maps. This level of mapping is designed for use by landowners, townships, and county natural resource planning and management. SSURGO is linked to a Map Unit Interpretations Record (MUIR) attribute database. The attribute database gives the proportionate extent of the component soils and their properties for each map unit. The Map Unit Interpretations Record database includes over 25 physical and chemical soil properties. SSURGO map data are available in modified Digital Line Graph (DLG-3) optional and Arc interchange file formats.

**Determination of Soils Associated With Pipes**

In order to determine soil types for various grids, a set of spatial analysis was done. As part of the data organization of the SLCWC, the area is divided into grids. These grids are overlaid with the SSURGO soils data. Figure 7.5 shows the grids overlaying the soils data.
In order for each grid to be assigned a unique soil id, it was assumed that the each grid would be assigned the id of the soil type the covers the highest area in the grid. Figure 7.6 illustrates this procedure.
In the figure, the grid with id = ‘16H41’ would be assigned the soil id = ‘18D’ since the soil id ‘18D’ is the most dominant in the grid. This procedure was repeated for all the grids. In the end, each pipe was related to a soil id through the grid in which the pipe was located. The attributes of the soil are the acquired from the SSURGO soils attribute table. Once each grid could be categorized with a particular soil id, the soil ids were then used to determine the properties of the soil from the soil attribute table contained in the SSURGO database. Not all the soil parameters required for the mechanistic model were available in the SSURGO database. The rest of the parameters were obtained from available literature.

SoilpH:
Obtained from SSURGO data. SSURGO reports both the low and high pH values for each soil. In this case the low pH value was used since that would provide to worst case pH condition.

**SoilResistivity:**

The soil resistivity values were estimated based on the values shown in Table 7.2.

**Table 7.2 Estimated Resistivities for Various Soil Classifications**

<table>
<thead>
<tr>
<th>UNIFIEDCLASS</th>
<th>Description</th>
<th>LowRes</th>
<th>HighRes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>Clay</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>GC</td>
<td>Clay Gravel</td>
<td>1400</td>
<td>3000</td>
</tr>
<tr>
<td>GM</td>
<td>Silty Gravel</td>
<td>2000</td>
<td>4100</td>
</tr>
<tr>
<td>GW</td>
<td>Gravel</td>
<td>1400</td>
<td>12000</td>
</tr>
<tr>
<td>MH</td>
<td>Sandy Silt</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>ML</td>
<td>Clay Silt</td>
<td>1400</td>
<td>6250</td>
</tr>
<tr>
<td>ML</td>
<td>Silty Clay</td>
<td>1250</td>
<td>3750</td>
</tr>
<tr>
<td>SC</td>
<td>Clay Sand</td>
<td>1300</td>
<td>5000</td>
</tr>
<tr>
<td>SM</td>
<td>Silt</td>
<td>2500</td>
<td>8750</td>
</tr>
<tr>
<td>SP</td>
<td>Sand</td>
<td>1300</td>
<td>6750</td>
</tr>
</tbody>
</table>


**SoilAeration:**

Inferred from SSURGO data. This parameter was estimated according to the following criteria: if the clay content of the soil is greater than 60 percent, the aeration was assumed to be poor; clay content between 30 percent and 60 percent was assumed to be fair aeration; and clay content less than 30 percent was assumed to be good aeration.

**SoilMoisture**

Typical soil moisture values were obtain from Terzaghi (1996)
Table 7.3 Porosity, Density and Soil Moisture of Typical soils in Natural State

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<tr>
<th>UNIFIEDCLASS</th>
<th>Description</th>
<th>Porosity</th>
<th>Moisture</th>
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<tr>
<td>GC</td>
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</tr>
<tr>
<td>GM</td>
<td>Silty Gravel</td>
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<tr>
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<td>Gravel</td>
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<td>9</td>
</tr>
<tr>
<td>MH</td>
<td>Sandy Silt</td>
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<tr>
<td>ML</td>
<td>Silty Clay</td>
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<td>SC</td>
<td>Clay Sand</td>
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<tr>
<td>SM</td>
<td>Silt</td>
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<tr>
<td>SP</td>
<td>Sand</td>
<td>30</td>
<td>16</td>
</tr>
</tbody>
</table>

Source: Terzaghi, 1996.

**Soil Liquid Limit:**
Obtained from SSURGO data. SSURGO reports both the low and high liquid limit values for each soil. In this case the high liquid limit value was used since that would provide the worst case liquid limit condition in the model.

**Soil Density:**
Obtained from SSURGO data. SSURGO reports both the low and high soil density values for each soil. In this case the high soil density value was used since that would provide the worst case soil density condition in the model.

**Soil Porosity:**
Estimated from Table 7.3, relevant for the frost load model.

**Soil Expansive:**
Obtained from SSURGO data. SSURGO reports the shrink swell potential for the soil.
Frost Susceptibility: Obtained from SSURGO data. SSURGO reports the frost action potential for the soil.

7.4.3 Regional/Environmental Data

The environmental data relates mostly the effect of changes in air and water temperature. 
Minimum Yearly Temperature: was obtained from St. Louis Climatic database.
Maximum Yearly Temperature: was obtained from St. Louis Climatic database.
Maximum Frost Depth: this was determined by considering the maximum frost depth recorded in the break database.
Maximum Sudden Water Temperature Change: was estimated at 6 degrees Fahrenheit based on discussion with water utility consultants.

Maximum Freeze Days: number of days of consecutive temperatures below freezing temperature. Obtained from St. Louis Climatic database.

Minimum Water Temperature: Determined from analysis of daily water temperature database obtained from SLCWC.

Maximum Water Temperature: Determined from analysis of daily water temperature database obtained from SLCWC

Water Velocity Change: this was estimated at 2 fps.

7.4.4 Other Required Data

Traffic Type: Assumed as heavy

Working Pressure: Provided by St. Louis County Water Company. SLCWC maintains a database of the various grids and the corresponding pressures in the grids.

Pipe Depth: obtained from break database as maximum depth of burial for the particular pipe.
Pavement Type: Assumed as paved


7.5 Results from Mechanistic Model

The data from SLCWC was used to run the model to determine the failure time for each pipe based on the mechanistic model. The critical safety factor was chosen as 1. Table 7.4 shows the results from the mechanistic analysis. The fields with no values in the table are the cases where the model did not converge within 200 years of analysis. In practical terms, cast iron pipes generally have a life span ranging from about 70 years to 150 years or more. Hence when the model does not converge for a safety factor it is assumed that failure of the pipe as a result of that safety factor being violated is not significant. For example, for pipe 1925PSC-1905-CI-12 in Table 7.4, it can be seen that the critical safety factor of 1 is violated in 1923 for the RingPlusHoopStress safety factor, in 1950 for the RingStress safety factor and in 2076 for FlexuralPlusLongitudinalStress safety factor. The relatively early replacement times for the RingPlusHoopStress safety factor and the RingStress safety factor is due partly to the factor that the pipe size is relatively large. Larger pipes are often more prone to failure due to ring and hoop stresses. In contrast, pipe 1925PSC-1907-CI-6, a smaller pipe, installed around the same time (1907) as 1925PSC-1905-CI-12, is shown to prone to failure due to flexural stresses in 2023. Practically, for a conservative analysis, for each pipe the safety factor producing the least failure time would be effective safety factor. In case of 1925PSC-1905-CI-12, the effective safety factor is the RingPlusHoopStress safety factor which yields a replacement time of 1923.

In the table, we see that the safety factors that reach the critical value of 1 soonest are the FlexuralPlusLongitudinalStress safety factor and RingPlusHoopStress safety factor. It must be noted that the FlexuralPlusLongitudinalStress safety factor is highly dependent on the length of beam span chosen. The 4 ft beam span used in this analysis is simply based on recommended estimate from literature. Presently, there is no robust standardized procedure for estimating the expected unsupported beam span.
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7.6 Comparison with GBRM

As stated earlier, the results from the mechanistic model is purely based on modeling the physical effects of the environment on how long the pipe will last. It does not account for the effects any constraining economic factors. On the other hand, the GBRM model is based on applying an economic optimality criterion to the break rate equation for a pipe. Obviously, the factors governing both models are vastly different and their results cannot be expected to be necessarily comparable. The comparison conducted here is mainly out of curiosity. Table 7.5 shows a comparison of the results from both models. As can be seen there are few cases where the results of both models are close. In most cases the difference is 20 years or more. It should be noted that the comparison is between the least failure time for the mechanistic model and the GBRM.

7.7 Issues relating to the Mechanistic Model

Because the mechanistic model is a physically based, the spatial variability of the physical parameters can greatly affect the results predicted from the model. In the current research, one of the main limitations has been the reliance on generalized data. In particular, the application of the model to the St. Louis system required the usage of data from a small scale, less detailed map hence the actual parameters in the immediate environment of the pipes could vary vastly from those reported in SSURGO.

By considering the smaller standardized segments of a given pipe, it is possible to collect data specific to a segment and conduct the mechanistic analysis. In the current analysis, 18-foot segments were considered. Generally, cast iron pipes are manufactured in 18 to 20 ft segments. Thus for a given water main under consideration of length L, this main would consist of S segments. If all the S segments are subject to the same condition, then an analysis of one of the segments can be used to generalize the condition of the whole main. On the other hand, if the various segments are subject to differing conditions, the mechanistic analysis could be performed for each of the segments. Such an analysis would yield different safety factor values for the same time period. These different safety factor values could then be averaged to determine the condition of the whole main.
Also, assuming all the pipes are subject to traffic loading conditions does also introduce some errors in the prediction. In the case of the traffic loading conditions, because the SLCWC at the time of analysis did not have the pipe inventory in a spatially referenced format such as in a GIS, it was virtually impossible to be able to correlate each pipe and the related traffic condition.

The mechanistic model is most useful when considering replacement in areas where public hazard and pipe reliability is of great concern. The approach is recommended for cases where the indirect cost of failure is difficult to determine but estimated to be high. In the following chapters, the physically based regression model is adopted within an economic analysis frame work to predict optimal replacement times for pipes.
Table 7.5 Comparison of Mechanistic model results with GRBM results

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<th>Mechanistic</th>
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<th>ABSDIFF</th>
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<td>49</td>
<td>49</td>
</tr>
<tr>
<td>B-6968-1962-CI-6</td>
<td>2005</td>
<td>2056</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>B-7745-1962-CI-6</td>
<td>2010</td>
<td>2061</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>2690-1939-CI-6</td>
<td>2008</td>
<td>1956</td>
<td>-52</td>
<td>52</td>
</tr>
<tr>
<td>7692-1948-CI-8</td>
<td>1999</td>
<td>2055</td>
<td>56</td>
<td>56</td>
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<tr>
<td>72-1126-1972-CI-6</td>
<td>1999</td>
<td>2055</td>
<td>56</td>
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<tr>
<td>B-7351-1962-CI-6</td>
<td>2002</td>
<td>2059</td>
<td>57</td>
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</tr>
<tr>
<td>9911-1949-CI-6</td>
<td>2028</td>
<td>1970</td>
<td>-58</td>
<td>58</td>
</tr>
<tr>
<td>B-8330-1962-CI-6</td>
<td>2003</td>
<td>2061</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>71-1724-1971-CI-6</td>
<td>2026</td>
<td>2084</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>71-1437-1971-CI-6</td>
<td>2010</td>
<td>2070</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>3384-1940-CI-12</td>
<td>2010</td>
<td>1944</td>
<td>-66</td>
<td>66</td>
</tr>
<tr>
<td>1925PSC-1911-CI-12</td>
<td>2050</td>
<td>1984</td>
<td>-66</td>
<td>66</td>
</tr>
<tr>
<td>4219-1941-CI-12</td>
<td>2014</td>
<td>1947</td>
<td>-67</td>
<td>67</td>
</tr>
<tr>
<td>72-2550-1972-CI-6</td>
<td>2002</td>
<td>2071</td>
<td>69</td>
<td>69</td>
</tr>
<tr>
<td>C-3830-1965-CI-6</td>
<td>1993</td>
<td>2064</td>
<td>71</td>
<td>71</td>
</tr>
<tr>
<td>4203-1941-CI-6</td>
<td>2037</td>
<td>1964</td>
<td>-73</td>
<td>73</td>
</tr>
<tr>
<td>23-1931-CI-6</td>
<td>2092</td>
<td>2018</td>
<td>-74</td>
<td>74</td>
</tr>
<tr>
<td>B-2661-1959-CI-8</td>
<td>2088</td>
<td>2011</td>
<td>-77</td>
<td>77</td>
</tr>
<tr>
<td>2539-1939-CI-6</td>
<td>2043</td>
<td>1966</td>
<td>-77</td>
<td>77</td>
</tr>
<tr>
<td>1925PSC-1903-CI-8</td>
<td>2023</td>
<td>1936</td>
<td>-87</td>
<td>87</td>
</tr>
<tr>
<td>2-1933-CI-12</td>
<td>2059</td>
<td>1972</td>
<td>-87</td>
<td>87</td>
</tr>
<tr>
<td>540-1935-CI-6</td>
<td>2022</td>
<td>2110</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>163-1934-CI-6</td>
<td>2005</td>
<td>2099</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td>7120-1947-CI-8</td>
<td>2058</td>
<td>1961</td>
<td>-97</td>
<td>97</td>
</tr>
<tr>
<td>1925PSC-1925-CI-4</td>
<td>2072</td>
<td>1971</td>
<td>-101</td>
<td>101</td>
</tr>
<tr>
<td>38-1931-CI-12</td>
<td>2098</td>
<td>1964</td>
<td>-134</td>
<td>134</td>
</tr>
</tbody>
</table>


Chapter 8 - A Physically Based Regression Model for Assessing Optimal Replacement Times

8.1 Threshold Break Rate

The mechanistic models presented in this dissertation enable the determination of structural condition of buried water mains at a given time. Based on a specific structural criterion, say a minimum safety factor, such models can be used to determine when pipes should be replaced. In practice, there is often a need to incorporate budgetary constraints to finalize the replacement decisions. This chapter demonstrates the development of a combined economic and physically based pipe replacement model for determining optimal replacement times for buried pipes.

In a previous work, Park (2000) showed that the economically sustainable critical break rate $\Pi_c$, can be defined as

$$\Pi_c = \ln \left( \frac{1 + \frac{r}{100}}{1 + \frac{C_{\text{repair}}}{C_{\text{replacement}} \cdot L}} \right)$$

in which

$\Pi_c$ is the number of breaks per year

r is the discount rate %,

L is the length of the pipe ft,

$C_{\text{repair}}$ is the cost of repairing the pipe per break, dollars

$C_{\text{replacement}}$ is the cost per foot of replacing the pipe, dollars.

The optimal threshold pipe break rate in (8.1) was obtained by minimizing the total discounted repair and replacement costs for a particular pipe. If (8.1) is coupled with the break rate from a physically based model, the optimal replacement time can be determined.
8.2 Relation between the Theoretical Threshold Breakrate and a Physically based Deterioration Model

Rossum (1969) described the extent of pitting, \( p_T \), in a buried water main as:

\[
p_T = A^a f^a K_a K_n \left[ \frac{(10 - pH)}{\omega} \right]^n T^n
\]  

(8.2)

Where:

- \( p_T \) = is the pit depth after \( T \) years, mils
- \( K_n \) and \( n \) = constants dependent on the soil aeration
- \( pH \) = soil pH
- \( \omega \) = the soil resistivity, ohm/cm
- \( A \) = the area of pipe exposed to the soil, ft²
- \( K_a \) and \( a \) = constants dependent on the pipe material
- \( f \) = fraction of pipe exposed to corrosion
- \( T \) = the time of exposure, years

By putting the pit depth in Equation (8.2) as the pipe wall thickness, \( t_0 \), the time to first leak, \( T_{L,1} \), may be estimated as:

\[
T_{L,1} = \left[ \frac{\omega}{(10 - pH)} \right] \left[ \frac{t_0}{K_n K_a} \right]^{1/n} \left[ \frac{1}{Af} \right]^{a/n}
\]  

(8.3)

\( t_0 \) = pipe design thickness, mils

\( T_{L,1} \) = the time to first leak, years

The time to \( N \)th leak is given by

\[
T_{L,N} = \left[ \frac{\omega}{(10 - pH)} \right] \left[ \frac{t_0}{K_n K_a} \right]^{1/n} \left[ \frac{N}{At} \right]^{a/n}
\]  

(8.4)

From equations (8.3) and (8.4), it is seen that

\[
T_{L,N} = T_{L,1} \left[ \frac{N}{t_0} \right]^{a/n}
\]  

(8.5)

Where \( N \), number of leaks = 1, 2, 3, …

Conversely, from (8.5),
\[
N_L = \left( \frac{T_{L,N}}{T_{L,1}} \right)^{n/a}
\]  \hspace{1cm} (8.6)

The leak rate at any time can be determined by differentiating (8.6) with respect to time. The leads to:

\[
\frac{dN}{dT} = \frac{n}{a} \left( \frac{1}{T_{L,1}} \right)^{n/a} T^{(n-a)}
\]  \hspace{1cm} (8.7)

If (8.7) is compared with (8.1), the theoretical threshold break rate, (8.7) can be rewritten as:

\[
\Pi = \frac{n}{a} \left( \frac{1}{T_{L,1}} \right)^{n/a} T^{(n-a)}
\]  \hspace{1cm} (8.8)

The optimal replacement time for the pipe can then be determined by solving for \( T \) in (8.8) to get \( T_c \), the critical replacement time.

\[
T_c = \left[ \frac{\Pi}{n} \left( \frac{T_{L,1}}{T_{L,1}} \right)^{n/a} \right]^{a/(n-a)}
\]  \hspace{1cm} (8.9)

\( T_c \) is the critical replacement time.

Equation (8.9) can be generally written as

\[
T_c = \left[ \frac{\Pi}{n} \left( \frac{T_{L,1}}{T_{L,1}} \right)^{n/(n-a)} \right]^{a/(n-a)}
\]  \hspace{1cm} (8.10)

\[
T_c = \Psi \left( T_{L,1} \right)^{\Omega}
\]  \hspace{1cm} (8.11)

Where \( \Psi = \left[ \frac{\Pi}{n} \left( \frac{T_{L,1}}{T_{L,1}} \right)^{n/(n-a)} \right]^{a/(n-a)} \) and \( \Omega = \frac{n}{n-a} \)

From (8.9), it is conditional that \( n > a \). This condition will be violated for cast iron that has \( a=0.22 \) for good aeration soil \( (n=1/6) \). This leads to three possible conclusions. Possibly, the proposed value of \( 1/6 \) for good aeration soil may be too low. It is also possible that the value of \( a \) for cast iron proposed in the literature may be too high. Thirdly, results of pipe deterioration in good aeration soil may be very erratic and unreliable. This third explanation is theoretically understandable as the deterioration of the pipe is dependent on the rate of corrosion and the less
the corrosion, the less the power of the model to predict the condition of the pipe. A good aeration soil does not promote much corrosion.

From (8.11) it is seen that the critical replacement time is a function of the first leak. The leak time could be adjusted based on the utilization of available data on pipe breaks. If a model can be fitted between the computed first leak time, $T_{L1}$, and recorded first break time, $T_{B1}$, the actual optimal replacement time can be represented as:

$$T_c = \Psi \left[ G \right]$$

Where $G$ is a general model representing the relationship between $T_{L1}$ and $T_{B1}$. Two general regression models are considered. These are called physically based regression model A (PBRMA) and physically based regression model B (PBRMB).

8.2.1 Physically Based Regression Model A (PBRMA)

The PBRMA is a linear regression model relating the first break times of all the pipes to the corresponding first leak times. The general form of the regression equation is

$$T_{B1} = \alpha_A T_{L1} + \beta_A$$

Where $\alpha_A$ and $\beta_A$ are the coefficient and constant of regression respectively for PBRMA. If equation (8.13) is plugged into (8.12), the following equation results:

$$T_{c,A} = \Psi \left[ \alpha_A T_{L1} + \beta_A \right]$$

Where $T_{c,A}$ is the critical replacement time based on PBRMA.

Figure 8.1 shows a scatter plot of the first break times and the first leak times for the pipe samples. As the figure shows, there is apparently no correlation between the first break and first leak times. A linear regression on the data yielded and $r^2$ of 0.002. Obviously, the linear regression model based on the first break and leak times is not appropriate in this case.
8.2.2 Physically Based Regression Model B (PBRMB)

The PBRMB is a log-linear regression model relating the first break times of all the pipes to the corresponding first leak times. The general form of the regression equation is

\[
\ln(T_{B1}) = \alpha_B \ln(T_{L1}) + \beta_B
\]

or

\[
T_{B1} = e^{\beta_B} [T_{L1}]^\alpha_B
\]  

(8.15)

(8.16)

Where \( \alpha_B \) and \( \beta_B \) and the coefficient and constant of regression respectively for PBRMB.

If equation (8.15) is plugged into (8.12), the following equation results:

\[
T_{c,B} = \Psi \left[ e^{\beta_B} [T_{L1}]^{\alpha_B} \right]^{\Omega}
\]

(8.17)

Where \( T_{c,B} \) is the critical replacement time based on PBRMB.
Figure 8.2 shows a scatter plot of the natural log of first break times and the natural log of first leak times for the pipe samples. As the figure shows, there is again, apparently no correlation between the natural log of first break and natural log of first leak times. A log-linear regression on the data yielded and $r^2$ of 0.0003. Obviously, the log-linear regression model based on the first break and leak times is also not appropriate in this case.

8.3 Relationship between Leak and Break times.

The regression models used for PBRMA and PBRMB did not show any correlation between the first break times and the first leak times. In this section the break records for each of the pipes are used together with the computed expected leak times to develop regression models.
It is theorized that there is a relationship between the computed leak times and actual recorded breaks. From equation (8.4), the time to the Nth leak is given as
\[ T_{L,N} = \left[ \frac{\omega}{(10 - pH)} \right] \left[ \frac{t_0}{K_nK_a} \right]^{1/n} \left[ \frac{N_L}{Af} \right]^{-a/n}. \]

If the time to the Nth break is considered as \( T_{B,N} \), then the following simple regression models relation \( T_{L,N} \) and \( T_{B,N} \) can be considered - Physically Based Regression Model C (PBRMC) and Physically Based Regression Model D (PBRMD).

8.3.1 Physically Based Regression Model C (PBRMC)

The PBRMC model is a linear regression model relating the recorded break times for each pipe with the corresponding leak times for the same pipe. The general form of the model is:
\[ T_{B,N} = \alpha_C T_{L,N} + \beta_C \] (8.18)

Where \( \alpha_C \) and \( \beta_C \) and the coefficient and constant of regression respectively for PBRMC. From equation (8.18), the time to the Nth leak can be rewritten as:
\[ T_{L,N} = \frac{1}{\alpha_C} T_{B,N} - \frac{\beta_C}{\alpha_C} \] (8.19)

Using equation (8.19) in equation (8.4), we have:
\[ \frac{1}{\alpha_C} (T_{B,N} - \beta_C) = \left[ \frac{\omega}{(10 - pH)} \right] \left[ \frac{t_0}{K_nK_a} \right]^{1/n} \left[ \frac{N_B}{Af} \right]^{-a/n} \] (8.20)

From (8.20), , the number of breaks, \( N_B \) after \( T_{B,N} \) years can be determined as follows
\[ \left[ \frac{N_B}{Af} \right]^{-a/n} = \left[ \frac{1}{\alpha_C} (T_{B,N} - \beta_C) \right] \left[ \frac{(10 - pH)}{\omega} \right] \left[ \frac{K_nK_a}{t_0} \right]^{-1/n} \] (8.21)

\[ N_B = (T_{B,N} - \beta_C)^{n/a} \left[ \frac{1}{\alpha_C} \right]^{n/a} \left[ \frac{(10 - pH)}{\omega} \right]^{n/a} \left[ \frac{K_nK_a}{t_0} \right]^{1/a} \] (8.22)

And the break rate at any time is
\[
\frac{dN_b}{dT} = \frac{n}{a} (T - \beta_c) \left( \frac{n}{a} \right) \left[ \frac{1}{\alpha_C} \right]^{n/a} \left[ \frac{10 - pH}{\omega} \right]^{n/a} \left[ \frac{K_n K_a}{t_0} \right]^{1/a} \]
(8.23)

From equation (8.1) using the threshold break rate, (8.23) can be rewritten as

\[
\Pi_c = \frac{n}{a} (T - \beta_c) \left( \frac{n}{a} \right) \left[ \frac{1}{\alpha_C} \right]^{n/a} \left[ \frac{10 - pH}{\omega} \right]^{n/a} \left[ \frac{K_n K_a}{t_0} \right]^{1/a} \]
(8.24)

Subsequently, the critical replacement time, \( T_c \), can therefore be determined manipulating (8.24) as follows:

\[
\left[ \frac{1}{\alpha_C} \right]^{n/a} \frac{n}{a} (T_{B,N} - \beta_c) \left( \frac{n}{a} \right) = \Pi_c \left[ \frac{10 - pH}{\omega} \right]^{n/a} \left[ \frac{t_0}{K_n K_a} \right]^{1/a} \frac{1}{[Af]} \]
(8.25)

\[
(T_{B,N} - \beta_c) \left( \frac{n}{a} \right) = \Pi_c \frac{n}{a} \left[ \alpha_C \right]^{n/a} \left[ \frac{10 - pH}{\omega} \right]^{n/a} \left[ \frac{t_0}{K_n K_a} \right]^{1/a} \frac{1}{[Af]} \]
(8.26)

\[
T_{c,c} = \Pi_c \frac{n}{a} \left[ \alpha_C \right]^{n/a} \left[ \frac{10 - pH}{\omega} \right]^{n/a} \left[ \frac{t_0}{K_n K_a} \right]^{1/a} \frac{1}{[Af]} \]
(8.27)

From equation (8.3) and (8.27)

\[
T_{c,c} = \Pi_c \frac{a}{n} \left[ \alpha_C \right]^{n/a} \left[ T_{L,1} \right]^{n/a} + \beta_c \]
(8.28)

Where \( T_{c,c} \) is the critical replacement time based on PBRMC.

8.3.2 Regression Results for PBRMC:

The following example will be used to illustrate the process involved with regression analysis and determination of the critical replacement time using PBRMC.

**Example 8.1 Sample Calculation Based on PBRMC**

**Given:**
Pipe 3027-1939-CI-6 has the following properties:

length = 962 ft
Installed in 1939
Size (Diameter)= 6 inches

Soil Properties
The associated soil parameters are
Soil type = Clay
Soil Class = 18C
pH = 5.6
Soil Aeration = fair
n = 0.33
Kn = 222

Resistivity = 2000 Ohm-cm

Other Parameters
a = 0.13
Ka = 1.40

Design thickness, t_0 = 0.28 inches or 280 mils

Table 8.1 Observed Break Times for PipeID: 3027-1939-CI-6

<table>
<thead>
<tr>
<th>Break No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time, yrs</td>
<td>38</td>
<td>41</td>
<td>43</td>
<td>49</td>
<td>49</td>
<td>50</td>
<td>51</td>
<td>51</td>
<td>54</td>
<td>54</td>
<td>55</td>
<td>55</td>
<td>57</td>
<td>58</td>
</tr>
</tbody>
</table>

**Find:**

(a) Determine the leak times
(b) Determine the regression coefficients $\alpha_C$ and $\beta_C$ and the corresponding $r^2$ value
(c) Compute the threshold break rate using equation (8.1)
(d) Compute Critical Replacement Time using equation (8.28):

**Solution:**

Step 1: Compute Times to Nth Leak
Equation (8.4) is used to compute times to the various leaks.

For first leak time:

\[
T_{L,1} = \left[ \frac{\omega}{(10 - pH)} \right] \left[ \frac{t_0}{K_n K_s} \right]^{1/n} \left[ \frac{N_L}{Af} \right]^{a/n}
\]

\[
T_{L,1} = \frac{2000}{(10 - 5.6)} \left[ \frac{280}{222 \times 1.40} \right]^{1/0.33} \left[ \frac{1}{(3.142 \times (6/12) \times 962) \times 1} \right]^{0.13/0.33}
\]

\[
T_{L,1} = 18.5
\]

\[
T_{L,2} = \frac{2000}{(10 - 5.6)} \left[ \frac{280}{222 \times 1.40} \right]^{1/0.33} \left[ \frac{2}{(3.142 \times (6/12) \times 962) \times 1} \right]^{0.13/0.33}
\]

\[
T_{L,2} = 24.3
\]

\[
T_{L,3} = \frac{2000}{(10 - 5.6)} \left[ \frac{280}{222 \times 1.40} \right]^{1/0.33} \left[ \frac{3}{(3.142 \times (6/12) \times 962) \times 1} \right]^{0.13/0.33}
\]

\[
T_{L,3} = 28.6
\]

The rest of the computed leak times are as follows:

Table 8.2 Computed Leak Times for PipeID: 3027-1939-CI-6

<table>
<thead>
<tr>
<th>Leak No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time To Leak, yrs</td>
<td>18.5</td>
<td>24.3</td>
<td>28.6</td>
<td>31.9</td>
<td>34.9</td>
<td>37.5</td>
<td>39.8</td>
<td>42.0</td>
<td>44.0</td>
<td>45.8</td>
<td>47.6</td>
<td>49.3</td>
<td>50.8</td>
<td>52.3</td>
</tr>
</tbody>
</table>

Step 2:

Using leak times and break times, a regression of observed break times vs computed leak times is conducted.

Table 8.3 Regression Data for PipeID: 3027-1939-CI-6

<table>
<thead>
<tr>
<th>Leak No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time To Leak, yrs</td>
<td>18.5</td>
<td>24.3</td>
<td>28.6</td>
<td>31.9</td>
<td>34.9</td>
<td>37.5</td>
<td>39.8</td>
<td>42.0</td>
<td>44.0</td>
<td>45.8</td>
<td>47.6</td>
<td>49.3</td>
<td>50.8</td>
<td>52.3</td>
</tr>
<tr>
<td>Times to break, yrs</td>
<td>38</td>
<td>41</td>
<td>43</td>
<td>49</td>
<td>49</td>
<td>50</td>
<td>51</td>
<td>51</td>
<td>54</td>
<td>54</td>
<td>55</td>
<td>55</td>
<td>57</td>
<td>58</td>
</tr>
</tbody>
</table>
AlphaC = 0.5719
BetaC = 27.977
$r^2 = 0.9681$

Table 8.4 Regression Results for PipeID:A-2279-1954-CI-12

<table>
<thead>
<tr>
<th>Break/Leak No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leak Time</td>
<td>18.53</td>
<td>24.34</td>
<td>28.6</td>
<td>32</td>
<td>34.92</td>
<td>37.52</td>
<td>39.87</td>
<td>42.03</td>
<td>44.02</td>
<td>45.89</td>
<td>47.64</td>
<td>49.31</td>
<td>50.9</td>
<td>52.4</td>
</tr>
<tr>
<td>Break Time</td>
<td></td>
<td>38</td>
<td>41</td>
<td>43</td>
<td>49</td>
<td>50</td>
<td>51</td>
<td>54</td>
<td>55</td>
<td>56</td>
<td>57</td>
<td>57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PBRMC</td>
<td>38</td>
<td>41</td>
<td>44</td>
<td>46</td>
<td>47</td>
<td>49</td>
<td>50</td>
<td>52</td>
<td>53</td>
<td>54</td>
<td>55</td>
<td>56</td>
<td>57</td>
<td>57</td>
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<tr>
<td>Sq. Error</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Step 3 Compute Threshold Break rate using equation (8.1):

\[
\Pi = \frac{\ln \left( \frac{1 + \frac{r}{100}}{1 + \frac{C_{\text{repair}}}{C_{\text{replacement}} \cdot L}} \right)}{\ln \left( \frac{C_{\text{repair}}}{C_{\text{replacement}} \cdot L} \right)}
\]

Discount rate \( r \), 7.7%.
Repair Cost, \( C_{\text{repair}} \) = $2814.00 per break.
Replacement Cost, \( C_{\text{replacement}} \) = $92.77 per ft
Length, \( L = 962 \) ft
\[
\Pi_t = \frac{\ln \left( 1 + \frac{7.7}{100} \right)}{\ln \left( 1 + \frac{2814}{92.77 \times 962} \right)}
\]

\[
\Pi_t = 2.39
\]

Step 4 Compute Critical Replacement Time using equation (8.28):

\[
T_{c,C} = \left[ \Pi_c \frac{a}{n} \left[ \alpha_c \sum_{l=1}^{n} T_{l,l} \right]^{\frac{a}{n-a}} + \beta_c \right]
\]

\[
T_{c,C} = 2.39 \times \frac{0.13}{0.33} \times \left[ 0.5719 \times (0.33) \times (18.5) \times (0.33/0.13) \right]^{0.33/0.13} + 27.977
\]

\[
T_{c,C} = 75 \text{ years}
\]

Table 8.5 is an excerpt of the results from PBRMC for the pipe samples in the database.

Table 8.5 Excerpt of Results for the pipe samples using PBRMC

<table>
<thead>
<tr>
<th>PipeID</th>
<th>Inst. Yr.</th>
<th>Length</th>
<th>Size</th>
<th>Soil</th>
<th>n</th>
<th>a</th>
<th>RFLT</th>
<th>BrkTh</th>
<th>OFBT</th>
<th>AlphaC</th>
<th>BetaC</th>
<th>r2C</th>
<th>DF</th>
<th>ChiC</th>
<th>CRTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3384-1940-CI-12</td>
<td>1940</td>
<td>2117</td>
<td>12</td>
<td>20B</td>
<td>0.33</td>
<td>0.13</td>
<td>26</td>
<td>2.328</td>
<td>23</td>
<td>0.513</td>
<td>17.32</td>
<td>0.77</td>
<td>8</td>
<td>3.8</td>
<td>86</td>
</tr>
<tr>
<td>1925PSC-1903-CI-8</td>
<td>1903</td>
<td>1650</td>
<td>8</td>
<td>18C</td>
<td>0.33</td>
<td>0.13</td>
<td>53</td>
<td>2.939</td>
<td>83</td>
<td>0.209</td>
<td>71.12</td>
<td>0.93</td>
<td>5</td>
<td>0.1</td>
<td>129</td>
</tr>
<tr>
<td>2-1933-CI-12</td>
<td>1933</td>
<td>1469</td>
<td>12</td>
<td>16C</td>
<td>0.33</td>
<td>0.13</td>
<td>87</td>
<td>1.626</td>
<td>33</td>
<td>0.323</td>
<td>4.75</td>
<td>0.92</td>
<td>5</td>
<td>1.4</td>
<td>190</td>
</tr>
<tr>
<td>1925PSC-1925-CI-8</td>
<td>1925</td>
<td>1309</td>
<td>8</td>
<td>20B</td>
<td>0.33</td>
<td>0.13</td>
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<td>60</td>
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<td>50.21</td>
<td>0.96</td>
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<td>0.1</td>
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</tr>
<tr>
<td>337-1935-CI-12</td>
<td>1935</td>
<td>778.5</td>
<td>12</td>
<td>16C</td>
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<td>0.13</td>
<td>112</td>
<td>0.878</td>
<td>40</td>
<td>0.112</td>
<td>28.28</td>
<td>0.96</td>
<td>8</td>
<td>0.3</td>
<td>61</td>
</tr>
<tr>
<td>A-2279-1954-CI-12</td>
<td>1954</td>
<td>721.2</td>
<td>8</td>
<td>21B</td>
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<td>65</td>
<td>0.816</td>
<td>24</td>
<td>0.096</td>
<td>50.21</td>
<td>0.96</td>
<td>8</td>
<td>0.1</td>
<td>28</td>
</tr>
<tr>
<td>1359-1937-CI-12</td>
<td>1937</td>
<td>684.8</td>
<td>12</td>
<td>18C</td>
<td>0.33</td>
<td>0.13</td>
<td>118</td>
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<td>45</td>
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<tr>
<td>937-1936-CI-12</td>
<td>1936</td>
<td>640.1</td>
<td>12</td>
<td>7B</td>
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<td>0.13</td>
<td>98</td>
<td>0.728</td>
<td>37</td>
<td>0.021</td>
<td>38.26</td>
<td>0.84</td>
<td>8</td>
<td>0.6</td>
<td>43</td>
</tr>
<tr>
<td>4212-1941-CI-12</td>
<td>1941</td>
<td>598.1</td>
<td>12</td>
<td>7B</td>
<td>0.16</td>
<td>0.13</td>
<td>12</td>
<td>0.683</td>
<td>36</td>
<td>0.235</td>
<td>34.02</td>
<td>0.91</td>
<td>8</td>
<td>0.5</td>
<td>50</td>
</tr>
<tr>
<td>C-9609-1968-CI-6</td>
<td>1968</td>
<td>519.8</td>
<td>6</td>
<td>10F</td>
<td>0.16</td>
<td>0.13</td>
<td>23</td>
<td>1.275</td>
<td>12</td>
<td>0.149</td>
<td>7.746</td>
<td>0.97</td>
<td>8</td>
<td>0.6</td>
<td>796</td>
</tr>
<tr>
<td>7120-1947-CI-8</td>
<td>1947</td>
<td>472.1</td>
<td>8</td>
<td>16D</td>
<td>0.33</td>
<td>0.13</td>
<td>33</td>
<td>0.866</td>
<td>17</td>
<td>0.727</td>
<td>-12.8</td>
<td>0.93</td>
<td>8</td>
<td>4.5</td>
<td>80</td>
</tr>
<tr>
<td>1925PSC-1911-CI-12</td>
<td>1911</td>
<td>462.4</td>
<td>12</td>
<td>20A</td>
<td>0.33</td>
<td>0.13</td>
<td>128</td>
<td>0.536</td>
<td>53</td>
<td>0.046</td>
<td>46.32</td>
<td>0.97</td>
<td>8</td>
<td>0.4</td>
<td>398</td>
</tr>
<tr>
<td>4219-1941-CI-12</td>
<td>1941</td>
<td>428.3</td>
<td>12</td>
<td>18D</td>
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<td>0.13</td>
<td>49</td>
<td>0.499</td>
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<td>B-2170-1961-CI-12</td>
<td>1961</td>
<td>402.2</td>
<td>8</td>
<td>17F</td>
<td>0.16</td>
<td>0.13</td>
<td>36</td>
<td>0.743</td>
<td>12</td>
<td>0.101</td>
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<td>0.9</td>
<td>8</td>
<td>2.6</td>
<td>118</td>
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<tr>
<td>1925PSC-1925-CI-6</td>
<td>1925</td>
<td>349.2</td>
<td>6</td>
<td>18C</td>
<td>0.33</td>
<td>0.13</td>
<td>110</td>
<td>0.708</td>
<td>73</td>
<td>0.112</td>
<td>59.28</td>
<td>0.87</td>
<td>4</td>
<td>0.2</td>
<td>87</td>
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<tr>
<td>1932-1932-CI-8</td>
<td>1932</td>
<td>314.9</td>
<td>8</td>
<td>18C</td>
<td>0.33</td>
<td>0.13</td>
<td>116</td>
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<td>53</td>
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<td>42.71</td>
<td>0.88</td>
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<tr>
<td>1943PSC-1910-CI-6</td>
<td>1910</td>
<td>281.9</td>
<td>6</td>
<td>18C</td>
<td>0.33</td>
<td>0.13</td>
<td>110</td>
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<td>73</td>
<td>0.112</td>
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<td>0.87</td>
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<tr>
<td>1976-1938-CI-12</td>
<td>1938</td>
<td>275.1</td>
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<td>7B</td>
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<td>196</td>
<td>0.333</td>
<td>39</td>
<td>0.01</td>
<td>39.23</td>
<td>0.87</td>
<td>7</td>
<td>0.3</td>
<td>39</td>
</tr>
<tr>
<td>23-1934-CI-6</td>
<td>1934</td>
<td>274.3</td>
<td>6</td>
<td>16C</td>
<td>0.33</td>
<td>0.13</td>
<td>111</td>
<td>0.690</td>
<td>54</td>
<td>0.032</td>
<td>50.23</td>
<td>0.8</td>
<td>2</td>
<td>0</td>
<td>54</td>
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<td>38-1931-CI-12</td>
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<td>0.13</td>
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<td>0.290</td>
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<td>0.114</td>
<td>25.89</td>
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<td>0.2</td>
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<td>1935</td>
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<td>6</td>
<td>18C</td>
<td>0.33</td>
<td>0.13</td>
<td>186</td>
<td>0.267</td>
<td>32</td>
<td>0.041</td>
<td>25.35</td>
<td>0.95</td>
<td>8</td>
<td>0.2</td>
<td>32</td>
</tr>
<tr>
<td>1943PSC-1921-CI-6</td>
<td>1921</td>
<td>209</td>
<td>6</td>
<td>23D</td>
<td>0.33</td>
<td>0.13</td>
<td>111</td>
<td>0.534</td>
<td>42</td>
<td>0.361</td>
<td>3.387</td>
<td>0.97</td>
<td>3</td>
<td>0.3</td>
<td>164</td>
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<tr>
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<td>1943</td>
<td>209</td>
<td>6</td>
<td>7B</td>
<td>0.16</td>
<td>0.13</td>
<td>7</td>
<td>0.534</td>
<td>42</td>
<td>0.659</td>
<td>38.42</td>
<td>0.87</td>
<td>3</td>
<td>0.3</td>
<td>137</td>
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<td>1925PSC-1925-CI-4</td>
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<td>199</td>
<td>4</td>
<td>20B</td>
<td>0.33</td>
<td>0.13</td>
<td>148</td>
<td>0.584</td>
<td>39</td>
<td>0.1</td>
<td>24.35</td>
<td>0.96</td>
<td>8</td>
<td>0.3</td>
<td>57</td>
</tr>
<tr>
<td>B-3592-1960-CI-6</td>
<td>1960</td>
<td>197.3</td>
<td>6</td>
<td>16C</td>
<td>0.33</td>
<td>0.13</td>
<td>87</td>
<td>0.506</td>
<td>5</td>
<td>0.188</td>
<td>-7.08</td>
<td>0.89</td>
<td>8</td>
<td>5.7</td>
<td>28</td>
</tr>
</tbody>
</table>

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Legend:

Pipe ID: Pipe identification number
Inst. Yr.: Year pipe was installed
Length: length of pipe
Size: size of pipe diameter
Soil: Soil class
n: Rossum Aeration factor for the soil value
a: Rossum constant for pipe material
RFLT: Computed First leak time
BrkTh: Threshold break rate
OFBT: Observed First leak time
Alpha C: Regression coefficient
Beta C: Regression constant
r2 C: R-squared from regression
DF: degrees of freedom
Chi C: Chi squared value
CRTC: Predicted optimal replacement time

8.3.3 Physically Based Regression Model D (PBRMD)

The PBRMD model is a log-linear regression model relating the recorded break times for each pipe with the corresponding leak times for the same pipe. The general form of the model is:

\[
\ln(T_{B,N}) = \alpha_D \ln(T_{L,N}) + \beta_D
\]  

(8.29)

Or

\[
T_{B,N} = e^{\beta_D \left[ T_{L,N} \right]^{\alpha_D}}
\]  

(8.30)

Where \( \alpha_D \) and \( \beta_D \) are the coefficients of regression respectively for PBRMD.

From (8.30), the time the Nth leak can be written as

\[
T_{L,N} = e^{-\frac{\beta_D}{\alpha_D}} \left[ T_{B,N} \right]^{-\alpha_D}
\]  

(8.31)

When the results from PBRMD shown in equation (8.31) are inserted into (8.4), we have:

\[
e^{-\frac{\beta_D}{\alpha_D}} \left[ T_{B,N} \right]^{-\alpha_D} = \left[ \frac{\omega}{(10 - pH)} \right] \frac{t_0}{K_a K_a} \left[ \frac{N_B}{A f} \right]^{\frac{1}{n}}
\]  

(8.32)

Subsequently, the number of breaks, \( N_B \) after \( T_{B,N} \) years can be determined as follows:

\[
\left[ \frac{N_B}{A f} \right]^{\frac{1}{n}} = e^{-\frac{\beta_D}{\alpha_D}} \left[ T_{B,N} \right]^{-\alpha_D} \left[ \frac{(10 - pH)}{\omega} \right] \frac{K_a K_a}{t_0} ^{-\frac{1}{n}}
\]  

(8.33)
\[ N_B = [A f] e^{\left(\frac{n \beta_D}{\alpha D}\right) T_{B,N}} \left[ \frac{n}{\alpha D} \right] \left( \frac{(10 - pH)}{\omega} \right)^{\frac{n}{\alpha}} \left[ \frac{K_nK_a}{t_0} \right]^{\frac{1}{\alpha}} \]  

Comparing (8.34) to (8.3), (8.34) can be rewritten as

\[ N_B = e^{\left(\frac{n \beta_D}{\alpha D}\right) T_{B,N}} \left[ \frac{n}{\alpha D} \right] \left( \frac{1}{T_{L,1}} \right)^{\frac{1}{n}} \]  

The break rate at any time, \( T \) is then determined by differentiating (8.33) get

\[ \frac{dN_B}{dT} = \left[ \frac{n}{\alpha D} \right] T \left[ \frac{n}{\alpha D} \right] e^{\left(\frac{n \beta_D}{\alpha D}\right) A f} \left( \frac{(10 - pH)}{\omega} \right)^{\frac{n}{\alpha}} \left[ \frac{K_nK_a}{t_0} \right]^{\frac{1}{\alpha}} \]  

Also, (8.36) can be rewritten as

\[ \frac{dN_B}{dT} = \left[ \frac{n}{\alpha D} \right] T \left[ \frac{n}{\alpha D} \right] e^{\left(\frac{n \beta_D}{\alpha D}\right) A f} \left( \frac{1}{T_{L,1}} \right)^{\frac{1}{n}} \]  

From (8.36) and (8.1), it can be seen that if \( T \) is set to \( T_{c,D} \), the critical replacement time, then

\[ \Pi_c = \left[ \frac{n}{\alpha D} \right] T_{c,D} \left[ \frac{n}{\alpha D} \right] e^{\left(\frac{n \beta_D}{\alpha D}\right) A f} \left( \frac{(10 - pH)}{\omega} \right)^{\frac{n}{\alpha}} \left[ \frac{K_nK_a}{t_0} \right]^{\frac{1}{\alpha}} \]  

From (8.38), the critical replacement, \( T_c \), time can therefore be determined as follows:

\[ T_{c,D} \left[ \frac{\alpha D}{\alpha D} \right] = \Pi_c \left[ \frac{\alpha D}{n} \right] e^{\left(\frac{n \beta_D}{\alpha D}\right) A f} \left( \frac{1}{A f} \right) \left( \frac{\omega}{(10 - pH)} \right)^{\frac{1}{\alpha}} \left[ \frac{1}{K_nK_a} \right]^{\frac{1}{\alpha}} \]  

\[ T_{c,D} = \left( \Pi_c \left[ \frac{\alpha D}{n} \right] e^{\left(\frac{n \beta_D}{\alpha D}\right) A f} \left( \frac{1}{A f} \right) \left( \frac{\omega}{(10 - pH)} \right)^{\frac{1}{\alpha}} \left[ \frac{1}{K_nK_a} \right]^{\frac{1}{\alpha}} \right) \]  

From equation (8.3), (8.40) can be rewritten as

\[ T_{c,D} = \left( \Pi_c \left[ \frac{\alpha D}{n} \right] e^{\left(\frac{n \beta_D}{\alpha D}\right) T_{L,1}} \left[ \frac{n}{\alpha D} \right]^{\frac{1}{\alpha}} \right) \]  

Where \( T_{c,D} \) is the critical replacement time based on PBRMD.

In equation (8.41), \( n > \alpha D \).
8.3.4 Regression Results for PBRMD:

The following example will be used to illustrate the process involved with regression analysis and determination of the critical replacement time using PBRMD.

Example 8.2 Sample Calculation Based on PBRMD

Given:
Pipe 3027-1939-CI-6 has the following properties given in Example 8.1

Find:
(a) Determine the leak times
(b) Determine the regression coefficients $\alpha_D$ and $\beta_D$ and the corresponding $r^2$ value
(c) Compute the threshold break rate using equation (8.1)
(d) Compute Critical Replacement Time using equation (8.41):

Solution:
Step 1: Compute Times to Nth Leak
Equation (8.4) is used to computed times to the various leaks.
For first leak time:

$$
T_{L,1} = \left[ \frac{2000}{(10 - 5.6)} \right] \left[ \frac{280}{222 \times 1.40} \right]^{1/0.33} \left[ \frac{1}{(3.142 \times (6/12) \times 962)^{1}} \right]^{0.13/0.33}
$$

$T_{L,1} = 18.5$

$$
T_{L,2} = \left[ \frac{2000}{(10 - 5.6)} \right] \left[ \frac{280}{222 \times 1.40} \right]^{1/0.33} \left( \frac{2}{(3.142 \times (6/12) \times 962)^{1}} \right)^{0.13/0.33}
$$

$T_{L,2} = 24.3$

$$
T_{L,3} = \left[ \frac{2000}{(10 - 5.6)} \right] \left[ \frac{280}{222 \times 1.40} \right]^{1/0.33} \left( \frac{3}{(3.142 \times (6/12) \times 962)^{1}} \right)^{0.13/0.33}
$$
$T_{e,3} = 28.6$

The rest of the computed leak times are shown in Table 8.2.

Step 2:
Using leak times and break times, a regression of Ln of observed break times vs Ln of computed leak times is conducted.

Table 8.6 Natural log Regression Data for PipeID: 3027-1939-CI-6

<table>
<thead>
<tr>
<th>Brk/Leak No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln of Leak</td>
<td>3.1</td>
<td>3.3</td>
<td>3.4</td>
<td>3.5</td>
<td>3.6</td>
<td>3.6</td>
<td>3.7</td>
<td>3.8</td>
<td>3.8</td>
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<td>3.9</td>
<td>3.9</td>
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<tr>
<td>Ln of Break</td>
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<td>3.8</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
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Plot of Natural Log of Break Times vs Natural Log of Leak Times
(PipeID: 3027-1939-CI-6)

\[ y = 0.4094x + 2.4266 \]

$R^2 = 0.9729$
AlphaD = 0.4094
BetaD = 2.4266
\( r^2 = 0.9729 \)

Table 8.7 Natural Log Regression Results for PipeID: 3027-1939-CI-6

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Plot of Observed Break Times vs Predicted Break Times (PBRRMD)
Step 3 Compute Threshold Break rate using equation (8.1):

\[
\Pi_c = \frac{\ln \left(1 + \frac{r}{100}\right)}{\ln \left(1 + \frac{C_{\text{repair}}}{C_{\text{replacement}} \cdot L}\right)}
\]

Discount rate \(r\), 7.7%.

Repair Cost, \(C_{\text{repair}} = \$2814.00\) per break.

Replacement Cost, \(C_{\text{replacement}} = \$92.77\) per ft

Length, \(L = 962\) ft

\[
\Pi_c = \frac{\ln \left(1 + \frac{7.7}{100}\right)}{\ln \left(1 + \frac{2814}{92.77 \times 962}\right)}
\]

\(\Pi_c = 2.39\)

AlphaD = 0.4094

BetaD = 2.4266

\(r^2 = 0.9729\)

Step 4 Compute Critical Replacement Time using equation (8.28):

\[
T_{c,D} = \left(\Pi_c \left[\frac{a\alpha_D}{n}\right] e^{\left(\frac{n\beta_D}{\alpha_D}\right)} \left[T_{L,1}\right]^{1/a}\right)^{\left(\frac{a\alpha_D}{n-a\alpha_D}\right)}
\]

\[
T_{c,D} = \left(2.39 \left[\frac{0.13 \times 0.4094}{0.33}\right] e^{\left(\frac{0.33 \times 2.4266}{0.13 \times 0.4094}\right)} \left[18.5\right]^{0.33/0.13}\right)^{\left(\frac{0.13 \times 0.4094}{0.33 - 0.13 \times 0.4094}\right)}
\]

\(T_{c,D} = 62\) years

Table 8.8 is an excerpt of the results from PBRMD for the pipe samples in the database.
Table 8.8 Excerpt of Results for the pipe samples using PBRMD

<table>
<thead>
<tr>
<th>PipeID</th>
<th>Inst. Yr.</th>
<th>Length</th>
<th>Size</th>
<th>Soil</th>
<th>n</th>
<th>a</th>
<th>RFLT</th>
<th>BrkTh</th>
<th>OFBT</th>
<th>AlphaD</th>
<th>BetaD</th>
<th>r2D</th>
<th>DF</th>
<th>ChID</th>
<th>CRTD</th>
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<td>0.792</td>
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<td>3</td>
<td>78</td>
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<tr>
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<td>1649.8</td>
<td>8</td>
<td>18C</td>
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<td>83</td>
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<td>3.669</td>
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<td>16C</td>
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<td>33</td>
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<td>0.931</td>
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</table>

Legend

PipeID: Pipe identification number
Inst. Yr.: Year pipe was installed
Length: length of pipe
Size: size of pipe diameter
Soil: Soil class
n: Rossum Aeration factor for the soil value
a: Rossum constant for pipe material
RFLT: Computed First leak time
BrkTh: Threshold break rate
OFBT: Observed First leak time
AlphaD: Regression coefficient
BetaD: Regression constant
r2D: R-squared from regression
DF: degrees of freedom
ChID: Chi squared value
CRTD: Predicted optimal replacement time

The results from the physically based model is compared with the results from the general break regression model from Park (2000). in section 8.4.
8.4 Comparison of PBRMD with GBRM

The results obtained from the PBRMD were compared with the results reported for GBRM in Park (2000). Table 8.9 shows the predicted replacement years for both models, the total predicted life span for each pipe, and the differences in the results for each model.

<table>
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<tr>
<th>PipeID</th>
<th>Yr Inst</th>
<th>Length</th>
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<th>PBRMD</th>
<th>GBRM</th>
<th>GBRM-PBRMD</th>
<th>AbsDiff</th>
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Comparison of Results From Physically Based Model with Results From GBRM (Continued)

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Legend:
PipeID: PipeID from Database
Yr Inst: Year Pipe was installed
Length: Length of Pipe
PBRMC: Results from linear model
PBRMD: Results from exponential model
GBRM: Results from General Break Regression Model
8.4.1 Sign Test Comparison of Results from GBRM and PBRMD

The signed test (Cangelosi, 1983) is also used to compare the two methods to determine whether either method generally produced earlier or later replacement time than the other. In this case, the goal is to determine if GBRM predicts longer replacement times than PBRMD. (See Table 8.10)

H₀: \( p = 0.5 \) (probability of plus = 0.5),
Hₐ: \( p > 0.5 \) (probability of plus > 0.5),
\( \alpha = 0.01 \)

Reject \( H₀ \) if \( Z_{test} > 2.33 \)

The following formula was used:

\[
E(k) = n\pi
\]

\[
s_k = \sqrt{[n\pi(1-\pi)]}
\]

where
\( E(k) \) = the expected average number of pluses
\( s_k \) = the standard deviation of the number of pluses
\( n \) = the sample size
\( \pi \) = the population proportion (0.5 when the number of pluses is expected to equal the number of minuses)

\[
Z_{test} = \frac{k \pm \frac{1}{2} - E(k)}{s_k}
\]

\( k \) = the number of pluses and minuses

Calculation
\( n = 61 \)
\( E(k) = n\pi = 61(0.5) = 30.5 \)
\( s_k = \sqrt{[n\pi(1-\pi)]} = \sqrt{[61(0.5)(1-0.5)]} = 3.90 \)

Solve for \( Z_{test} \)
\( Z_{test} = \frac{k \pm \frac{1}{2} - E(k)}{s_k} \)
\[ Z_{\text{test}} = \left( 54 + 0.5 - 30.5 \right) / 3.90 = 6.15 \]

Conclusion
Reject \( H_0 \). These results indicate that the GBRM model predicts longer replacement times than PBRMD.

Fundamentally the two methods utilize different sets of parameters to obtain the replacement time. In the case of GBRM, only the break times are used. PBRMD uses both the break times and the soil characteristics. The strength of PBRMD is the ability to utilize the site specific conditions to assist in developing the replacement model. Unfortunately, this is also the weakness of the model. By using the site conditions, the model is vulnerable the extra errors inherent in the soil parameters. Issues such as resolution of data and detail are critical. In this case, the data used was the Natural Resources Conservation Service (NRCS) SSURGO data. because of the generalize form of the data, it is possible the actual soil conditions proximal to the pipe varies greatly from those reported in the SSURGO data.
Table 8.10 Application of Sign Test for Comparing Two Mathematical Models Used For Predicting Pipe Replacement

<table>
<thead>
<tr>
<th>PipeID</th>
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<th>GBRM</th>
<th>GBRM-PBRMD</th>
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</table>

- : GBRM less than PBRMD
+ : GBRM greater than PBRMD
8.5 Comparison of Mechanistic, General Break Regression, and Physically Based Regression Models

The strength of the physically based regression model is the fact that it incorporates the physical conditions surrounding the pipe, the pipe break history and the economic constraints to predict the optimal time to replace the pipe. The advantages and disadvantages of the mechanistic model, the physically based model, and the general break regression model are shown in Table 8.11.
<table>
<thead>
<tr>
<th>Model</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Mechanistic                  | 1. Does NOT rely on pipe failure history though failed pipes may provide valuable samples for testing and parameter estimates for running the model.  
2. Recommended for use where unexpected pipe failure is highly intolerable and pipe reliability is of extreme importance  
3. It is also recommended where there are high and undeterminable indirect costs of failure.  
4. It has the ability to predict vulnerable pipes before the pipes actually fail. | 1. Highly dependent on soil environment and pipe structural properties.  
2. Data requirements can be costly and require extra effort and may require extra training for crew to collect data.  
3. Traffic loads, unsupported beam span loads, expansive soil loads are difficult to determine and may thereby affect the results of the model.  
4. Lacks the ability to incorporate economic constraints and does not take into account any direct economic factors (repair/replacement costs)  
5. Sensitive to estimated length of unsupported beam span |
| General Break Regression Model (GBRM) | 1. Models different pipe types and sizes  
2. Data required for the model is more easily acquired. Least cost for data acquisition and training of crew for data acquisition.  
3. Based on simple regression procedure. | 1. Requires data from failed pipes. Pipes must have at least 3 failures for data to be usable for analysis  
2. Does not take into account the environment in which the pipe exists. |
| Physically Based Regression Model (PBRM) | 1. Combines the advantages of both GBRM and Mechanistic Model  
2. Takes into account pipe physical conditions.  
3. Allows determination of pipe life based on physical properties and corroborated by pipe history  
4. It also incorporates an economic dimension | 1. Extra environmental data requirements may introduce more errors  
2. Pipe must have failed a number of times to enable development of regression model. |
Chapter 9 - Accelerated and Delayed Replacement of Pipes

9.1 Introduction

In this chapter, the penalty resulting from accelerated and delayed replacement of a failure prone pipe is derived. Clearly, such penalty will be zero for replacement at the optimal time. An analytical expression for the optimal replacement time is presented. This analytical expression is verified by numerical experiments using different discount rates, costs and break rates. This analysis should help the decision makers in assessing the economic loss for not replacing pipes at the optimal time.

9.2 Optimal Replacement Time

It is assumed that a location being served by a pipe will continue to require the use of such a pipe. Therefore there will be continued expenditure and this expenditure is to be minimized in terms of the annual cost. Consider the 5-year cost stream shown in Figure 9.1 for a pipe that is currently in use.

![Cash Flow Diagram](image)

**Figure 9.1 Cash Flow**

In Figure 9.1, \( a_i \) denotes the repair cost for year \( i \), \( C_f \) denotes the replacement cost, and \( A \) is the equal annual cost that is equivalent to the repair and replacement cost stream. The equal annual cost \( A \) is obtained by
A = \left( \sum_{i=1}^{k} \frac{a_i}{(1+r)^i} + \frac{C_f}{(1+r)^k} \right) \left[ \frac{r(1+r)^k}{(1+r)^k-1} \right]

(9.1)

in which \( r \) is the discount rate. In (9.1), the first term is the total cost discounted to year “0” and the second term is the annualizing factor.

In general, for \( k \)-year cost stream, equation (9.1) can be written as

\[ A_k = \left( \sum_{i=1}^{k} \frac{a_i}{(1+r)^i} + \frac{C_f}{(1+r)^k} \right) \left[ \frac{r(1+r)^k}{(1+r)^k-1} \right] \]

(9.2)

For optimal replacement time, we assume that \( A_k \) is a unimodal function with \( A_k \) attaining the minimum value at time \( J \). From the unimodal assumption, it follows that the optimum

\[ A_J < A_{J+1} \]

(9.3)

which yeilds

\[ \left( \sum_{i=1}^{J+1} \frac{a_i}{(1+r)^i} + \frac{C_f}{(1+r)^{J+1}} \right) \left[ \frac{r(1+r)^{J+1}}{(1+r)^{J+1}-1} \right] > \left( \sum_{i=1}^{J} \frac{a_i}{(1+r)^i} + \frac{C_f}{(1+r)^J} \right) \left[ \frac{r(1+r)^J}{(1+r)^J-1} \right] \]

(9.4)

\[ \left( \sum_{i=1}^{J+1} \frac{a_i}{(1+r)^i} + \frac{C_f}{(1+r)^{J+1}} \right) \left[ \frac{1}{(1+r)^J} \right] > \left( \sum_{i=1}^{J} \frac{a_i}{(1+r)^i} + \frac{C_f}{(1+r)^J} \right) \left[ \frac{1}{(1+r)^J} \right] \]

(9.5)

considering that the discount rate is between 0.05 and 0.15 and \( J \) is between 50 and 75 years, we can approximate

\[ (1+r)^J - \frac{1}{(1+r)} = (1+r)^J - 1 \]

(9.6)

Using equation (9.6) in equation (9.5) we obtain

\[ \frac{a_{J+1}}{(1+r)^{J+1}} + \frac{C_f}{(1+r)^{J+1}} - \frac{C_f}{(1+r)^J} > 0 \]

(9.7)

We like to rewrite equation (9.7) in terms of the times of occurrence of breaks. Assuming the optimum occurs at the \( n \)th break, we can rewrite equation (9.7) in terms of the break occurrence times as

\[ \frac{C_{n+1}}{(1+r)^{n+1}} + \frac{C_f}{(1+r)^{n+1}} - \frac{C_f}{(1+r)^n} > 0 \]

(9.8)

in which \( C_{n+1} \) is the repair cost for the \((n+1)\)th break and results in the condition
\[ C_{n+1} > C_f (1 + r)^{T_{n+1} - T_n} - C_f \]  \hspace{1cm} (9.9)

in which \( T_{n+1} - T_n = \Delta T_n \) is the time between the nth and (n+1)th breaks. We can simplify equation (9.9) as

\[ \ln(1 + \frac{C_{n+1}}{C_f}) > \Delta T_n \ln(1 + r) \]  \hspace{1cm} (9.10)

and recognizing \( \frac{1}{\Delta T_n} = B_{th} \), break rate at the time of the nth break, we have

\[ B_{th} > \frac{\ln(1 + r)}{\ln(1 + \frac{C}{C_f})} \]  \hspace{1cm} (9.11)

Condition (9.11) asserts that whenever the break rate exceeds the ratio \( \frac{\ln(1 + r)}{\ln(1 + \frac{C}{C_f})} \), the pipe should be replaced. For the threshold break rate condition (9.11) to coincide with the minimum annual cost criterion (9.3), the discount rate-time to replacement condition (9.6) given by

\[ (1 + r)^t - \frac{1}{(1 + r)} = (1 + r)^t - 1 \]

must be satisfied. However, the computer program given here computes the minimum annual cost without imposing condition (9.6) and therefore will always find the minimum annual cost.

9.3 Penalty for Accelerated Replacement

We know the optimal replacement for a pipe under consideration to be \( T_{opt} \). For this pipe, beginning from time period 1, we incur total repair cost, \( a_i \) for each period i, until end of period \( T_{opt} \) at which we incur the installation cost \( C_f \) in addition to the repair cost \( a_{T_{opt}} \) in the optimal replacement year. The repair rate per year is given by a regression equation such as the PBRRM (Physically based regression replacement model). Let the interest rate be r.

Using \( a_i \) for each i, up to and including period \( T_{opt} \), and the installation cost \( C_f \) at time \( T_{opt} \), with an interest rate, r, we can calculate equal annual cost A, beginning from period 1 and ending in period \( T_{opt} \). In Table 9.1 the cash flow over the life time of the pipe is illustrated. For the purpose of illustration, let us assume \( T_{opt} = 5 \) years. Note that we can identify the \( T_{opt} \) from the
threshold break rate criterion (9.11) provided the discount rate, time of replacement criterion (9.6) is satisfied.

Table 9.1 Illustration of cash flow over the life of the a pipe

<table>
<thead>
<tr>
<th>Period</th>
<th>Cost</th>
<th>Equal cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$C_f$</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$a_1$</td>
<td>$A$</td>
</tr>
<tr>
<td>2</td>
<td>$a_2$</td>
<td>$A$</td>
</tr>
<tr>
<td>3</td>
<td>$a_3$</td>
<td>$A$</td>
</tr>
<tr>
<td>4</td>
<td>$a_4$</td>
<td>$A$</td>
</tr>
<tr>
<td>5</td>
<td>$a_5 + C_f$</td>
<td>$A$</td>
</tr>
<tr>
<td>6</td>
<td>$a_1$</td>
<td>$A$</td>
</tr>
<tr>
<td>7</td>
<td>$a_2$</td>
<td>$A$</td>
</tr>
<tr>
<td>8</td>
<td>$a_3$</td>
<td>$A$</td>
</tr>
<tr>
<td>9</td>
<td>$a_4$</td>
<td>$A$</td>
</tr>
<tr>
<td>10</td>
<td>$a_5 + C_f$</td>
<td>$A$</td>
</tr>
<tr>
<td>11</td>
<td>$a_1$</td>
<td>$A$</td>
</tr>
</tbody>
</table>

That equal annual cost $A$ is determined by

$$A = \left( \frac{C_f}{(1+r)^{T_{opt}}} + \sum_{i=1}^{T_{opt}} \frac{a_i}{(1+r)^i} \right) \left[ \frac{r(1+r)^{T_{opt}}}{(1+r)^{T_{opt}} - 1} \right]$$

(9.12)

where

$C_f =$ total replacement cost, dollars

$a_i = C_{\text{repair}} \cdot n_i$

(9.13)

$n_i =$ number of breaks in year $i$ derived from PBRRM,

$C_{\text{Repair}} =$ present repair cost per break year, dollars

Now assume that the pipe is replaced 2 years earlier than the optimal time of 5 years. That is the old pipe has lasted for 3 years. For the case under consideration, if the pipe is replaced 2 years earlier, the resulting cost table, Table 9.2 is shown below.
Table 9.2 Costs for accelerated replacement

<table>
<thead>
<tr>
<th>Period</th>
<th>Cost</th>
<th>Equal cost</th>
<th>Early Replace Cost</th>
<th>Early Replace Eq. Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a1</td>
<td>A</td>
<td>a1</td>
<td>a1</td>
</tr>
<tr>
<td>2</td>
<td>a2</td>
<td>A</td>
<td>a2</td>
<td>a2</td>
</tr>
<tr>
<td>3</td>
<td>a3</td>
<td>A</td>
<td>a3 + Cf</td>
<td>a3 + Cf</td>
</tr>
<tr>
<td>4</td>
<td>a4</td>
<td>A</td>
<td>a1</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>a5 + Cf</td>
<td>A</td>
<td>a2</td>
<td>A</td>
</tr>
<tr>
<td>6</td>
<td>a1</td>
<td>A</td>
<td>a3</td>
<td>A</td>
</tr>
<tr>
<td>7</td>
<td>a2</td>
<td>A</td>
<td>a4</td>
<td>A</td>
</tr>
<tr>
<td>8</td>
<td>a3</td>
<td>A</td>
<td>a5 + Cf</td>
<td>A</td>
</tr>
<tr>
<td>9</td>
<td>a4</td>
<td>A</td>
<td>a1</td>
<td>A</td>
</tr>
<tr>
<td>10</td>
<td>a5 + Cf</td>
<td>A</td>
<td>a2</td>
<td>A</td>
</tr>
<tr>
<td>11</td>
<td>a1</td>
<td>A</td>
<td>a3</td>
<td>A</td>
</tr>
</tbody>
</table>

From Table 9.2, by subtracting column 3 from column 5, we observe the penalty in terms of the present cost for a pipe that was kept for 3 years is given by

\[ \text{PEN}_{3} = \frac{C_{f}(1+r)^{2}}{(1+r)^{2}} + \left( \frac{a_{1}}{(1+r)} - \frac{A}{(1+r)} \right) + \left( \frac{a_{2}}{(1+r)^{2}} - \frac{A}{(1+r)^{2}} \right) + \left( \frac{a_{3}}{(1+r)^{3}} - \frac{A}{(1+r)^{3}} \right) \]  \hfil (9.14)

In general, for early replacement in year \( j < T_{\text{opt}} \), we can write the penalty for replacement after year \( j \), \( \text{PEN}_{j} \) as

\[ \text{PEN}_{j} = \sum_{i=1}^{j} \left( \frac{(a_{i} - A)}{(1+r)^{i}} \right) + \frac{C_{f}}{(1+r)^{j}} \]  \hfil (9.15)

9.4 Delayed Replacement

Now consider two-year delayed replacement. The corresponding cost table is Table 9.3.
Table 9.3 Illustration of costs for accelerated replacement

<table>
<thead>
<tr>
<th>Period (1)</th>
<th>Cost with Optimal Replacement (2)</th>
<th>Equal cost with Optimal Replacement (3)</th>
<th>Cost without Optimal Replacement (4)</th>
<th>Equivalent Cost Cash flow based on (4) (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a₁</td>
<td>A</td>
<td>a₁</td>
<td>a₁</td>
</tr>
<tr>
<td>2</td>
<td>a₂</td>
<td>A</td>
<td>a₂</td>
<td>a₂</td>
</tr>
<tr>
<td>3</td>
<td>a₃</td>
<td>A</td>
<td>a₃</td>
<td>a₃</td>
</tr>
<tr>
<td>4</td>
<td>a₄</td>
<td>A</td>
<td>a₄</td>
<td>a₄</td>
</tr>
<tr>
<td>5</td>
<td>a₅ + Cf</td>
<td>A</td>
<td>a₅</td>
<td>a₅</td>
</tr>
<tr>
<td>6</td>
<td>a₁</td>
<td>A</td>
<td>a₆</td>
<td>a₆</td>
</tr>
<tr>
<td>7</td>
<td>a₂</td>
<td>A</td>
<td>a₇ + Cf</td>
<td>a₇ + Cf</td>
</tr>
<tr>
<td>8</td>
<td>a₃</td>
<td>A</td>
<td>a₁</td>
<td>A</td>
</tr>
<tr>
<td>9</td>
<td>a₄</td>
<td>A</td>
<td>a₂</td>
<td>A</td>
</tr>
<tr>
<td>10</td>
<td>a₅ + Cf</td>
<td>A</td>
<td>a₃</td>
<td>A</td>
</tr>
<tr>
<td>11</td>
<td>a₁</td>
<td>A</td>
<td>a₄</td>
<td>A</td>
</tr>
<tr>
<td>12</td>
<td>a₂</td>
<td>A</td>
<td>a₅ + Cf</td>
<td>A</td>
</tr>
<tr>
<td>13</td>
<td>a₃</td>
<td>A</td>
<td>a₁</td>
<td>A</td>
</tr>
<tr>
<td>14</td>
<td>a₄</td>
<td>A</td>
<td>a₂</td>
<td>A</td>
</tr>
<tr>
<td>. .</td>
<td>A</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>. .</td>
<td>A</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>∞</td>
<td>A</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>

Now, the penalty for the delayed replacement can be computed by subtracting the summation of the costs in column (2) from the summation of the costs in column (4). This implies the penalty for replacing the pipe in year 7 is

\[ \text{PEN}_7 = \sum_{i=1}^{\infty} \text{Column}(4) - \sum_{i=1}^{\infty} \text{Column}(2) \]  \hspace{1cm} (9.16)

Further, since

\[ \sum_{i=1}^{\infty} \text{Column}(2) \equiv \sum_{i=1}^{\infty} \text{Column}(3) \]  \hspace{1cm} (9.17)

and

\[ \sum_{i=1}^{\infty} \text{Column}(4) \equiv \sum_{i=1}^{\infty} \text{Column}(5) \]  \hspace{1cm} (9.18)
it implies that

\[ \text{PEN}_j = \sum_{i=1}^{\infty} \text{Column}(5) - \sum_{i=1}^{\infty} \text{Column}(3) \]  

(9.19)

Now, for column (3), considering the present worth sum, \( \sum_{i=1}^{\infty} \text{Column}(3) \) can be written as

\[
\sum_{i=1}^{\infty} \frac{A}{(1+r)^i} = \frac{A}{(1+r)^1} + \frac{A}{(1+r)^2} + \ldots + \frac{A}{(1+r)^{n-1}} + \frac{A}{(1+r)^n}
\]  

(9.20)

Let \( k = \frac{1}{1+r} \)

Then

\[
\sum_{i=1}^{n} \frac{A}{(1+r)^i} = S_n = A k^1 + A k^2 + \ldots + A k^{n-1} + A k^n
\]  

(9.21)

Multiplying (9.21) by \( k \), we get

\[
k S_n = A k^2 + A k^3 + \ldots + A k^n + A k^{n+1}
\]  

(9.22)

subtracting (9.21) from (9.22), we get

\[
k S_n - S_n = A k^{n+1} - A k^1
\]  

(9.23)

\[
S_n (k - 1) = A k^{n+1} - A k
\]  

(9.24)

\[
S_n = \frac{A (k^{n+1} - k)}{(k - 1)}
\]  

(9.25)

\[
S_n = \frac{A (k - k^{n+1})}{(1-k)}
\]  

(9.26)

The limit of \( S_n \) as \( n \) approaches infinity is

\[
\lim_{n \to \infty} S_n = A \left( \frac{k}{1-k} \right) = S
\]  

(9.27)

Hence

\[
\sum_{i=1}^{\infty} \text{Column}(3) = S
\]  

(9.28)
For Column 5, considering the present worth sum, $\sum_{i=1}^{\infty} \text{Column}(3)$ can be written as

$$\sum_{i=1}^{\infty} \text{Column}(5) = \frac{C_i}{(1+r)^i} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \left[ \frac{A}{(1+r)^{i+1}} + \frac{A}{(1+r)^{i+2}} + \ldots + \frac{A}{(1+r)^{n+j}} \right]$$

Factoring out $\frac{1}{(1+r)^j}$ in (9.29), we get

$$\sum_{i=1}^{\infty} \text{Column}(5) = \frac{C_i}{(1+r)^i} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \frac{1}{(1+r)^j} \left[ \frac{A}{(1+r)^{i+1}} + \frac{A}{(1+r)^{i+2}} + \ldots + \frac{A}{(1+r)^{n+j}} \right]$$

From (9.30),

$$\frac{A}{(1+r)^1} + \frac{A}{(1+r)^2} + \ldots + \frac{A}{(1+r)^{n+j}} + \frac{A}{(1+r)^{n+j}}$$

$$= \left[ \frac{A}{(1+r)^1} + \frac{A}{(1+r)^2} + \ldots + \frac{A}{(1+r)^n} \right] - \left[ \frac{A}{(1+r)^{n+j}} + \frac{A}{(1+r)^{n+j+1}} + \frac{A}{(1+r)^{n+j+2}} + \ldots + \frac{A}{(1+r)^{n+j+n}} \right]$$

it is already known that

$$\left[ \frac{A}{(1+r)^1} + \frac{A}{(1+r)^2} + \ldots + \frac{A}{(1+r)^n} + \frac{A}{(1+r)^n} \right] = A \left( \frac{k}{1-k} \right)$$

where $k = \frac{1}{1+r}$

Hence

$$\frac{A}{(1+r)^1} + \frac{A}{(1+r)^2} + \ldots + \frac{A}{(1+r)^{n+j}} + \frac{A}{(1+r)^{n+j}}$$

$$= A \left( \frac{k}{1-k} \right) - \frac{1}{(1+r)^{n+j}} \left( \sum_{i=1}^{j} \frac{A}{(1+r)^i} \right)$$

From (9.33),

$$\frac{A}{(1+r)^1} + \frac{A}{(1+r)^2} + \ldots + \frac{A}{(1+r)^{n+j}} + \frac{A}{(1+r)^{n+j}} = A \left( \frac{k}{1-k} \right) - \frac{1}{(1+r)^{n+j}} \left( \sum_{i=1}^{j} \frac{A}{(1+r)^i} \right)$$

Inserting (9.34) into (9.30), we get

$$\sum_{i=1}^{\infty} \text{Column}(5) = \frac{C_i}{(1+r)^i} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \frac{1}{(1+r)^j} \left[ A \left( \frac{k}{1-k} \right) - \frac{1}{(1+r)^{n+j}} \left( \sum_{i=1}^{j} \frac{A}{(1+r)^i} \right) \right]$$
From (9.35) as n approaches infinity, n>>>j and \(\frac{1}{(1+r)^{n-j}} \to 0\)

Hence

\[
\sum_{i=1}^{\infty} \text{Column}(5) = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \frac{1}{(1+r)^j} \left[ A \left( \frac{k}{1-k} \right) \right]
\]

(9.36)

\[
\sum_{i=1}^{\infty} \text{Column}(5) = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \frac{1}{(1+r)^j} [S]
\]

(9.37)

\[\text{PEN}_j = \sum_{i=1}^{\infty} \text{Column}(5) - \sum_{i=1}^{\infty} \text{Column}(3)\]

(9.38)

\[\text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \frac{1}{(1+r)^j} [S] - S\]

(9.39)

\[\text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + S \left( \frac{1}{(1+r)^j} - 1 \right)\]

(9.40)

\[\text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + A \left( \frac{1}{(1+r)} \right) \left( \frac{1}{1-(1+r)} \right) \left( \frac{1}{(1+r)^j} - 1 \right)\]

(9.41)

Let \(k = \frac{1}{(1+r)} \Rightarrow 1+r = \frac{1}{k}\) and \(r = \frac{1}{k} - 1\)

\[\text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + A \left( \frac{k}{1-k} \right) (k^j - 1)\]

(9.42)

\[\text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + A \left( \frac{k^{i+1} - k}{1-k} \right)\]

(9.43)
\[
PEN_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + A(-1)\left(\frac{k-k^{j+1}}{1-k}\right) \quad (9.44)
\]

\[
PEN_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} - \sum_{i=1}^{j} \frac{A}{(1+r)^i} \quad (9.45)
\]

\[
PEN_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i - A}{(1+r)^i} \quad (9.46)
\]

Which is the same as the result given in equation (9.15) and the cost difference statement in (9.19).

Hence penalty for two year delayed replacement in present cost,

\[
PEN_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{7} \frac{a_i - A}{(1+r)^i} = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{7} \frac{a_i}{(1+r)^i} - \sum_{i=1}^{7} \frac{A}{(1+r)^i} \quad (9.47)
\]

Alternatively, from (9.41),

\[
PEN_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + A\left(\frac{1}{r}\right)\left(\frac{1}{(1+r)^j}\right) - 1 \quad (9.48)
\]

\[
PEN_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + A\left(\frac{1-(1+r)^j}{r(1+r)^j}\right) \quad (9.49)
\]

But from (9.12), it is know that

\[
A = \left(\frac{C_f}{(1+r)^{t_{opt}}} + \sum_{i=1}^{t_{opt}} \frac{a_i}{(1+r)^i}\right)\left[\frac{r(1+r)^{t_{opt}}}{(1+r)^{t_{opt}} - 1}\right],
\]

therefore, by substituting for A in (9.49), we get

\[
PEN_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \left(\frac{C_f}{(1+r)^{t_{opt}}} + \sum_{i=1}^{t_{opt}} \frac{a_i}{(1+r)^i}\right)\left[\frac{r(1+r)^{t_{opt}}}{(1+r)^{t_{opt}} - 1}\right] \left[\frac{1-(1+r)^j}{r(1+r)^j}\right] \quad (9.50)
\]

\[
PEN_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \left(\frac{C_f}{(1+r)^{t_{opt}}} + \sum_{i=1}^{t_{opt}} \frac{a_i}{(1+r)^i}\right)\left[\frac{r(1+r)^{t_{opt}} - r(1+r)^{t_{opt}}(1+r)^j}{(1+r)^{t_{opt}} r(1+r)^j - r(1+r)^j}\right] \quad (9.51)
\]
\[ \text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \left( \frac{C_f}{(1+r)^{t_{\text{opt}}}^{\text{op}}} + \sum_{i=1}^{t_{\text{opt}}} \frac{a_i}{(1+r)^i} \right) \left[ \frac{r(1+r)^{t_{\text{op}}^{\text{op}}} - r(1+r)^{t_{\text{op}}^{\text{op}}}(1+r)^j}{(1+r)^{t_{\text{op}}^{\text{op}}} - 1} \right] \] (9.52)

\[ \text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \left( \frac{C_f}{(1+r)^{t_{\text{op}}}^{\text{op}}} + \sum_{i=1}^{t_{\text{op}}} \frac{a_i}{(1+r)^i} \right) \left[ \frac{(1+r)^{t_{\text{op}}^{\text{op}}-j} - (1+r)^{t_{\text{op}}^{\text{op}}} - (1+r)^{t_{\text{op}}^{\text{op}}}}{(1+r)^{t_{\text{op}}^{\text{op}}}} \right] \] (9.53)

\[ \text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \left( \frac{C_f}{(1+r)^{t_{\text{op}}}^{\text{op}}} + \sum_{i=1}^{t_{\text{op}}} \frac{a_i}{(1+r)^i} \right) \left[ \frac{(1+r)^{t_{\text{op}}^{\text{op}}} - (1+r)^{t_{\text{op}}^{\text{op}}}}{(1+r)^{t_{\text{op}}^{\text{op}}}} \right] \] (9.54)

\[ \text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \left( \frac{C_f}{(1+r)^{t_{\text{op}}}^{\text{op}}} + \sum_{i=1}^{t_{\text{op}}} \frac{a_i}{(1+r)^i} \right) \left[ \frac{1}{(1+r)^{t_{\text{op}}^{\text{op}}}} \right] \] (9.55)

\[ \text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \left( \frac{C_f}{(1+r)^{t_{\text{op}}}^{\text{op}}} + \sum_{i=1}^{t_{\text{op}}} \frac{a_i}{(1+r)^i} \right) \left[ \frac{1-(1+r)^j}{(1+r)^{t_{\text{op}}^{\text{op}}}} \right] \] (9.56)

\[ \text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} + \left( \frac{C_f}{(1+r)^{t_{\text{op}}}^{\text{op}}} + \sum_{i=1}^{t_{\text{op}}} \frac{a_i}{(1+r)^i} \right) (1+r)^{t_{\text{op}}^{\text{op}}-j} \left[ \frac{1-(1+r)^j}{(1+r)^{t_{\text{op}}^{\text{op}}}} \right] \] (9.57)

\[ \text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} - \left( \frac{C_f}{(1+r)^{t_{\text{op}}}^{\text{op}}} + \sum_{i=1}^{t_{\text{op}}} \frac{a_i}{(1+r)^i} \right) (1+r)^{t_{\text{op}}^{\text{op}}-j} \left[ \frac{1-(1+r)^j}{(1+r)^{t_{\text{op}}^{\text{op}}}} \right] \] (9.58)

### 9.5 Illustrative Examples

Consider the example problem with the data Table 9.4. Use a discount rate of 5% and per break cost of $2,000. The replacement cost is $175,000. The optimal equal annual cost is reached at time 10.
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Table 9.4 Equivalent Annual Cost of Maintenance Plus Capital Recovery with a return for a pipe

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<td>0.071</td>
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<td>3666.88</td>
<td>45761.77</td>
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</table>
The equal annual cost of $34309.64 corresponding to the optimal replacement period of 10 years is used to perform the accelerated/delayed replacement penalty analyses.

**Example:**
Determine the penalty for replacing the pipe (a) 2 years prior to the recommended optimal replacement year, (b) 2 years after the recommended optimal replacement year.

**Solution:**
Calculate the Equal Annual Cost, $A$ corresponding to the optimal replacement time of 10 years ($T_{opt} = 10$ years) as determined in Table 9.4.

\[
A = \left( \frac{C_{f}}{(1+r)^{T_{opt}}} + \sum_{i=1}^{T_{opt}} \frac{a_{i}}{(1+r)^{i}} \right) \left[ \frac{r(1+r)^{T_{opt}}}{(1+r)^{T_{opt}}-1} \right]
\]

$C_{f}$ = total replacement cost, dollars

$n_{i}$ = number of breaks in year $i$,

$C_{Repair}$ = present repair cost per break year, dollars

\[
\sum_{i=1}^{10} \frac{a_{i}}{(1+r)^{i}} = \frac{4000}{(1+0.05)^{1}} + \frac{8000}{(1+0.05)^{2}} + \frac{12000}{(1+0.05)^{3}} + \frac{16000}{(1+0.05)^{4}} + \frac{20000}{(1+0.05)^{5}} + \frac{24000}{(1+0.05)^{6}} + \frac{28000}{(1+0.05)^{7}} + \frac{32000}{(1+0.05)^{8}} + \frac{36000}{(1+0.05)^{9}} + \frac{40000}{(1+0.05)^{10}}
\]

\[
\sum_{i=1}^{10} \frac{a_{i}}{(1+r)^{i}} = \$157495.13
\]

\[
\frac{175000}{(1+0.05)^{10}} = \$107434.82
\]

\[
\frac{r(1+r)^{T_{opt}}}{(1+r)^{T_{opt}}-1} = \frac{0.05(1+0.05)^{10}}{(1+0.05)^{10}-1} = 0.1295
\]

\[
A = \left( \$107434.82 + \$157495.13 \right) \times 0.1295 = \$34309.64
\]

(a) Penalty for replacement two years earlier than recommended optimal replacement time
$$\text{PEN}_j = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} - \sum_{i=1}^{j} \frac{A}{(1+r)^i}$$

$$\text{PEN}_g = \frac{175000}{(1+0.05)^8} + \sum_{i=1}^{8} \frac{a_i}{(1+0.05)^i} - \sum_{i=1}^{8} \frac{A}{(1+0.05)^i}$$

$$\sum_{i=1}^{8} \frac{a_i}{(1+0.05)^i} = \frac{4000}{(1+0.05)^1} + \frac{8000}{(1+0.05)^2} + \frac{12000}{(1+0.05)^3} + \frac{16000}{(1+0.05)^4} + \frac{20000}{(1+0.05)^5} + \frac{24000}{(1+0.05)^6} + \frac{28000}{(1+0.05)^7} + \frac{32000}{(1+0.05)^8}$$

$$\sum_{i=1}^{8} \frac{a_i}{(1+0.05)^i} = \$109732.68$$

$$\sum_{i=1}^{8} \frac{A}{(1+0.05)^i} = \$34309.64 \times \left( \frac{1}{(1+0.05)^1} + \frac{1}{(1+0.05)^2} + \frac{1}{(1+0.05)^3} + \frac{1}{(1+0.05)^4} + \frac{1}{(1+0.05)^5} + \frac{1}{(1+0.05)^6} + \frac{1}{(1+0.05)^7} + \frac{1}{(1+0.05)^8} \right)$$

$$\sum_{i=1}^{8} \frac{A}{(1+0.05)^i} = \$34309.64 \times 6.4632 = \$303983.41$$

$$\frac{C_f}{(1+0.05)^j} = \frac{175000}{(1+0.05)^8} = \$118446.89$$

$$\text{PEN}_g = \$118446.89 + \$109732.68 - \$221750.07$$

$$\text{PEN}_g = \$6429.50$$

(b) Penalty for replacement two years later than recommended optimal replacement time

$$\text{PEN}_{j12} = \frac{C_f}{(1+r)^j} + \sum_{i=1}^{j} \frac{a_i}{(1+r)^i} - \sum_{i=1}^{j} \frac{A}{(1+r)^i}$$

$$\text{PEN}_{12} = \frac{175000}{(1+0.05)^{12}} + \sum_{i=1}^{12} \frac{a_i}{(1+0.05)^i} - \sum_{i=1}^{12} \frac{A}{(1+0.05)^i}$$
\[
\sum_{i=1}^{12} \frac{a_i}{(1+0.05)^i} = \frac{4000}{(1+0.05)^1} + \frac{8000}{(1+0.05)^2} + \frac{12000}{(1+0.05)^3} + \frac{16000}{(1+0.05)^4} \\
+ \frac{20000}{(1+0.05)^5} + \frac{24000}{(1+0.05)^6} + \frac{28000}{(1+0.05)^7} + \frac{32000}{(1+0.05)^8} \\
+ \frac{36000}{(1+0.05)^9} + \frac{40000}{(1+0.05)^{10}} + \frac{44000}{(1+0.05)^{11}} + \frac{48000}{(1+0.05)^{12}}
\]

\[\sum_{i=1}^{12} \frac{a_i}{(1+0.05)^i} = 209949.21\]

\[
\sum_{i=1}^{12} \frac{A}{(1+0.05)^i} = 34309.64 \times \left( \frac{1}{(1+0.05)^1} + \frac{1}{(1+0.05)^2} + \frac{1}{(1+0.05)^3} + \frac{1}{(1+0.05)^4} \right) \\
+ \frac{1}{(1+0.05)^5} + \frac{1}{(1+0.05)^6} + \frac{1}{(1+0.05)^7} + \frac{1}{(1+0.05)^8} \\
+ \frac{1}{(1+0.05)^9} + \frac{1}{(1+0.05)^{10}} + \frac{1}{(1+0.05)^{11}} + \frac{1}{(1+0.05)^{12}}
\]

\[\sum_{i=1}^{12} \frac{A}{(1+0.05)^i} = 34309.64 \times 8.86325 = 304094.91\]

\[
\frac{C_f}{(1+r)^{12}} = \frac{175000}{(1+0.05)^{12}} = 97446.55
\]

\[\text{PEN}_{12} = 97446.55 + 209949.21 - 304094.91\]

\[\text{PEN}_{12} = 3300.84\]
Table 9.5 shows the computation of replacement penalties for each year. The penalty decreases from year to year till the optimal year, 10 and then begins to rise when the replacement is delayed. Figure 9.2 also illustrates the effect of accelerating or delaying replacement. It should be noted that the 2 year delay penalty of $3,300.78 is relatively small compared to the installation cost of $175,000.00. Therefore based on the budgetary restrictions the engineer may decide to postpone the replacement and allocate funds for another project. However, Table 9.5 shows that a delay of more than three years increases the penalty significantly. For year 20 with a 10 year delay, the penalty is $82,184 which is the additional cost that has been incurred for not having followed the optimal 10 year schedule.
Table 9.5 Listing of Present Cost Replacement Penalties with Time

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<th>CostPerBreak</th>
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9.6 Significance of Accelerated/Delayed Replacement Analysis

The accelerated/delayed replacement analysis provides a universal methodology for utility managers/engineers to financially evaluate the cost of delaying or replacing a pipe which has been targeted for replacement in a certain year. The procedure also provides a means to determine possible financial repercussions resulting from the margin of error in pipe replacement prediction models. Another advantage is in coordinating the pipe replacement with road resurfacing activity. In such a case, the penalty cost is compared with the cost saving and a maximum delay or the acceptable earliest replacement time can be calculated.
Chapter 10 - Summary, Conclusions and Recommendations

10.1 Summary and Conclusions:

Aging water mains, especially, those in larger and older cities and municipalities are experiencing increasingly frequent failures due to their deteriorated condition. These failures often lead to damage to property and loss of service to customers. By replacing pipes before they fail, proper planning can be put in place for securing of finances and labor force needed to rehabilitate the pipes. With this approach, service interruptions are minimized as the loss of service time is limited to the times used in replacing the pipe. In the case where pipes fail before they are replaced, loss of service includes the duration from pipe failure time to the time the failure is reported; time taken to locate the failed pipe; and time taken to repair the pipe.

Besides reducing the number of pipe breaks, it is important for utilities to develop a prioritized schedule of replacing pipes in their inventory. Water utilities have found from experience that “do nothing until a system component fails” is not the best decision due to costly repairs, customer dissatisfaction and potential environmental problems. When pipes are replaced ahead of time, the number of unanticipated breaks or failures are reduced.

Several methodologies have been developed by researchers for use in predicting pipe breaks and or prioritizing the pipes for replacement. A literature search identified several methods used to prioritize pipes for replacement in a water main renewal program. Some methods used a scoring system to assign points to pipes based on various characteristics of the pipe and its environment. Others used economics to compare the costs of repair versus replacement. Still others attempted to predict the probability of future failures based on existing pipe break histories. Mechanistic models have also been developed. These simulate the deterioration of a pipe over time and compare the residual strength to the loads to which the pipe is subjected. These mechanistic models require more detailed pipe and environmental data.

A mechanistic model for predicting pipe vulnerability and failure has been proposed in this research. This model predicts the growth of corrosion pits in the pipe wall and computes the resulting pipe strength based on the extent of the corrosion. A recommendation for modifying the Rossum corrosion model for practical use is also presented. As part of the pipe deterioration model, an equation relating the pit depth and fracture toughness with pipe strength has also been
developed. This equation enables the determination of the effect of corrosion pit growth on the change in pipe structural strength over time. Safety factors derived from the computed residual strength enable the recommended replacement time for the pipe. By ranking the resulting safety factors, pipes can be prioritized for replacement taking into account the budgetary constraints.

The PBM developed in this research was able to predict changes in the safety factor of cast iron pipe based upon age, soil type, and year of manufacture. Soil type had the most pronounced effect on the predicted safety factor for the pipes. There was greater variability in the predicted safety factor for combined ring and hoop stress than for combined flexural and longitudinal stress. The predicted flexural and longitudinal safety factor (SF_{f,l}) were slightly lower than the combined ring and hoop stress safety factor (SF_{h,r}) on average. However, the test case break history indicates that circumferential breaks (that would be caused by flexural and longitudinal stresses) occur much more frequently than longitudinal breaks (caused by ring and hoop stresses). Therefore, it would be expected that SF_{f,l} would be lower than SF_{h,r}. The PLM may be over-predicting the external loads for critical conditions used to calculate safety factor.

As with all mechanistic models, data is the key requirement for this model. In this research, some parameters had to be assumed due to data unavailability. Most data requirements for the model are reasonable and obtainable by most water utility companies. The accuracy of any mechanistic model is closely linked to how uniquely the pipe is defined by the characteristics. The major setup for such a unique definition of a pipe for mechanistic analysis is the availability of information on the pipe. The type of system that is able to provide such a detailed definition of a pipe would be a well-designed GIS system. Unfortunately, many utilities are just now investing in the use of GIS to keep track of water distribution system inventory. Certain information pertaining to the soil however will for a while remain hard to come by. With time, as agencies and utilities accurately map soils and update their GISs, the strength of mechanistic models will increase. Till these are reached, reasonable generalizations must be made in defining pipes for mechanistic analysis.

Overburden loads for pipes laid under streets must also be applied to the entire pipe for worst case scenario analysis. The result of such a generalized definition of a pipe is that, the mechanistic model produces a worst case scenario for pipe failure or in practical terms, time of first failure. This first failure will actually occur at the section of the pipe actually experiencing the conditions used to define the pipe. Subsequent failures will occur progressively at points
with less severe loads and deteriorative conditions. Other variables of importance in the
definition of a pipe form mechanistic analysis include: pipe pressure, size, surface loading
(traffic load and frequency), frost susceptibility, and age.

Two main factors (soil corrosivity and estimated beam span length) seemed to be the
most significant in determining the condition of the pipe and failure mode. The soil environment
plays an important role in determining the deterioration rate of an unprotected buried main.
Again, if we assume a main of uniform material type passing through soils of varying
corrosivity, the portion in the higher corrosivity soil would experience a failure earlier the
portion in the lower corrosivity soil (assuming the pipe failure is due to deterioration). It has
been shown in this research how the estimated beam span affects the predicted failure time and
failure mode. There is a need for characterization of the nature disruption of pipe beds observed
by field crew to enable easier identification and reporting the extent of the pipe bed disruption.

Water main breaks are a continuing maintenance issue for all water utilities. Without
effective water main renewal programs, it is likely that the rate of water main breaks will
increase for many utilities into the future. Utilities must take advantage of the opportunities
presented by water main breaks to gather the data necessary to assess the condition of pipes in
their distribution systems.

Utilities can use the PBM to predict future pipe failure probabilities based on the pipe
condition and develop water main renewal programs. The mechanistic model could be a useful
tool for prioritizing water main renewal programs, however it was apparent that calibration and
field verification of model predictions are necessary to improve the usefulness of the model.
Due to the complex nature of corrosion and the fact that the mechanistic model was limited to
external corrosion from corrosive soils, the mechanistic model is recommend for use as a break
prediction tool for comparing the relative conditions of pipes and estimating the worst case
condition of the buried main.

In addition to the mechanistic model, a physically based regression model has also been
presented in this dissertation. The strength of the physically based regression model is the fact
that it incorporates the physical conditions surrounding the pipe, the pipe break history and the
economic constraints to predict the optimal time to replace the pipe.

A penalty cost analysis methodology is also developed to guide utilities in estimation the
associated penalties for deviating from the recommended replacement times. The
accelerated/delayed replacement analysis provides a universal methodology for utility managers/engineers to financially evaluate the cost of delaying or replacing a pipe which has been targeted for replacement in a certain year. The procedure also provides a means to determine possible financial repercussions resulting from the margin of error in pipe replacement prediction models. Another advantage is in coordinating the pipe replacement with road resurfacing activity. In such a case, the penalty cost is compared with the cost saving and a maximum delay or the acceptable earliest replacement time can be calculated.

10.2 Important Issues Relating to the Mechanistic Model

Though most of the data required for the mechanistic model can be obtained from pipe, soil and environmental data, the accuracy of the model is significantly dependent on the best estimate of a number of parameters that are required for input into the model. These factors include the initial design parameters such as pipe strengths and design thickness. Provision is made in the model to incorporate thickness and strength values that may be obtained from pipe samples that are obtained from the system and examined in the lab. Testing may also provide a means of estimating the pipe strength at the time of installation. In this research, reasonable estimates of the design strength and thickness values design practices in place at the time of installation of the particular pipe in question were used. Actual pipe samples obtained from a number of utilities in the United States in some cases also provided supplementary information for constructing and using the model.

Other parameters such as length of unsupported beam span, frost load, and expansive soil load also play a vital role. Though there are a number of models available that are able to provide reasonable estimates of these parameters, further research is still needed to provide better estimates of these parameters.

Currently the mechanistic model provides three methods of incorporating the magnitude of the frost load used in modeling the pipe condition. These include twice earth load estimate (based on DIPRA handbook), computation by the Rajani-Zahn frost load model, and thirdly, the user may specify a frost load amount. In the third option, the user may use some other available trusted means of estimating the frost load to estimate the frost load and then enter the estimated value into the model.
Expansive soil loads are computed based on a model developed by Issa (1997). The actual direction and magnitude of expansive soil load is difficult to determine. In this research consultation with available literature and experts in geotechnical area did not help in resolving what direction the most effect of expansive soil was felt in. As such, it was assumed that in the worst case, the extra load due to the expansive soil is added the external vertical loads on the pipe.

It is difficult to determine the length of unsupported beam span which is vital for determining both the residual life of the pipe. The value used in the research is 4 ft. This values was obtained from recommendations in available literature. In this research it was shown that the beam span can be specified as a function of the pipe age. The results obtained are similar to those obtained from using an estimated beam span length of 4 ft. Estimation of the unsupported beam span length is a difficult process. Often, by the time a break is discovered the leaking water may have contributed extra to the wearing away of the bed thus making it impossible for accurately determining the unsupported beam span prior to the break. With improvements in GPR technology it is possible to begin to make more accurate estimates of pipe soil conditions surrounding the pipe.

In the mechanistic model, the internal corrosion is not explicitly taken into account because of a number of factors. When pipes corrode internally, the corrosion products may precipitate and resettle causing the formation for tubercles that eventually inhibiting the corrosion process through the tuberculation of the pipe. Also modeling internal corrosion is a complex process affected by the water quality and the location of a pipe in the network. Pipes closer to the treatment plant may tend to be more exposed to corrosive waters that those farther away. As the water travels through the network, it loses its capacity to corrode that pipe. In the mechanistic model, whiles the corrosion of the pipe is based on external corrosion, a means is provided for the incorporation of a gross corrosion rate that may be used to account for both external and internal corrosion.

10.3 Recommendations:

In order for utilities to take full advantage of the mechanistic models such as the one developed in this dissertation, many have to improve their data collection procedures. Soil analysis must be made whenever it is financially and technically feasible.
All utilities should collect and maintain water main break data using guidelines developed in this study. Data collection program must be coordinated with field crews in order for it to be effective. There is a need for the development of a standardized protocol for water main data collection and management. Such a standard will facilitate the sharing of valuable information among utilities performing break prediction analysis.

A computerized database should be developed for collection, analysis and management of water main break data. The implementation of a GIS system is highly recommended as it greatly enhances the database storage and management. The extent of water main break data collection depends on the end use of the data. The main break data collected should be used in developing decision criteria to prioritize renewal of water mains.
References


Appendix
Appendix A
## Appendix A-1: Tables and Figures

### Table A-1.2 Pit Depth and Soil Sample Data

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<td>2037</td>
<td></td>
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<td>C-3830-1965-CI-6</td>
<td>1965</td>
<td>-</td>
<td>2123</td>
<td>-</td>
<td>2161</td>
<td>2064</td>
<td>2064</td>
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</tr>
<tr>
<td>C-7352-1967-CI-6</td>
<td>1967</td>
<td>-</td>
<td>2125</td>
<td>-</td>
<td>2163</td>
<td>2066</td>
<td>2066</td>
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</tr>
<tr>
<td>C-9607-1968-CI-6</td>
<td>1968</td>
<td>-</td>
<td>2140</td>
<td>-</td>
<td>2146</td>
<td>2073</td>
<td>2073</td>
<td></td>
</tr>
<tr>
<td>C-9608-1968-CI-8</td>
<td>1968</td>
<td>-</td>
<td>2089</td>
<td>-</td>
<td>-</td>
<td>2037</td>
<td>2037</td>
<td></td>
</tr>
<tr>
<td>C-9609-1968-CI-6</td>
<td>1968</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>F-47-1934-CI-6</td>
<td>1934</td>
<td>-</td>
<td>2130</td>
<td>-</td>
<td>2111</td>
<td>2060</td>
<td>2060</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B
B-1 Determination of Flexural Stress on a pipe

The flexural stress in the pipe can be determined by

\[ f = \frac{Me}{I} \]  

(1)

Where:
M = maximum moment acting across the pipe cross-section in the plane of the bedding, lb-in.
e = the distance from the neutral axis of flexure to the extreme fiber stressed in bedding, in.
I = pipe cross-sectional moment of inertia in the plane of bending, in^4
f = flexural stress at extreme fiber, psi.

In equation (1), M, e, and I can be defined as follows:

\[ M = \frac{12UL^2}{8} \]  

(2)

Where: 
U = effective vertical load distributed along the unsupported pipe length, plf
L = length of unsupported span

\[ I = \frac{(pi)(D^4 - d^4)}{64} \]  

(3)

Where: 
D = outside diameter of the pipe
d = inside diameter of the pipe
pi = 3.1416

\[ e = \frac{D}{2} \]  

(4)

Where D is the outside diameter of the pipe.

Combining (2), (3), and (4 into (1), we get:

\[ f = \frac{(15.28)UL^2}{(D^4 - d^4)} \]  

(5)
B-2 Determination of Modulus of Rupture

\[ t = \text{thickness} \]

\[ d = 0.5" \]

\[ I = \frac{td^3}{12} \]

\[ e = \frac{d}{2} \]
B-4 Determination of Ring Modulus

\[ M_\theta = WR \left( \frac{1}{\pi} - \frac{\sin \theta}{2} \right) \]

For \( \theta = 0 \), \( M_0 = M_b \) and
\[ M_0 = \frac{WR}{\pi} \]

For \( \theta = 180 \), \( M_{180} = M_t \) and
\[ M_{180} = \frac{WR}{\pi} \]

Now the moment of inertia of the rectangular cross section of the ring is
\[ I = \frac{bt^3}{12} \]
Appendix C
C-1 Review of Rajani and Zhan (1996) Frost Load Prediction Model

The model by Rajani and Zhan is based fundamentally on the “frustum” view of the trench in which the load is to be determined (see Figure 1).

Figure 1. Schematic of “frustrum” model for frost load (Rajani and Zhan, 1996)

When the soil begins to freeze after extended exposure to freezing temperatures, the freezing front $d_f(t)$, can be estimated by the modified Bergen equation:

$$d_f^i = \kappa \sqrt{\frac{2k_f}{L_s} I_{sf}^i}$$  \(1\)

where $k_f$ is the thermal conductivity of the frozen soil, $L_s$ is the latent heat for the frozen soil, $I_{sf}^i$ is the freezing index at time step $i$ and $\kappa$ is a correction factor (always less than unity).

As the freezing front advances, frost heave results from both pore in situ ice growth and growth due to water migration. Frost heave resulting from in situ pore water $(\Delta h_p)$ is given by

$$\Delta h_p = 0.09n \left(1 - \frac{w_{uf}}{n}\right) \Delta z$$  \(2\)

where $n$ is the porosity, 0.09 represents the volumetric expansion of water when it freezes, $w_{uf}$ represents the volumetric unfrozen water content, and $\Delta z$ is the increase in frost depth.
Additional heave also results from ice growth due to water migration. This is determined by the segregation potential across the freezing front. The velocity of water arriving at the freezing front \( v \) is given by

\[
v = SP \nabla T
\]

where \( SP \) is the segregation potential, and \( \nabla T \) is the temperature gradient adjacent to the growing ice lens.

The frost heave increment \( h_j^i \), which results from the arrival of pore water during the time interval \( \Delta t \) is

\[
h_j^i = 1.09 v (t^i - t^{i-1})
\]

The total frost heave \( h_j^f \), is determined by combining [3] and [4] to get

\[
h_j^f = 0.09 n \left( 1 - \frac{w_{sf}^f}{n} \right) (d_j^i - d_j^{i-1}) + 1.09 SP \left( \frac{dT}{dZ} \right) (t^i - t^{i-1})
\]

During frost heave, the frozen soil expands. This expansion of frozen soil has to be accounted for in the downward displacement of the unfrozen soil beneath the freezing front and the displacement \( w^i \) of the rigid mass above the freezing front. This implies

\[
\frac{P^i}{k_{tip}} + w^i = \beta h_j^i
\]

where \( P^i \) is the frost load generated at the freezing front during the period \( (t^i - t^{i-1}) \), \( k_{tip} \) is the stiffness of the elastic half space of the unfrozen soil mass below the freezing front, and \( \beta \) is an attenuation factor. The estimate of \( k_{tip} \) is based on the suggestion by Scott (1981) in which \( k_{tip} = G_s / 2B_d \), where \( G_s \) is the soil shear modulus and \( B_d \) is the trench width.

From the vertical force equilibrium, for an element \( dz \), at a distance \( z \) (see Figure 1) above the freezing front,

\[
\frac{dq}{dz} - \frac{2\tau}{B_d} = 0
\]

where \( \tau \) is the shear stress assumed to be mobilized at the backfill-sidefill interface, and \( q \) is the normal stress in increment in frozen soil during \( (t^i - t^{i-1}) \). It is assumed that shear stress-displacement relation for the frozen backfill-sidefill interface is given by the linear function

\[
\tau = k_s w
\]
where \( k_s \) is the shear stiffness at the frozen backfill-sidefill interface and \( w \) is the corresponding displacement.

According to Rajani and Zhan, data on the shear stiffness at the frozen backfill-sidefill interface are not currently available. The \( k_s \) value is estimated by establishing similitude between the movement of a rigid frozen soil mass in a trench and the axial displacement of a buried pipe. The elastic shear stiffness relationship is

\[
k_s = \frac{G_s}{4(1-\nu_s)} \left( \frac{B_d}{2} \right)
\]

where \( G_s \) is the soil shear modulus, and \( \nu_s \) is the soil’s Poisson’s ratio.

The equilibrium condition after substituting for \( \bar{r} \) in [7] and assuming linear variation in displacement along backfill-sidefill interface (ie \( w(z) = Az \)) is

\[
dq \left( \frac{2k_s w(z)}{B_d} \right) - dq \left( \frac{2k_s Az}{B_d} \right) = 0
\]

where \( A \) is constant determined by applying appropriate boundary conditions.

In this method of frost load estimation, it is assumed that frost heave and additional stress due to the develop at the freezing front where the boundary conditions are

\[
q(z = 0) = 0 \text{ and } q(z = d_f^i) = p^i
\]

The boundary condition that relates the frost load \( p^i \) at the freezing front and the displacement of the rigid mass along the backfill-sidefill interface is

\[
w(z = d_f^i) = w^i = \frac{B_dp^i}{k_s d_f^i}
\]

Thus the additional stress \( (p^i) \) resulting from frost heave is

\[
p^i = \frac{\beta h_f^i}{\frac{1}{k_{tip}} + \left( \frac{B_d}{k_s d_f^i} \right)}
\]

The stress at any depth, \( s \), along the centerline of the trench is determined by the use of the Bousinesq equation as
\[
\sigma^i(\bar{z}^i) = \frac{2p^i}{\pi} \left[ \frac{\bar{z}^i b}{(\bar{z}^i + b^2)} + \arctan \left( \frac{b}{\bar{z}^i} \right) \right]
\]  

(14)

in which \( b = B_d/2, \: \bar{z}^i = (s - \bar{d}_f) \), and \( s \) is the vertical distance from the surface to where the stress needs to be determined.

The total stress (frost load) at any point is determined by the sum of all stresses in the vertical at that point given by

\[
\sigma_v^* = \sum \sigma^i(\bar{z}^i)
\]

(15)

From this, the total earth pressure is determined by

\[
\sigma_v = C_d \gamma_s s + \sigma_v^*
\]

(16)

where \( \gamma_s \) is the soil unit weight, and \( C_d \) the load coefficient.

---

Table 1. Reference data for soil properties and trench geometry (From Rajani and Zhan, 1996)

<table>
<thead>
<tr>
<th></th>
<th>Silty Clay</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus, ( E_s ) (Mpa)</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Poisson’s ratio, ( v_s )</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Shear modulus, ( G_s ) (Mpa)</td>
<td>7.69</td>
<td>15.38</td>
</tr>
<tr>
<td>Dry soil unit weight, ( \gamma_s ) (kN/m(^3))</td>
<td>12.00</td>
<td>16.00</td>
</tr>
<tr>
<td>Trench width, ( B_d ) (m)</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Tip stiffness, ( k_{tip} ) (kPa/m)</td>
<td>4808</td>
<td>9615</td>
</tr>
<tr>
<td>Frozen shear stiffness, ( k_s ) (MPa/m)</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Porosity of backfill soil, ( n ) (%)</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>Volumetric Unfrozen water content (%)</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Backfill segregation potential SP (mm(^2)/s, °C)</td>
<td>3.5x10(^{-4})</td>
<td>10(^{-6})</td>
</tr>
<tr>
<td>Attenuation factor, ( \beta )</td>
<td>0.03</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

References:

## C-2 Temperature Induced Stresses In Water Distribution Pipes

When exposed to a temperature differential, materials tend to expand or contract. In water distribution mains, the expansion or contraction of both the pipe material and the water contained within are of concern. The degree of expansion of water due to temperature change is greater than that of the pipe material. In the pipe, expansion of water leads to extra internal pressure whereas the expansion in the pipe leads to the creation of additional stresses in the pipe. In order to determine the effect of temperature change on a closed pipe, the pipe-water system must be analyzed from the basic understanding of stress-strain relationships involved. The following variables to be used in the analysis are defined as follows:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Typical Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td>Original inside cross-sectional area of the pipe.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>α</strong></td>
<td>Coefficient of linear thermal expansion of pipe wall material.</td>
<td>1.01x10⁻⁵ m/m/°C or 6.2x10⁻⁶ ft/ft/°F</td>
<td></td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>Coefficient of volume thermal expansion of liquid, dV/(VdT).</td>
<td>0.000115 ft³/ft³/°F</td>
<td></td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>Original inside diameter of pipe.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>d</strong></td>
<td>Denotes unit incremental change; dP, incremental pressure change; dV, incremental volume change; dT, incremental temperature change, etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>E</strong></td>
<td>Modulus of elasticity of pipe wall material</td>
<td>15000000 psi</td>
<td></td>
</tr>
<tr>
<td><strong>e</strong></td>
<td>Unit strain of pipe wall material; eₓ, axial; eᵧ, transverse</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>k</strong></td>
<td>Bulk modulus of liquid, - dP / (dV/V).</td>
<td>319953 psi at 20 degrees</td>
<td></td>
</tr>
<tr>
<td><strong>L</strong></td>
<td>Total length of pipe.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>P</strong></td>
<td>Internal pressure in pipe wall; Sₓ, axial stress; Sᵧ, hoop stress.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>S</strong></td>
<td>Unit stress in pipe wall; Sₓ, axial stress; Sᵧ, hoop stress</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>Temperature of pipe/liquid system.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>t</strong></td>
<td>Wall thickness of pipe material.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>u</strong></td>
<td>Poisson’s ratio of the pipe wall material.</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td><strong>V</strong></td>
<td>Original volume of the pipe segment or contained liquid.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Unrestrained Pipe
In closed pipe, the water contained in the pipe must equal the volume of the pipe. This implies that, for any increase in water volume, there must be a corresponding increase in pipe volume to accommodate the water volume change. Mathematically, this can be represented as:

$$dV_{\text{pipe}} = dV_{\text{liquid}}$$  \hspace{1cm} (1)

The total change in liquid volume is the sum of the change in volume due to temperature change and the change in volume due to stress on the water. The temperature related volume change is defined by:

$$dV_{\text{liquid}} = dV_{\text{liquid},t} + dV_{\text{liquid},p}$$  \hspace{1cm} (2)

Now from the thermal expansion of liquids,

$$dV_{\text{liquid},t} = BVdT$$  \hspace{1cm} (3)

And from the definition of the bulk modulus of a liquid, the change in volume due to stress change is (recall $$k = -\frac{VdP}{dV}$$)

$$dV_{\text{liquid},p} = -\frac{VdP}{k}$$  \hspace{1cm} (4)

Combining (3) and (4), the total volume change in the liquid is

$$dV_{\text{liquid}} = BVdT - \frac{VdP}{k}$$  \hspace{1cm} (5)

Similarly, pipe volume change results from pressure induced and temperature induced strains and can be stated as:

$$dV_{\text{pipe}} = dV_{\text{pipe},p} + dV_{\text{pipe},t}$$
\[ e_x = \frac{S_x}{E} - \frac{uS_y}{E} \]  

(6a)

And the strain in the \( y \) or radial direction is

\[ e_y = \frac{S_y}{E} - \frac{uS_x}{E} \]  

(6b)

The hoop stress on the pipe in the radial direction is defined by

\[ S_y = \frac{PD}{2t} \]  

(7a)

and change in hoop stress is

\[ dS_y = \frac{dPD}{2t} \]  

(7b)

Now, the longitudinal stress in the pipe is defined by

\[ S_x = \frac{PD}{4t} \]  

(8a)

And change in longitudinal stress is

\[ dS_x = \frac{dPD}{4t} \]  

(8b)

For an incremental strain, a substitution of (7b) and (8b) in (6a) results in

\[ de_x = \left[ \frac{DdP}{2tE} \right] (0.5 - u) \]  

(9a)

A similar substitution in (6b) results in

\[ de_y = \left[ \frac{DdP}{2tE} \right] (1 - 0.5u) \]  

(9b)

From (9a), the incremental change in the pipe length is given by

\[ dL = Lde_x = L \left[ \frac{DdP}{2tE} \right] (0.5 - u) \]  

(10a)
And from (9b), the incremental change in the diameter is given by

\[ dD = D \frac{DdP}{2tE}(1 - 0.5u) \]  

(10b)

The total volume change due to pressure is the sum of volume change due to change in diameter only plus volume change due to change in diameter and length plus volume change due to change in length only. These can be stated mathematically as:

\[ dV_{\text{pipe}, p} = \frac{\pi DdD}{2} + \frac{\pi DdDdL}{2} + \frac{\pi D^2 dL}{4} \]  

(11)

The product dD*dL can be dropped since it will be miniscule. A simplification of (11) and the substitution of the dD and dL from (10a) and (10b) leads to:

\[ dV_{\text{pipe}, p} = dP\left[ \frac{\pi D^2 L}{4} \right]\frac{D}{tE}(1.25 - u) \]  

(12)

Now, recall that \( V = \pi D^2 L/4 \). This implies that (12) can be rewritten as

\[ dV_{\text{pipe}, p} = VdP\left[ \frac{D}{tE} \right](1.25 - u) \]  

(13)

Next, the volume change due to temperature will be considered. As with the change due to pressure, the total change due to temperature will be the sum of volume change due to change in diameter only plus volume change due to change in diameter and length plus volume change due to change in length only. These can be stated mathematically as:

\[ dV_{\text{pipe}, T} = \frac{\pi DdD}{2} + \frac{\pi DdDdL}{2} + \frac{\pi D^2 dL}{4} \]  

(14)

Again the product dD and dL will be dropped because of their small value. Next, the substitution for dL and dD will be made with the definition of dL and dD in thermal expansion (dD = D\(\alpha\)dT and dL = L\(\alpha\)dT). Equation (14) can therefore be rewritten as

\[ dV_{\text{pipe}, T} = \frac{2\pi D(D\alphadT)L + \pi D^2 (L\alphadT)}{4} \]  

(15)

A simplification of (15) leads to
From (16),

\[ dV_{pipe,t} = 3V \alpha dT \]  

(17)

The total change in the pipe volume can therefore be written as a combination of (13) and (17)

\[ dV_{pipe} = VdP \left[ \frac{D}{tE} \right] (1.25 - u) + 3V \alpha dT \]  

(18)

Furthermore, from (1)

\[ VdP \left[ \frac{D}{tE} \right] (1.25 - u) + 3V \alpha dT = BVdT - \frac{VdP}{k} \]  

(19)

Dropping the V term from (19) and rearranging the equation to solve for dP, we get

\[ dP = \frac{(B - 3\alpha)kdT}{1 + \frac{Dk}{Et} (1.25 - u)} \]  

(20)

Equation (20) therefore defines the pressure change in an unrestrained pipe as a result of a temperature change.

**Restrained Pipe**

When the pipe is restrained along its length as in the case of buried pipes, the axial expansion can be assumed as zero. Because of the axial restraint, a significant axial stress can be induced from a change in temperature. The induced stress will tend to be a compressive axial stress. The zero strain assumption means that the length of the pipe will not change due to the friction between the pipe and the surrounding soil. A compressive axial stress, tensile hoop stress, and thermal will tend to increase the pipe diameter. Strain in the diameter due to thermal expansion and hoop stress can be easily derived. The axial stress can be derived by the sum of change in stress due to temperature change and change in stress due to stress in the radial direction.

\[ S_x = E\alpha dT - uS_y \]  

(21)

Combining (21) with the thermal and hoop stress in the radial direction, we get
\[
d e_y = \frac{dS_y}{E} - u \left[ \alpha dT - \frac{u dS_y}{E} \right] + a dT
\]  

(22)

The change in the pipe diameter is defined as \( dD = Dd_e \). The length of the restrained pipe does not change with rise in temperature therefore any volume change is due to change in cross sectional area of the pipe. The change in cross sectional area is \( dA = dV = \pi D dD/2 = (\pi D/2) D d_e \). Where \( dV \) is the volume change per unit length of pipe. Substituting this into (22) and simplifying, we get

\[
dV_{pipe} = \frac{\pi D^2}{2} \left[ \frac{dS_y}{E} \left( 1 - u^2 \right) + \alpha dT (1 + u) \right]
\]  

(23)

Multiplying the numerator and denominator by 2, the result is

\[
dV_{pipe} = \frac{\pi D^2}{4} \left[ \frac{2dS_y}{E} \left( 1 - u^2 \right) + 2\alpha dT (1 + u) \right]
\]  

(24)

From (24), it can be seen that the term \( = \pi D^2/4 \) is the volume per unit length. From (7b), \( dS_y = dPD/2t \). Equation (24) can therefore be rewritten as

\[
dV_{pipe} = V \left[ \frac{dPD}{tE} \left( 1 - u^2 \right) + 2\alpha dT (1 + u) \right]
\]  

(25)

Since \( dV_{liquid} = dV_{pipe} \), (2) and (25) can be combined to get

\[
V \left[ \frac{dPD}{tE} \left( 1 - u^2 \right) + 2\alpha dT (1 + u) \right] = BVdT - \frac{VdP}{k}
\]  

(26)

Now, the \( V \) term can be dropped and the equation rearranged to solve for \( dP \), the change in pressure due to change in temperature. This results in

\[
dP = \left[ B - 2\alpha(1 + u) \right] dT \left[ \frac{1}{k} + \frac{D}{tE} \left( 1 - u^2 \right) \right]
\]  

(27)

According to Wedge (1996), the thermal pressure rise will always be greater in the restrained pipe than the unrestrained pipe. From the final definition change in internal pressure, \( dP \), due to change in temperature \( dT \), the resulting stress induced in the pipe can
be determined by equations 7b and 8b. The resulting total stress in the pipe can then be compared with the pipe strength over time to determine whether or not the pipe will fail. A limitation of the above definition of temperature induced pressure is that it does not differentiate between sudden temperature changes and gradual temperature changes. The excess stress induced by sudden temperature changes is greater than that induced by gradual temperature changes.
Appendix D

Software Manual
PIPEADDIN Software Manual

The software was developed as an ADD-IN that runs in Microsoft Excel. The Excel environment was chosen to facilitate ease of use of the software and also to provide the modeling tool for utilities in and environment that most of them use for tracking pipe data.

Description of Software

The software is composed of two excel workbook files. The first file (pipeaddin.xls) contains the macros and functions that make up the pipe analysis program. This file also contains sheets that contain default design values for the fracture toughness, modulus of rupture, ring modulus, tensile strength, bursting tensile strength, and design thickness. These sheets will be discussed again later in this document. The second excel workbook (testdata.xls) contains the data for the pipes to be analyzed. This workbook may be saved under any name but the data format must be maintained.

System Requirements:

Design System Configuration:
The software was developed on a Pentium II 400 computer with the following configuration:

RAM: 128 MB RAM
OS: Microsoft Windows NT Workstation 4.0.
STORAGE: 8.4 GB
SOFTWARE: Microsoft Excel 97

The program has been tested successfully on Microsoft Windows 95 and 98, and 2000. It has also been successfully tested on Microsoft Excel 2000. Typically, about 50 MB hard drive space is needed for the data preprocessing.

Recommended Minimum System Requirements:
Minimum system requirements for running Microsoft Office 97
64 MB of RAM (More memory improves performance)
**Installation:**

*Important Installation Notes:*

In order to run the program,

1. Make sure you have *Microsoft Office 97* installed
2. In Excel, make sure that the *Analysis ToolPak* and *Analysis ToolPak-VBA* addins are installed and activated.

If you are not sure whether you have the addins installed, do the following:

a. in the Excel menu, click 'Tools'
b. Select 'Add-ins..' This should give you a list of all the available Addins make sure that the *Analysis ToolPak* and *Analysis ToolPak-VBA* addins are Checked. If you can't find them, it means you probably did not install them.

*Required files:*

The main program consists of the following files:

1. pipeaddin.xls
2. testdata.xls or user data file.

*Installation procedure:*

Select a directory to install the program in. Copy the pipeaddin.xls file to that directory. The data file (example testdata.xls) may reside in the same folder or in a different folder.

*Running The Program:*

Both the pipeaddin.xls and the data file are needed to run the program successfully. The following is how the program can be started:

1. Load the file pipeaddin.xls. If prompted to enable macros, choose to enable macros.
2. Once this file is loaded, you should see a menu item added to the excel menu. As shown in Figure 1.
3. Load the testdata.xls file or the appropriate data file that you would like to use.
Note: If using your own data file, please make sure the data in the workbook and the sheets are in the same format as the testdata.xls.

Figure 1.
Required Data and Data Input

It is recommended that the user edit the sample file provided with the software. This section describes the critical and optional data needs. Data for the software is input in three main sheets in the data workbook. These sheets are *BrkInventory*, *Soils*, and *Regions*.

The *BrkInventory* Sheet:

This sheet (see Figure 2) contains data related to each pipe to be analyzed. Table 1 contains each pipe, its description and whether or not it is required. This sheet also allows specific information to be provided for each pipe.

![Figure 2 Pipe Inventory Sheet.](image)

**Table 1 List of Parameters in Inventory Sheet**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIPEID</td>
<td>This is the unique identification for the pipe.</td>
<td>y</td>
</tr>
<tr>
<td>RegionID</td>
<td>This is an ID cross listed in the ‘Regions’ sheet used to specify environment factors affecting the pipe.</td>
<td>y</td>
</tr>
<tr>
<td>SoilClass</td>
<td>This is an ID cross listed in the ‘Soils’ sheet</td>
<td>y</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Required</td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>AnalysisYear</td>
<td>This is the year in which the pipe is being analyzed.</td>
<td>y</td>
</tr>
<tr>
<td>PipeType</td>
<td>spun cast or pit cast</td>
<td>y</td>
</tr>
<tr>
<td>PipeDiameter</td>
<td>Pipe size, inches</td>
<td>y</td>
</tr>
<tr>
<td>PipeYearInstalled</td>
<td>Year in which pipe was installed</td>
<td>y</td>
</tr>
<tr>
<td>PipeLength</td>
<td>Length of pipe, ft</td>
<td>n</td>
</tr>
<tr>
<td>TrafficType</td>
<td>Traffic volume if applicable, heavy, medium, light, none</td>
<td>y</td>
</tr>
<tr>
<td>WorkingPressure</td>
<td>The pressure within the pipe, psi</td>
<td>y</td>
</tr>
<tr>
<td>PipeDepth</td>
<td>Depth at which the pipe is buried, ft</td>
<td>y</td>
</tr>
<tr>
<td>PavementType</td>
<td>Whether street is paved or unpaved</td>
<td>y</td>
</tr>
<tr>
<td>BeamSpan</td>
<td>Estimated unsupported beam span length, ft</td>
<td>y</td>
</tr>
<tr>
<td>SoilpH</td>
<td>Soil pH, this can be provided if the soil around this pipe has been sampled.</td>
<td>n</td>
</tr>
<tr>
<td></td>
<td>Value entered here over rides the pH for the soil class on the ‘Soils’ sheet</td>
<td></td>
</tr>
<tr>
<td>SoilResistivity</td>
<td>Soil resistivity (ohm-cm), this can be provided if the soil around this pipe has been sampled. Value entered here over rides the resistivity for the soil class on the ‘Soils’ sheet</td>
<td></td>
</tr>
<tr>
<td>SoilType</td>
<td>Soil type, this can be provided if the soil around this pipe has been sampled. Value entered here over rides the type for the soil class on the ‘Soils’ sheet</td>
<td>n</td>
</tr>
<tr>
<td>SoilAeration</td>
<td>Soil aeration (good, fair, poor), this can be provided if the soil around this pipe has been sampled. Value entered here over rides the aeration for the soil class on the ‘Soils’ sheet</td>
<td>n</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Required</td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>SoilMoisture</td>
<td>Soil moisture content, this can be provided if the soil around this pipe has been sampled. Value entered here over rides the moisture content for the soil class on the ‘Soils’ sheet</td>
<td>n</td>
</tr>
<tr>
<td>SoilLiquidlimit</td>
<td>Soil liquidlimit, this can be provided if the soil around this pipe has been sampled. Value entered here over rides the liquidlimit for the soil class on the ‘Soils’ sheet</td>
<td>n</td>
</tr>
<tr>
<td>SoilDensity</td>
<td>Soil density (lb/ft³), this can be provided if the soil around this pipe has been sampled. Value entered here over rides the density for the soil class on the ‘Soils’ sheet</td>
<td>n</td>
</tr>
<tr>
<td>SoilPorosity</td>
<td>Soil porosity (%), this can be provided if the soil around this pipe has been sampled. Value entered here over rides the porosity for the soil class on the ‘Soils’ sheet</td>
<td>n</td>
</tr>
<tr>
<td>SoilExpansive</td>
<td>Soil expansive (y, n) This states whether the soil is expansive or not. If a ‘n’ is selected, no expansive soil loads will be computed. Value entered here over rides the soil expansive for the soil class on the ‘Soils’ sheet</td>
<td>n</td>
</tr>
<tr>
<td>FrostSusceptible</td>
<td>Frost susceptible (y, n) This states whether the soil is expansive or not. If a ‘n’ is selected, no frost loads will be computed. Value entered here over rides the frost susceptibility for the soil class on the ‘Soils’ sheet</td>
<td>n</td>
</tr>
<tr>
<td>CorrosionRate</td>
<td>Corrosion Rate (in/yr) If a corrosion is specified, it used to compute the pit depth over time. Otherwise, the Adjusted Rossum model is used to compute the pit depth.</td>
<td>n</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Required</td>
</tr>
<tr>
<td>----------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>DesignThickness</td>
<td>Design thickness, inches. This is the thickness of the pipe at the time it</td>
<td></td>
</tr>
<tr>
<td></td>
<td>installed. Value entered here overrides the design thickness on the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>‘DesignThickness’ sheet in the pipeaddin.xls workbook.</td>
<td></td>
</tr>
<tr>
<td>TensileStrength</td>
<td>Tensile Strength, psi. This is the tensile strength of the pipe at the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>time it installed. Value entered here overrides the tensile strength on the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>‘TensileStrength’ sheet in the pipeaddin.xls workbook.</td>
<td></td>
</tr>
<tr>
<td>BurstingTensileStrength</td>
<td>Bursting Tensile Strength, psi. This is the bursting tensile strength of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the pipe at the time it installed. Value entered here overrides the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>bursting tensile strength on the ‘BurstingTensileStrength’ sheet in the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pipeaddin.xls workbook.</td>
<td></td>
</tr>
<tr>
<td>RingModulus</td>
<td>Ring Modulus, psi. This is the ring modulus of the pipe at the time it</td>
<td></td>
</tr>
<tr>
<td></td>
<td>installed. Value entered here overrides the bursting tensile strength on</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the ‘RingModulus’ sheet in the pipeaddin.xls workbook.</td>
<td></td>
</tr>
<tr>
<td>ModulusRupture</td>
<td>Modulus of Rupture, psi. This is the modulus of rupture of the pipe at the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>time it installed. Value entered here overrides the modulus of rupture on</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the ‘ModulusRupture’ sheet in the pipeaddin.xls workbook.</td>
<td></td>
</tr>
<tr>
<td>FractureToughness</td>
<td>Fracture Toughness, psi. This is the fracture toughness of the pipe at the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>time it installed. Value entered here overrides the fracture toughness on</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the ‘FractureToughness’ sheet in</td>
<td></td>
</tr>
</tbody>
</table>
The *Regions* Sheet:

This sheet (see Figure 3) contains data related to the environmental and regional parameters related to the pipes. Table 2 contains the description of the region parameters and whether or not they are required.

![Microsoft Excel - testdata.xls](image)

**Figure 3 Regions Sheet.**

**Table 2 List of Parameters in Regions Sheet**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>RegionID</td>
<td>Unique Identifier for the region for which analysis is being performed</td>
<td>y</td>
</tr>
<tr>
<td>MinYearlyTemp</td>
<td>Minimum temperature recorded in a year, F</td>
<td>y</td>
</tr>
<tr>
<td>MaxYearlyTemp</td>
<td>Maximum temperature recorded in a year, F</td>
<td>y</td>
</tr>
<tr>
<td>MaxFrostDepth</td>
<td>Maximum frost depth recorded, inches</td>
<td>y</td>
</tr>
<tr>
<td>MaxSuddenWaterTempChange</td>
<td>Maximum expect sudden drop or increase in water temperature, F</td>
<td>y</td>
</tr>
</tbody>
</table>
MaxFreezeDays  Maximum number of consecutive days below freezing, days
MinWaterTemp  Minimum water temperature per year, F
MaxWaterTemp  Maximum water temperature per year, F
WaterVelocityChange  Expected sudden water velocity change due to value shut down or change in pumping operations, ft/s

The Soils Sheet:
This sheet (see Figure 4) contains data related to the various soil classifications used in the pipe analysis. Table 3 contains the description of the soil parameters and whether or not they are required. This table is useful for grouping soils into general categories or classes and assigning each pipe to these soil classes on the by designating the ‘SoilClass’ on the BrkInventory sheet.

![Soils Sheet](image)

Figure 4 Soils Sheet.

Table 3 List of Parameters in Soils Sheet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>SoilClass</td>
<td>This is an ID cross listed in the ‘BrkInventory’</td>
<td>y</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Required</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>SoilpH</td>
<td>Soil pH, this is needed in computing the corrosion pit depth over time.</td>
<td>y</td>
</tr>
<tr>
<td>SoilResistivity</td>
<td>Soil resistivity (ohm-cm), this is needed in computing the corrosion pit depth over time.</td>
<td>y</td>
</tr>
<tr>
<td>SoilType</td>
<td>Soil type</td>
<td>y</td>
</tr>
<tr>
<td>SoilAeration</td>
<td>Soil aeration (good, fair, poor), this is needed in computing the corrosion pit depth over time.</td>
<td>y</td>
</tr>
<tr>
<td>SoilMoisture</td>
<td>Soil moisture content (%)</td>
<td>y</td>
</tr>
<tr>
<td>SoilLiquidlimit</td>
<td>Soil liquidlimit (%)</td>
<td>y</td>
</tr>
<tr>
<td>SoilDensity</td>
<td>Soil density (lb/ft³)</td>
<td>y</td>
</tr>
<tr>
<td>SoilPorosity</td>
<td>Soil porosity (%)</td>
<td>y</td>
</tr>
<tr>
<td>SoilExpansive</td>
<td>Soil expansive (y, n) This states whether the soil is expansive or not. If a ‘n’ is selected, no expansive soil loads will be computed.</td>
<td>y</td>
</tr>
<tr>
<td>FrostSusceptible</td>
<td>Frost susceptible (y, n) This states whether the soil is expansive or not. If a ‘n’ is selected, no frost loads will be computed.</td>
<td>y</td>
</tr>
</tbody>
</table>

**Default Design Parameters**

The sheets shown in figures 5 to 10 are contained within the pipeaddin.xls file. These sheets contain estimated design parameters for pipes based on size and year of installation. They may be edited by the user.
**Figure 5**. Default Bursting Tensile Strength Values

![Excel spreadsheet](image1)

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1803</td>
<td>11000</td>
</tr>
<tr>
<td>1804</td>
<td>11000</td>
</tr>
<tr>
<td>1805</td>
<td>11000</td>
</tr>
<tr>
<td>1806</td>
<td>11000</td>
</tr>
<tr>
<td>1807</td>
<td>11000</td>
</tr>
<tr>
<td><strong>1808</strong></td>
<td><strong>11000</strong></td>
</tr>
<tr>
<td>1809</td>
<td>11000</td>
</tr>
<tr>
<td>1810</td>
<td>11000</td>
</tr>
<tr>
<td>1811</td>
<td>11000</td>
</tr>
</tbody>
</table>

**Figure 6**. Default Design Thickness Values

![Excel spreadsheet](image2)

<table>
<thead>
<tr>
<th>Year</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1803</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.58</td>
<td>0.63</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>1804</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.58</td>
<td>0.63</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>1805</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.58</td>
<td>0.63</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>1806</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.58</td>
<td>0.63</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>1807</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.58</td>
<td>0.63</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>1808</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.58</td>
<td>0.63</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>1809</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.58</td>
<td>0.63</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>1810</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.58</td>
<td>0.63</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>1811</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.58</td>
<td>0.63</td>
<td>0.63</td>
<td></td>
</tr>
</tbody>
</table>
Figure 7. Default Fracture Toughness Values

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>12032</td>
</tr>
<tr>
<td>161</td>
<td>12032</td>
</tr>
<tr>
<td>162</td>
<td>12032</td>
</tr>
<tr>
<td>163</td>
<td>12032</td>
</tr>
<tr>
<td>164</td>
<td>12032</td>
</tr>
<tr>
<td>165</td>
<td>12032</td>
</tr>
<tr>
<td>166</td>
<td>12032</td>
</tr>
<tr>
<td>167</td>
<td>12032</td>
</tr>
<tr>
<td>168</td>
<td>12032</td>
</tr>
</tbody>
</table>

Figure 8. Default Ring Modulus Values

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>31000</td>
</tr>
<tr>
<td>6</td>
<td>31000</td>
</tr>
<tr>
<td>7</td>
<td>31000</td>
</tr>
<tr>
<td>8</td>
<td>31000</td>
</tr>
<tr>
<td>9</td>
<td>31000</td>
</tr>
<tr>
<td>10</td>
<td>31000</td>
</tr>
<tr>
<td>11</td>
<td>31000</td>
</tr>
<tr>
<td>12</td>
<td>31000</td>
</tr>
<tr>
<td>13</td>
<td>31000</td>
</tr>
</tbody>
</table>
Figure 9. Default Modulus of Rupture Values

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>167</td>
<td>27426</td>
</tr>
<tr>
<td>168</td>
<td>27426</td>
</tr>
<tr>
<td>169</td>
<td>27426</td>
</tr>
<tr>
<td>170</td>
<td>27426</td>
</tr>
<tr>
<td>171</td>
<td>27426</td>
</tr>
<tr>
<td>172</td>
<td>27426</td>
</tr>
<tr>
<td>173</td>
<td>27426</td>
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<tr>
<td>174</td>
<td>27426</td>
</tr>
<tr>
<td>175</td>
<td>27426</td>
</tr>
</tbody>
</table>

Figure 10 Default Tensile Strength Values

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>145</td>
<td>20000</td>
</tr>
<tr>
<td>146</td>
<td>20000</td>
</tr>
<tr>
<td>147</td>
<td>20000</td>
</tr>
<tr>
<td>148</td>
<td>20000</td>
</tr>
<tr>
<td>149</td>
<td>20000</td>
</tr>
<tr>
<td>150</td>
<td>20000</td>
</tr>
<tr>
<td>151</td>
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</tr>
<tr>
<td>152</td>
<td>30000</td>
</tr>
<tr>
<td>153</td>
<td>30000</td>
</tr>
</tbody>
</table>
Using The Program:

All the actions need to perform the analysis are accomplished through the menu items in the drop down menu in Figure 2.

![Figure 11. Analysis Options](image)

The software permits the analysis of pipes in two ways: 1. Pipes could be analyzed individually permitting the user to alter both original and derived data for the individual pipe and observe how the pipe condition changes in response to the various scenarios. 2. Pipes can also be analyzed in batch mode allowing numerous pipes in a water distribution system to be analyzed at once.

Single Pipe Mode:

In the single pipe mode, the software can be used to conduct detailed analysis on a pipe. To use the software in single pipe mode, select ‘Individual Analysis’ from the ‘VT Pipe’ Menu (see Figure 11). This brings up the form shown in Figure 12. The user can then select a pipe to be analyzed from the combo box at the top. Whenever a pipe is selected, the properties related to the pipe are automatically read from the BrkInventory, Soils, and Regions sheet and and the corresponding fields are updated in figures 12 to 15. The user can then edit each of the editable fields in figures 12 to 15 and then run the pipe analysis program. In this mode, the user can also chose to bypass the load models and specify specific estimated loads (see Figure 14). Once the
user has specified the parameters for the pipe, the button ‘View Results’ can then be clicked and the various are printed as shown in Figure 16. In addition to the results printed in Figure 16, the software also prints a formatted summarized report on the sheet ‘Summary’ in the data workbook. The summarized report sample is shown in Figures 17 and 18. Figure 17 contains the results for the pipe at the time it was installed and figure 18 is a summary of the current condition of the pipe. Finally, a year by year condition of the pipe (from the installation year to the analysis year) is printed on the sheet ‘ResultsIndividualPipe’ (see Figure 19).

![Figure 12 Pipe Properties For Individual Pipe Mode.](image-url)
Figure 13. Soil Properties For Individual Pipe Mode
Figure 14. Pipe Loads For Individual Pipe Mode
Figure 15 Region Properties For Individual Pipe Mode
Figure 16. Output Report For Individual Pipe Mode
Figure 17 Formatted Output on Excel Sheet For Individual Pipe Mode (Year 0).
<table>
<thead>
<tr>
<th>Pipe ID</th>
<th>Conditions at Year 71</th>
<th>Year</th>
<th>Age, yrs</th>
<th>Size, in</th>
<th>Length, ft</th>
<th>Pitdepth, in</th>
<th>Thickness, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>123-CH-6</td>
<td></td>
<td>2000</td>
<td>71</td>
<td>6</td>
<td>1988</td>
<td>0.161</td>
<td>0.253</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load</th>
<th>Pressure</th>
<th>Ring</th>
<th>Hoop</th>
<th>Flexural</th>
<th>Longitudinal</th>
<th>F-L</th>
<th>Ring-Hoop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bL,F</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>439.49</td>
<td>4598.17</td>
<td>1969.27</td>
<td></td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic</td>
<td>330.00</td>
<td>2415.57</td>
<td>904.69</td>
<td></td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expansion</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal Pressure</th>
<th>Thermal Load on Pipe</th>
<th>Thermal Increase in Pressure</th>
<th>Water Hammer</th>
<th>Longitudinal Component of Hoop Stress</th>
<th>Expansion/Contraction Thermal Stress</th>
<th>Total Stress</th>
<th>Yield Strength</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100.00</td>
<td>140.03</td>
<td>570.02</td>
<td>837.58</td>
<td>3255.30</td>
<td>975.49</td>
<td>3100.90</td>
<td>4.20</td>
</tr>
<tr>
<td></td>
<td>0.00</td>
<td>310.00</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>7377.79</td>
<td>12270.92</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Figure 18 Formatted Output on Excel Sheet For Individual Pipe Mode (Analysis Year).
Multiple Pipe Mode:
In the multiple pipe mode, several pipes can be analyzed together. This is useful when making generalizations about pipes in the system. In order to analyze pipes in multiple mode, all the pipes and their properties must be entered in the ‘BrkInventory’ sheet. To use to multiple mode, select ‘Multiple Analysis’ from the ‘VT Pipe’ Menu (see Figure 20). The results are printed on two sheets ‘ResultsAtZeroYear’ and ‘ResultsAtAnalysisYear’. The sheet ‘ResultsAtZeroYear’ contains the conditions of all the pipes at the time they were installed. The sheet ‘ResultsAtAnalysisYear’ contains the conditions of all the pipes at the analysis year.
Figure 20 Multiple Pipe Mode Menu

Figure 21 Pipe by Pipe Output on Excel Sheet For Individual Pipe (Year Zero).
<table>
<thead>
<tr>
<th>L</th>
<th>M</th>
<th>N</th>
<th>O</th>
<th>P</th>
<th>Q</th>
<th>R</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BeamSpan</td>
<td>TrafficType</td>
<td>Pavement</td>
<td>PipeType</td>
<td>Earthload</td>
<td>Trafficload</td>
<td>ExpSols</td>
</tr>
<tr>
<td>2</td>
<td>4 heavy</td>
<td>paved</td>
<td>ptcast</td>
<td>639.4885</td>
<td>289.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>4 none</td>
<td>unpaved</td>
<td>spuncast</td>
<td>546.82352</td>
<td>0</td>
<td>0</td>
<td>299.3816</td>
</tr>
<tr>
<td>4</td>
<td>4 light</td>
<td>paved</td>
<td>ptcast</td>
<td>982.4565</td>
<td>233.1</td>
<td>4716.25</td>
<td>354.7017</td>
</tr>
<tr>
<td>5</td>
<td>4 medium</td>
<td>unpaved</td>
<td>spuncast</td>
<td>646.1345</td>
<td>540</td>
<td>6232</td>
<td>333.294</td>
</tr>
<tr>
<td>6</td>
<td>4 medium</td>
<td>paved</td>
<td>ptcast</td>
<td>640.9392</td>
<td>669.34</td>
<td>12348</td>
<td>457.7949</td>
</tr>
<tr>
<td>7</td>
<td>4 light</td>
<td>unpaved</td>
<td>spuncast</td>
<td>982.4565</td>
<td>336</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 22 Pipe by Pipe Output on Excel Sheet For Individual Pipe (Analysis Year)
Appendix E

Computer Code
Computer Program

Software Description (See Software Manual In Appendix D)
Module Name: PPADNMACROS1

Option Base 1

'Menu variables
Public glMenuBar As CommandBar
Public Const glTopMenuName As String = "VT Pipe"

'Path Variables
Public glDefaultPath As String 'Default Path for files
Public glSessionPath As String 'Path for session files

'Various workbooks
Public ppadnDataWorkBook As Workbook

'Various sheets
Public glSessionSheet As Worksheet
Public glResultsSheet As Worksheet
Public glBadDataSheet As Worksheet
Public glTempSheet As Worksheet
Public glBrkInventorySheet As Worksheet
Public glSoilsSheet As Worksheet
Public glRegionsSheet As Worksheet
Public glSummarySheet As Worksheet
Public glOptReplacementSheet As Worksheet
Public glResultsFile As String
Public glActiveSheet As Worksheet 'The worksheet that was active before each action

'Define WorkSheet Names
Public Const glSessionSheetName As String = "SessionSheet"
Public Const glBreaksSheetName As String = "Breakdata"
Public Const glResultsSheetName As String = "Results"
Public Const glBadDataSheetName As String = "BadData"
Public Const glTempSheetName As String = "TempSheet"
Public Const glBrkInventorySheetName As String = "BrkInventory"
Public Const glSoilsSheetName As String = "Soils"
Public Const glRegionsSheetName As String = "Regions"
Public Const glSummarySheetName As String = "Summary"
Public Const glOptReplacementSheetName As String = "OptReplacement"

'Headers for sheets
Public Const glSizeColH As String = "PipeDiameter"
Public Const glTypeColH As String = "PipeType"
Public Const glJointColH As String = "JOINT"
Public Const glYearAcqColH As String = "PipeYearInstalled"
Public Const glAnalysisYearColH As String = "AnalysisYear"
Public Const glFootageColH As String = "PipeLength"
Public Const glCategoryColH As String = "CATEGORY"
Public Const glPipeIDColH As String = "PipeID"
Public Const glPipeBeamSpanColH As String = "BeamSpan"
Public Const glWorkingPressureColH As String = "WorkingPressure"
Public Const glFlowColH As String = "Flow"
Public Const glCommentColH As String = "Comment"
Public Const glRetiredPipeColH As String = "Retired" 'Column to indicate pipe has been retired
Public Const glTrafficTypeColH As String = "TrafficType" 'Traffic Density (vehicles per hour)
Public Const glPipeDepthColH As String = "PipeDepth"
Public Const glPavementTypeColH As String = "PavementType"
Public Const glTrenchWidthColH As String = "TrenchWidth"
Public Const glPipeAgeColH As String = "PipeAge"
Public Const glSubTitleColH As String = "SubTitle"

'Soil Headers
Public Const glSoilClassColH As String = "SoilClass"
Public Const glSoilAerationColH As String = "SoilAeration"
Public Const glSoilPorosityColH As String = "SoilPorosity"
Public Const glSoilpHColH As String = "SoilpH"
Public Const glSoilMoistureColH As String = "SoilMoisture"
Public Const glSoilLiquidlimitColH As String = "SoilLiquidlimit"
Public Const glSoilResistivityColH As String = "SoilResistivity"
Public Const glSoilTypeColH As String = "SoilType"
Public Const glSoilDensityColH As String = "SoilDensity"
Public Const glSoilExpansiveColH As String = "SoilExpansive"
Public Const glFrostSusceptibleColH As String = "FrostSusceptible"

Public glSoilHeatCapacity As Single
Public glSoilHeatConductivity As Single
Public glSoilSegregationPotential As Single
Public glSoilShearModulus As Single
Public glSoilPoissonRatio As Single
Public glBeta As Single
Public glVolUnfWater As Single
Public glku As Single
Public g1kf As Single
Public glktip As Single
Public glks As Single
Public glks As Single
Public glSegregationPotential As Single

'Regions
Public Const glRegionIDColH As String = "RegionID"
Public Const glRegionStateColH As String = "RegionState"
Public Const glRegionCityColH As String = "RegionCity"
Public Const glMinYearlyTempColH As String = "MinYearlyTemp"
Public Const glMaxYearlyTempColH As String = "MaxYearlyTemp"
Public Const glMaxFrostDepthColH As String = "MaxFrostDepth"
Public Const glFreezeIndexColH As String = "FreezeIndex"
Public Const glExpansivityIndexColH As String = "SoilExpansivityIndex"
Public Const glMaxFreezeDaysColH As String = "MaxFreezeDays"
Public Const glWaterVelocityChangeColH As String = "WaterVelocityChange"
Public Const glMaxSuddenWaterTempChangeColH As String = "MaxSuddenWaterTempChange"
Public Const glMinWaterTempColH As String = "MinWaterTemp"
Public Const glMaxWaterTempColH As String = "MaxWaterTemp"

'Chart
Public Const glLoadVsStrengthChartName As String = "LoadVsStrengthChart"
Public Const glLoadVsStrengthChartTitle As String = "Load Vs Pipe Strength"
Public Const glLoadVsStrengthXaxisTitle As String = "Days"
Public Const glLoadVsStrengthYaxisTitle As String = "Load (lb)"

'Constants
Public Const glWaterCoeffVolExp As Single = 0.000115 'Coeff of volume expansion of water
Public Const glWaterBulkModulus As Single = 315000 'Bulk Modulus of Water (psi)
Public Const glPI As Single = 3.142 'PI
Public Const glRoomTemp As Single = 70
Public Const glBeddingCondition As String = "A"
Public Const glRossumRegConst As Single = 0.6183 'Regression Coeff obtained from rossum eqn
Public Const glRossumYearsAdj As Single = 1 'Recommended years adjustment from rossum regression
Public Const glDiscountRate As Single = 7.7 'Discount Rate

Global glCurrentPipe As IndividualPipe
Global glSummaryTemplateRange As Range

Type PipeCondition
    PipeID As String
    SubTitle As String
    PipeType As String
    Rossuma As Single
End Type
RossumKa As Single
PipeDepth As Single
PipeTrenchWidth As Single
PipeDiameter As Integer
PipeLength As Single
PipeYearInstalled As Integer
PipeAge As Integer
TrafficType As String
PavementType As String
AnalysisYear As Long
DesignThickness As Single
RegionID As String
MaxFrostDepth As Single
MaxFreezeDays As Long
MinYearlyTemp As Single
MaxYearlyTemp As Single
BeamSpan As Single
WaterVelocityChange As Single
MaxSuddenWaterTempChange As Single
MinWaterTemp As Single
MaxWaterTemp As Single
CorrosionRate As Single
SoilClass As String
SoilDensity As Single
SoilPorosity As Single
SoilMoisture As Single
SoilLiquidLimit As Single
SoilpH As Single
SoilResistivity As Single
SoilAeration As String
SoilType As String
Rossumn As Single
RossumKn As Single
SoilExpansive As String
FrostSusceptible As String
Earthload As Single
Trafficload As Single
ExpSoilload As Single
Frostload As Single
TotalVerticalload As Single
FractureToughness As Single
ExpSoilloadRingStress As Single
FrostloadRingStress As Single

ThermalRingStress As Single
TotalRingStress As Single
SafetyFactorRingStress As Single

WorkingPressureHoopStress As Single
WaterHammerPressureHoopStress As Single
ThermalPressureHoopStress As Single
TotalHoopStress As Single
SafetyFactorHoopStress As Single

HoopComponentLongitudinalStress As Single
ExpansionContractionThermalLongitudinalStress As Single
WorkingPressureLongitudinalStress As Single
WaterHammerPressureLongitudinalStress As Single
ThermalPressureLongitudinalStress As Single
TotalLongitudinalStress As Single
SafetyFactorLongitudinalStress As Single

TotalFlexuralPlusLongitudinalStress As Single
SafetyFactorFlexuralPlusLongitudinalStress As Single
SafetyFactorRingPlusHoopStress As Single

'Fracture toughness derived parameters
StrengthReductionFactor As Single
FractSafetyFactorFlexuralStress As Single
FractSafetyFactorRingStress As Single
FractSafetyFactorHoopStress As Single
FractSafetyFactorLongitudinalStress As Single
FractSafetyFactorFlexuralPlusLongitudinalStress As Single
FractSafetyFactorRingPlusHoopStress As Single
FractRingModulus As Single
FractTensileStrength As Single
FractBurstingTensileStrength As Single
FractModulusRupture As Single

CipraFailureThickness As Single
CipraDesignThickness As Single
CipraFailurePitDepth As Single

CipraRingFailureStrength As Single
CipraTensileFailureStrength As Single
CipraBurstingFailureStrength As Single
CipraRuptureFailureStrength As Single
CipraRingSafetyFactor As Single
CipraTensileSafetyFactor As Single
CipraBurstingSafetyFactor As Single
CipraRuptureSafetyFactor As Single
CipraFlexuralPlusLongitudinalStress As Single
CipraRingPlusHoopStress As Single
CipraFailureTime As Single
End Type

Type IndividualPipe
    Condition(3) As PipeCondition
End Type

Sub ppadnDefineNames()
    glDefaultPath = ThisWorkbook.Path "Default Path for files"
    glSessionPath = "" 'Path for session files'
End Sub

Sub ppadnInitialize()
    Dim lcCurWorkSheetName As String
    Dim lcSheet as Worksheet
    Dim lci As Long

    'Store the sheet that was active at the begining
    Set glActiveSheet = ActiveSheet

    'Allow Alerts to be displayed
    Application.DisplayAlerts = True

    'Define the worksheet names and header names
    Call ppadnDefineNames

    'Set the data workbook
    Set ppadnDataWorkBook = ppadnSetDataWorkBook

    'Set the worksheets
    'If these sheets do not exist, make them
    On Error GoTo SheetMaker
    lcCurWorkSheetName = glTempSheetName
    Set glTempSheet = ppadnDataWorkBook.Sheets(lcCurWorkSheetName)

lcCurWorkSheetName = glBrkInventorySheetName
Set glBrkInventorySheet = ppadnDataWorkBook.Sheets(lcCurWorkSheetName)

lcCurWorkSheetName = glSoilsSheetName
Set glSoilsSheet = ppadnDataWorkBook.Sheets(lcCurWorkSheetName)

lcCurWorkSheetName = glSummarySheetName
Set glSummarySheet = ppadnDataWorkBook.Sheets(lcCurWorkSheetName)

lcCurWorkSheetName = glRegionsSheetName
Set glRegionsSheet = ppadnDataWorkBook.Sheets(lcCurWorkSheetName)

lcCurWorkSheetName = glOptReplacementSheetName
Set glOptReplacementSheet = ppadnDataWorkBook.Sheets(lcCurWorkSheetName)

'If these sheets do not exist, quit
On Error GoTo ErrorHandler

'Define the session path
glSessionPath = ppadnDataWorkBook.Path 'Path for session files

'Turn off error capturing
On Error GoTo 0

'Define Filenames
glResultsFile = glSessionPath & "\" & ppadnDataWorkBook.Name

'Exit the subroutine
Exit Sub

'if the sheet does not exist, quit
ErrorHandler:
    MsgBox "The sheet named '" & lcCurWorkSheetName & '" could not be found!' & vbCrLf & vbCrLf & _
        "Current Workbook Name: " & ppadnDataWorkBook.Name & vbCrLf & vbCrLf & _
        "Current Workbook FileName: " & ppadnDataWorkBook.Path & "\" & ppadnDataWorkBook.Name
    End

'if the sheet does not exist, create it and continue
SheetMaker:
    ppadnDataWorkBook.Sheets.Add
    ActiveSheet.Name = lcCurWorkSheetName
    Resume Next

WorkBookGetter:
End Sub
'Called after each action is performed
Sub ppadnTerminate()
    glActiveSheet.Activate
    glActiveSheet.Cells(1, 1).Select
End Sub

'Sets the data workbook to be used
Function ppadnSetDataWorkBook() As Workbook
    Dim lcWorkbook As Workbook
    'Set the data workbook's name
    If ThisWorkbook.IsAddin = True Then
        If Workbooks.Count > 1 Then
            MsgBox "Only ONE data workbook may be open in addition to the " 
                & ThisWorkbook.Name & "' during analysis!"
        End
        ElseIf Workbooks.Count < 1 Then
            MsgBox "You do not have a data workbook open!"
        End
        Else
            Set lcWorkbook = Workbooks(1)
        End If
    Else
        If Workbooks.Count > 2 Then
            MsgBox "Only ONE data workbook may be open in addition to the " 
                & ThisWorkbook.Name & "' during analysis!"
        End
        ElseIf Workbooks.Count < 2 Then
            MsgBox "You do not have a data workbook open!"
        End
        Else
            If Workbooks(1).Name = ThisWorkbook.Name Then
                Set lcWorkbook = Workbooks(2)
            Else
                Set lcWorkbook = Workbooks(1)
            End If
        End If
    End If
    Set ppadnSetDataWorkBook = lcWorkbook
End Function
Module Name: PPADNMACROS2

Option Explicit ' Force explicit variable declaration.
Option Base 1

'Main function for st louis system
Sub ppadnMain()
  'Initialize
  Call ppadnInitialize
End
End Sub

'Generates Pipe IDs
Function ppadnGetPipeID(ByVal lcWorkord As Variant, ByVal lcYearAcq As Variant, ByVal lcType As Variant, ByVal lcSize As Variant)
  ppadnGetPipeID = lcWorkord & "-" & lcYearAcq & "-" & lcType & "-" & lcSize
End Function

'Used to categorize Pipes in a sheet
Sub ppadnAssignCategory(ByVal lcSheet As Worksheet)
  Dim lci, lcLastRow As Long
  Dim lcHeader, lcSizeCol, lcYearAcqCol, lcTypeCol, lcCategoryCol As String
  lci = 0
  'Check if the category column exists and delete it
  If excelColNum(glCategoryColH, lcSheet) > 0 Then
    lcSheet.Range(excelColAlpha(glCategoryColH, lcSheet) & "1").EntireColumn.Delete
  End If
  'Check for the size column
  lcHeader = glSizeColH
  If excelColNum(lcHeader, lcSheet) = 0 Then
    MsgBox "The column named '" & lcHeader & '" was not found in table ('" & lcSheet.Name & ")!"
  End If
  'Store the Size col address
  lcSizeCol = excelColAlpha(lcHeader, lcSheet)
  'Check for the type column
  lcHeader = glTypeColH
  If excelColNum(lcHeader, lcSheet) = 0 Then
    MsgBox "The column named '" & lcHeader & '" was not found in table ('" & lcSheet.Name & ")!"
  End If
  'Store the Type address
  lcTypeCol = excelColAlpha(lcHeader, lcSheet)
End Sub
'Check for the yearacq column
lcHeader = glYearAcqColH
If excelColNum(lcHeader, lcSheet) = 0 Then
    MsgBox "The column named '" & lcHeader & "' was not found in table (" & lcSheet.Name & ")!"
End If
End If
'Store the Category YearAcq address
lcYearAcqCol = excelColAlpha(lcHeader, lcSheet)

'Now get the last column where we will add the category column
lci = excelFirstColNum("", 1, lcSheet)
If lci = 0 Then
    MsgBox "The CATEGORY Column could not be added in table (" & lcSheet.Name & ")!"
End If
End If

'Print the category column title
lcSheet.Range(lcCategoryCol & "1") = glCategoryColH

'Now Start assigning categories
lci = 2
'lcLastRow = excelFirstRowNum("", 1, lcSheet)
Do
    Application.StatusBar = "Assigning Categories: Now processing row " & lci & " of " & lcLastRow & " rows."
    lcSheet.Range(lcCategoryCol & lci) = ppadnGetCategory(CInt(lcSheet.Range(lcSizeCol & lci)), _
        lcSheet.Range(lcYearAcqCol & lci), _
        lcSheet.Range(lcTypeCol & lci))
    lci = lci + 1
    'while the first col is not empty
Loop While Trim(lcSheet.Cells(lci, 1)) <> ""
End Sub

Function ppadnGetCategory(ByVal lcSize As Long, ByVal lcYearAcq As String, ByVal lcType As String) As String
    Dim lcTempCat As String
    '1900-1928 pit cast iron (can ignore material)
    If Val(lcYearAcq) <= 1928 Then
        lcTempCat = "PitCI"
    End If
    If lcType = "CI" Then
        lcTempCat = "PitCI"
    End If
    ppadnGetCategory = lcTempCat
End Function
'1929-1956 spun cast iron, rigid joint (can ignore material)
ElseIf Val(lcYearAcq) >= 1929 And Val(lcYearAcq) <= 1956 Then
    lcTempCat = "SpunCIRigid"

'1957-1974 spun cast iron, flex joint (both cast and ductile were used
' in this period - must look at material reference in main break database to
determine material)
ElseIf Val(lcYearAcq) >= 1957 And Val(lcYearAcq) <= 1974 Then
    If lcType = "DI" Or lcType = "DP" Then
        lcTempCat = "DI"
    Else
        lcTempCat = "SpunCIFlex"
    End If

'1974-1977 ductile iron, unwrapped (both cast and ductile were used in
'this period - must look at material reference in main break database to
determine material)
ElseIf Val(lcYearAcq) >= 1974 And Val(lcYearAcq) <= 1977 Then
    If lcType = "DI" Or lcType = "DP" Then
        lcTempCat = "DI"
    Else
        lcTempCat = "SpunCIFlex"
    End If

'1978-present ductile iron, wrapped (can ignore material)
ElseIf Val(lcYearAcq) >= 1978 Then
    lcTempCat = "DI"
Else
    lcTempCat = "Unknown"
End If

'Attach the Size
'For Jungoo and Newland
'lcTempCat = lcTempCat & Trim(lcSize)

'For Weston
If CInt(lcSize) <= 10 Then
    lcTempCat = lcTempCat & "<=10"
ElseIf CInt(lcSize) = 12 Then
    lcTempCat = lcTempCat & "=12"
Else
    lcTempCat = lcTempCat & ">=16"
End If

ppadnGetCategory = lcTempCat
End Function
Function ppadnGetPipeType(ByVal lcYearAcq As String, ByVal lcType As String) As String
Dim lcTempType As String
'1900-1928 pit cast iron (can ignore material)
If Val(lcYearAcq) <= 1928 Then
    lcTempType = "PitCI"
'1929-1956 spun cast iron, rigid joint (can ignore material)
ElseIf Val(lcYearAcq) >= 1929 And Val(lcYearAcq) <= 1956 Then
    lcTempType = "SpunCIRigid"
'1957-1974 spun cast iron, flex joint (both cast and ductile were used
'in this period - must look at material reference in main break database to
determine material)
ElseIf Val(lcYearAcq) >= 1957 And Val(lcYearAcq) <= 1974 Then
    If lcType = "DI" Or lcType = "DP" Then
        lcTempType = "DI"
    Else
        lcTempType = "SpunCIFlex"
    End If
'1974-1977 ductile iron, unwrapped (both cast and ductile were used in
'this period - must look at material reference in main break database to
determine material)
ElseIf Val(lcYearAcq) >= 1974 And Val(lcYearAcq) <= 1977 Then
    If lcType = "DI" Or lcType = "DP" Then
        lcTempType = "DI"
    Else
        lcTempType = "SpunCIFlex"
    End If
'1978-present ductile iron, wrapped (can ignore material)
ElseIf Val(lcYearAcq) >= 1978 Then
    lcTempType = "DI"
Else
    lcTempType = "Unknown"
End If
ppadnGetPipeType = lcTempType
End Function

'Function ppadnGetCategory(ByVal lcSize As long, ByVal lcYearACQ As String, ByVal lcType As String) As String
'    Dim lcTempCat As String
'    If Val(lcYearACQ) <= 1928 Then
'        lcTempCat = "PitCI"
'    End If
If Val(lcYearACQ) >= 1929 And Val(lcYearACQ) <= 1956 Then
    lcTempCat = "SpunCIRigid"
End If
If Val(lcYearACQ) >= 1957 And Val(lcYearACQ) <= 1974 Then
    lcTempCat = "SpunCIFlex"
End If
If Val(lcYearACQ) >= 1974 Then
    lcTempCat = "DI"
End If
lcTempCat = lcTempCat & Trim(lcSize)
ppadnGetCategory = lcTempCat
End Function

Determines the Traffic Type for a PipeID based on abbreviation
Function ppadnGetTrafficType(ByVal lcTrafficType As String) As String
    lcTrafficType = Trim(lcTrafficType)
    If LCase(Left(lcTrafficType, 2)) = "he" Then
        lcTrafficType = "HEAVY"
    ElseIf LCase(Left(lcTrafficType, 2)) = "me" Then
        lcTrafficType = "MEDIUM"
    ElseIf LCase(Left(lcTrafficType, 2)) = "li" Then
        lcTrafficType = "LIGHT"
    Else
        lcTrafficType = "NONE"
    End If
    ppadnGetTrafficType = lcTrafficType
End Function

Determines the Pavement Type for a PipeID based on abbreviation
Function ppadnGetPavementType(ByVal lcPavementType As String) As String
    lcPavementType = Trim(lcPavementType)
    If LCase(Left(lcPavementType, 2)) = "pa" Then
        lcPavementType = "PAVED"
    ElseIf LCase(Left(lcPavementType, 2)) = "un" Then
        lcPavementType = "UNPAVED"
    Else
        lcPavementType = "UNPAVED"
    End If
    ppadnGetPavementType = lcPavementType
End Function

Determines the Aeration Type for a PipeID based on abbreviation
Function ppadnGetAerationType(ByVal lcAerationType As String) As String
    lcAerationType = Trim(lcAerationType)
    If LCase(Left(lcAerationType, 2)) = "go" Then
        lcAerationType = "GOOD"
    ElseIf LCase(Left(lcAerationType, 2)) = "fa" Then
        lcAerationType = "FAIR"
    ElseIf LCase(Left(lcAerationType, 2)) = "po" Then
        lcAerationType = "POOR"
    Else
        lcAerationType = "POOR"
    End If
End Function

Sub ppadnFormPipeChange(ByVal lcPipe As String)
    Dim lcSoilID As String
    lcSoilID = excelReadProperty(lcPipe, glSoilClassColH, glBrkInventorySheet)
    frmViewPipe.txtCorrosionRate.Text = excelReadProperty(lcPipe, "CorrosionRate", glBrkInventorySheet)
    frmViewPipe.txtSoilID.Text = lcSoilID
    frmViewPipe.comboSoilType.Text = IIf( LCase(Trim(excelReadProperty(lcPipe, glSoilTypeColH, glBrkInventorySheet))) <> ",", _
        LCase(Trim(excelReadProperty(lcPipe, glSoilTypeColH, glBrkInventorySheet))), _
        LCase(Trim(excelReadProperty(lcSoilID, glSoilTypeColH, glSoilsSheet))))
    frmViewPipe.cmbSoilAeration.Text = IIf( LCase(Trim(excelReadProperty(lcPipe, glSoilAerationColH, glBrkInventorySheet))) <> "", _
        LCase(Trim(excelReadProperty(lcPipe, glSoilAerationColH, glBrkInventorySheet))), _
        LCase(Trim(excelReadProperty(lcSoilID, glSoilAerationColH, glSoilsSheet))))
    frmViewPipe.txtSoilMoisture.Text = IIf( LCase(Trim(excelReadProperty(lcPipe, glSoilMoistureColH, glBrkInventorySheet))) <> "", _
        LCase(Trim(excelReadProperty(lcPipe, glSoilMoistureColH, glBrkInventorySheet))), _
        LCase(Trim(excelReadProperty(lcSoilID, glSoilMoistureColH, glSoilsSheet))))
    frmViewPipe.txtSoilpH.Text = IIf( LCase(Trim(excelReadProperty(lcPipe, glSoilpHColH, glBrkInventorySheet))) <> "", _
        LCase(Trim(excelReadProperty(lcPipe, glSoilpHColH, glBrkInventorySheet))), _
        LCase(Trim(excelReadProperty(lcSoilID, glSoilpHColH, glSoilsSheet))))
    frmViewPipe.txtSoilResistivity.Text = IIf( LCase(Trim(excelReadProperty(lcPipe, glSoilResistivityColH, glBrkInventorySheet))) <> "", _
        LCase(Trim(excelReadProperty(lcPipe, glSoilResistivityColH, glBrkInventorySheet))), _
        LCase(Trim(excelReadProperty(lcSoilID, glSoilResistivityColH, glBrkInventorySheet))))
End Sub
LCase(Trim(excelReadProperty(lcSoilID, glSoilResistivityColH, glSoilsSheet))))

frmViewPipe.txtSoilDensity.Text = IIf(_LCase(Trim(excelReadProperty(lcPipe, glSoilDensityColH, glBrkInventorySheet))) <> "", _LCase(Trim(excelReadProperty(lcPipe, glSoilDensityColH, glBrkInventorySheet))), _LCase(Trim(excelReadProperty(lcSoilID, glSoilDensityColH, glSoilsSheet)))))

frmViewPipe.txtSoilPorosity.Text = IIf(_LCase(Trim(excelReadProperty(lcPipe, glSoilPorosityColH, glBrkInventorySheet))) <> "", _LCase(Trim(excelReadProperty(lcPipe, glSoilPorosityColH, glBrkInventorySheet))), _LCase(Trim(excelReadProperty(lcSoilID, glSoilPorosityColH, glSoilsSheet)))))

frmViewPipe.txtSoilLiquidLimit.Text = IIf(_LCase(Trim(excelReadProperty(lcPipe, glSoilLiquidlimitColH, glBrkInventorySheet))) <> "", _LCase(Trim(excelReadProperty(lcPipe, glSoilLiquidlimitColH, glBrkInventorySheet))), _LCase(Trim(excelReadProperty(lcSoilID, glSoilLiquidlimitColH, glSoilsSheet)))))

frmViewPipe.comboSoilExpansive.Text = IIf(_LCase(Trim(excelReadProperty(lcPipe, glSoilExpansiveColH, glBrkInventorySheet))) <> "", _LCase(Trim(excelReadProperty(lcPipe, glSoilExpansiveColH, glBrkInventorySheet))), _LCase(Trim(excelReadProperty(lcSoilID, glSoilExpansiveColH, glSoilsSheet)))))

frmViewPipe.comboFrostSusceptible.Text = IIf(_LCase(Trim(excelReadProperty(lcPipe, glFrostSusceptibleColH, glBrkInventorySheet))) <> "", _LCase(Trim(excelReadProperty(lcPipe, glFrostSusceptibleColH, glBrkInventorySheet))), _LCase(Trim(excelReadProperty(lcSoilID, glFrostSusceptibleColH, glSoilsSheet)))))

'Pipe Properties
frmViewPipe.txtPipeDepth.Text = _excleReadProperty(lcPipe, glPipeDepthColH, glBrkInventorySheet)
frmViewPipe.cmbPavementType.Text = ppadnGetPavementType(_excleReadProperty(lcPipe, glPavementTypeColH, glBrkInventorySheet))

frmViewPipe.cmbTrafficType.Text = ppadnGetTrafficType(_excleReadProperty(lcPipe, glTrafficTypeColH, glBrkInventorySheet))
frmViewPipe.txtWorkingPressure.Text = _excleReadProperty(lcPipe, glWorkingPressureColH, glBrkInventorySheet)
frmViewPipe.txtPipeBeamSpan.Text = _excleReadProperty(lcPipe, glPipeBeamSpanColH, glBrkInventorySheet)

'Update pipe properties
'Set Pipe Properties
frmViewPipe.txtPipeDiameter.Text = excleReadProperty(lcPipe, glSizeColH, glBrkInventorySheet)
frmViewPipe.txtPipeType.Text = excleReadProperty(lcPipe, glTypeColH, glBrkInventorySheet)
frmViewPipe.txtPipeLength.Text = excleReadProperty(lcPipe, glFootageColH, glBrkInventorySheet)
frmViewPipe.txtPipeYearAcq.Text = excelReadProperty(lcPipe, glYearAcqColH, glBrkInventorySheet)

frmViewPipe.txtDesignThickness.Text = _
  ppadnGetDesignThickness(lcPipe, CLng(Val(frmViewPipe.txtPipeYearAcq)),
  CLng(Val(frmViewPipe.txtPipeDiameter)))
frmViewPipe.txtDesignRM.Text = ppadnGetDesignRM(lcPipe, CLng(Val(frmViewPipe.txtPipeYearAcq)))
frmViewPipe.txtDesignTS.Text = ppadnGetDesignTS(lcPipe, CLng(Val(frmViewPipe.txtPipeYearAcq)))
frmViewPipe.txtDesignBTS.Text = ppadnGetDesignBTS(lcPipe, CLng(Val(frmViewPipe.txtPipeYearAcq)))
frmViewPipe.txtDesignModulusRupture.Text = ppadnGetDesignModulusRupture(lcPipe,
  CLng(Val(frmViewPipe.txtPipeYearAcq)))
frmViewPipe.txtDesignFractureToughness.Text = _
  ppadnGetFractureToughness(lcPipe, CLng(Val(frmViewPipe.txtPipeType)) ,
  CLng(Val(frmViewPipe.txtPipeYearAcq)))
frmViewPipe.comboRegions.Text = _
  excelReadProperty(lcPipe, glRegionIDColH, glBrkInventorySheet)
DoEvents
End Sub

Sub ppadnFormTimeChange()

'Calculate pipe age
If Trim(frmViewPipe.comboAnalysisYear.Text) <> "" And _
  Trim(frmViewPipe.txtPipeYearAcq.Text) <> "" Then

  frmViewPipe.txtPipeAge.Text = CLng(frmViewPipe.comboAnalysisYear.Text) _
  - CLng(frmViewPipe.txtPipeYearAcq)

'frmViewPipe.txtCurrentPitDepth.Text = _
  ppadnGetCurrentPitDepth( _
  CLng(Val(frmViewPipe.txtPipeDiameter)), _
  CLng(Val(frmViewPipe.txtPipeAge)), _
  CSng(Val(frmViewPipe.txtSoilResistivity)), _
  CSng(Val(frmViewPipe.txtSoilpH)), _
  frmViewPipe.cmbSoilAeration, _
  frmViewPipe.txtPipeType _
  )

'frmViewPipe.txtCurrentThickness.Text = _
  ppadnGetCurrentThickness( _
  CSng(Val(frmViewPipe.txtDesignThickness)), _
  CLng(Val(frmViewPipe.txtPipeDiameter)), _
  CLng(Val(frmViewPipe.txtPipeAge)), _
  CSng(Val(frmViewPipe.txtSoilResistivity)), _
  CSng(Val(frmViewPipe.txtSoilpH)), _
  )
```vba
frmViewPipe.cmbSoilAeration.Text = _
frmViewPipe.txtPipeType.Text = _

' frmViewPipe.txtCurrentRM.Text = _
ppadnGetCurrentRM(CSng(Val(frmViewPipe.txtDesignRM)), CLng(Val(frmViewPipe.txtPipeYearAcq)), CLng(Val(frmViewPipe.comboAnalysisYear.Text)))
' frmViewPipe.txtCurrentTS.Text = _
ppadnGetCurrentTS(CSng(Val(frmViewPipe.txtDesignTS)), CLng(Val(frmViewPipe.txtPipeYearAcq)), CLng(Val(frmViewPipe.comboAnalysisYear.Text)))
' frmViewPipe.txtCurrentBTS.Text = _
ppadnGetCurrentBTS(CSng(Val(frmViewPipe.txtDesignBTS)), CLng(Val(frmViewPipe.txtPipeYearAcq)), CLng(Val(frmViewPipe.comboAnalysisYear.Text)))

End If
End Sub

Sub ppadnFormRegionChange()
Dim lcRegion As String
lcRegion = Trim(frmViewPipe.comboRegions.Text)
frmViewPipe.txtMinYearlyTemp.Text = excelReadProperty(lcRegion, glMinYearlyTempColH, glRegionsSheet)
frmViewPipe.txtMaxYearlyTemp.Text = excelReadProperty(lcRegion, glMaxYearlyTempColH, glRegionsSheet)
frmViewPipe.txtMaxFrostDepth.Text = excelReadProperty(lcRegion, glMaxFrostDepthColH, glRegionsSheet)
frmViewPipe.txtMaxFreezeDays.Text = excelReadProperty(lcRegion, glMaxFreezeDaysColH, glRegionsSheet)
frmViewPipe.txtMinSuddenWaterTempChange.Text = excelReadProperty(lcRegion, glMinSuddenWaterTempChangeColH, glRegionsSheet)
frmViewPipe.txtMaxWaterTemp.Text = excelReadProperty(lcRegion, glMaxWaterTempColH, glRegionsSheet)
frmViewPipe.txtMaxWaterTemp.Text = excelReadProperty(lcRegion, glMaxWaterTempColH, glRegionsSheet)
frmViewPipe.txtWaterVelocityChange.Text = excelReadProperty(lcRegion, glWaterVelocityChangeColH, glRegionsSheet)
End Sub

Sub ppadnSetPipeProperty(ByVal lcMode As String, lcCondition As PipeCondition, _
ByVal lcProperty As String, ByVal lcPipeID As String, ByVal lcCurrYear As Long, _
Optional ByVal lcRowNum As Long)
' On Error GoTo ErrorHandler
With lcCondition
Select Case lcProperty
Case glPipeIDColH
 .PipeID = lcPipeID
Case glTypeColH
 .PipeType = excelReadProperty(.PipeID, glTypeColH, glBrkInventorySheet, lcRowNum)
Case "Rossuma"
 .Rossuma = ppadnGetRossuma(.PipeType)
Case "RossumKa"
End Select
End With
End Sub
```
RossumKa = ppadnGetRossumKa(.PipeType)

Case glTypeColH
  .PipeType = excelReadProperty(.PipeID, glTypeColH, glBrkInventorySheet, lcRowNum)
Case glPipeDepthColH
  .PipeDepth = CSng(excelReadProperty(.PipeID, glPipeDepthColH, glBrkInventorySheet, lcRowNum))
Case glFootageColH
  .PipeLength = CSng(excelReadProperty(.PipeID, glFootageColH, glBrkInventorySheet, lcRowNum))
Case glSizeColH
  .PipeDiameter = CLng(excelReadProperty(.PipeID, glSizeColH, glBrkInventorySheet, lcRowNum))
Case glTrenchWidthColH
  .PipeTrenchWidth = CSng((.PipeDiameter / 12) + 2)
Case glYearAcqColH
  .PipeYearInstalled = CLng(excelReadProperty(.PipeID, glYearAcqColH, glBrkInventorySheet, lcRowNum))
Case glAnalysisYearColH
  .AnalysisYear = lcCurrYear
Case glPipeAgeColH
  .PipeAge = .AnalysisYear - .PipeYearInstalled
Case "DesignThickness"
  If LCase(Left(Trim(lcMode), 1)) = "s" Then
    .DesignThickness = CSng(frmViewPipe.txtDesignThickness)
  Else
    .DesignThickness = _
    CSng(ppadnGetDesignThickness(.PipeID, .PipeYearInstalled, .PipeDiameter))
  End If
Case glSubTitleColH
  .SubTitle = "Conditions at Year " & .PipeAge
Case glTrafficTypeColH
  If LCase(Left(Trim(lcMode), 1)) = "s" Then
    .TrafficType = frmViewPipe.cmbTrafficType
  Else
    .TrafficType = ppadnGetTrafficType(_
    excelReadProperty(.PipeID, glTrafficTypeColH, glBrkInventorySheet, lcRowNum))
  End If
Case glPavementTypeColH
  If LCase(Left(Trim(lcMode), 1)) = "s" Then
    .PavementType = frmViewPipe.cmbPavementType
  Else
    .PavementType = ppadnGetPavementType(_
    excelReadProperty(.PipeID, glPavementTypeColH, glBrkInventorySheet, lcRowNum))
  End If
Case glPipeBeamSpanColH
  If LCase(Left(Trim(lcMode), 1)) = "s" Then
    .BeamSpan = CSng(frmViewPipe.txtPipeBeamSpan)
  Else
    .BeamSpan = CSng(excelReadProperty(.PipeID, glPipeBeamSpanColH, glBrkInventorySheet, lcRowNum))
End If
Case glRegionIDColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .RegionID = frmViewPipe.comboRegions.Text
    Else
        .RegionID = excelReadProperty(.PipeID, glRegionIDColH, glBrkInventorySheet, lcRowNum)
    End If
End If
Case glWaterVelocityChangeColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .WaterVelocityChange = CSng(frmViewPipe.txtWaterVelocityChange)
    Else
        .WaterVelocityChange = CSng(excelReadProperty(.RegionID, glWaterVelocityChangeColH, glRegionsSheet))
    End If
End If
Case glMaxFrostDepthColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .MaxFrostDepth = CSng(frmViewPipe.txtMaxFrostDepth)
    Else
        .MaxFrostDepth = CSng(excelReadProperty(.RegionID, glMaxFrostDepthColH, glRegionsSheet))
    End If
End If
Case glMaxFreezeDaysColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .MaxFreezeDays = CLng(frmViewPipe.txtMaxFreezeDays)
    Else
        .MaxFreezeDays = CLng(excelReadProperty(.RegionID, glMaxFreezeDaysColH, glRegionsSheet))
    End If
End If
Case glMinYearlyTempColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .MinYearlyTemp = CSng(frmViewPipe.txtMinYearlyTemp)
    Else
        .MinYearlyTemp = CSng(excelReadProperty(.RegionID, glMinYearlyTempColH, glRegionsSheet))
    End If
End If
Case glMaxYearlyTempColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .MaxYearlyTemp = CSng(frmViewPipe.txtMaxYearlyTemp)
    Else
        .MaxYearlyTemp = CSng(excelReadProperty(.RegionID, glMaxYearlyTempColH, glRegionsSheet))
    End If
End If
Case glMaxSuddenWaterTempChangeColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .MaxSuddenWaterTempChange = _
            CSng(frmViewPipe.txtMaxSuddenWaterTempChange)
    Else
        .MaxSuddenWaterTempChange = _
            CSng(excelReadProperty(.RegionID, glMaxSuddenWaterTempChangeColH, _
               glRegionsSheet))
End If
Case glMinWaterTempColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .MinWaterTemp = CSng(frmViewPipe.txtMinWaterTemp)
    Else
        .MinWaterTemp = CSng(excelReadProperty(.RegionID, glMinWaterTempColH, glRegionsSheet))
    End If
Case glMaxWaterTempColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .MaxWaterTemp = CSng(frmViewPipe.txtMaxWaterTemp)
    Else
        .MaxWaterTemp = CSng(excelReadProperty(.RegionID, glMaxWaterTempColH, glRegionsSheet))
    End If
Case glSoilClassColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .SoilClass = frmViewPipe.txtSoilID
    Else
        .SoilClass = excelReadProperty(.PipeID, glSoilClassColH, glBrkInventorySheet, lcRowNum)
    End If
Case "CorrosionRate"
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .CorrosionRate = CSng(Val(frmViewPipe.txtCorrosionRate))
    Else
        .CorrosionRate = CSng(excelReadProperty(.PipeID, "CorrosionRate", glBrkInventorySheet, lcRowNum))
    End If
Case glSoilDensityColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .SoilDensity = CSng(frmViewPipe.txtSoilDensity)
    Else
        If Val(Trim(excelReadProperty(.PipeID, glSoilDensityColH, glBrkInventorySheet, lcRowNum))) > 0 Then
            .SoilDensity = CSng(Val(Trim(excelReadProperty(.PipeID, glSoilDensityColH, glBrkInventorySheet, lcRowNum))))
        Else
            .SoilDensity = CSng(Val(Trim(excelReadProperty(.SoilClass, glSoilDensityColH, glSoilsSheet))))
        End If
    End If
Case glSoilPorosityColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .SoilPorosity = CSng(frmViewPipe.txtSoilPorosity)
    Else
        If Val(Trim(excelReadProperty(.PipeID, glSoilPorosityColH, glBrkInventorySheet, lcRowNum))) > 0 Then
            .SoilPorosity = CSng(Val(Trim(excelReadProperty(.PipeID, glSoilPorosityColH, glBrkInventorySheet, lcRowNum))))
        Else
            excelReadProperty(.PipeID, glSoilPorosityColH, glBrkInventorySheet, lcRowNum))
        End If
    End If
.SoilPorosity = CSng(Val(Trim(_
    excelReadProperty(.SoilClass, glSoilPorosityColH, glSoilsSheet))))
End If
End If
Case glSoilMoistureColH
If LCase(Left(Trim(lcMode), 1)) = "s" Then
    .SoilMoisture = CSng(frmViewPipe.txtSoilMoisture)
Else
    If Val(Trim(excelReadProperty(.PipeID, glSoilMoistureColH, glBrkInventorySheet, lcRowNum))) > 0 Then
        .SoilMoisture = CSng(Val(Trim(_
            excelReadProperty(.PipeID, glSoilMoistureColH, glBrkInventorySheet, lcRowNum))))
    Else
        .SoilMoisture = CSng(Val(Trim( _
            excelReadProperty(.SoilClass, glSoilMoistureColH, glSoilsSheet))))
    End If
End If
Case glSoilLiquidlimitColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .SoilLiquidlimit = CSng(frmViewPipe.txtSoilLiquidLimit)
    Else
        If Val(Trim(excelReadProperty(.PipeID, glSoilLiquidlimitColH, glBrkInventorySheet, lcRowNum))) > 0 Then
            .SoilLiquidlimit = CSng(Val(Trim(_
                excelReadProperty(.PipeID, glSoilLiquidlimitColH, glBrkInventorySheet, lcRowNum))))
        Else
            .SoilLiquidlimit = CSng(Val(Trim( _
                excelReadProperty(.SoilClass, glSoilLiquidlimitColH, glSoilsSheet))))
        End If
End If
Case glSoilpHColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .SoilpH = CSng(frmViewPipe.txtSoilpH)
    Else
        If Val(Trim(excelReadProperty(.PipeID, glSoilpHColH, glBrkInventorySheet, lcRowNum))) > 0 Then
            .SoilpH = CSng(Val(Trim(_
                excelReadProperty(.PipeID, glSoilpHColH, glBrkInventorySheet, lcRowNum))))
        Else
            .SoilpH = CSng(Val(Trim( _
                excelReadProperty(.SoilClass, glSoilpHColH, glSoilsSheet))))
        End If
End If
Case glSoilResistivityColH
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .SoilResistivity = CSng(frmViewPipe.txtSoilResistivity)
    Else
        If Val(Trim(excelReadProperty(.PipeID, glSoilResistivityColH, glBrkInventorySheet, lcRowNum))) > 0 Then
.SoilResistivity = CSng(Val(Trim(_
excelReadProperty(.PipeID, glSoilResistivityColH, glBrkInventorySheet, lcRowNum))))
Else
  .SoilResistivity = CSng(Val(Trim( _
excelReadProperty(.SoilClass, glSoilResistivityColH, glSoilsSheet))))
End If
End If
Case glSoilAerationColH
If LCase(Left(Trim(lcMode), 1)) = "s" Then
  .SoilAeration = frmViewPipe.cmbSoilAeration
Else
  If Trim(excelReadProperty(.PipeID, glSoilAerationColH, glBrkInventorySheet, lcRowNum)) <> "" Then
    .SoilAeration = Trim( _
    excelReadProperty(.PipeID, glSoilAerationColH, glBrkInventorySheet, lcRowNum))
  Else
    .SoilAeration = Trim( _
    excelReadProperty(.SoilClass, glSoilAerationColH, glSoilsSheet))
  End If
End If
End If
Case glSoilTypeColH
If LCase(Left(Trim(lcMode), 1)) = "s" Then
  .SoilType = frmViewPipe.comboSoilType
Else
  If Trim(excelReadProperty(.PipeID, glSoilTypeColH, glBrkInventorySheet, lcRowNum)) <> "" Then
    .SoilType = Trim( _
    excelReadProperty(.PipeID, glSoilTypeColH, glBrkInventorySheet, lcRowNum))
  Else
    .SoilType = Trim( _
    excelReadProperty(.SoilClass, glSoilTypeColH, glSoilsSheet))
  End If
End If
End If
Case glSoilExpansiveColH
If LCase(Left(Trim(lcMode), 1)) = "s" Then
  .SoilExpansive = frmViewPipe.comboSoilExpansive.Text
Else
  If Trim(excelReadProperty(.PipeID, glSoilExpansiveColH, glBrkInventorySheet, lcRowNum)) <> "" Then
    .SoilExpansive = Trim( _
    excelReadProperty(.PipeID, glSoilExpansiveColH, glBrkInventorySheet, lcRowNum))
  Else
    .SoilExpansive = Trim( _
    excelReadProperty(.SoilClass, glSoilExpansiveColH, glSoilsSheet))
  End If
End If
End If
Case glFrostSusceptibleColH
If LCase(Left(Trim(lcMode), 1)) = "s" Then
.FrostSusceptible = frmViewPipe.comboFrostSusceptible.Text
Else
    If Trim(excelReadProperty(.PipeID, glFrostSusceptibleColH, glBrkInventorySheet, lcRowNum)) <> "" Then
        .FrostSusceptible = Trim(_
            excelReadProperty(.PipeID, glFrostSusceptibleColH, glBrkInventorySheet, lcRowNum))
    Else
        .FrostSusceptible = Trim( _
            excelReadProperty(.SoilClass, glFrostSusceptibleColH, glSoilsSheet))
    End If
End If
Case "Rossumn"
    .Rossumn = ppadnGetRossumn(.SoilAeration)
Case "RossumKn"
    .RossumKn = ppadnGetRossumKn(.SoilAeration)
Case "Earthload"
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .Earthload = CSng(frmViewPipe.txtEarthLoad)
    Else
        .Earthload = ppadnGetEarthLoad(.PipeDiameter, .PipeDepth, .SoilDensity)
    End If
Case "Trafficload"
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .Trafficload = CSng(frmViewPipe.txtTruckLoad)
    Else
        .Trafficload = ppadnGetTrafficLoad(.PipeDiameter, _
            .PipeDepth, .TrafficType, .PavementType)
    End If
Case "ExpSoilload"
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .ExpSoilload = _
            IIf(LCase(Trim(frmViewPipe.comboSoilExpansive.Value)) = "y", _
                CSng(frmViewPipe.txtEarthLoad), 0)
    Else
        If LCase(Trim(.SoilExpansive)) = "y" Then
            .ExpSoilload = ppadnGetExpSoilLoad(.SoilMoisture, _
                .SoilLiquidlimit, .PipeDiameter, .PipeDepth)
        Else
            .ExpSoilload = 0
        End If
    End If
Case "Frostload"
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .Frostload = _
            IIf(LCase(Trim(frmViewPipe.comboFrostSusceptible.Value)) = "y", _
                CSng(frmViewPipe.txtFrostLoad), 0)
Else
    If LCase(Trim(.FrostSusceptible)) = "y" Then
    Else
        .Frostload = 0
    End If
End If
Case "TotalVerticalload"
Case "FractureToughness"
    If LCase(Left(Trim(lcMode), 1)) = "s" Then
        .FractureToughness = CSng(frmViewPipe.txtDesignFractureToughness)
    Else
        .FractureToughness = CSng(ppadnGetFractureToughness(.PipeID, .PipeType, .PipeYearInstalled))
    End If
End If
'Pit Depth
Case "Pitdepth"
    If .PipeAge = 0 Then
        .Pitdepth = 0
    Else
        If .CorrosionRate > 0 Then
            .Pitdepth = .CorrosionRate * .PipeAge
        Else
            Dim lcCorrCoeff As Single
        End If
    End If
End If
Case "Thickness"
  If LCase(Left(Trim(lcMode), 1)) = "s" Then
    Thickness = CSng(frmViewPipe.txtDesignThickness) - .Pitdepth
  Else
    Thickness = CSng(ppadnGetDesignThickness(.PipeID, .PipeYearInstalled, .PipeDiameter)) - .Pitdepth
  End If
  Thickness = IIf(Thickness <= 0, 0.00001, Thickness)

'** Not in Weston
Case "RepairCost"
  'RepairCost = 2000
  RepairCost = CSng(Val(Trim(excelReadProperty(.PipeDiameter, "RepairCost", _
    ThisWorkbook.Sheets("Costs")))))

'** Not in Weston
Case "ReplacementCost"
  'ReplacementCost = 100
  ReplacementCost = CSng(Val(Trim(excelReadProperty(.PipeDiameter, "ReplacementCost", _
    ThisWorkbook.Sheets("Costs")))))

'** Not in Weston
Case "DiscountRate"
  DiscountRate = glDiscountRate

'** Not in Weston
Case "TheoreticalThresholdBreakRate"
  TheoreticalThresholdBreakRate = _
    FormatNumber(ppadnTheoreticalThresholdBRKRate(.RepairCost, .ReplacementCost, _
      .PipeLength, .DiscountRate), 3)

'** Not in Weston
Case "YearsToBreakTimeSeries"
  YearsToBreakTimeSeries = _
    YTBTimeSeries(ppadnDataWorkbook.Sheets("Brkhistory"), .PipeID)

'** Not in Weston
Case "ObservedFirstBreakTime"
  If Trim(.YearsToBreakTimeSeries) <> "" Then
    ObservedFirstBreakTime = _
      Left(.YearsToBreakTimeSeries, InStr(1, .YearsToBreakTimeSeries, ",") - 1)
  Else
    ObservedFirstBreakTime = ""
End If

'** Not in Weston
Case "RossumFractionExposed"
    '.RossumFractionExposed = ppadnGetRossumFractionExposed
        (.PipeDiameter, .RossumFirstLeakTime, .DesignThickness, _
         .PipeType, glRossumRegConst, glRossumYearsAdj)

    '.RossumFractionExposed = ppadnGetRossumFractionExposed
        (.PipeDiameter, CSng(Val(.ObservedFirstBreakTime)), .DesignThickness, _
         .PipeType, 1, 0)
    ' ** Not in Weston
    Case "RossumFirstLeakTime"
        '.RossumFirstLeakTime = _
            ppadnGetRossumFirstLeakTime(.PipeDiameter, .RossumFractionExposed, _
                .SoilAeration, .PipeType, glRossumRegConst, glRossumYearsAdj)

        '.RossumFirstLeakTime = _
            FormatNumber(ppadnGetRossumFirstLeakTime(.PipeDiameter, 1, _
                .SoilAeration, .PipeType, 1, 0), 2)
    ' ** Not in Weston
    Case "TheoreticalThresholdBreakRateOptRepTime"
        '.TheoreticalThresholdBreakRateOptRepTime = _
            ppadnTheoreticalThresholdBRKRateOptRepTime(.TheoreticalThresholdBreakRate, _
                .SoilResistivity, .SoilpH, .SoilAeration, .PipeType, glRossumRegConst, _
                glRossumYearsAdj)

        '.TheoreticalThresholdBreakRateOptRepTime = _
            ppadnTheoreticalThresholdBRKRateOptRepTime(.TheoreticalThresholdBreakRate, _
                .SoilResistivity, .SoilpH, .SoilAeration, .PipeType, 1, _
                0)
    ' ** Not in Weston
    Case "RossumNLeaksTimeSeries"
        '.RossumNLeaksTimeSeries = _
            ppadmGetRossumNLeaksTimeSeries(.PipeDiameter, 1, _
                0)
.DesignThickness, 18, 15, .SoilResistivity, .SoilpH, _
 .SoilAeration, .PipeType, 1, 1)

 .RossumNLeaksTimeSeries = _
 ppadnGetRossumNLeaksTimeSeries(.PipeDiameter, 1, _,
 .SoilAeration, .PipeType, 1, 0)

 *** Not in Weston
 Case "RossumNLeaksTimePowerSeries"
   .RossumNLeaksTimePowerSeries = _
   ppadnGetRossumNLeaksTimePowerSeries(.PipeDiameter, 1, _,
   .DesignThickness, 18, 15, .SoilResistivity, .SoilpH, _
   .SoilAeration, .PipeType, 1, 1)

   .RossumNLeaksTimePowerSeries = _
   ppadnGetRossumNLeaksTimePowerSeries(.PipeDiameter, 1, _,
   .SoilAeration, .PipeType, 1, 0)

 Case "LinRegResults"
 If Trim(.RossumNLeaksTimeSeries) <> "" And _
   Trim(.YearsToBreakTimeSeries) <> "" Then
   LinRegResults = _
   Regress(.RossumNLeaksTimeSeries, .YearsToBreakTimeSeries, 1, True, .PipeID)
   LinRegResultsArray = Split(.LinRegResults, ",")
 Else
   LinRegResults = ""
 End If

 *** Not in Weston
 Case "LognRegResults"
 If Trim(.RossumNLeaksTimeSeries) <> "" And _
   Trim(.YearsToBreakTimeSeries) <> "" Then
   LognRegResults = _
   Regress(.RossumNLeaksTimeSeries, .YearsToBreakTimeSeries, 2, True, .PipeID)
   LognRegResultsArray = Split(.LognRegResults, ",")
 Else
   LognRegResults = ""
 End If

 *** Not in Weston
 Case "CriticalRepTimeA"
 If Trim(.RossumNLeaksTimeSeries) <> "" And _
   Trim(.YearsToBreakTimeSeries) <> "" Then
   CriticalRepTimeA = _
   CriticalRepTimeA()
.CriticalRepTimeA = FormatNumber(.CriticalRepTimeA, 2)
Else
  .CriticalRepTimeA = 0
End If
'** Not in Weston
Case "CriticalRepTimeB"
  If Trim(.RossumNLeaksTimeSeries) <> "" And _
    Trim(.YearsToBreakTimeSeries) <> "" Then
    .CriticalRepTimeB = _
      CriticalRepTimeB()
    .CriticalRepTimeB = FormatNumber(.CriticalRepTimeB, 2)
  Else
    .CriticalRepTimeB = 0
  End If
'** Not in Weston
Case "CriticalRepTimeC"
  If Trim(.RossumNLeaksTimeSeries) <> "" And _
    Trim(.YearsToBreakTimeSeries) <> "" Then
    .CriticalRepTimeC = _
      CriticalRepTimeC(CSng(.LinRegResultsArray(0)), _CSng(.LinRegResultsArray(1)), .TheoreticalThresholdBreakRate, _
        .RossumFirstLeakTime, .PipeType, .SoilAeration)
    .CriticalRepTimeC = FormatNumber(.CriticalRepTimeC, 2)
  Else
    .CriticalRepTimeC = 0
  End If
'** Not in Weston
Case "CriticalRepTimeD"
  If Trim(.RossumNLeaksTimeSeries) <> "" And _
    Trim(.YearsToBreakTimeSeries) <> "" Then
    .CriticalRepTimeD = _
      CriticalRepTimeD(CSng(.LognRegResultsArray(0)), _CSng(.LognRegResultsArray(1)), .TheoreticalThresholdBreakRate, _
        .RossumFirstLeakTime, .PipeType, .SoilAeration)
    .CriticalRepTimeD = FormatNumber(.CriticalRepTimeD, 2)
  Else
    .CriticalRepTimeD = 0
  End If
'** Not in Weston
Case "RingModulus"
  If LCase(Left(Trim(lcMode), 1)) = "s" Then
    .RingModulus = CSng(frmViewPipe.txtDesignRM)
  Else
    .RingModulus = CSng(ppadnGetDesignRM(.PipeID, .PipeYearInstalled))
End If
Case "TensileStrength"
If LCase(Left(Trim(lcMode), 1)) = "s" Then
  .TensileStrength = CSng(frmViewPipe.txtDesignTS)
Else
  .TensileStrength = CSng(ppadnGetDesignTS(.PipeID, .PipeYearInstalled))
End If
Case "BurstingTensileStrength"
If LCase(Left(Trim(lcMode), 1)) = "s" Then
  .BurstingTensileStrength = CSng(frmViewPipe.txtDesignBTS)
Else
  .BurstingTensileStrength = CSng(ppadnGetDesignBTS(.PipeID, .PipeYearInstalled))
End If
Case "ModulusRupture"
If LCase(Left(Trim(lcMode), 1)) = "s" Then
  .ModulusRupture = CSng(frmViewPipe.txtDesignModulusRupture)
Else
  .ModulusRupture = CSng(ppadnGetDesignModulusRupture(.PipeID, .PipeYearInstalled))
End If
Case "WorkingPressure"
If LCase(Left(Trim(lcMode), 1)) = "s" Then
  .WorkingPressure = CSng(frmViewPipe.txtWorkingPressure)
Else
  .WorkingPressure = CSng(excelReadProperty(.PipeID, glWorkingPressureColH, glBrkInventorySheet))
End If
Case "WaterHammerPressure"
  .WaterHammerPressure = ppadnGetWaterHammerPressure(.PipeDiameter, .Thickness, .PipeType, .WaterVelocityChange)
Case "ThermalPressure"
  .ThermalPressure = ppadnGetThermalPressure(.PipeDiameter, .Thickness, .PipeType, .MaxSuddenWaterTempChange)
Case "TotalPressure"
Case "EarthloadFlexuralStress"
Case "TrafficloadFlexuralStress"
Case "ExpSoilloadFlexuralStress"
Case "FrostloadFlexuralStress"
  .FrostloadFlexuralStress = ppadnGetFlexuralStress(.PipeDiameter, _
    .Frostload, .Thickness, .BeamSpan)
Case "TotalFlexuralStress"
  .TotalFlexuralStress = .EarthloadFlexuralStress + .TrafficloadFlexuralStress + _
    .ExpSoilloadFlexuralStress + .FrostloadFlexuralStress
Case "SafetyFactorFlexuralStress"
  .SafetyFactorFlexuralStress = .ModulusRupture / .TotalFlexuralStress
Case "EarthloadRingStress"
  .EarthloadRingStress = _
    ppadnGetRingStress(.PipeDiameter, .Earthload, .Thickness)
Case "TrafficloadRingStress"
  .TrafficloadRingStress = _
    ppadnGetRingStress(.PipeDiameter, .Trafficload, .Thickness)
Case "ExpSoilloadRingStress"
  .ExpSoilloadRingStress = _
    ppadnGetRingStress(.PipeDiameter, .ExpSoilload, .Thickness)
Case "FrostloadRingStress"
  .FrostloadRingStress = _
    ppadnGetRingStress(.PipeDiameter, .Frostload, .Thickness)
Case "ThermalRingStress"
  .ThermalRingStress = ppadnGetRingThermalStress _
    (.PipeDiameter, .Thickness, .PipeType, .MaxSuddenWaterTempChange)
Case "TotalRingStress"
  .TotalRingStress = .EarthloadRingStress + .TrafficloadRingStress + _
    .ExpSoilloadRingStress + .FrostloadRingStress + .ThermalRingStress
Case "SafetyFactorRingStress"
  .SafetyFactorRingStress = .RingModulus / .TotalRingStress
Case "WorkingPressureHoopStress"
  .WorkingPressureHoopStress = _
    ppadnGetHoopStress(.PipeDiameter, .WorkingPressure, .Thickness)
Case "WaterHammerPressureHoopStress"
    .WaterHammerPressureHoopStress = 
        _ppadnGetHoopStress(.PipeDiameter, .WaterHammerPressure, .Thickness)
Case "ThermalPressureHoopStress"
    .ThermalPressureHoopStress = 
        _ppadnGetHoopStress(.PipeDiameter, .ThermalPressure, .Thickness)

Case "TotalHoopStress"
    .TotalHoopStress = .WorkingPressureHoopStress + 
        _WaterHammerPressureHoopStress + _ThermalPressureHoopStress

Case "SafetyFactorHoopStress"
    .SafetyFactorHoopStress = .BurstingTensileStrength / .TotalHoopStress

Case "ExpansionContractionThermalLongitudinalStress"
    .ExpansionContractionThermalLongitudinalStress = 
        _ppadnGetExpansionContractionThermalLongitudinalStress( _.PipeType, Abs(glRoomTemp - .MinWaterTemp))

Case "HoopComponentLongitudinalStress"
    .HoopComponentLongitudinalStress = _
        _ppadnGetPoissonRatio(.PipeType) * .TotalHoopStress
Case "WorkingPressureLongitudinalStress"
    .WorkingPressureLongitudinalStress = 
        _ppadnGetLongitudinalStress(.PipeDiameter, .WorkingPressure, .Thickness)
Case "WaterHammerPressureLongitudinalStress"
    .WaterHammerPressureLongitudinalStress = 
        _ppadnGetLongitudinalStress(.PipeDiameter, .WaterHammerPressure, .Thickness)
Case "ThermalPressureLongitudinalStress"
    .ThermalPressureLongitudinalStress = 
        _ppadnGetLongitudinalStress(.PipeDiameter, .ThermalPressure, .Thickness)
Case "ThermalLongitudinalStress"
    .ThermalLongitudinalStress = ppadnGetLongitudinalThermalStress 
        (.PipeDiameter, .Thickness, .PipeType, .MaxSuddenWaterTempChange)

Case "TotalLongitudinalStress"
    .TotalLongitudinalStress = 
        _WorkingPressureLongitudinalStress + _
        _WaterHammerPressureLongitudinalStress + _
        _ThermalPressureLongitudinalStress + _
        _ThermalLongitudinalStress + _
        _HoopComponentLongitudinalStress + _
        _ExpansionContractionThermalLongitudinalStress

Case "SafetyFactorLongitudinalStress"
.SafetyFactorLongitudinalStress = 
  .TensileStrength / .TotalLongitudinalStress

Case "TotalFlexuralPlusLongitudinalStress"
  .TotalFlexuralPlusLongitudinalStress = _
  .TotalLongitudinalStress + .TotalFlexuralStress

Case "SafetyFactorFlexuralPlusLongitudinalStress"
  .SafetyFactorFlexuralPlusLongitudinalStress = _
  .TensileStrength / .TotalFlexuralPlusLongitudinalStress

Case "SafetyFactorRingPlusHoopStress"
  .SafetyFactorRingPlusHoopStress = _
  ppadnGetSafetyFactorRingPlusHoopStress(.PipeDiameter, _
    .Thickness, .BurstingTensileStrength, _
    .RingModulus, .TotalVerticalload, .TotalPressure)

'Fracture toughness derived parameters
Case "StrengthReductionFactor"
  If .Pitdepth > 0 Then
    .StrengthReductionFactor = ppadnGetStrengthReductionFactor( _
      .Pitdepth, .TensileStrength, .FractureToughness)
  Else
    .StrengthReductionFactor = 1
  End If

Case "FractRingModulus"
  If .Pitdepth > 0 Then
    .FractRingModulus = ppadnGetFractureToughnessResidualStrength( _
      .Pitdepth, .RingModulus, .FractureToughness)
  Else
    .FractRingModulus = .RingModulus
  End If

Case "FractTensileStrength"
  If .Pitdepth > 0 Then
    .FractTensileStrength = ppadnGetFractureToughnessResidualStrength( _
      .Pitdepth, .TensileStrength, .FractureToughness)
  Else
    .FractTensileStrength = .TensileStrength
  End If

Case "FractBurstingTensileStrength"
  If .Pitdepth > 0 Then
    .FractBurstingTensileStrength = ppadnGetFractureToughnessResidualStrength( _
  Else
    .FractBurstingTensileStrength = .BurstingTensileStrength
  End If
Case "FractModulusRupture"
  If .Pitdepth > 0 Then
    .FractModulusRupture = ppadnGetFractureToughnessResidualStrength(_, _
      .Pitdepth, .ModulusRupture, .FractureToughness)
  Else
    .FractModulusRupture = .ModulusRupture
  End If
Case "FractSafetyFactorFlexuralStress"
  .FractSafetyFactorFlexuralStress = .FractModulusRupture / .TotalFlexuralStress
Case "FractSafetyFactorRingStress"
  .FractSafetyFactorRingStress = .FractRingModulus / .TotalRingStress
Case "FractSafetyFactorHoopStress"
  .FractSafetyFactorHoopStress = .FractBurstingTensileStrength / .TotalHoopStress
Case "FractSafetyFactorLongitudinalStress"
  .FractSafetyFactorLongitudinalStress = .FractTensileStrength / .TotalLongitudinalStress
Case "FractSafetyFactorFlexuralPlusLongitudinalStress"
  .FractSafetyFactorFlexuralPlusLongitudinalStress =
    .FractTensileStrength / .TotalFlexuralPlusLongitudinalStress
Case "FractSafetyFactorRingPlusHoopStress"
  .FractSafetyFactorRingPlusHoopStress =
    ppadnGetSafetyFactorRingPlusHoopStress(_
      .PipeDiameter, .Thickness, .FractBurstingTensileStrength, _, _
      .FractRingModulus, .TotalVerticalload, .TotalPressure)
Case "CipraDesignThickness"
  If LCase(Left(Trim(lcMode), 1)) = "s" Then
    .CipraDesignThickness = CSng(frmViewPipe.txtDesignThickness) - .Pitdepth
  Else
    .CipraDesignThickness =
    CSng(cipraThickness(.PipeDiameter, 2.5, .Earthload, .Trafficload, _
      .RingModulus, glBeddingCondition))
  End If
Case "CipraFailureThickness"
  .CipraFailureThickness = CSng(cipraThickness(.PipeDiameter, 1, .Earthload, .Trafficload, _
    .RingModulus, glBeddingCondition))
Case "CipraFailurePitDepth"
  .CipraFailurePitDepth = .DesignThickness - .CipraFailureThickness
Case "CipraRingFailureStrength"
  .CipraRingFailureStrength = ppadnGetFractureToughnessResidualStrength(_, _
    .CipraFailurePitDepth, .RingModulus, .FractureToughness)
Case "CipraTensileFailureStrength"
    .CipraTensileFailureStrength = ppadnGetFractureToughnessResidualStrength( _
        .CipraFailurePitDepth, .TensileStrength, .FractureToughness)
Case "CipraBurstingFailureStrength"
    .CipraBurstingFailureStrength = ppadnGetFractureToughnessResidualStrength( _
        .CipraFailurePitDepth, .BurstingTensileStrength, .FractureToughness)
Case "CipraRuptureFailureStrength"
    .CipraRuptureFailureStrength = ppadnGetFractureToughnessResidualStrength( _
        .CipraFailurePitDepth, .ModulusRupture, .FractureToughness)
Case "CipraRingSafetyFactor"
    .CipraRingSafetyFactor = .FractRingModulus / .CipraRingFailureStrength
Case "CipraTensileSafetyFactor"
    .CipraTensileSafetyFactor = .FractTensileStrength / .CipraTensileFailureStrength
Case "CipraBurstingSafetyFactor"
    .CipraBurstingSafetyFactor = .FractBurstingTensileStrength / .CipraBurstingFailureStrength
Case "CipraRuptureSafetyFactor"
Case "CipraSafetyFactorFlexuralPlusLongitudinalStress"
    .CipraSafetyFactorFlexuralPlusLongitudinalStress = _
        .FractTensileStrength / .CipraTensileFailureStrength
Case "CipraSafetyFactorRingPlusHoopStress"
    .CipraSafetyFactorRingPlusHoopStress = _
        ppadnGetSafetyFactorRingPlusHoopStress( _
            .PipeDiameter, .Thickness, .CipraBurstingFailureStrength, _
            .CipraRingFailureStrength, .TotalVerticalLoad, .TotalPressure)
Case "CipraFailureTime"
    .CipraFailureTime = .PipeYearInstalled + __
        cipraGetFailureTime(.CipraFailurePitDepth, .SoilResistivity, __
            .SoilpH, .PipeDiameter, .SoilAeration, .PipeType, .CorrosionRate)
End Select
End With
Exit Sub
ErrorHandler:
    MsgBox Err.Number & ": " & Err.Description
End Sub

Function ppadnGetPipeProperty(lcPipe As PipeCondition, ByVal lcProperty As String) As String
    Select Case lcProperty
        Case glPipeIDColH
            ppadnGetPipeProperty = lcPipe.PipeID
        Case glSubTitleColH
ppadnGetPipeProperty = lcPipe.SubTitle
Case glYearAcqColH
  ppadnGetPipeProperty = lcPipe.PipeYearInstalled
Case glAnalysisYearColH
  ppadnGetPipeProperty = lcPipe.AnalysisYear
Case glPipeAgeColH
  ppadnGetPipeProperty = lcPipe.PipeAge
Case glSizeColH
  ppadnGetPipeProperty = lcPipe.PipeDiameter
Case glPipeDepthColH
  ppadnGetPipeProperty = lcPipe.PipeDepth
Case glFootageColH
  ppadnGetPipeProperty = lcPipe.PipeLength
Case glTrenchWidthColH
  ppadnGetPipeProperty = lcPipe.PipeTrenchWidth
Case glYearAcqColH
  ppadnGetPipeProperty = lcPipe.PipeYearInstalled
Case "BeamSpan"
  ppadnGetPipeProperty = lcPipe.BeanSpan
Case "PipeType"
  ppadnGetPipeProperty = lcPipe.PipeType
Case "Rossuma"
  ppadnGetPipeProperty = lcPipe.Rossuma
Case "RossumKa"
  ppadnGetPipeProperty = lcPipe.RossumKa
Case "TrafficType"
  ppadnGetPipeProperty = lcPipe.TrafficType
Case "PavementType"
  ppadnGetPipeProperty = lcPipe.PavementType
Case "CorrosionRate"
  ppadnGetPipeProperty = lcPipe.CorrosionRate
Case "SoilClass"
  ppadnGetPipeProperty = lcPipe.SoilClass
Case "SoilpH"
  ppadnGetPipeProperty = lcPipe.SoilpH
Case "SoilMoisture"
  ppadnGetPipeProperty = lcPipe.SoilMoisture
Case "SoilPorosity"
  ppadnGetPipeProperty = lcPipe.SoilPorosity
Case "SoilDensity"
  ppadnGetPipeProperty = lcPipe.SoilDensity
Case "SoilResistivity"
  ppadnGetPipeProperty = lcPipe.SoilResistivity
Case "SoilAeration"
  ppadnGetPipeProperty = lcPipe.SoilAeration
Case "SoilLiquidlimit"
  ppadnGetPipeProperty = lcPipe.SoilLiquidlimit
Case "SoilType"
  ppadnGetPipeProperty = lcPipe.SoilType
Case "SoilExpansive"
  ppadnGetPipeProperty = lcPipe.SoilExpansive
Case "FrostSusceptible"
  ppadnGetPipeProperty = lcPipe.FrostSusceptible
Case "Rossumn"
  ppadnGetPipeProperty = lcPipe.Rossumn
Case "RossumKn"
  ppadnGetPipeProperty = lcPipe.RossumKn
Case "RegionID"
  ppadnGetPipeProperty = lcPipe.RegionID
Case "MaxSuddenWaterTempChange"
  ppadnGetPipeProperty = lcPipe.MaxSuddenWaterTempChange
Case "MinWaterTemp"
  ppadnGetPipeProperty = lcPipe.MinWaterTemp
Case "MaxWaterTemp"
  ppadnGetPipeProperty = lcPipe.MaxWaterTemp
Case "MinYearlyTemp"
  ppadnGetPipeProperty = lcPipe.MinYearlyTemp
Case "MaxYearlyTemp"
  ppadnGetPipeProperty = lcPipe.MaxYearlyTemp
Case "MaxFrostDepth"
  ppadnGetPipeProperty = lcPipe.MaxFrostDepth
Case "MaxFreezeDays"
  ppadnGetPipeProperty = lcPipe.MaxFreezeDays
Case "WaterVelocityChange"
  ppadnGetPipeProperty = lcPipe.WaterVelocityChange
Case "Earthload"
  ppadnGetPipeProperty = lcPipe.Earthload
Case "Trafficload"
  ppadnGetPipeProperty = lcPipe.Trafficload
Case "ExpSoilload"
  ppadnGetPipeProperty = lcPipe.ExpSoilload
Case "Frostload"
  ppadnGetPipeProperty = lcPipe.Frostload
Case "TotalVerticalload"
  ppadnGetPipeProperty = lcPipe.TotalVerticalload
Case "FractureToughness"
  ppadnGetPipeProperty = lcPipe.FractureToughness
Case "Pitdepth"
  ppadnGetPipeProperty = lcPipe.Pitdepth
Case "Thickness"
ppadnGetPipeProperty = lcPipe.Thickness

Case "ObservedFirstBreakTime"
  ppadnGetPipeProperty = lcPipe.ObservedFirstBreakTime
Case "RepairCost"
  ppadnGetPipeProperty = lcPipe.RepairCost
Case "ReplacementCost"
  ppadnGetPipeProperty = lcPipe.ReplacementCost
Case "DiscountRate"
  ppadnGetPipeProperty = lcPipe.DiscountRate
Case "TheoreticalThresholdBreakRate"
  ppadnGetPipeProperty = lcPipe.TheoreticalThresholdBreakRate
Case "YearsToBreakTimeSeries"
  ppadnGetPipeProperty = lcPipe.YearsToBreakTimeSeries
Case "RossumFractionExposed"
  ppadnGetPipeProperty = lcPipe.RossumFractionExposed
Case "RossumFirstLeakTime"
  ppadnGetPipeProperty = lcPipe.RossumFirstLeakTime
Case "RossumNLeaksTime"
  ppadnGetPipeProperty = lcPipe.RossumNLeaksTime
Case "RossumNLeaksTimeSeries"
  ppadnGetPipeProperty = lcPipe.RossumNLeaksTimeSeries

Case "CriticalRepTimeA"
  ppadnGetPipeProperty = lcPipe.CriticalRepTimeA
Case "CriticalRepTimeB"
  ppadnGetPipeProperty = lcPipe.CriticalRepTimeB
Case "CriticalRepTimeC"
  ppadnGetPipeProperty = lcPipe.CriticalRepTimeC
Case "CriticalRepTimeD"
  ppadnGetPipeProperty = lcPipe.CriticalRepTimeD
Case "TheoreticalThresholdBreakRateOptRepTime"
  ppadnGetPipeProperty = lcPipe.TheoreticalThresholdBreakRateOptRepTime
Case "LinRegResults"
  ppadnGetPipeProperty = lcPipe.LinRegResults
Case "LognRegResults"
  ppadnGetPipeProperty = lcPipe.LognRegResults
Case "DesignThickness"
  ppadnGetPipeProperty = lcPipe.DesignThickness
Case "RingModulus"
  ppadnGetPipeProperty = lcPipe.RingModulus
Case "TensileStrength"
  ppadnGetPipeProperty = lcPipe.TensileStrength
Case "BurstingTensileStrength"
ppadnGetPipeProperty = lcPipe.BurstingTensileStrength
Case "ModulusRupture"
ppadnGetPipeProperty = lcPipe.ModulusRupture
Case "WorkingPressure"
ppadnGetPipeProperty = lcPipe.WorkingPressure
Case "WaterHammerPressure"
ppadnGetPipeProperty = lcPipe.WaterHammerPressure
Case "ThermalPressure"
ppadnGetPipeProperty = lcPipe.ThermalPressure
Case "TotalPressure"
ppadnGetPipeProperty = lcPipe.TotalPressure
Case "EarthloadFlexuralStress"
ppadnGetPipeProperty = lcPipe.EarthloadFlexuralStress
Case "TrafficloadFlexuralStress"
ppadnGetPipeProperty = lcPipe.TrafficloadFlexuralStress
Case "ExpSoilloadFlexuralStress"
ppadnGetPipeProperty = lcPipe.ExpSoilloadFlexuralStress
Case "FrostloadFlexuralStress"
ppadnGetPipeProperty = lcPipe.FrostloadFlexuralStress
Case "TotalFlexuralStress"
ppadnGetPipeProperty = lcPipe.TotalFlexuralStress
Case "SafetyFactorFlexuralStress"
ppadnGetPipeProperty = lcPipe.SafetyFactorFlexuralStress
Case "EarthloadRingStress"
ppadnGetPipeProperty = lcPipe.EarthloadRingStress
Case "TrafficloadRingStress"
ppadnGetPipeProperty = lcPipe.TrafficloadRingStress
Case "ExpSoilloadRingStress"
ppadnGetPipeProperty = lcPipe.ExpSoilloadRingStress
Case "FrostloadRingStress"
ppadnGetPipeProperty = lcPipe.FrostloadRingStress
Case "ThermalRingStress"
ppadnGetPipeProperty = lcPipe.ThermalRingStress
Case "TotalRingStress"
ppadnGetPipeProperty = lcPipe.TotalRingStress
Case "SafetyFactorRingStress"
ppadnGetPipeProperty = lcPipe.SafetyFactorRingStress
Case "WorkingPressureHoopStress"
ppadnGetPipeProperty = lcPipe.WorkingPressureHoopStress
Case "WaterHammerPressureHoopStress"
ppadnGetPipeProperty = lcPipe.WaterHammerPressureHoopStress
Case "ThermalPressureHoopStress"
ppadnGetPipeProperty = lcPipe.ThermalPressureHoopStress
Case "TotalHoopStress"
ppadnGetPipeProperty = lcPipe.TotalHoopStress
Case "SafetyFactorHoopStress"
    ppadnGetPipeProperty = lcPipe.SafetyFactorHoopStress
Case "ExpansionContractionThermalLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.ExpansionContractionThermalLongitudinalStress
Case "HoopComponentLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.HoopComponentLongitudinalStress
Case "WorkingPressureLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.WorkingPressureLongitudinalStress
Case "WaterHammerPressureLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.WaterHammerPressureLongitudinalStress
Case "ThermalPressureLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.ThermalPressureLongitudinalStress
Case "ThermalLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.ThermalLongitudinalStress
Case "TotalLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.TotalLongitudinalStress
Case "SafetyFactorLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.SafetyFactorLongitudinalStress
Case "TotalFlexuralPlusLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.TotalFlexuralPlusLongitudinalStress
Case "SafetyFactorFlexuralPlusLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.SafetyFactorFlexuralPlusLongitudinalStress
Case "SafetyFactorRingPlusHoopStress"
    ppadnGetPipeProperty = lcPipe.SafetyFactorRingPlusHoopStress
Case "FractRingModulus"
    ppadnGetPipeProperty = lcPipe.FractRingModulus
Case "FractTensileStrength"
    ppadnGetPipeProperty = lcPipe.FractTensileStrength
Case "FractBurstingTensileStrength"
    ppadnGetPipeProperty = lcPipe.FractBurstingTensileStrength
Case "FractModulusRupture"
    ppadnGetPipeProperty = lcPipe.FractModulusRupture
Case "FractSafetyFactorFlexuralStress"
    ppadnGetPipeProperty = lcPipe.FractSafetyFactorFlexuralStress
Case "FractSafetyFactorRingStress"
    ppadnGetPipeProperty = lcPipe.FractSafetyFactorRingStress
Case "FractSafetyFactorHoopStress"
    ppadnGetPipeProperty = lcPipe.FractSafetyFactorHoopStress
Case "FractSafetyFactorLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.FractSafetyFactorLongitudinalStress
Case "FractSafetyFactorFlexuralPlusLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.FractSafetyFactorFlexuralPlusLongitudinalStress
Case "FractSafetyFactorRingPlusHoopStress"
    ppadnGetPipeProperty = lcPipe.FractSafetyFactorRingPlusHoopStress
Case "CipraDesignThickness"
    ppadnGetPipeProperty = lcPipe.CipraDesignThickness
Case "CipraFailureThickness"
    ppadnGetPipeProperty = lcPipe.CipraFailureThickness
Case "CipraFailurePitDepth"
    ppadnGetPipeProperty = lcPipe.CipraFailurePitDepth
Case "CipraRingFailureStrength"
    ppadnGetPipeProperty = lcPipe.CipraRingFailureStrength
Case "CipraTensileFailureStrength"
    ppadnGetPipeProperty = lcPipe.CipraTensileFailureStrength
Case "CipraBurstingFailureStrength"
    ppadnGetPipeProperty = lcPipe.CipraBurstingFailureStrength
Case "CipraRuptureFailureStrength"
    ppadnGetPipeProperty = lcPipe.CipraRuptureFailureStrength
Case "CipraRingSafetyFactor"
    ppadnGetPipeProperty = lcPipe.CipraRingSafetyFactor
Case "CipraTensileSafetyFactor"
    ppadnGetPipeProperty = lcPipe.CipraTensileSafetyFactor
Case "CipraBurstingSafetyFactor"
    ppadnGetPipeProperty = lcPipe.CipraBurstingSafetyFactor
Case "CipraRuptureSafetyFactor"
    ppadnGetPipeProperty = lcPipe.CipraRuptureSafetyFactor
Case "CipraSafetyFactorFlexuralPlusLongitudinalStress"
    ppadnGetPipeProperty = lcPipe.CipraSafetyFactorFlexuralPlusLongitudinalStress
Case "CipraSafetyFactorRingPlusHoopStress"
    ppadnGetPipeProperty = lcPipe.CipraSafetyFactorRingPlusHoopStress
Case "CipraFailureTime"
    ppadnGetPipeProperty = lcPipe.CipraFailureTime
End Select
End Function
ModuleName: Regression

Function Regress(ByVal lcXData As String, ByVal lcYData As String, _
    ByVal lcOption As Long, ByVal lcConst As Boolean, _
    Optional ByVal lcDataID As String) As String

    Dim lcX() As Double
    Dim lcY() As Double
    Dim lcLnX() As Double
    Dim lcLnY() As Double
    Dim li As Variant
    Dim lcE() As Double
    Dim lcDiff() As Double
    Dim lcChi As Double

    lcX = AdjustArrays(lcXData, lcYData, "x")
lcY = AdjustArrays(lcXData, lcYData, "y")

    If lcOption = 2 Then
        li = Application.WorksheetFunction.LinEst(LnArray(lcY), LnArray(lcX), lcConst, True)
lcE = ExpExpectedValues(lcX, li(1, 1), li(1, 2))
    Else
        li = Application.WorksheetFunction.LinEst(lcY, lcX, lcConst, True)
lcE = LinExpectedValues(lcX, li(1, 1), li(1, 2))
    End If

    lcDiff = Difference(lcY, lcE)
lcChi = ChiSquare(lcY, lcE)

    Open ThisWorkbook.Path & "\regression.log" For Append As #1
Print #1, lcDataID
Print #1, "Rossum," & JunkJoin(lcX, ",")
Print #1, "Observed," & JunkJoin(lcY, ",")
Print #1, "Computed," & JunkJoin(lcE, ",")
Print #1, "Difference," & JunkJoin(lcDiff, ",")
Print #1, Format(li(1, 1), "#.000") & "," & Format(li(1, 2), "#.000") & _
    "," & FormatNumber(li(3, 1), 3) & "," & lcChi
Print #1, ""
Close #1

Regress = Format(li(1, 1), "#.000") & "," & Format(li(1, 2), "#.000") & _
    "," & Format(li(3, 1), "0.##0") & "," & Format(li(4, 1), "##0.0") _
    & "," & li(4, 2) & "," & lcChi

End Function
Sub RegressOutput()
End Sub'
takes two comma delimited strings, splits them and then
'converts them to an array returning the array of shortest
'length
Function AdjustArrays(ByVal lcXArray As String, _
    ByVal lcYArray As String, ByVal lcOption As String) As Variant
    Dim lcX() As Double
    Dim lcY() As Double
    Dim lcXTemp() As String
    Dim lcYTemp() As String
    Dim lcArraySize As Long
    lcXTemp = Split(lcXArray, ",")
    lcYTemp = Split(lcYArray, ",")
    lcArraySize = IIf(UBound(lcXTemp) > UBound(lcYTemp), UBound(lcYTemp), UBound(lcXTemp))
    ' Debug.Print lcArraySize & " & UBound(lcXTemp) & " & UBound(lcYTemp)
    Dim i As Long
    Dim j As Long
    j = 0
    For i = 0 To lcArraySize
        If Trim(lcXTemp(i)) <> "" And Trim(lcYTemp(i)) <> "" Then
            If i = 0 Then
                ReDim Preserve lcX(1)
                ReDim Preserve lcY(1)
            Else
                ReDim Preserve lcX(j)
                ReDim Preserve lcY(j)
            End If
            lcX(j) = CDbl(lcXTemp(i))
            lcY(j) = CDbl(lcYTemp(i))
            j = j + 1
        End If
    Next i
    If LCase(lcOption) = "x" Then
        AdjustArrays = lcX
    Else
        AdjustArrays = lcY
'Computes Chi Square
Function ChiSquare(ByVal lcO As Variant, ByVal lcE As Variant)
    Dim lcChiSquare As Single
    lcChiSquare = 0
    For i = 0 To UBound(lcO)
        lcChiSquare = lcChiSquare + ((lcO(i) - lcE(i)) ^ 2) / lcO(i)
    Next i
    ChiSquare = Format(lcChiSquare, "##0.0")
End Function

'Computes LinearExpected Values
Function LinExpectedValues(ByVal lcM As Variant, ByVal lcCoeff As Double, ByVal lcConst As Double) As Variant
    Dim lcE() As Double
    ReDim lcE(UBound(lcM))
    For i = 0 To UBound(lcM)
        lcE(i) = lcCoeff * lcM(i) + lcConst
    Next i
    LinExpectedValues = lcE
End Function

'Computes Difference between observed and expected values
Function Difference(ByVal lcO As Variant, ByVal lcE As Variant) As Variant
    Dim lcDiff() As Double
    ReDim lcDiff(UBound(lcO))
    For i = 0 To UBound(lcO)
        lcDiff(i) = lcO(i) - lcE(i)
    Next i
    Difference = lcDiff
End Function

'Computes LinearExpected Values
Function ExpExpectedValues(ByVal lcM As Variant, ByVal lcCoeff As Double, ByVal lcConst As Double) As Variant
    Dim lcE() As Double
    ReDim lcE(UBound(lcM))
For i = 0 To UBound(lcM)
    lcE(i) = (lcM(i) ^ lcCoeff) * (2.7182 ^ lcConst)
Next i
ExpExpectedValues = lcE
End Function

'Computes CombinedLinearExponentialExpected Values
Function ComLinExpExpectedValues(ByVal lcX As Variant, _
    ByVal lcLinCoeff As Double, ByVal lcLinConst As Double, _
    ByVal lcExpCoeff As Double, ByVal lcExpConst As Double, _
    ByVal lcEps As Double) As Variant
Dim lcE As Variant
lcE = lcX
For i = 1 To UBound(lcX)
    lcE(i) = (lcEps) * (lcLinCoeff * lcX(i)) + _
        (1 - lcEps) * (lcExpConst * (lcExpCoeff ^ lcX(i)))
Next i
ComLinExpExpectedValues = lcE
End Function

Function JunkJoin(lcA, lcDelim)
Dim pp
For i = 1 To UBound(lcA)
    pp = pp & FormatNumber(lcA(i), 0) & lcDelim
Next i
JunkJoin = pp
End Function

'Computes an returns ln of an array
Function LnArray(ByVal lcX As Variant) As Variant
    Dim lcTemp() As Double
    ReDim lcTemp(UBound(lcX))
    For i = 0 To UBound(lcX)
        lcTemp(i) = Application.WorksheetFunction.Ln(lcX(i))
    Next i
    LnArray = lcTemp
End Function

'Gets a string f
Function YTBTimeSeries(ByVal lcSheet As Worksheet, ByVal lcPipeID As String) As String
    lcAgeString = ""
    lci = 2
    While Trim(lcSheet.Cells(lci, 1)) <> ""
        If Trim(LCase(lcSheet.Cells(lci, 1))) = Trim(LCase(lcPipeID)) Then
lcJ = 2
While Trim(lcSheet.Cells(lci, lcJ)) <> ""
    If lcJ <> 2 Then
        lcAgeString = lcAgeString & "\n"
    End If
    lcAgeString = lcAgeString & Trim(lcSheet.Cells(lci, lcJ))
    lcJ = lcJ + 1
Wend
End If
lci = lci + 1
Wend
YTBTimeseries = lcAgeString
End Function
Option Explicit

'Calls external program to calculate frost loads
Function ppadnGetFrostLoad( _
    ByVal lcCrowndepth As Single, ByVal lcTrenchwidth As Single, _
    ByVal lcSoilDensity As Single, ByVal lcPorosity As Single, _
    ByVal lcTemp, ByVal lcMoistureContent As Single, _
    ByVal lcFreezeDays As Long, lcMaxFrostDepth _
) As Single
    'Compute frost load
    Dim lcValue As Single
    'Set parameters needed for frost load
    frostSetParameters

    lcValue = frost_calculateRajaniZahn( _
        CSng(lcCrowndepth), _
        CSng(lcTrenchwidth), _
        glkf, glktip, glks, _
        CSng(lcSoilDensity), _
        CSng(lcPorosity), _
        glVolUnfWater, _
        glBeta, glSegregationPotential, _
        CSng(lcTemp), _
        CSng(lcMoistureContent), _
        CSng(lcFreezeDays), _
        CSng(lcMaxFrostDepth) _
    )

    ppadnGetFrostLoad = lcValue
End Function

Sub frostSetParameters()
    'Definition of general parameters
    'Depth of pipe crown, ft
    'Depth of pipe crown, ft
    'Trench width, ft
    'Source Spangler 1982 pp 336
    'Source Spangler 1982 pp 336
    'Soil unfrozen Thermal Conductivity, Btu/ft^2-hr-°F/ft = Btu/ft-hr-°F
    '4808,000 Pa/m [(4808,000/47.88)*3.2808 = 329,450 lb/ft^2/ft ]
    'Soil frozen Thermal Conductivity, Btu/ft^2-hr-°F/ft = Btu/ft-hr-°F
    'Soil Tip Stiffness, borrowed from Rajani,Zahn 1996
    '4808,000 Pa/m [(4808,000/47.88)*3.2808 = 329,450 lb/ft^2/ft ]
    'Source Spangler 1982 pp 336
    'Soil Frozen Shear stiffness, borrowed from Rajani,Zahn 1996
    '1500,000,000 Pa/m [(1500,000,000/47.88)*3.2808 = 102,781,955 lb/ft^2/ft]
    glku = 0.9
    glkf = 1
    glktip = 329450
    glks = 102781955
End Sub
'glSoilDensity = 120 'Soil Density, 120 lb/ft^3
'glPorosity = 55 'Soil Porosity, 55%
glVolUnfWater = 15 'Soil Volumetric unfrozen water content, 15%
glBeta = 0.03 'Attenuation factor, 0.03
glSegregationPotential = 7.53 * 10^-6 'Segregation Potential, borrowed from Rajani,Zahn 1996
'o.00035 mm^2/(s.ºC) [{(0.00035 / {(25.4*25.4)* (12 *12)})} * 1.8} * 3600 = ft^2/(hr.ºF)]

'Definition of air temperature
'lcMinTemp = 0 'Fahrenheit

'Definition of soil moisture
'lcMoistureContent = 25 'Percent
'lcFrostdepth = 30 'inches
'lcFreezeDays = 15 'Days

End Sub

'Calls external program to calculate expsoil loads
Function ppadnGetExpSoilLoad(ByVal lcSoilMoisture As Single, _
    ByVal lcSoilMoistureLimit As Single, _
    ByVal lcPipeSize As Long, ByVal lcPipeDepth As Single _) As Single
    Dim lcExpSoilload As Single
    Const lcAlpha1 = 630 'lb/ft^2; // 0.0300MPa,
    Const lcAlpha2 = 514.5 'lb/ft^2; // 0.0245MPa,
    Const lcAlpha3 = 514.5 'lb/ft^2; // 0.0245MPa,

    'Calculate the load
    If lcSoilMoisture <= 18.8 Then
        lcExpSoilload = lcAlpha1 * (lcSoilMoistureLimit - 46)
    ElseIf ((lcSoilMoisture > 18.8) And (lcSoilMoisture <= 30)) Then
        lcExpSoilload = lcAlpha2 * (lcSoilMoistureLimit - 56)
    ElseIf lcSoilMoisture > 30 Then
        lcExpSoilload = lcAlpha3 * (lcSoilMoistureLimit - 77)
    End If

    If lcExpSoilload < 0 Then
        lcExpSoilload = 0
    End If

    lcExpSoilload = lcExpSoilload * CSng(lcPipeSize) / 12
    ppadnGetExpSoilLoad = lcExpSoilload
End Function
'Calls external program to calculate Thermal Pressure
Function ppadnGetThermalPressure( _
    ByVal lcPipeDiameter As Single, ByVal lcPipeThickness As Single, _
    ByVal lcPipeType As String, ByVal lcDeltaT As Single _
)"

Dim lcPipeLinExpCoeff, lcPipeElasticMod, lcPipePoissonRatio As Single
lcPipeLinExpCoeff = ppadnGetLinExpCoeff(lcPipeType)
lcPipeElasticMod = ppadnGetElasticModulus(lcPipeType)
lcPipePoissonRatio = ppadnGetPoissonRatio(lcPipeType)

'Initialize
Call ppadnInitialize

'a = Coefficient of linear thermal expansion of pipe wall material.
'b = Coefficient of volume thermal expansion of liquid, dV/(VdT).
'E = Modulus of elasticity of pipe wall material
'k = Bulk modulus of liquid, -dP/(dV/V).
'u = Poisson’s ratio of the pipe wall material.

'Calculate the thermal load
ppadnGetThermalPressure = _
    (glWaterCoeffVolExp - (2 * lcPipeLinExpCoeff * (1 + lcPipePoissonRatio))) * lcDeltaT _
/(_(1 / glWaterBulkModulus) + (lcPipeDiameter / (lcPipeThickness * lcPipeElasticMod)) * (1 - lcPipePoissonRatio ^ 2))
End Function

'Function FlexuralStress(ByVal lcLoad As Single, ByVal lcSpan As Single, _
    ByVal lcOutDiam As Single, ByVal lcThickness As Single) As Single'
    FlexuralStress = 15.28 * lcLoad * lcOutDiam * lcSpan ^ 2 /
        (lcOutDiam ^ 4 - (lcOutDiam - 2 * lcThickness) ^ 4)
'End Function

Function ppadnGetMidSpanDeflection(ByVal lcFStress As Single, ByVal lcSpan As Single, _
    ByVal lcOutDiam As Single, ByVal lcEModulus As Single) As Single
    ppadnGetMidSpanDeflection = 30 * lcFStress * lcSpan ^ 2 / (lcOutDiam * lcEModulus)
End Function

'Gets the design Thickness
Function ppadnGetDesignThickness(ByVal lcPipeID As String, _
Dim lcThickness As Single

' Try reading from the inventory sheet
lcThickness = CSng(Val(excelReadProperty(lcPipeID, "DesignThickness", _
glBrkInventorySheet)))

If lcThickness <= 0 Then
    lcThickness = CSng(Val(excelReadProperty(CStr(lcYearAcq), CStr(lcSize), _
ThisWorkbook.Sheets("DesignThickness"))))
End If

If lcThickness <= 0 Then
    ' Source: Dept. of Public Works, Bureau of water Specification, 1901
    If lcYearAcq < 1901 Then
        If lcSize <= 6 Then
            lcThickness = 0.47
        ElseIf lcSize <= 8 And lcSize > 6 Then
            lcThickness = 0.47
        ElseIf lcSize <= 10 And lcSize > 8 Then
            lcThickness = 0.58
        ElseIf lcSize <= 12 And lcSize > 10 Then
            lcThickness = 0.63
        ElseIf lcSize > 12 Then
            lcThickness = 0.63
        End If
    End If
    ' Source: Laying Condition A, Internal pressure=43psi, 4.5ft cover, thickness class 1, AWWA Standards
    End If
    ' Source: Laying Condition B, Internal pressure=100psi, 3.5ft cover, AWWA Standards
If lcYearAcq >= 1909 And lcYearAcq < 1939 Then
     If lcSize <= 6 Then
         lcThickness = 0.43
     ElseIf lcSize <= 8 And lcSize > 6 Then
         lcThickness = 0.46
     ElseIf lcSize <= 10 And lcSize > 8 Then
         lcThickness = 0.5
     ElseIf lcSize <= 12 And lcSize > 10 Then
         lcThickness = 0.54
     ElseIf lcSize > 12 Then
         lcThickness = 0.54
     End If
End If

'Source: Centrifugal 18/40, Laying Cond. F, Internal Pressure 250 psi, 4ft cover, class 56
If lcYearAcq >= 1939 And lcYearAcq < 1952 Then
     If lcSize <= 6 Then
         lcThickness = 0.28
     ElseIf lcSize <= 8 And lcSize > 6 Then
         lcThickness = 0.32
     ElseIf lcSize <= 10 And lcSize > 8 Then
         lcThickness = 0.37
     ElseIf lcSize <= 12 And lcSize > 10 Then
         lcThickness = 0.38
     ElseIf lcSize > 12 Then
         lcThickness = 0.38
     End If
End If

'Source: Centrifugal 18/40, Laying Cond. F, Internal Pressure 250 psi, 4ft cover, class 56
If lcYearAcq >= 1952 And lcYearAcq <= 1966 Then
     If lcSize <= 6 Then
         lcThickness = 0.38
     ElseIf lcSize <= 8 And lcSize > 6 Then
         lcThickness = 0.41
     ElseIf lcSize <= 10 And lcSize > 8 Then
         lcThickness = 0.44
     ElseIf lcSize <= 12 And lcSize > 10 Then
         lcThickness = 0.48
     ElseIf lcSize > 12 Then
         lcThickness = 0.48
     End If
End If
End If
'Use DIPRA/CIPRA standards
    If lcYearAcq > 1966 Then
        End If
    End If

ppadnGetDesignThickness = lcThickness
End Function

'Gets the design Bursting Tensile Strength
Function ppadnGetDesignBTS(ByVal lcPipeID As String, ByVal lcYearAcq As Long) As Single
    Dim lcBTS As Single

    'Try reading from the inventory sheet
    lcBTS = CStr(Val(excelReadProperty(lcPipeID, "BurstingTensileStrength", _
        glBrkInventorySheet)))
    If lcBTS <= 0 Then
        lcBTS = CStr(Val(excelReadProperty(lcYearAcq, "Value", _
            ThisWorkbook.Sheets("BurstingTensileStrength"))))
    End If

    If lcBTS <= 0 Then
        'Source: Water main Structural Condition Assessment Model, June 14 1985
        If lcYearAcq < 1907 Then
            lcBTS = 11000
        End If
        If lcYearAcq >= 1908 And lcYearAcq <= 1929 Then
            lcBTS = 11000
        End If
        If lcYearAcq >= 1930 And lcYearAcq <= 1949 Then
            lcBTS = 18000
        End If
        If lcYearAcq >= 1950 And lcYearAcq <= 1970 Then
            lcBTS = 21000
        End If
        If lcYearAcq > 1970 Then
            lcBTS = 21000
        End If
    End If

    ppadnGetDesignBTS = lcBTS
End Function

'Gets the design Tensile Strength
Function ppadnGetDesignTS(ByVal lcPipeID As String, ByVal lcYearAcq As Long) As Single
Dim lcTS As Single

'Try reading from the inventory sheet
lcTS = CSng(Val(excelReadProperty(lcPipeID, "TensileStrength", _
    glBrkInventorySheet)))

If lcTS <= 0 Then
    lcTS = CSng(Val(excelReadProperty(lcYearAcq, "Value", _
        ThisWorkbook.Sheets("TensileStrength"))))
End If

If lcTS <= 0 Then
    'Source: Water main Structural Condition Assessment Model, June 14 1985
    If lcYearAcq < 1907 Then
        lcTS = 18000
        End If
    If lcYearAcq >= 1908 And lcYearAcq <= 1929 Then
        lcTS = 20000
        End If
    If lcYearAcq >= 1930 And lcYearAcq <= 1949 Then
        lcTS = 30000
        End If
    If lcYearAcq >= 1950 And lcYearAcq <= 1970 Then
        lcTS = 30000
        End If
    If lcYearAcq > 1970 Then
        lcTS = 30000
        End If
End If
ppadnGetDesignTS = lcTS
End Function

'Gets the design Ring Modulus Strength
Function ppadnGetDesignRM(ByVal lcPipeID As String, ByVal lcYearAcq As Long) As Single
Dim lcRM As Single

'Try reading from the inventory sheet
lcRM = CSng(Val(excelReadProperty(lcPipeID, "RingModulus", _
    glBrkInventorySheet)))

If lcRM <= 0 Then
    lcRM = CSng(Val(excelReadProperty(lcYearAcq, "Value", _
        ThisWorkbook.Sheets("RingModulus"))))
End If
If lcRM <= 0 Then
    'Source: Water main Structural Condition Assessment Model, June 14 1985
    If lcYearAcq < 1907 Then
        lcRM = 31000
    End If
    If lcYearAcq >= 1908 And lcYearAcq <= 1929 Then
        lcRM = 31000
    End If
    If lcYearAcq >= 1930 And lcYearAcq <= 1949 Then
        lcRM = 40000
    End If
    If lcYearAcq >= 1950 And lcYearAcq <= 1970 Then
        lcRM = 45000
    End If
    If lcYearAcq > 1970 Then
        lcRM = 45000
    End If
End If

ppadnGetDesignRM = lcRM
End Function

'Gets the design Modulus of Rupture
Function ppadnGetDesignModulusRupture(ByVal lcPipeID As String, ByVal lcYearAcq As Long) As Single
Dim lcRM As Single
    'Try reading from the inventory sheet
    lcRM = CSng(Val(excelReadProperty(lcPipeID, "ModulusRupture", _
        glBrkInventorySheet)))
    If lcRM <= 0 Then
        lcRM = CSng(Val(excelReadProperty(lcYearAcq, "Value", _
            ThisWorkbook.Sheets("ModulusRupture"))))
    End If
    If lcRM <= 0 Then
        '* need to update from statistical analysis
        If lcYearAcq < 1931 Then
            'Estimated value
            lcRM = 20000
        Else
            'From average of sample collected during awwarf 459 study
            lcRM = 27426
        End If
    End If
End If
ppadnGetDesignModulusRupture = lcRM
End Function

'Gets the Thickness at any year
Function ppadnGetCurrentThickness(_
    ByVal lcDesignThickness As Single, ByVal lcPipeSize As Single, _
    ByVal lcAge As Long, _
    ByVal lcResistance As Single, ByVal lcPH As Single, _
    ByVal lcAeration As String, ByVal lcPipeType As String _
) As Single

Dim lcCurrThickness As Single
lcCurrThickness = lcDesignThickness - ppadnGetCurrentPitDepth( _
    lcPipeSize, lcAge, lcResistance, lcPH, lcAeration, lcPipeType _
)
If lcCurrThickness < 0 Then
    lcCurrThickness = 0
End If

ppadnGetCurrentThickness = lcCurrThickness
End Function

'Gets the Pit Depth at any year
Function ppadnGetCurrentPitDepth(_
    ByVal lcPipeSize As Single, ByVal lcAge As Long, _
    ByVal lcResistance As Single, ByVal lcPH As Single, _
    ByVal lcAeration As String, ByVal lcPipeType As String _
) As Single

Dim lcCurrPitDepth, lcYearOnePitDepth, lcKn, lcKa, _
    lcn, lcA, lcSpan, lcCorrCoeff As Single
lcn = ppadnGetRossumn(lcAeration)
lKn = ppadnGetRossumKn(lcAeration)
lKa = ppadnGetRossumKa(lcPipeType)
lA = ppadnGetRossumA(lcPipeType)
lcSpan = 18 'ft

lcCurrPitDepth = _
    lcKa * lKn * (10 - lcPH) ^ lcn * lcResistance ^ -(lcn) * _
    lcAge ^ lcn * (glPI * (lcPipeSize / 12) * lcSpan) ^ lcA

'convert from mils to inches
lcCurrPitDepth = lcCurrPitDepth / 1000
End Function

Sub nenene()
    'MsgBox ppadnTheoreticalThresholdBRKRateOptRepTime(4, 6, 0.1, 0.2, 1200, 2000, 8, "poor", "pit", 0.6, 1)
    'MsgBox ppadnTheoreticalThresholdBRKRateOptRepTime(4, 6, 0.1, 0.2, 1200, 2000, 8, "poor", "pit", 1, 0)
    'MsgBox ppadnTheoreticalThresholdBRKRateOptRepTime(4, 6, 0.1, 0.2, 1200, 2000, 8, "poor", "pit", 0.6, 0)
    'MsgBox ppadnTheoreticalThresholdBRKRateOptRepTime(2, 6, 1, 0.4, 1200, 2000, 8, "poor", "pit", 1, 0)
    MsgBox ppadnGetRossumNLeaksTimeSeries _
        (6, 1, 0.409, 18, 5, 2000, 6, "poor", "pitcast", _
         1, 0)
End Sub

' Theoretical Threshold Break Rate Optimal Replacement Time
Function ppadnTheoreticalThresholdBRKRateOptRepTime _
    (ByVal lcCriticalBrkRate As Single, ByVal lcPipeSize As Single, _
     ByVal lcFraction As Single, _
     ByVal lcPipeThickness As Single, ByVal lcPipeLength As Single, _
     ByVal lcResistivity As Single, ByVal lcPH As Single, _
     ByVal lcAeration As String, ByVal lcPipeType As String, _
     ByVal lcRegConst As Single, ByVal lcYearsAdj As Single _) _
    ) As Long
    'ByVal lcT1 As Single, ByVal lcA As Single, _
    'ByVal lcn As Single, ByVal lcNumPits As Single) As Single

    Dim lcKn, lcKa, lcn, lca As Single
    Dim lcSoilConst As Single
    Dim lcArea As Single
    Dim lcCurBrkRate As Single
    Dim lcK1 As Single
    Dim lcK2 As Single
    Dim lcK3 As Single
    Dim lcAge As Long

    'Formula Definition
    lcn = ppadnGetRosumnn(lcAeration)
    lcKn = ppadnGetRossumKn(lcAeration)

    lcKa = ppadnGetRossumKa(lcPipeType)
    lca = ppadnGetRossuma(lcPipeType)

    'convert from inches to mils
lcPipeThickness = lcPipeThickness * 1000

lcArea = glPI * lcPipeLength * (lcPipeSize / 12) * lcFraction

For lcAge = 1 To 500000
    lcK1 = (lcRegConst * lcKa * lcKn / lcPipeThickness) ^ (1 / lca)
    lcK1 = (lcKa * lcKn / lcPipeThickness) ^ (1 / lca)
    lcK2 = ((10 - lcPH) / lcResistivity) ^ (lcN / lca)
    lcK3 = (lcN / lca) * ((lcAge - 1) * lcYearsAdj ^ lcn) ^ (1 / lca - 1) * (lcAge ^ (lcn - 1))
    lcK3 = (lcN / lca) * (lcAge ^ (lcN / lca - 1))

    lcCurBrkRate = lcArea * lcK1 * lcK2 * lcK3
    If lcCurBrkRate >= lcCriticalBrkRate Then Exit For
Next lcAge

ppadnTheoreticalThresholdBRKRateOptRepTime = lcAge 'End Function

Function ppadnTheoreticalThresholdBRKRateOptRepTime _
    (ByVal lcCriticalBrkRate As Single, ByVal lcPipeSize As Single, _
    ByVal lcFraction As Single, _
    ByVal lcPipeThickness As Single, ByVal lcPipeLength As Single, _
    ByVal lcResistivity As Single, ByVal lcPH As Single, _
    ByVal lcAeration As String, ByVal lcPipeType As String, _
    ByVal lcRegConst As Single, ByVal lcYearsAdj As Single _) As Long

    Dim lcKn, lcKa, lcN, lca As Single
    Dim lcSoilConst As Single
    Dim lcArea As Single
    Dim lcCurBrkRate As Single
    Dim lcK1 As Single
    Dim lcK2 As Single
    Dim lcK3 As Single
    Dim lcAge As Long

    'Formula Definition

    lcn = ppadnGetRossum(lcAeration)
lcKn = ppadnGetRossumKn(lcAeration)
lcKa = ppadnGetRossumKa(lcPipeType)
lcA = ppadnGetRossumKa(lcPipeType)

'convert from inches to mils
lcPipeThickness = lcPipeThickness * 1000

lcArea = gIPI * lcPipeLength * (lcPipeSize / 12) * lcFraction

'lcK1 = (lcRegConst * lcKa * lcKn / lcPipeThickness) ^ (1 / lcA)
lcK1 = (lcKa * lcKn / lcPipeThickness) ^ (1 / lcA)
lcK2 = ((10 - lcpH) / lc Resistivity) ^ (lcn / lcA)
'lckK3 = (lcn / lcA) * ((lcAge ^ lcn - lcYearsAdj ^ lcn) ^ (1 / lcA - 1)) * (lcAge ^ (lcn - 1))
lcK3 = (lcn / lcA) * (lcAge ^ (lcn / lcA - 1))

lcAge = (lcCriticalBrkRate / (lcArea * lcK1 * lcK2)) ^ (lcA / (lcn - lcA))

'If lcCurBrkRate >= lcCriticalBrkRate Then
'  Exit For
'End If

ppadnTheoreticalThresholdBRKRateOptRepTime = lcAge
End Function

'Theoretical Threshold BreakRate
Function ppadnTheoreticalThresholdBRKRate( lcRepairCost, lcReplacementCost, lcPipeLength, lcDiscountRate) As Single
'  MsgBox ppadnTheoreticalThresholdBRKRate(2000, 100, 1000, 7.5)
ppadnTheoreticalThresholdBRKRate = (Application.Ln(1 + lcDiscountRate / 100)) / _
(Application.Ln(1 + ((lcRepairCost) / (lcReplacementCost * lcPipeLength))))
End Function

'Gets the number of leaks at anytime
Function ppadnGetRossumNumLeaksAtTime( ByVal lcPipeSize As Single, ByVal lcFraction As Single, _
ByVal lcPipeThickness As Single, ByVal lcPipeLength As Single, _
ByVal lcResistivity As Single, ByVal lcpH As Single, _
ByVal lcAeration As String, ByVal lcPipeType As String, _
ByVal lcRegConst As Single, ByVal lcYearsAdj As Single _) As Single
'MsgBox ppadnGetRossumFirstLeakTime(_
{6, 0.02666666, 0.109, 1200, 3000, 8, "poor", "pitcast"}, _
Dim lcKn, lcKa, lcn, lcA As Single
Dim lcSoilConst As Single
Dim lcArea As Single
Dim lcFirstLeakTime As Single
Dim lcK1 As Single

'Formula Definition
lcn = ppadnGetRossumn(lcAeration)
lcKn = ppadnGetRossumKn(lcAeration)
lcKa = ppadnGetRossumKa(lcPipeType)
lcA = ppadnGetRossuma(lcPipeType)

'convert from inches to mils
lcPipeThickness = lcPipeThickness * 1000
lcArea = glPI * lcPipeLength * (lcPipeSize / 12)

lcSoilConst = lcKa * lcKn * (((10 - lcpH) / lcResistivity) ^ lcn)
lcK1 = lcRegConst * lcSoilConst * (lcArea * lcFraction) ^ lcA
lcFirstLeakTime = ((lcPipeThickness / lcK1) + lcYearsAdj) ^ (1 / lcn)

ppadnGetRossumNumLeaksAtTime = lcFirstLeakTime

End Function

'Gets the time to the nth leak
Function ppadnGetRossumNLeaksTime( _
ByVal lcPipeSize As Single, ByVal lcFraction As Single, _
ByVal lcPipeThickness As Single, ByVal lcPipeLength As Single, _
ByVal lcNLeak As Long, ByVal lcResistivity As Single, ByVal lcpH As Single, _
ByVal lcAeration As String, ByVal lcPipeType As String, _
ByVal lcRegConst As Single, ByVal lcYearsAdj As Single _
) As Single

'MsgBox ppadnGetRossumNLeaksTime _
   (6, 1, 0.109, 18,4, 3000, 6, "poor", "pitcast", _
   .6, 1)

Dim lcKn, lcKa, lcn, lcA As Single
Dim lcSoilConst As Single
Dim lcArea As Single
Dim lcNLeaksTime As Single
Dim lcK1 As Single

'Formula Definition

lcn = ppadnGetRossumn(lcAeration)
lcKn = ppadnGetRossumKn(lcAeration)
lcKa = ppadnGetRossumKa(lcPipeType)
lcA = ppadnGetRossuma(lcPipeType)

'convert from inches to mils
lcPipeThickness = lcPipeThickness * 1000

lcArea = glPI * lcPipeLength * (lcPipeSize / 12)
lcSoilConst = lcKa * lcKn * (((10 - lcpH) / lcResistivity) ^ lcn)
lcK1 = lcRegConst * lcSoilConst * (lcArea * lcFraction) ^ lcA

lcNLeaksTime = (lcNLeak ^ lcA) / 
{ 
    (lcArea * lcFraction) ^ lcA) * 
    (lcRegConst * lcKa * lcKn) / lcPipeThickness) * 
    (((10 - lcpH) / lcResistivity) ^ lcn) _
}

lcNLeaksTime = (lcNLeaksTime + lcYearsAdj ^ (lcn)) ^ (1 / lcn)

' lcNLeaksTime = Format(lcNLeaksTime, "####")

'ppadnGetRossumNLeaksTime = Val(Format(lcNLeaksTime, "######"))
ppadnGetRossumNLeaksTime = lcNLeaksTime

End Function

'Gets the times for 1 to nth leak as a comma delimited string
Function ppadnGetRossumNLeaksTimeSeries(_
    ByVal lcPipeSize As Single, ByVal lcFraction As Single, _
    ByVal lcPipeThickness As Single, ByVal lcPipeLength As Single, _
    ByVal lcAeration As String, ByVal lcPipeType As String, _
    ByVal lcRegConst As Single, ByVal lcYearsAdj As Single _
)
As String

Dim lcSeries As String
Dim lci As Long
lcSeries = ""

For lci = 1 To lcNLeak
    If lci <> 1 Then
        lcSeries = lcSeries & ","
    End If
    lcSeries = lcSeries & CStr(FormatNumber(ppadnGetRossumNLeaksTime(lcPipeSize, lcFraction, lcPipeThickness, lcPipeLength, _lci, lcResistivity, lcpH, lcAeration, lcPipeType, _lcRegConst, lcYearsAdj), 2))
Next lci

ppadnGetRossumNLeaksTimeSeries = CStr(lcSeries)
End Function

'Gets the times to the power n (soil parameter) for 1 to Nth leak as a comma delimited string
Function ppadnGetRossumNLeaksTimePowernSeries(_
    ByVal lcPipeSize As Single, ByVal lcFraction As Single, _
    ByVal lcPipeThickness As Single, ByVal lcPipeLength As Single, _
    ByVal lcNLeak As Long, ByVal lcResistivity As Single, ByVal lcpH As Single, _
    ByVal lcAeration As String, ByVal lcPipeType As String, _
    ByVal lcRegConst As Single, ByVal lcYearsAdj As Single _
) As String
define Dim lcSeries As String
Dim lci As Long
Dim lcn As Single
lcSeries = ""
lcn = ppadnGetRossumn(lcAeration)

For lci = 1 To lcNLeak
    If lci <> 1 Then
        lcSeries = lcSeries & ","
    End If
    lcSeries = lcSeries & (ppadnGetRossumNLeaksTime(lcPipeSize, lcFraction, lcPipeThickness, lcPipeLength, _lci, lcResistivity, lcpH, lcAeration, lcPipeType, _lcRegConst, lcYearsAdj)) ^ lcn
Next lci

ppadnGetRossumNLeaksTimePowernSeries = lcSeries
End Function

'Gets the time to First Leak
Function ppadnGetRossumFirstLeakTime(  ByVal lcPipeSize As Single, ByVal lcFraction As Single,  ByVal lcPipeThickness As Single, ByVal lcPipeLength As Single,  ByVal lcPipeType As String, ByVal lcAeration As String, ByVal lcRegConst As Single, ByVal lcYearsAdj As Single) As Single

    MsgBox ppadnGetRossumFirstLeakTime(  6, 0.0266666, 0.109, 1200, 3000, 8, "poor", "pitcast",  glRossumRegConst, glRossumYearsAdj)

    Dim lcKn, lcKa, lcn, lcA As Single
    Dim lcSoilConst As Single
    Dim lcArea As Single
    Dim lcFirstLeakTime As Single
    Dim lcK1 As Single

    'Formula Definition
    lcn = ppadnGetRossumn(lcAeration)
    lcKn = ppadnGetRossumKn(lcAeration)
    lcKa = ppadnGetRossumKa(lcPipeType)
    lcA = ppadnGetRossumA(lcPipeType)
    'convert from inches to mils
    lcPipeThickness = lcPipeThickness * 1000
    lcArea = glPI * lcPipeLength * (lcPipeSize / 12)
    lcSoilConst = lcKa * lcKn * ((10 - lcPH) / lcResistivity) ^ lcn
    lcK1 = lcRegConst * lcSoilConst * (lcArea * lcFraction) ^ lcA
    lcFirstLeakTime = ((lcPipeThickness / lcK1) + lcYearsAdj) ^ (1 / lcn)
    ppadnGetRossumFirstLeakTime = lcFirstLeakTime
End Function
'Gets the Fraction Exposed to corrosion
Function ppadnGetRossumFractionExposed( _
    ByVal lcPipeSize As Single, ByVal lcTimeToFirstBrk As Single, _
    ByVal lcPipeThickness As Single, ByVal lcPipeLength As Single, _
    ByVal lcPipeAeration As String, ByVal lcPipeType As String, _
    ByVal lcRegConst As Single, ByVal lcYearsAdj As Single _
) As Single
    'MsgBox ppadnGetRossumFractionExposed(6, 25, 0.109, 1200, 3000, 8, "poor", "pitcast", _
        glRossumRegConst, glRossumYearsAdj)
    Dim lcKn, lcKa, lcn, lcA As Single
    Dim lcSoilConst As Single
    Dim lcArea As Single
    Dim lcFraction As Single
    Dim lcK1 As Single

    'Formula Definition
    'Fraction = (P/(RegCoeff * SoilK * (T^n-1) * (PI * SIZE * LENGTH)^a))^(1/a)
    lcn = ppadnGetRossumn(lcAeration)
    lcKn = ppadnGetRossumKn(lcAeration)
    lcKa = ppadnGetRossumKa(lcPipeType)
    lcA = ppadnGetRossuma(lcPipeType)

    'convert from inches to mils
    lcPipeThickness = lcPipeThickness * 1000
    lcArea = glPI * lcPipeLength * (lcPipeSize / 12)
    lcSoilConst = lcKa * lcKn * (((10 - lcpH) / lcResistivity) ^ lcn)
    lcK1 = lcRegConst * lcSoilConst * ((lcTimeToFirstBrk ^ lcn) - lcYearsAdj) * (lcArea) ^ lcA
    lcFraction = (lcPipeThickness / lcK1) ^ (1 / lcA)
    ppadnGetRossumFractionExposed = IIf(lcFraction >= 1, 1, lcFraction)
End Function

'Critical Replacement Time, Regression Model A
Function CriticalRepTimeA()
    CriticalRepTimeA = 0
End Function
'Critical Replacement Time, Regression Model B
Function CriticalRepTimeB()
    CriticalRepTimeB = 0
End Function

'Critical Replacement Time, Regression Model C
Function CriticalRepTimeC(ByVal lcAlphaC As Single, ByVal lcBetaC As Single, _
    ByVal lcThBrkRate As Single, ByVal lcFirstLeakTime As Single, ByVal lcPipeType As String, _
    ByVal lcAeration As String)
    Dim lcKn, lcKa, lcn, lcA As Single
    lcn = ppadnGetRossumn(lcAeration)
    lcKn = ppadnGetRossumKn(lcAeration)
    lcKa = ppadnGetRossumKa(lcPipeType)
    lcA = ppadnGetRossuma(lcPipeType)
    CriticalRepTimeC = _
        (lcThBrkRate * (lcA / lcn) * ((lcAlphaC) ^ (lcn / lcA)) * lcFirstLeakTime ^ (lcn / lcA)) ^ (lcA / (lcn - lcA)) + _
        (lcBetaC / lcAlphaC)
End Function

'Critical Replacement Time, Regression Model D
Function CriticalRepTimeD(ByVal lcAlphaD As Single, ByVal lcBetaD As Single, _
    ByVal lcThBrkRate As Single, ByVal lcFirstLeakTime As Single, ByVal lcPipeType As String, _
    ByVal lcAeration As String)
    Dim lcKn, lcKa, lcn, lcA As Single
    lcn = ppadnGetRossumn(lcAeration)
    lcKn = ppadnGetRossumKn(lcAeration)
    lcKa = ppadnGetRossumKa(lcPipeType)
    lcA = ppadnGetRossuma(lcPipeType)
    CriticalRepTimeD = _
        (lcThBrkRate * (lcA / lcn) * ((lcAlphaC) ^ (lcn / lcA)) * lcFirstLeakTime ^ (lcn / lcA)) ^ (lcA / (lcn - lcA)) + _
        lcBetaC
End Function
ByVal lcAeration As String)
Dim lcKn, lcKa, lcn, lcA, lcE As Single
lcE = 2.7182
lcn = ppadnGetRossumn(lcAeration)
lcKn = ppadnGetRossumKn(lcAeration)
lcKa = ppadnGetRossumKa(lcPipeType)
lcA = ppadnGetRossuma(lcPipeType)
CriticalRepTimeD = _
    (lcThBrkRate * (lcA / (lcn * lcAlphaD)) * lcE ^ (((lcn * lcBetaD) / (lcA * lcAlphaD))) * lcFirstLeakTime ^ (lcn / lcA)) ^ _
    (lcA / (lcn * lcAlphaD - lcA))
End Function

'Critical Replacement Time, Regression Model D
Function CriticalRepTimeD(ByVal lcAlphaD As Single, ByVal lcBetaD As Single, ByVal lcThBrkRate As Single, _
    ByVal lcFirstLeakTime As Single, ByVal lcPipeType As String, ByVal lcAeration As String)
    Dim lcKn, lcKa, lcn, lcA, lcE As Single
    lcE = 2.7182
    lcn = ppadnGetRossumn(lcAeration)
lcKn = ppadnGetRossumKn(lcAeration)
lcKa = ppadnGetRossumKa(lcPipeType)
lcA = ppadnGetRossuma(lcPipeType)
    CriticalRepTimeD = _
        (lcThBrkRate * (lcA * lcAlphaD / lcn) * lcE ^ (((lcn * lcBetaD) / (lcA * lcAlphaD))) * lcFirstLeakTime ^
        (lcn / lcA)) ^ _
        ((lcA * lcAlphaD) / (lcn - lcA * lcAlphaD))
End Function

'Gets the Strength Reduction Factor
Function ppadnGetStrengthReductionFactor(ByVal lcPitDepth As Single, ByVal lcStrength As Long, _
    ByVal lcFractureToughness As Long) As Single
    ppadnGetStrengthReductionFactor = _
        ppadnGetFractureToughnessResidualStrength(_
            lcPitDepth, lcStrength, lcFractureToughness) / lcStrength
End Function
Function ppadnGetEarthLoad (ByVal lcPipeSize As Integer, ByVal lcDepth As Single, ByVal lcSoilDensity As Single) As Single
    ppadnGetEarthLoad = cipraEarthload(lcPipeSize, lcDepth, lcSoilDensity)
End Function

Function ppadnGetTrafficLoad (ByVal lcPipeSize As Integer, ByVal lcPipeDepth As String, ByVal lcTrafficType As String, ByVal lcPavementType As String) As Single
    ppadnGetTrafficLoad = cipraTrafficLoad(lcPipeSize, lcPipeDepth, lcTrafficType, lcPavementType)
End Function

Function ppadnGetFlexuralStress (ByVal lcSize As Integer, ByVal lcLoad As Single, ByVal lcThickness As Single, ByVal lcSpan As Single) As Single
    ppadnGetFlexuralStress = (15.28 * lcLoad * (lcSize + 2 * lcThickness) * (lcSpan ^ 2)) / ((lcSize + 2 * lcThickness) ^ 4 - lcSize ^ 4)
End Function

Function ppadnGetHoopStress (ByVal lcSize As Integer, ByVal lcPressure As Single, ByVal lcThickness As Single) As Single
    ppadnGetHoopStress = (lcPressure * CSng(lcSize)) / (2 * lcThickness)
End Function

Function ppadnGetRingStress (ByVal lcSize As Integer, ByVal lcLoad As Single, ByVal lcThickness As Single) As Single
    ppadnGetRingStress = (0.0795 * lcLoad * (lcSize + lcThickness)) / lcThickness ^ 2
End Function

Function ppadnGetLongitudinalStress (ByVal lcSize As Integer, ByVal lcPressure As Single, ByVal lcThickness As Single) As Single
    ppadnGetLongitudinalStress = (lcPressure * CSng(lcSize)) / (4 * lcThickness)
End Function

Function ppadnGetLongitudinalThermalStress (ByVal lcSize As Long, ByVal lcThickness As Single, ByVal lcPipeType As String, ByVal lcDeltaT As Single)
As Single

Dim lcInnerStress, lcOuterStress, lcMaxStress As Single

lcInnerStress = Abs(thermalSigma_z(lcSize, lcThickness, CSng(lcSize / 2), lcPipeType, lcDeltaT))
lcOuterStress = Abs(thermalSigma_z(lcSize, lcThickness, CSng(lcSize / 2) + lcThickness, lcPipeType, lcDeltaT))

lcMaxStress = lcOuterStress
If lcMaxStress < lcInnerStress Then
    lcMaxStress = lcInnerStress
End If

ppadnGetLongitudinalThermalStress = lcMaxStress

End Function

Function ppadnGetRingThermalStress
    (ByVal lcSize As Long, ByVal lcThickness As Single, ByVal lcPipeType As String, ByVal lcDeltaT As Single) As Single

Dim lcInnerStress, lcOuterStress, lcMaxStress As Single

lcInnerStress = Abs(thermalSigma_theta(lcSize, lcThickness, CSng(lcSize / 2), lcPipeType, lcDeltaT))
lcOuterStress = Abs(thermalSigma_theta(lcSize, lcThickness, CSng(lcSize / 2) + lcThickness, lcPipeType, lcDeltaT))

lcMaxStress = lcOuterStress
If lcMaxStress < lcInnerStress Then
    lcMaxStress = lcInnerStress
End If

ppadnGetRingThermalStress = lcMaxStress

End Function

'Computes Waterhammer pressure
Function ppadnGetWaterHammerPressure
    (ByVal lcSize As Integer, ByVal lcThickness As Single, ByVal lcPipeType As String, ByVal lcWaterVelocityChange As String) As Single

Dim lcElasticModulus As Single

)}
lcElasticModulus = ppadnGetElasticModulus(lcPipeType)

ppadnGetWaterHammerPressure = (lcWaterVelocityChange * 62.5) / 
(1 + (glWaterBulkModulus * (CSng(lcSize) / 12)) / (lcElasticModulus * lcThickness))
End Function

Function ppadnGetExpansionContractionThermalLongitudinalStress( _
    ByVal lcPipeType As String, ByVal lcDeltaT As Single _
) As Single
Dim lcElasticModulus, lcLinExpCoeff As Single
lcElasticModulus = ppadnGetElasticModulus(lcPipeType)
lcLinExpCoeff = ppadnGetLinExpCoeff(lcPipeType)
ppadnGetExpansionContractionThermalLongitudinalStress = _
lcElasticModulus * lcLinExpCoeff * lcDeltaT
End Function

'Computes Rossum Kn
Function ppadnGetRossumKn(ByVal lcAeration As String) As Single
    'Aeration n Kn
    'Good  0.16  170
    'Fair   0.33  222
    'Poor  0.50  355
    'Source: Rossum , June 1969.
    'For cast iron Ka = 1.40, a=0.22
    If Left(Trim(LCase(lcAeration)), 2) = "go" Then
        ppadnGetRossumKn = 170
    ElseIf Left(Trim(LCase(lcAeration)), 2) = "fa" Then
        ppadnGetRossumKn = 222
    ElseIf Left(Trim(LCase(lcAeration)), 2) = "po" Then
        ppadnGetRossumKn = 355
    Else
        ppadnGetRossumKn = 355
    End If
End Function

'Computes Rossum n
Function ppadnGetRossumn(ByVal lcAeration As String) As Single
    If Left(Trim(LCase(lcAeration)), 2) = "go" Then
        ppadnGetRossumn = 0.16
    ElseIf Left(Trim(LCase(lcAeration)), 2) = "fa" Then
        ppadnGetRossumn = 0.33
ElseIf Left(Trim(LCase(lcAeration)), 2) = "po" Then
    ppadnGetRossumn = 0.5
Else
    ppadnGetRossumn = 0.5
End If
End Function

'Computes Rossum Ka
Function ppadnGetRossumKa(ByVal lcPipeType As String) As Single
    If Left(Trim(LCase(lcPipeType)), 2) = "pi" Then
        ppadnGetRossumKa = 1.4
    ElseIf Left(Trim(LCase(lcPipeType)), 2) = "sp" Then
        ppadnGetRossumKa = 1.4
    Else
        ppadnGetRossumKa = 1.4
    End If
End Function

'Computes Rossum a
Function ppadnGetRossuma(ByVal lcPipeType As String) As Single
    If Left(Trim(LCase(lcPipeType)), 2) = "pi" Then
        ppadnGetRossuma = 0.13
    ElseIf Left(Trim(LCase(lcPipeType)), 2) = "sp" Then
        ppadnGetRossuma = 0.13
    Else
        ppadnGetRossuma = 0.13
    End If
End Function

'Determine elastic modulus based on pipe type
Function ppadnGetElasticModulus(ByVal lcPipeType As String) As Single
    Dim lcElasticModulus As Single
    If LCase(Left(Trim(lcPipeType), 2)) = "pi" Then
        lcElasticModulus = 150000000
    ElseIf LCase(Left(Trim(lcPipeType), 2)) = "sp" Then
        lcElasticModulus = 150000000
    ElseIf LCase(Left(Trim(lcPipeType), 2)) = "du" Then
        lcElasticModulus = 240000000
    Else
        lcElasticModulus = 150000000
    End If
    ppadnGetElasticModulus = lcElasticModulus
End Function
'Determine linear exp coeff based on pipe type
Function ppadnGetLinExpCoeff(ByVal lcPipeType As String) As Single
    Dim lcLinExpCoeff As Single
    If LCase(Left(Trim(lcPipeType), 2)) = "pi" Then
        lcLinExpCoeff = 0.0000062
    ElseIf LCase(Left(Trim(lcPipeType), 2)) = "sp" Then
        lcLinExpCoeff = 0.0000062
    Else
        lcLinExpCoeff = 0.0000062
    End If
    ppadnGetLinExpCoeff = lcLinExpCoeff
End Function

'Determine poisson ratio based on pipe type
Function ppadnGetPoissonRatio(ByVal lcPipeType As String) As Single
    Dim lcPoissonRatio As Single
    If LCase(Left(Trim(lcPipeType), 2)) = "pi" Then
        lcPoissonRatio = 0.21
    ElseIf LCase(Left(Trim(lcPipeType), 2)) = "sp" Then
        lcPoissonRatio = 0.21
    Else
        lcPoissonRatio = 0.21
    End If
    ppadnGetPoissonRatio = lcPoissonRatio
End Function

'Determine Fracture Toughness based on pipe type
Function ppadnGetFractureToughness(ByVal lcPipeID As String, ByVal lcPipeType As String, ByVal lcYearAcq As Long) As Single
    Dim lcFractureToughness As Single
    'Try reading from the inventory sheet
    lcFractureToughness = CSng(Val(excelReadProperty(lcPipeID, "FractureToughness", _
glBrkInventorySheet)))
    If lcFractureToughness <= 0 Then
        lcFractureToughness = CSng(Val(excelReadProperty(lcYearAcq, "Value", _
ThisWorkbook.Sheets("FractureToughness"))))
    End If
    If lcFractureToughness <= 0 Then
        If LCase(Left(Trim(lcPipeType), 2)) = "pi" Then
            'Units psi in^.5
'from average of NRC data
lcFractureToughness = 9289
ElseIf LCase(Left(Trim(lcPipeType), 2)) = "sp" Then
  'Statistical Analysis did not show any significant relationship
  'of age with fracture toughness for spun cast iron
  'Therefore used average value
  'Units psi in^-.5
  'from average of NRC data
  lcFractureToughness = 12032
Else
  lcFractureToughness = 9289
End If
End If
ppadnGetFractureToughness = lcFractureToughness
End Function

'Determine the critical tensile stress based on Fracture Toughness and pit dimensions
Function ppadnGetFractureToughnessResidualStrength( _
  ByVal lcPitDepth As Single, ByVal lcStrength As Single, _
  ByVal lcFractureToughness As Single _) As Single
  Dim lcA, lcb, lcC, lcD As Single
  Dim lcFractureToughnessResidualStrength As Single
  lcA = (lcFractureToughness / lcStrength) ^ 2
  lcb = 12.75 * lcA / (glPI * lcPitDepth)
  lcC = (1 + lcb) ^ 0.5
  lcD = (lcStrength ^ 2 / 6) * (lcC - 1)
  lcFractureToughnessResidualStrength = lcD ^ 0.5
  ppadnGetFractureToughnessResidualStrength = _
    IIf(lcFractureToughnessResidualStrength > lcStrength, _
      lcStrength, lcFractureToughnessResidualStrength)
End Function

'Determine the critical tensile stress based on Fracture Toughness and pit dimensions
Function ppadnGetFractureToughnessResidualStrengthBAK( _
  ByVal lcPitDepth As Single, ByVal lcPitlength As Single, _
  ByVal lcThickness As Single, lcFractureToughness As Single _) As Single
  Dim lcFractureToughnessResidualStrength, lcF As Single
  lcF = 1.25 * (1 - (lcPitDepth / lcThickness) ^ 1.47) ^ 2.4
lcFractureToughnessResidualStrength = lcFractureToughness / (lcF * (glPI * lcPitlength) ^ 0.5)

ppadnGetFractureToughnessResidualStrengthBAK = _
   lcFractureToughnessResidualStrength
End Function

'Computes the safety factor for combined Ring and Hoop Stress
Function ppadnGetSafetyFactorRingPlusHoopStress(ByVal lcPipeSize As Long, _
   ByVal lcThickness As Single, ByVal lcBurstingStrength As Single, _
   ByVal lcRingModulus As Single, ByVal lcExternalLoad As Single, _
   ByVal lcInternalPressure As Single) As Single
  Dim lcX, lcY, lcSF As Single
  lcX = lcExternalLoad / _
      ppadnGetRingCrushingLoad(lcPipeSize, lcThickness, lcRingModulus)  
  lcY = lcInternalPressure / _
      ppadnGetBurstingPressure(lcPipeSize, lcThickness, lcRingModulus)
  lcSF = (lcY ^ 2 / (4 * lcX ^ 4) + 1 / lcX ^ 2) ^ 0.5 - lcY / (2 * lcX ^ 2)

  ppadnGetSafetyFactorRingPlusHoopStress = lcSF
End Function

'Computes the bursting pressure
Function ppadnGetBurstingPressure(ByVal lcPipeSize As Long, _
   ByVal lcThickness As Single, ByVal lcBurstingStrength As Single) As Single
  ppadnGetBurstingPressure = 2 * lcBurstingStrength * lcThickness / lcPipeSize
End Function

'Computes the Crushing Load
Function ppadnGetRingCrushingLoad(ByVal lcPipeSize As Long, _
   ByVal lcThickness As Single, ByVal lcRingModulus As Single) As Single
  ppadnGetRingCrushingLoad = lcRingModulus * lcThickness ^ 2 / _
      (0.0975 * (lcPipeSize + lcThickness))
End Function
Option Explicit ' Force explicit variable declaration.
Option Base 1

Global Const glTopMenuName As String = "Repl_Analysis"
Global Const glInterestRateCell As String = "i3"
Global Const glReplacementCostCell As String = "i4"
Global Const glRepairCostCell As String = "i5"
Global Const glOptimalReplacementTimeCell As String = "i6"
Global Const glStartRow As Long = 3

Sub ReCompute()
    Dim i As Long
    Dim lcBrkSheet As Worksheet
    Set lcBrkSheet = Sheets("BreakHistory")

    'UnProtect worksheet
    lcBrkSheet.Unprotect

    ' 'Update Replacement Time
    ReadOptimalReplacementTime

    i = glStartRow
    While (Trim(lcBrkSheet.Cells(i, 2)) <> "")
        lcBrkSheet.Cells(i, 5) = ComputeReplacementPenalty(CSng(lcBrkSheet.Range(glReplacementCostCell)), _
            CSng(lcBrkSheet.Range(glOptimalReplacementTimeCell)), CSng(lcBrkSheet.Cells(i, 2)), _
            CSng(lcBrkSheet.Range(glInterestRateCell)))
        i = i + 1
    Wend

    'Protect worksheet
    lcBrkSheet.Protect
End Sub

'Computes Equal Annual Cost
Function ComputeAnnualCost(ByVal ReplacementCost As Single, ByVal OptimalReplacementTime As Single, ByVal InterestRate As Single)
    Dim lcBrkSheet As Worksheet
    Set lcBrkSheet = Sheets("BreakHistory")

    Dim AnnualizedCost As Single

    AnnualizedCost = ReplacementCost / ((1 + InterestRate) ^ OptimalReplacementTimeCell)
Dim i As Long
For i = 1 To OptimalReplacementTime
    AnnualizedCost = AnnualizedCost + (lcBrkSheet.Cells(glStartRow + i - 1, 3) * _
        lcBrkSheet.Cells(glStartRow + i - 1, 4)) / ((1 + InterestRate) ^ i)
Next i

AnnualizedCost = AnnualizedCost * A_P_i_n(InterestRate, OptimalReplacementTime)

ComputeAnnualCost = AnnualizedCost
End Function

'Computes Penalty for Accelerated/Delayed Replacement
Function ComputeReplacementPenalty(ByVal ReplacementCost As Single, _
    ByVal OptimalReplacementTime As Single, ByVal ActualReplacementTime As Single, _
    ByVal InterestRate As Single)
    Dim lcBrkSheet As Worksheet
    Set lcBrkSheet = Sheets("BreakHistory")
    Dim AnnualizedCost As Single
    AnnualizedCost = _
        ComputeAnnualCost(ReplacementCost, OptimalReplacementTime, InterestRate)
    Dim ReplacementPenalty As Single
    ReplacementPenalty = ReplacementCost / ((1 + InterestRate) ^ ActualReplacementTime)
    Dim i As Long
    For i = 1 To ActualReplacementTime
        ReplacementPenalty = ReplacementPenalty + _
            (lcBrkSheet.Cells(glStartRow + i - 1, 3) * lcBrkSheet.Cells(glStartRow + i - 1, 4) _
                - AnnualizedCost) / ((1 + InterestRate) ^ i)
    Next i
    ComputeReplacementPenalty = ReplacementPenalty
End Function

'Computes Repair Cost when
Function ComputeRepairCost(ByVal RepairCost As Single, _
    ByVal InterestRate As Single, ByVal ThresholdBreakRate As Single)
    ComputeRepairCost = RepairCost / ((1 + InterestRate) ^ (1 / ThresholdBreakRate) - 1)
End Function

'Computes ThresholdBreakRate when
Function ComputeThresholdBreakRate(ByVal InterestRate As Single, _
ByVal RepairCost As Single, ByVal ReplacementCost As Single)
    ComputeThresholdBreakRate = Application.WorksheetFunction.Ln(1 + InterestRate) / _
    Application.WorksheetFunction.Ln(1 + RepairCost / ReplacementCost)
End Function

'Computes F_P_i_n (Single Payment Compound Amount Factor)
Function F_P_i_n(ByVal i As Single, ByVal n As Single)
    F_P_i_n = (1 + i) ^ n
End Function

'Computes P_F_i_n (Single Payment Present Worth Factor)
Function P_F_i_n(ByVal i As Single, ByVal n As Single)
    P_F_i_n = 1 / (1 + i) ^ n
End Function

'Computes A_P_i_n (Equal Payment Series Capital Recovery Factor)
Function A_P_i_n(ByVal i As Single, ByVal n As Single)
    A_P_i_n = (i * (1 + i) ^ n) / ((1 + i) ^ n - 1)
End Function

'Computes P_A_i_n (Equal Payment Series Present Worth Factor)
Function P_A_i_n(ByVal i As Single, ByVal n As Single)
    P_A_i_n = ((1 + i) ^ n - 1) / (i * (1 + i) ^ n)
End Function

'Computes A_F_i_n (Equal Payment Series Sinking Fund Factor)
Function A_F_i_n(ByVal i As Single, ByVal n As Single)
    A_F_i_n = i / ((1 + i) ^ n - 1)
End Function

'Computes F_A_i_n (Equal Payment Series Compound Amount Factor)
Function F_A_i_n(ByVal i As Single, ByVal n As Single)
    F_A_i_n = ((1 + i) ^ n - 1) / i
End Function

Sub ReadOptimalReplacementTime()
    Dim i As Long
    Dim OptimalRowNum As Long
    Dim lcBrkSheet As Worksheet
    Set lcBrkSheet = Sheets("MinLifeCost")

    Dim MinCost As Double
    MinCost = 10000000000000#

    'Read optimal replacement time from MinLifeCost sheet
    OptimalRowNum = 1
    For i = 1 To Min(lcBrkSheet.UsedRange.Rows.Count - 1)
        If lcBrkSheet.Cells(i, 1).Value < MinCost Then
            OptimalRowNum = i + 1
            MinCost = lcBrkSheet.Cells(i, 1).Value
        End If
    Next i

    'Display optimal replacement time
    MsgBox "Optimal replacement time: Row " & OptimalRowNum"
End Sub
Dim OptimalReplacementTime As Long
OptimalReplacementTime = 0

OptimalRowNum = 0
i = 4
While (Trim(lcBrkSheet.Cells(i, 2)) <> "")
    If MinCost > lcBrkSheet.Range("l" & i) Then
        MinCost = lcBrkSheet.Range("l" & i)
        OptimalReplacementTime = lcBrkSheet.Range("b" & i)
        OptimalRowNum = i
    End If
    i = i + 1
Wend

If OptimalRowNum <> 0 Then
    lcBrkSheet.Unprotect
    lcBrkSheet.Cells.Interior.ColorIndex = xlNone
    lcBrkSheet.Cells.Select
    Selection.Interior.ColorIndex = xlNone
    lcBrkSheet.Protect
End If

Sheets("BreakHistory").Range("i6") = OptimalReplacementTime

End Sub
Vita

Newland Agbenowosi was born in Leklebi, Ghana on May 16, 1972 to Patrick Agbenowosi and Patience Agbenowosi. After completing his primary education in Datus Preparatory School, Tema, 1984, he enrolled in Presbyterian Boys’ Secondary and Sixth Form Science College (PRESEC). Upon completion, he went on to attend Central State University in 1990 where he earned his Bachelor of Science Degree in Water Resources Management in 1993. Newland then entered Virginia Polytechnic Institute and State University for a master of science degree in Civil Engineering concentrating in Hydrosystems Engineering and completed in May 1996. Subsequently, he enrolled in the Ph. D. program in Civil Engineering which he completed in December of 2000. Currently, he is employed by the Virginia Tech Civil Engineering Department as a GIS Research Associate.