A Discrete Choice Mean Variance (EV) Cost Model to Measure Impact of Household Risk from Drinking Water Pipe Corrosion

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Academic Abstract

In traditional investment decision making, one tool commonly used is the mean variance model, also known as an expected-value variance (EV) model, which evaluates the anticipated payout of different assets with respect to uncertainty where portfolios with higher risk demand higher expected returns from an individual. This thesis adapts this framework to a cost setting where decision makers are evaluating alternative physical assets that carry lifetime cost uncertainty for maintenance. Specifically, this paper examines homeowner choices for their home plumbing systems in the event of a pinhole leak, a tiny pin-sized hole that forms in copper, drinking-water pipes. These leaks can cause substantial damage and cost homeowners thousands of dollars in repairs. Since pinhole leaks are not related to the age of pipe material, a homeowner is subject to the risk of additional costs if a pinhole leak occurs again despite their repair efforts.

The EV cost model in this paper defines two discrete choices for the homeowner in the event of a leak: to apply a simple repair at lower cost and higher future cost uncertainty; or to replace their plumbing with new pipe material, usually made of plastic, at a higher upfront cost but lower likelihood of future expenses. The risk preference of homeowners are demonstrated by their repair strategy selection, as well as the level of cost they incur to reduce uncertainty. Risk neutral individuals will select the repair strategy with the lowest lifetime expected cost and high variance, while risk averse homeowners will prefer to replace their plumbing with higher cost but lower variance. Risk averse individuals are also exposed to indirect costs, which is an additional unobserved cost in the form of a risk premium the homeowner is willing to pay to remove all uncertainty of future pinhole leak expense.

Expected costs and variances are also higher for regions in the U.S. that experience elevated leak incident rates, known as hotspots. Using this mean variance cost framework, indirect cost can be quantified for homeowners in hotspot regions and compared to the rest of the U.S. to evaluate the magnitude of pinhole leak risk. The EV cost model estimates risk premiums on pinhole leaks to be $442 for homeowners in hotspots and $305 for those in the rest of the U.S. Finally, this paper examines the impact of pinhole leak cost uncertainty on the U.S. economy. Of an estimated $692 million in annual pinhole leak costs to homeowners, this study estimates a lower bound cost of $54 million per year (7.8% of estimated national annual cost) in risk premium that homeowners would be willing to pay to avoid pinhole leak cost uncertainty.

Information in this study on the role of risk in home plumbing decisions and indirect costs would be helpful to policymakers and water utility managers as they deal with infrastructure management decisions. Furthermore, the EV cost methodology established in this paper demonstrates an effective use of mean variance modeling under cost uncertainty.

A Discrete Choice Mean Variance (EV) Cost Model to Measure Impact of Household Risk from Drinking Water Pipe Corrosion

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General Audience Abstract

This paper examines homeowner choices for their home plumbing systems in the event of a pinhole leak, a tiny pin-sized hole that forms in copper, drinking-water pipes. These leaks can cause substantial damage and cost homeowners thousands of dollars in repairs. Since pinhole leaks are not related to the age of pipe material, a homeowner is subject to the risk of additional costs if a pinhole leak occurs again despite their repair efforts. This paper also examined costs in regions of the U.S. that experience elevated leak incident rates, known as hotspots.

There were two primary choices assessed in this study for homeowners facing pinhole leaks: to either apply a simple repair today at lower cost but take on a higher chance of more pinhole leaks; or to replace their plumbing with new pipe material, usually made of plastic, at a higher overall cost but lower risk of another leak.

Using a cost focused investment analysis, it was estimated that homeowners selecting the 'safer' replacement strategy would be willing to pay a minimum of $305 in additional cost if able to eliminate all possibility of another leak compared to those who opted for the more 'riskier' repair choice. Additionally, homeowners who live in hotspot regions who selected the replacement strategy were estimated to be willing to pay a minimum of $442 in additional cost to avoid pinhole leaks. At a national level, these pinhole leak-avoiding premiums equate to $54 million, about 7.8% of the estimated $692 million in costs spent on fixing pinhole leaks by U.S. homeowners each year.

Information in this study on homeowner preferences and pinhole leak would be helpful to policymakers and water utility managers as they deal with infrastructure management decisions.

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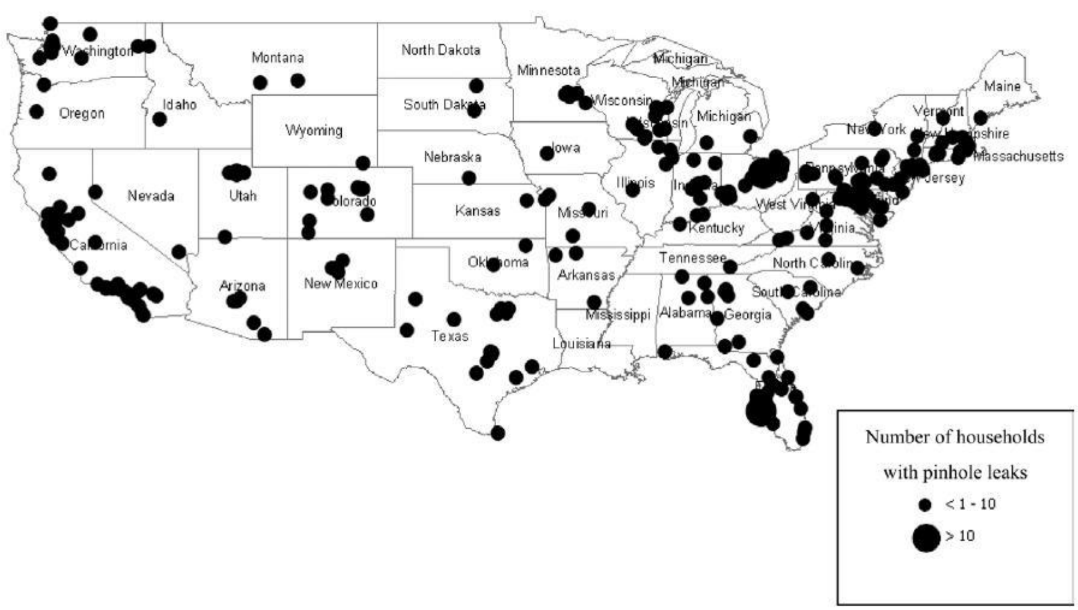
1. INTRODUCTION

1.1 Problem Statement

Across the U.S., many communities have experienced problems with “pinhole leaks”, which are tiny holes forming in home drinking water plumbing. These leaks often form in copper pipes, also known as copper pitting, which can cause substantial physical damage to homes and buildings and carry high financial repair cost. Articles on pinhole leaks have appeared for over a decade in national newspapers (Washington Post, 2002), homeowner association bulletins (Rarity Bay HOA, 2007), and lawsuits (OC Register, 2013). When pinhole leaks first began to cause widespread problems in Maryland, the governor even appointed a special task force to investigate the issue (State of Maryland, 2004).

Information obtained from the Copper Development Association (CDA) shows nationwide occurrences of pinhole leaks, illustrated in the map below (Loganathan, 2005). However, pinhole leaks do not strike equally among regions. Four “hotspots” were identified where pinhole leak rates have been observed to be significantly higher than the national average. These hotspots are Butler County, Ohio; Sarasota, Florida; Montgomery County, Maryland; and the western California coast (Edwards 2003).

Figure 1.1 Nationwide distributions of reported pinhole leaks



Although the exact cause for pinhole leaks is uncertain, it is believed to be the result of a complex interaction between chemicals from water treatment, hydraulics, electrical interactions with plumbing, and other water chemistry factors according to Dr. Marc Edwards of Virginia Tech’s Civil and Environmental Engineering department (Edwards, 2005). These factors can concentrate ‘normal’ corrosion that occurs at a slow rate over a period of 40 years, and intensify the effects into single ‘pinhole’ points and create leaks in just 1 to 2 years’ time.

Pinhole leaks cause substantial damage to homes and commercial buildings. Costs include replacing plumbing, damage to walls, flooring, and cleaning mold. There are also indirect costs related to loss of time, wages, or revenue for commercial buildings that close while undergoing repairs. In 2006, the American Water Works Association (AWWA) funded research to determine the economic impact of pinhole leaks in the U.S. They found that pinhole leaks cost the American economy $967 million per year (Bosch & Sarver 2006). The largest segment impacted by pinhole leak cost was homeowners, which made up 58%, compared to 23% and 19% for water utilities and the combination of commercial businesses and apartment buildings, respectively.

One area not examined by Bosch and Sarver was the risk attitudes of homeowners when deciding how to repair pinhole leak damage. These decisions have a large effect on the total cost since the response to risk among homeowners greatly varied. In some instances, homeowners decided to repair singular pipe segments with a clamp over the holes. Others chose to tear-out all existing pipes and re-plumb their home with new pipes. In still more extreme-cases observed in Florida (Sarasota Report 2006), homeowners who never had a pinhole leak pre-emptively decided to replace all plumbing in their entire home after receiving news of their neighbors getting leaks.

There has been no analysis why certain homeowners chose less expensive repairs while others opted for measures that are more expensive. This paper will examine the risk related decisions by homeowners, controlling for location, leak frequency, along with other factors to understand how uncertainty can affect the pinhole leak costs to the U.S. economy. Information on the role of risk in home plumbing decisions and the effects of risk on cost of plumbing failures would be helpful to policymakers and water utility managers as they deal with water infrastructure management and investment decisions.

1.2 Research Objectives

This paper seeks to develop a framework for assessing homeowner plumbing repair decisions when faced with cost uncertainty (risk) scenarios. The objectives are summarized into two components:

> **Objective 1** – To estimate how risk affects homeowners’ plumbing repair decisions and the costs homeowners’ incur from plumbing failures.
>
> **Objective 2** – To measure the impact that pinhole leak hotspots have on homeowner pinhole leak repair choices.

To satisfy Objective 1, a mean-variance risk analysis framework is used to measure the costs related to pinhole leaks for each repair strategy available to homeowners. Earlier approaches to estimating repair or replace decisions focused on marginal cost and life expectancy, however the pinhole leak epidemic has exposed that homeowners may be basing decisions on risk (Sarasota 2006) rather than a simple cost-benefit approach based on the assumption of certainty.

A traditional mean-variance (E-V) model used to differentiate income investment decisions has been adapted to a home-investment decision where cost is uncertain. The expected quantifiable likelihood of loss, which is the probability of the leak multiplied by the cost, and variance in future costs will be assessed in this study using a "mean-variance" (E-V) model, which is a common tool for estimating both of these, mean and variance, risk-related quantities (Chavas, p. 75). This new methodology is applied to the pinhole leak problem to explain the differences in plumbing repair choices by homeowners in context of varying future expectations of cost.

For Objective 2, it is important to assess the impact that high risk areas have on pinhole leak costs in regards to homeowner repair decisions. Based on past studies (Edwards 2003), "hotspot" regions are more prone to pinhole leaks and should have higher expected cost. Furthermore, they face different risks and may choose alternative repair strategies than those in the rest of the U.S. The risk model developed for Objective 1 can also be used to compare the different regional risk and cost choices.

1.3 Hypotheses

Below are the hypotheses for the objectives, described above, for examining pinhole leak cost in a risk analysis framework:

1. Based on the assumption that consumers are expected to behave as risk averse decision makers, it is expected that homeowner repair strategies will fit an EV cost framework where risk averse, *a,* individuals' choice represents an expected cost greater than those with a risk neutral, *n*, strategy, and for which the variance of the risk neutral option is greater than that of the risk averse strategy for fixing pinhole leaks where:
   a. $E(cost_a) > E(cost_n)$ and
   b. $Var(cost_a) < Var(cost_n)$
2. Consumers in hotspot regions are expected to opt for more expensive replace versus repair decisions. This will be tested as a shift in the EV frontier for both risk averse *a* and risk neutral *n*, such that:
   a. $E(cost_{a,\ hotspot}) > E(cost_{a,\ US})$ and
   b. $E(cost_{n,\ hotspot}) > E(cost_{n,\ US})$

1.4 Organization of the Study

Chapter 2 is devoted to the conceptual and theoretical framework. In that chapter, risk analysis practices are reviewed and adaptation of mean-variance (EV) methods to a cost framework is outlined. Chapter 3 details the procedures for calculating EV risk measures, including survey collection and data preparation. The results of this analysis are shown in Chapter 4, along with some concluding remarks and discussion in Chapter 5.

2. CONCEPTUAL FRAMEWORK

The desire to manage risk provides insight into homeowners' reaction to pinhole leaks and the costs that homeowners are willing to accept to insure against the threat of pinhole leaks. Common repair vs. replace cost decisions mainly focus on life expectancy (life-cycle costs) of when replacement costs outweigh those of repair (Plant Maintenance 1999). However, these methods do not always take into consideration risk factors that consumers inherently evaluate when making a decision. Therefore, this paper presents a new risk model for repair vs. replace cost decisions that accounts for risk-related decisions by adapting the classical mean-variance (EV) model used in portfolio risk management (Robison and Barry, 1987; Chavas, 2004) to a cost framework.

2.1 Literature Review

In seeking to address the objectives of this paper, assessing costs associated with pinhole leaks due to risk, the section below references several textbooks and papers that describe useful techniques for building an appropriate model.

2.1.1. 50% Rule for Repair vs. Replace Decisions

Many people when confronted with repair or replace decisions are presented with the 50% rule or lifecycle cost framework. The 50% rule is commonly used in real estate, insurance, and disaster recovery (Art of Troubleshooting 2014). This rule states:

Equation 2.1

$$\text{Repair if: Repair Cost} < \text{Replacement Threshold} \times 50\%$$

This method is widely prescribed for repair vs. replace decision. Consumer reports advised, "Don't spend more than 50 percent of the cost of a new product on repairing an old one" (Consumer Reports 2014). Likewise, the US government employs the 50% rule when determining repair and replace decisions (FEMA 9524.4).

2.1.2. Lifecycle Costing for Repair vs. Replace Decisions

Another approach recommended in repair vs. replace decision planning is lifecycle costing. The goal of this method is to compare the total costs over a long-term time horizon for repairs and replacement. Costs should include removal, rebuild, maintenance, labor, and materials in order to find the option that gives the lowest possible cost (Plant Maintenance 1999).

Lifecycle cost (LLC) models are designed to help asset manager understand the entire cost of an asset rather than just its initial purchase price. Typical models range from 7 to 15 years, however some can go up to 30 or 50 years depending on the estimated life of the asset (Reliability Web). These models also account for the time value of money using net present value (NPV) to compare the repair and replace choices.

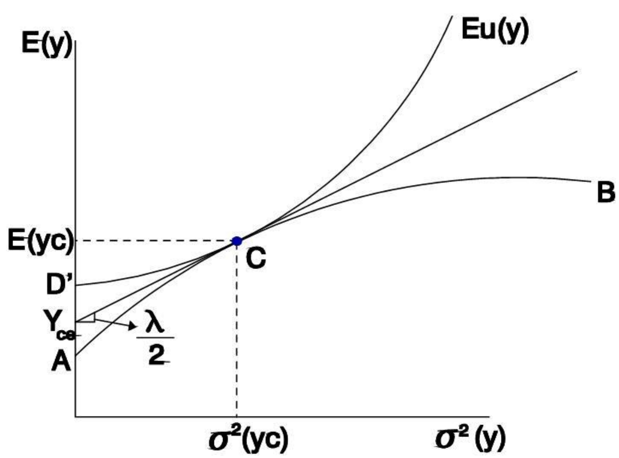
However, in the case of our homeowners with pinhole leak damage, both the 50% rule and life cycle costing methods do not address risk preferences that are underlying decisions since some with the same leak events chose to repair while others replaced plumbing.

2.1.3. Robison and Barry – The Competitive Firm's Response to Risk

To account for risk-based choices, Robison and Barry discuss a "popular method for ordering choices" in Decision Theory with the expected values (E) and variances (V), or EV method (Robison and Barry, p.71 -72). This analytical approach defines different sets of choices by their alternative levels of expected return.

In an EV model, the y-axis E(y) is the different expected returns for income and the x-axis σ^2(y) are the different levels of variance in income. Consumers' preference for value is plotted by the expected-utility curve Eu(y), which shows that with a higher variance in income, there is a higher expected return. This framework is shown in the graph below:

Figure 2.1 - Mean-Variance Graph (Robison and Barry, p. 74)



Curve B, is the expected value / variance (EV) frontier, which represents all the possible investment offers available in the market. The tangency of the consumer's preference 'utility-curve' and the EV frontier, at point C, is the maximum value provided to the consumer with this set of investments. Nothing with more variance on curve B meets the consumers' minimum expected return, E(y), on their utility curve, Eu (y).

Different consumers may have different preferences for risk and reward, which are shown by the Eu(y) curve at different locations in the graph. For the risk averter, as variance increases, so does the expected income required to compensate for the increased risk. A risk neutral individual is defined as not concerned with risk and will just maximize expected income at any level of variance. However, a risk averse individual will wish to reduce his variance in exchange for accepting a lower expected income.

> "Since expected utility itself is considered an approximation to the true unknown preference function of the population of investors, and since exact estimates of probability distributions are difficult to obtain, it is reasonable and acceptable to use the expected value-variance framework." (Robison and Barry, p. 6)

2.1.4. Chavas – Risk Analysis in Theory and Practice

Chavas suggests that empirical estimation of means and variances from sample information has a long tradition in statistics and econometrics and that mean-variance analysis is a powerful framework for conducting applied risk analysis (Chavas, p. 75). It is also an attractive method given that the estimations of the expected value E(x) as the mean and Var(x) being the variance of x, are relatively easy to obtain empirically (Chavas, p. 69).

Chavas describes two approaches to assessing probability distributions. The distribution can be plotted without making any priori assumptions about the shape which is a nonparametric approach. This distribution can be smoothed to improve statistical quality (Chavas, p. 13). Another way to develop a probability distribution is through a parametric approach. In this case, the distribution can be assumed to belong to a class of parametric functions chosen using a maximum likelihood method (Chavas, p.14).

Chavas defines the risk premium (R) as "the sure amount of money a decision-maker would be willing to receive to become indifferent between receiving the risky return 'a' versus receiving the sure amount [E(a)-R], where E(a) is the expected value of 'a' (Chavas, p.34)." "A decision maker is said to be risk neutral if the risk premium (R) is zero and risk averse if positive (R>0)" (Chavas, p. 35).

2.1.5. Anderson and Dillon – Risk Analysis in Dryland Farming Systems

Anderson and Dillon apply risk to analyze agricultural production in arid climates. Chapter 3 of their report contains many useful techniques in assessing subjective probability as well as risk aversion.

On the discussion of subjective probability, they mention the long-term debate over effective ways to elicit a decision maker's subjective probabilities. Although it is difficult to standardize a certain method for obtaining these probabilities, there are a few common guidelines to follow when assessing them. They are personal judgments and in short,

> "They [subjective probabilities] should reflect the decision-maker's true feelings of uncertainty, taking account of all the information to hand about the uncertain events of concern. A rational person will thus strive to make subjective probability judgments that are as "objective" as possible." (Anderson and Dillon, p. 41)

Anderson and Dillon describe an indirect approach to estimate a value for the coefficient of absolute risk aversion, which is a base for measuring how risk averse an individual is:

> "The indirect approach is based on the notion that, over restricted ranges of risky payoffs, measures of risk aversion may be approximately constant. It is then possible to use equation [$r_A = r_R/w$] in conjunction with an estimate or the wealth of the individual(s) facing the risks of concern, and an estimate of their unit-free degree of relative risk aversion r_R." (Anderson and Dillon, p. 55)

Furthermore, they suggest a range for relative risk aversion based on presented data. A value of 0.5 represents an individual hardly concerned with risk, values of 2 to 3 represent fairly risk averse individuals, and finally, a value of 4 represents extremely risk averse individuals (Anderson and Dillon, p. 55). Using the conversion of relative risk aversion into absolute risk aversion, $r_A = r_R/w$, the certainty equivalent can be found to be CE = Expected Value – 0.5 r_A(Variance), and thus provide another measure of risk aversion.

2.2 Conceptual Risk Model

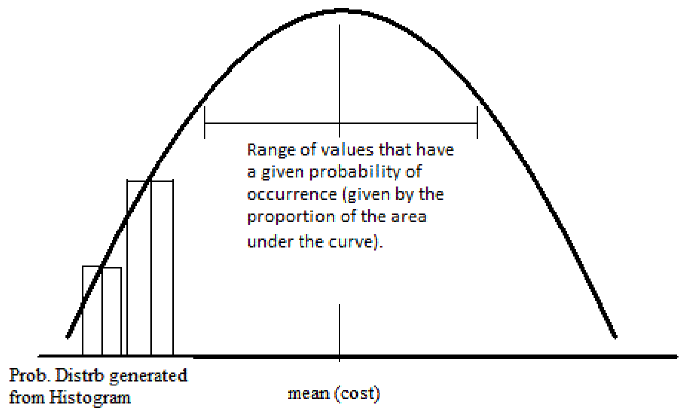
The mean-variance (EV) model described by Robison and Barry, as well as Chavas, analyzes the trade-off between income-earning investments with respect to risk. This paper applies the mean-variance approach to investment decisions that are cost centric. Instead of an investor choosing between different portfolio options, each with a different expected payout and variance in future income, a mean-variance cost framework analyzes an investor attempting to decide between various depreciating assets that deliver some common goods to the buyer.

In the traditional EV model, investors are weighing investment products that all deliver a common good, which is typically money. Here, the goods received from the asset (delivery of potable water to the home) are identical in nature, the buyer is only assessing his choices between assets that require an initial purchase that have uncertain future costs (represented as lost or negative income), that represent maintenance costs or deterioration of the asset (negative return on investment).

An example of this mean-variance cost trade-off, presented in this paper, is a homeowner deciding between different types of pipes, or pipe repair, that all deliver the same good, which is potable water in this case. The different options for pipe assets all carry different upfront costs as well as future unknown costs. Another example of this cost centric decision trade-off could be weighing options between types of industrial power plants (coal fired, nuclear, hydro, etc.) that each incur differ investment and maintenance costs but deliver the same good--electricity. Each asset has a different expected cost associated with it, as well as varying degrees of cost uncertainty (risk) that it may experience in its lifetime.

Underlying the mean-variance analysis is a distribution of observed costs from homeowners who experienced a leak. Not all homeowners with a pinhole leak will experience the same amount of cost damage. The costs vary due to the random impact of pinhole leak damage on pipes, non-pipe damage such as to walls and floors, as well as varying time costs dependent on the severity in the number of leaks or leak location that can make repair time longer or shorter. This range of costs can be represented by a hypothetical distribution shown in Figure 2.2 below. In this example, some pinhole leaks on the left side of the plot will be relatively inexpensive, while on the right side a few homeowners will experience significantly high costs.

Figure 2.2 – Hypothetical Distribution of Observed Costs



The expected value for the E-V cost model is the sum of each cost observation's probability $P(x_c)$, which is the frequency on the distribution's y-axis, multiplied by each individual cost observation x_c on the distribution's x-axis and is defined in Equation 2.2 below (Anderson and Dillon, p. 43).

Equation 2.2

$$\mathrm{E}[x] = \sum_{c=1}^{N} P(x_c)x_c$$

The spread of pinhole leaks costs, which is variance in the E-V cost model shown in Equation 2.3, is each observation's probability $P(x_c)$ multiplied by the squared difference of the observation's cost x_c less the expected value $\mathrm{E}[x]$ (Anderson and Dillon, p. 43).

Equation 2.3

$$\mathrm{Var}[x] = \sum_{c=1}^{N} P(x_c)(x_c - \mathrm{E}[x])^2$$

As mentioned later in Section 3.3, the observations on pinhole leak cost are taken from survey data. When the reported costs in a survey are unique values for each homeowner, then each observation's probability $P(x_c)$ is equal to $\frac{1}{N}$.

In addition to the expected cost and variance as defined by Equations 2.2 and 2.3 above, the EV cost model is subject to an additional element of the probability, which is the likelihood of incurring a cost in the first place. Each investment choice *i* available to the decision maker will have a different probability π_i of exposure to the cost distribution. For example, say a homeowner has a choice to invest in one of three types of pipes. The first is a very cheap material with a 50% chance of developing leaks, the second is a medium grade material with 10% chance and the third is a high-quality material with only 1% chance. If a leak occurs in any of these materials, the homeowner would have an expected cost that varies due to the severity and location of the leak following the distribution shown in Figure 2.2 and represented by Equation 2.2, even if they had invested in the highest quality material. The same holds true if they selected the cheapest, leak-prone material. The probability of incurring a leak π_i can be estimated from historical data, simulated, or the subjective opinion of an expert.

Therefore, the expected cost of an investment *i* is equal to the subjective probability of exposure π_i multiplied by the distributional expected cost from Equation 2.2, where $P(x_c)$ is equal to $\frac{1}{N}$ for survey cost observations unique in value. Mathematically, this formula is reduced to π_i multiplied by the mean cost μ_i of the leak cost distribution, as shown in Equation 2.4 below.

Equation 2.4

$$\text{Expected Cost}(i) = \pi_i * \left[\sum_{c=1}^{N} P(x_c)x_c\right]_i$$

$$= \pi_i * \left[\sum_{c=1}^{N} \left[\frac{1}{N}\right] x_c\right]_i$$

$$= \pi_i * \left[\frac{\sum_{c=1}^{N} x_c}{N}\right]_i$$

$$= \pi_i \mu_i$$

Where μ is the population mean (StatTrek, 2016)

For example, say there was a survey of five homeowners with reported costs of ($100, $200, $500, $700, and $1,000). The probability in the cost distribution (frequency) of each observation is 1/5 (20%). The distributional expected cost then is the sum of each observation multiplied by 1/5 that equals of $500, which also is the average ($2500/5). The average cost is then multiplied by the investment's likelihood to develop a leak, say a 10% chance of having a leak for a homeowner who chose a medium grade material. Then the expected cost for this investment would be $50, which is the subjective probability multiplied by the mean cost (0.10 * $500).

Similarly, the pinhole leak cost variance of is the distribution's variance from Equation 2.3 multiplied by the subjective likelihood of incurring leak cost π_i. When cost observations are unique values, with $P(x_c)$ equal to $\frac{1}{N}$, the variance of cost is reduced to π_i multiplied by the distribution variance $\sigma^2{}_i$ for the investment choice *i* , as shown in Equation 2.5 below.

Equation 2.5

$$\text{Variance Cost}(i) = \pi_i * \left[\sum_{c=1}^{N} P(x_c)(x_c - \mathrm{E}[x])^2\right]_i$$

$$= \pi_i * \left[\sum_{c=1}^{N} \left[\frac{1}{N}\right](x_c - \mu)^2\right]_i$$

$$= \pi_i * \left[\frac{[\sum_{c=1}^{N}(x_c - \mu)^2]}{N}\right]_i$$

$$= \pi_i \sigma^2{}_i$$

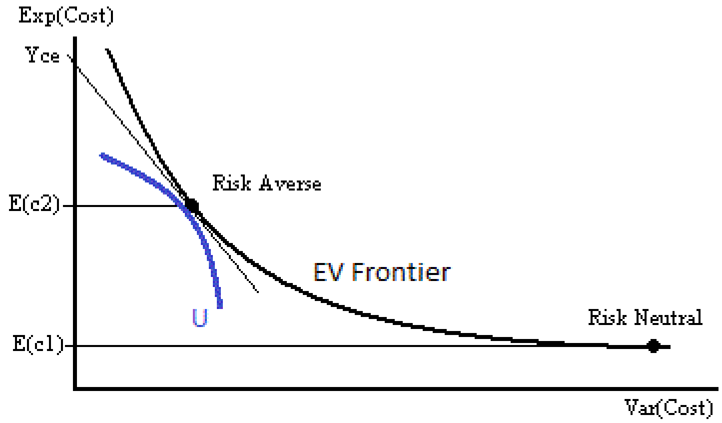
Where σ^2 is the population variance (StatTrek, 2016)

Each asset choice available to the decision maker will have a unique set of these three inputs, π_i, μ_i, and σ_i^2, forming an Expected Value and Variance [E(i),V(i)] set for each investment *i*. The EV Frontier is made up of the collection of EV sets, containing asset choice 1 with set (E1,V1), asset 2 with (E2,V2), and so on through the n^{th} asset investment choice (E{n}, V{n}).

In a scenario of infinite investment choices, the EV frontier becomes a smooth curve with each expected value-variance plotted side-by-side, as described by Robinson and Barry and mentioned in Section 2.1.3. However, unlike a convex EV frontier shown in Figure 2.1, the EV frontier for a cost model is concave. Rather than income (y), the EV cost framework uses the loss (-y), which is the cost of the asset, for the mean and standard deviation μi, and σ_i^2 inputs. The sign is flipped so that cost (c) is represented as a positive value (-y = c). The EV cost curve is then downward sloping, where "safer" assets with lower variance and higher expected cost are on the left side of the graph, while "riskier" assets with higher cost uncertainty but low expected cost are on the right side of the graph.

Similarly, the utility curve follows the same principle of maximizing income subject to a given level of variance, max{y}, but now negative income is maximized max{-y} which is the same as minimizing cost, min{c}. Graphically, the y-axis for expected income is now flipped to expected cost E(-y) = E(c), while the variance stays positive since it is a squared value. "A decision problem exists when an individual has alternative choices, each with significant consequences, and is unsure about which choice is best" (Robison and Barry, p. 2). The choice preferences are represented by the utility curve, shown as the blue line denoted U in Figure 2.3.

Figure 2.3 – Mean-Variance Cost Curve



2.2.1. Definitions in Risk Analysis

Risk Neutral: Risk neutral individuals do not regard cost uncertainty in their decisions and will favor a choice with the highest expected income, which in this framework is the lowest expected cost. In Figure 2.3 above, the risk neutral utility curve is tangent to the EV frontier at the point with the lowest expected cost at E(c1).

Risk Averse: A risk averse individual prefers a risk-less investment over a risky investment when expected income is constant. A risk averse individual will expect increased expected income as compensation for taking on additional risk (Robison and Barry, p. 4). In Figure 2.3 above, risk averse individuals will choose a point to the left of the risk neutral decision maker. Compared to the risk neutral decision maker, their utility functions are tangent to the EV frontier with lower variance in cost but larger expected cost. An example is shown at point E(c2).

Certainty Equivalent (Yce): In Figure 2.3, the linear approximation to the certainty equivalent for the risk averter is Yce at the vertical intercept of a tangency line for the Utility curve and the Expected Value-Variance (EV) set. This is the amount of cost (e.g. money or utility) that an agent would be willing to pay to be indifferent between this cost and a given risky cost represented by E(c2) (Robison and Barry, p. 4). Since Yce has zero variance, it is considered a completely certain return that is equivalent in terms of expected utility to the risky choice with the expected return E(c2) (Robison and Barry, p. 73).

Risk Premium: The risk premium is the amount a risk averse individual would pay to hold zero risk. “Risk aversion means that individuals must be compensated for taking risks in the form of a premium over and above the return on a completely certain investment” (Robison and Barry, p. 4). “The risk premium is the difference between an expected return on the risky investment and the return on the riskless investment that leaves the firm indifferent between the two choices” (Robison and Barry, p. 4). Mathematically, this is calculated as E(y)-Yce (Robison and Barry, p.

38). For a cost framework, where income (y) is negative, the sign on this equation is flipped and becomes Yce – E(y).

2.2.2. Assumptions in Risk Modeling

Risk averters are assumed to operate along this frontier line with a feasible region above the curve. A risk neutral individual seeks to minimize expected cost without concern for risk, shown as the variance of cost. However, a risk averse individual chooses a preventive investment strategy to the left of the risk neutral, where his utility curve would be tangent to the E-V cost frontier.

1. Economic theory under risk in most cases begins with the assumption that a decision maker's preferences are represented by a concave utility function (Robison and Barry, p. 2)."

2. Assumption for Expected-Utility Maximization: "The utility function should be continuous, differentiable, and concave to the origin to ensure that a maximum exists (Robison and Barry, p. 2)."

3. For the EV analysis, three sufficient conditions are commonly invoked. "If one of these conditions is met, then an expected utility-maximizing choice is made from the efficient set. However, both quadratic utility and normality are highly restrictive conditions (Robison and Barry, p. 6)":

   3.1. The first is the investors utility function is quadratic, reflecting preferences only for expected values and variances of outcome distributions. "Quadratic utility implies that marginal utility becomes negative beyond some level of monetary outcome and that the investor being modeled is characterized by increasing absolute risk aversion (Robison and Barry, p. 72)."

   3.2. The second is the investors' expectations are modeled by normal distributions that are fully specified by their expected values and variances.

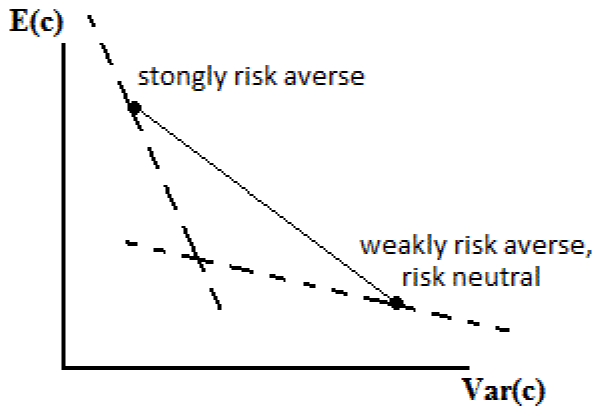
   3.3. A third, less restrictive, sufficient condition is the location and scale condition (Meyer and Rasche, p. 91). This condition requires each random alternative to be equal in distribution to the others except for location and scale (LS).

Location can be statistically defined as the "mean - the mean is the sum of the data points divided by the number of data points" (NIST - Location, 2016), while scale can be defined as "the spread, or variability, of a data set" represented by the variance or standard deviation of the data (NIST – Scale, 2016). According to Meyer and Rasche, "because the LS condition does not require a specific functional form for the distribution function, the lack of symmetry and unusual tail properties are not a cause for rejection as they are when testing for normality" (p. 91).

2.3 The Discrete Case

In the case of limited options for asset choice such as home plumbing, the EV cost curve becomes a discrete set of nodes. Without infinite choices between these assets, a risk averse individual's utility curve will be tangent to the EV curve at the point where the slope is less than or equal to the EV frontier slope between nodes. Individuals with a utility curve that coincides with a segment of the EV curve joining two nodes will value the two nodes equally in terms of risk and expected cost.

Figure 2.4 – EV Cost Curve with Discrete Choices



All individuals with slightly more risk aversion than risk neutral will select the lowest expected cost point up until the absolute value of their utility tangent slope becomes greater than the slope of the EV cost curve, thus switching to the next higher expected cost node. This preference selection continues until no additional asset choice nodes with higher expected cost exist for the highest risk aversion individual.

Figure 2.4 is an example of a two asset choice problem, where risk neutral and weakly risk averse individuals whose utility curve tangents are less than or equal to the slope between the two nodes, will prefer the point on the right. Strongly risk averse individuals whose utility curve tangents are greater than the slope between the nodes will select the asset point on the left. Therefore, in a discrete choice setting, individuals that do not cross the threshold can be assumed to be the same as a risk neutral individual on a continuous curve. Furthermore, they may be indistinguishable from risk neutral individuals; subsequently there is no need to estimate their risk premiums, which are likely to be small.

2.4 Life Cycle Costing in EV Modeling

Finally, the EV cost model combines the cash flow elements of the life-cycle costing (LCC) approach by accounting for the full impact of future costs on the repair or replace decision. Costs should encompass all of the components of the asset to "include removal, rebuilding, maintenance, labor, and materials" (Plant Maintenance 1999). In order to properly compare the full cost between a choice of two assets, each asset must reflect the full price of that decision which includes initial cost and future cost of repairs.

Including life-cycle costs in the EV cost framework is consistent with the EV modeling, since in an investment framework the portfolios being compared by the risk averse individual should reflect expected value and variance of the full return on investment over its lifetime. Life cycle cost for investment asset *i* can be represented by the initial cost investment at time 0 and the sum of all expected costs in the future from time 1 to N periods when the asset reaches the end of its life, as shown in the following equation:

Equation 2.6

$$\text{Lifetime Cost}_{\text{i}} = \text{Initial Cost} + \sum_{\text{i,t}=1}^{\text{N}} (\text{Expected Cost}_{\text{i,t}})$$

Where: *t* is from time 1 to the expiration of life of the asset in *N* periods;

and $\text{Expected Cost}_{\text{i}} = (\pi_{\text{i,t}}\mu_{\text{i,t}})$ from Equation 2.4

3. METHODOLOGY & PROCEDURES

3.1 Overview

As mentioned in Chapter 1, the main objective for this research is to better understand the cost of pinhole leak repair decisions in the context of risk preferences between homeowners who choose repair or replacement for both hotspot and non-hotspot regions in the US.

The conceptual model in Chapter 2 demonstrated how the cost of risk can be represented by the risk premium an individual is willing to pay to avoid the uncertainty of cost faced in an asset investment like pipe repairs on pinhole leaks. The risk premium can be derived from the EV cost frontier of discrete asset choices faced by the decision maker. To generate the EV cost frontier, we need two major components of an EV model, the expected values (E) and the variances (V) that represent risk for each choice an individual faces to create at least two sets of [E(i),V(i)] points to form an EV frontier, for each investment i. Three inputs are needed, π_i, μ_i, and σ_i^2, to calculate each E(i) and V(i), where π_i is the subjective probability of incurring additional cost, μ_i is the mean of the distribution of observed costs, and σ_i^2 is the variance for that distribution of observed costs.

Chapter 3 will describe the repair options available to a homeowner with a pinhole leak in the form of discrete asset choices [E(i),V(i)], as well as formulate each asset's three major inputs, π_i, μ_i, and σ_i^2 of cost for these choices. This chapter is organized into the following sections that describe the application of the EV Cost framework to the pinhole leak problem:

Section 3.2 – Empirical Model

Section 3.3 – Data Sources

Section 3.4 – Calculation Procedure

Section 3.2 – 'Empirical Model' will translate the conceptual EV cost framework into the specifics of the pinhole leak problem. Section 3.3 – 'Data Sources' will describe what data are available for measuring the inputs of the model. Finally, Section 3.4 – 'Calculation Procedure' will describe the specific steps of calculating the three major inputs to the EV set (π_i, μ_i, and σ_i^2) using the available data sources on pinhole leaks.

3.2 Empirical Model

A pinhole leak will produce different costs for each homeowner depending on the severity of the damage. These costs represent the cost distribution shown in Figure 2.2. The pinhole leak problem also meets the risk decision criteria, as a homeowner is presented with generally two separate options to fix the pinhole leak:

Investment Choice 1 - To repair only the small section of pipe with the leak and keep all the non-leaking pipes that exist, or

Investment Choice 2 – To remove all the existing pipes (made of the same material) in the home and replace them with brand new water pipes, also known as replumbing.

A typical Choice 2 would normally be made at the end of life of the existing pipes when they are all beginning to fail around the same time. However, in the case of pinhole leaks, which concentrate corrosion into a single segment of pipe, the remaining pipe system may still have useful life.

Each decision carries with it a unique probability for the occurrence of future cost from additional leaks. Risk aversion comes into play as homeowners' tolerance for risk of future leaks determines their preferences for repair strategies. For example, a simple repair may not mitigate the risk of another pinhole leak occurring in their existing pipe, while new pipes (assuming lower likelihood of leaking) will carry higher costs upfront. Risk neutral and weakly risk averse homeowners should prefer a repair strategy which has the lower cost without regard for risk of future costs, while strongly risk averse homeowners should prefer to replace their plumbing, most often with PVC plastic pipes, which has a higher cost than repair but has less risk for future leaks represented by lower cost variance.

To compare the expected costs between each repair strategy, the full life-cycle cost of the decision must be captured by the EV sets of repair or replace. The repair of the pipe segment would be the initial cost to fix the spot of the leak plus the future potential cost of a leak given the existing pipe material. Alternatively, the replacement strategy cost would include the upfront investment in new pipe materials and the future expected cost of repairing a leak in that new material. In both cases, future costs can also include damage by leaks to the dwelling.

3.2.1. Leak Cost

Costs are variable and depend on a variety of situations and circumstances. For modeling pinhole leak cost, the cost should be derived from the distribution of observed costs for pinhole leaks. Important costs to include are the replacement materials and labor costs, damage to non-piping material like walls and floors, mold removal, and finally the homeowner's wage-equivalent loss of time spent on dealing with the leak. These costs are all summed up for an individual homeowner data observation, and a collection of observations will reveal the cost distribution for an initial pinhole repair.

Equation 3.1

$$\text{Pinhole Cost per Leak} = (\text{materials and labor}) + (\text{non-pipe damage}) + (\text{time cost})$$

Since homeowners may have more than one leak, to construct a distribution all costs should be normalized by the cost per leak. This distribution in costing is used to estimate the mean and variance of the total cost of pinhole leaks by strategy where μ_{repair} is the average repair cost per leak, given repair choice, σ_{repair} is the standard deviation in repair costs per leak, given repair choice, and $\mu_{replace}$ is the average cost per leak, given replacement choice.

3.2.2. Future Cost (Discount Rate)

Cost in the future is less than an equivalent nominal present cost due to the time value of money. Therefore, when calculating the future expected cost for pinhole leaks not only is probability considered but also the dollars should be discounted because leaks cost may occur at different time periods depending on the repair strategy.

The future expected cost is the average repair cost of the distribution of observed pinhole leaks multiplied by the probability of that repair occurring in the time period. This future expected cost will be multiplied by the discount rate in each time period and then summed to a present value for both repair and replace strategies.

As for the discount rate, one option is to use a risk free interest rate, which represents a rate of return of an investment with zero risk. In the pinhole leak problem, a homeowner is setting aside money for pipe repair or replacement that could otherwise have been invested. Investment returns are risky so, to analyze the value of their future earnings without loss, a risk-free rate (R_f) will represent the minimum return an investor expects for any investment because he will not accept additional risk unless the potential rate of return is greater than the risk-free rate.

Equation 3.2

$$\text{Present Value Cost} = \sum_{t=1}^{N} \frac{\text{Expected Cost}_t}{(1 + R_f)^t}$$

In practice, however, the risk-free rate does not exist because even the safest investments carry a very small amount of risk. Thus, the interest rate on a U.S. Treasury bill is often used as the risk-free rate for U.S.-based investors (Investopedia, rate of return basics).

Finally, since homeowner piping investments will last for many years, especially if replacing all pipes with new plumbing, the risk free rate should account for inflation. The real risk free rate can be calculated using the nominal risk-free rate, like a treasury bill and the future inflation rate in the following equation (Investopedia, 2016):

Equation 3.3

$$\text{Real Risk Free Rate } (R_f) = \frac{(1 + \text{nominal risk free rate})}{(1 + \text{inflation rate})} - 1$$

3.2.3. Future Leak Probability

Next, the probability of having a future leak must be obtained. This distribution can be constructed with leak event data, but in the case of the more recent phenomenon of pinhole leaks, it may be best to use subjective probability based on expert opinion. If typical pipes last about 30 years, the probability distribution should be the likelihood during each year over this time horizon. The probability of the pipe “failing” with a leak will generally rise each year until it reaches the life expectancy of the material at which point each year will be assigned a 100% probability of leak. Risk of leaks for homeowners whose pipes are past their life-expectancy would then be defined as:

$\pi_{repair,t}$: Probability incurring a future leak at time t, given repair choice

$\pi_{replace,t}$: Probability incurring a future leak at time t, given replacement choice

3.2.4. EV Cost Model for Pinhole Leaks

This section consolidates the concepts discussed in the previous sections into an empirical calculation for a two asset {repair, replace} uncertainty decision for homeowners using the EV cost framework.

When a homeowner makes the repair choice, they are opting to keep the majority of their existing equipment, in this case home plumbing, and fix a 'part' of that system which is generally the minimum required components to reestablish that system's functionality. In Equation 3.4, the expected cost can be represented by the average initial cost of fixing the 'parts', $\mu_{\text{total repair},t=0}$, plus the probability of an additional leak repair $\pi_{\text{repair},t}$ in each future time period multiplied by a discounted average cost of additional leak repair $\frac{(\mu_{\text{repair per leak},t})}{(1+R_f)^t}$, from time t=1 to N periods when the asset reaches the end of life. The mean repair cost is discounted by the discount rate, shown as R_f which is the risk free rate of return from Equation 3.3, to account for time-value of money.

Equation 3.4

$$\text{Repair Choice Expected Cost} = \mu_{\text{total repair},t=0} + \sum_{t=1}^{N} \pi_{\text{repair},t} * \left[\frac{(\mu_{\text{repair per leak},t})}{(1+R_f)^t}\right]$$

Note that the average cost per leak component, $\mu_{\text{repair per leak},t}$, is derived from a distribution of historically observed cost occurrences, as homeowners experienced different levels of cost damage from pinhole leaks due to the variability of material and labor, non-pipe damage, and time costs as stated in Equation 3.1. The probability of future repair $\pi_{\text{repair},t}$ however is based separately on a subjective likelihood that a homeowner will be exposed to this potential range of repair costs in the first place.

To illustrate this difference, an extreme example would be a homeowner who experienced a pinhole leak and due to some extreme fear of a repeated leak would choose to rip out all their pipes and consume only bottled water, eat on paper plates, take showers and do laundry outside the home. In this scenario, a homeowner would still have an expected cost from the initial activity of the plumber removing their pipes, but would have a zero probability of experiencing the range of costs, historically observed, of a pinhole leak in the future.

In Equation 3.5, the variance in the repair choice set is represented by the same probability of an additional leak $\pi_{\text{repair,t}}$ in each future time period t. It is multiplied by the square of the discounted standard deviation of costs for an additional leak $\left[\frac{(\sigma_{\text{repair per leak,t}})}{(1+R_f)^t}\right]^2$, where the standard deviation represents the range of observed pinhole leak repair costs from the expected cost average and R_f represents the risk free rate of return.

Equation 3.5

$$\text{Repair Choice Variance} = \sum_{t=1}^{N} \pi_{\text{repair,t}} * \left[\frac{(\sigma_{\text{repair per leak,t}})}{(1+R_f)^t}\right]^2$$

Here also, the standard deviation of repair costs per leak, $\sigma_{\text{repair per leak,t}}$, is derived from a distribution of historically observed cost occurrences, as homeowners experienced different levels of cost damage from pinhole leaks, while the probability of future repair is based separately on a subjective likelihood that a homeowner will be exposed to this potential range of costs in the first place.

When a homeowner makes the replacement choice, they are opting to remove their entire existing plumbing and install new piping for the ‘whole’ of that system. Often the replacement pipes can be an entirely new material that can carry different expected costs for future maintenance and repair. For example, many homeowners who experienced pinhole leaks in their copper pipes chose to replace with plastic (PVC or CPVC) pipes (Homeowners Survey: Willis-Walton, 2006a). Initial costs tend to be greater for this strategy, but since the material is newer, it tends to be less likely to leak (Plumbers Survey: Willis-Walton, 2006b).

In Equation 3.6, the expected cost can be represented by the average initial cost of replacing the ‘whole’ piping, $\mu_{\text{total replace,t=0}}$, plus the probability of an additional leak repair for the replacement material $\pi_{\text{replace,t}}$ in each future time period. The average cost per leak is multiplied by the risk-free discount factor R_f shown as $\frac{(\mu_{\text{repair per leak,t}})}{(1+R_f)^t}$, from time t=1 to N periods when the asset reaches the end of life.

Similar to the repair strategy, the average cost per leak component for replacement, $\mu_{\text{repair per leak,t}}$, is derived from a distribution of historically observed cost occurrences, as homeowners experienced different levels of cost damage from pinhole leaks due to the variability of material and labor, non-pipe damage, and time costs as stated in Equation 3.1. The probability of future repair costs for replacement pipes $\pi_{\text{replace,t}}$ is based separately on a subjective likelihood that a homeowner will be exposed to this potential range of costs at all, given their new pipes’ propensity to leak.

Equation 3.6

$$\text{Replacement Choice Expected Cost} = \mu_{\text{total replace},t=0} + \sum_{t=1}^{N} \pi_{\text{replace},t} * \left[\frac{(\mu_{\text{repair per leak},t})}{(1+R_f)^t} \right]$$

The variance in the repair choice set is represented by the probability of an additional leak for the replacement material $\pi_{\text{replace},t}$ in each future time period t. It is multiplied by the square of the discounted standard deviation of costs for an additional leak $\left[\frac{(\sigma_{\text{repair per leak},t})}{(1+R_f)^t} \right]^2$, where the standard deviation represents the range of observed pinhole leak repair costs from the expected cost average and R_f represents the risk free rate of return, as shown below:

Equation 3.7

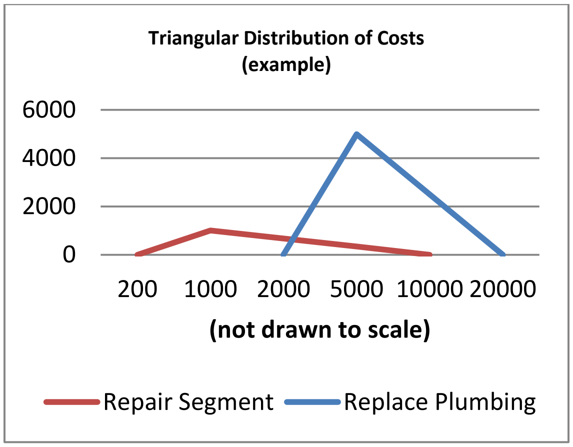
$$\text{Replacement Choice Variance} = \sum_{t=1}^{N} \pi_{\text{replace},t} * \left[\frac{(\sigma_{\text{repair per leak},t})}{(1+R_f)^t} \right]^2$$

3.2.5. Example of EV Cost Calculation

The example in the following section helps to demonstrate how this empirical model would operate given some hypothetical costs and subjective probabilities to calculate an EV set and plot an EV cost curve.

Suppose you have two very simple distributions of observed costs, one for repair and another for replacement, shown as triangular distributions in Figure 3.1. For this simplified distribution, the minimum, most likely, and maximum values are used to derive the mean and variance of cost for each strategy. The red triangle represents the observed costs reported by homeowners who repaired, and varies due to differences in damage to pipe, non-pipe, and time costs, as presented earlier in Equation 3.1. Likewise, the blue triangle represents this variability in costs experienced by homeowners who choose to replace their plumbing with new material.

Figure 3.1 - Triangular Distribution Cost Example



The mean and variance in costs from Figure 3.1 above can be derived from these triangular distributions (Anderson and Dillion, p. 46) with mean calculated as $\frac{(a+b+c)}{3}$ and variance $\frac{(a^2+b^2+c^2-ab-ac-bc)}{18}$. The values for min, max, and most likely, as well as the calculated mean and variance for each repair strategy are displayed below in Table 3.1:

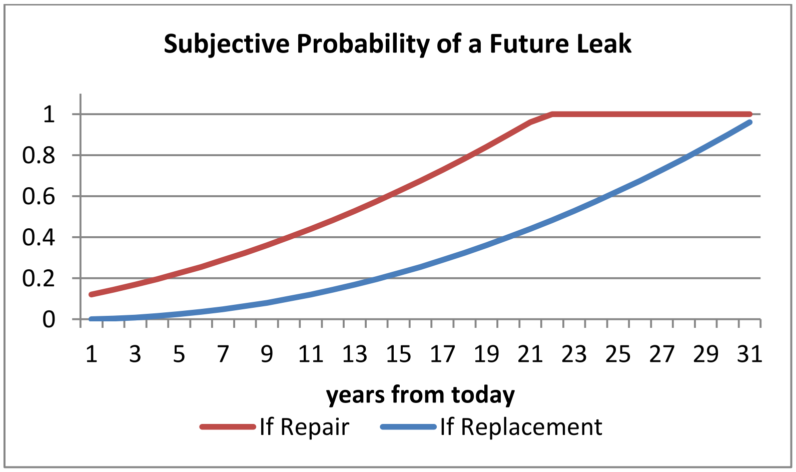
Table 3.1 – Triangular Distribution Example of Observed Costs by Strategy

	Component	Repair Cost	Replacement Cost
a	Min	$200	$2,000
b	Max	$10,000	$20,000
c	Most likely	$1,000	$5,000
	Mean	$3,733	$9,000
	Variance	$4,935,556	$15,500,000
	St dev	$2,222	$3,937

The next component needed for the construction of the EV cost curve is the subjective probability of incurring cost after the initial expenses associated with restoring the plumbing system to functional operation. Each strategy will have a different probability over time as the likelihood for incurring an additional leak.

In Figure 3.2 below, suppose you have a plot of the future probability of a pinhole leak for each strategy, repair in red and replacement in blue. Each point on the line represents the probability of a leak in that specific year. The curves are increasing, as it is assumed that as the pipe ages the risk of a leak increases slightly in each time period, up until it reaches 100% which represents the end of viable life of the pipe material. The red line for repair presumably reaches the end of life (100% probability of leak in each year) sooner than that of the replacement strategy (blue line), since brand new pipes installed in this option will last longer.

Figure 3.2 – Example Cumulative Probability of Pinhole Leak in Each Year by Strategy



Before multiplying the cost in each future period by the probability measures in Figure 3.2, the cost is discounted to account for time value of money so that a cost far in the future is not as impactful as a cost closer to the current time period. For the purpose of this simple example, let us assume a rate of 3% in the discount rate formula.

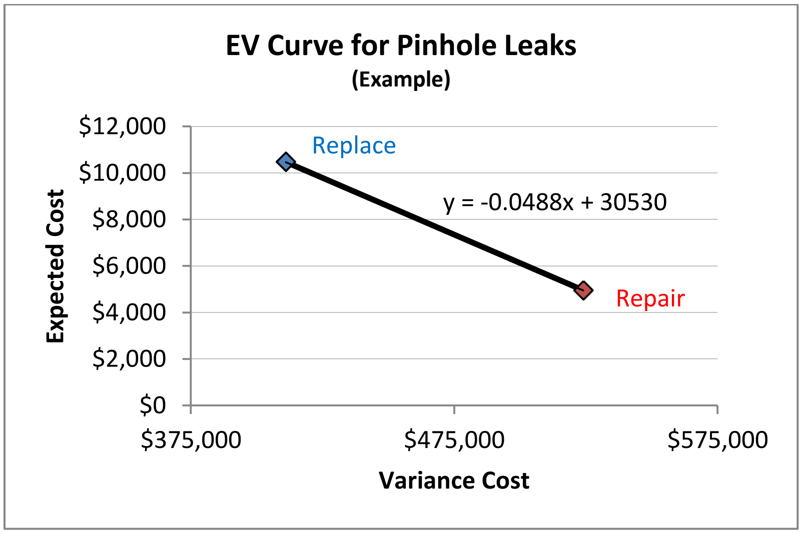
After the cost distribution, discount rate, and subjective probability curves for repair and replacement have been determined, the EV values are calculated in Table 3.2 below:

Table 3.2– Example of Two Asset Choice EV Sets

		Repair	Replace
a	Initial Cost (mean)	$3,733	$9,000
b	Future Cost Sum	$1,217	$1,466
	Expected Cost (a + b)	$4,950	$10,466
	Variance	$524,089	$411,081

The values for the E and V of each of the two choices (repair and replace) from Table 3.2 are plotted in Figure 3.3. The equation for the EV curve in the figure below is calculated by the slope of line (y2-y1/x2-x1) between the replace and repair points, with the intercept at x=0. The replacement strategy, when compared to repair, carries higher expected cost due largely to high initial costs but has a smaller variance since the new piping material presumably has lower chances of additional cost in the future. The repair strategy, by contrast, shows lower expected cost since replacing the 'parts' tends to be less expensive than the replacement 'whole', however it has higher variance since there is more uncertainty about costs in the future. The homeowner who chooses to repair may experience substantial future costs should pinhole leaks appear again in his/her existing pipe material.

Figure 3.3 – Example of EV Frontier of Two Discrete Asset Choices



The set of choices, here repair or replace plumbing, makes up the EV curve which is the frontier of possibilities that minimizes the homeowners' costs given their risk preferences. As discussed in Chapter 2 – 'Conceptual Framework', a replacement option (risk averse) has a higher expected cost, but lower variance due to the reduction in the probability of future leaks. The repair option (risk neutral) has less expected cost, mostly from today's cheaper expense, but carries a higher probability of future cost that results in the larger variance.

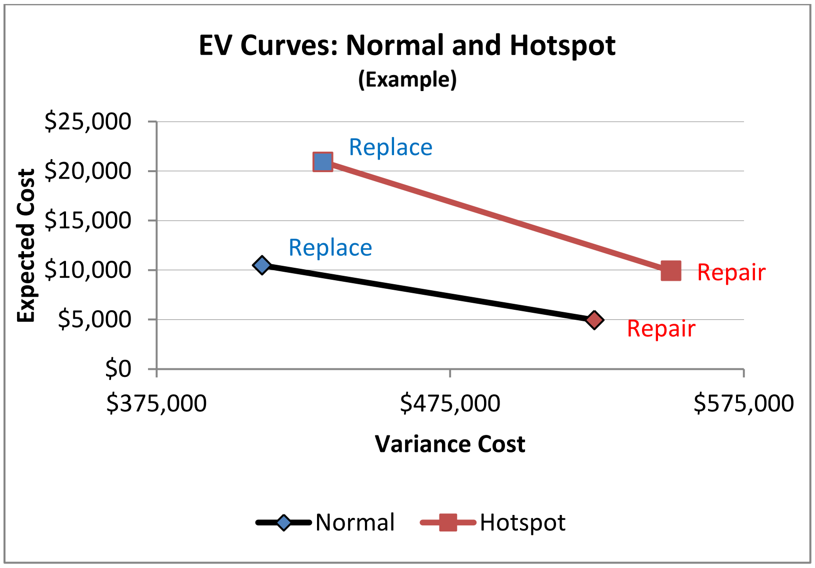
Finally, once the EV curve is plotted and the slope and intercept of the line are determined, the risk premium is measured for the risk averse option (the blue point marked 'Replace in Figure 3.3) as the certainty equivalent, Yce (which is the intercept) less the expected value of the risk averse choice (replacement) from Table 3.2. In this example, Yce – Expected Replace Cost is 30,530 – 10,466, or $20,064, which is the cost at which a homeowner would be willing to pay to avoid all risk of pinhole leaks, given the inputs in this example.

3.2.5.1. Example of Assessing Multiple EV Curves

Finally, the pinhole problem contains an additional geographic element existent in areas of higher pinhole leak occurrence, e.g. hotspots. As mentioned in chapter 1, these regions are: Sarasota, FL; Butler County, OH; Montgomery and Prince Georges County, MD; and the state of California. These hotspots are hypothesized to carry higher risk premiums and would represent a separate EV frontier than one for the rest of the U.S.

In Figure 3.4 below, the two example EV curves have been plotted, one for a 'normal' leak occurrence region in black and another for a hypothetical hotspot region, shown in red, that would have a higher likelihood of pinhole leaks. For the pinhole leak analysis, there are expected to be two mutually exclusive EV curves. Here, the hotspot curve acts an upward shift in the normal curve due to the increased likelihood of leaks in these areas.

Figure 3.4 – Example of Two EV Frontiers in Regions of Different Risk Levels



The shift in the hotspot EV curve is the result of a greater frequency of pinhole leaks at origination that yields more upfront costs, a higher distribution in costs overall, and a much greater probability of having a future leak. The two EV curves can be compared to estimate the increased risk premiums that hotspots have over more normal areas of pinhole leak incidence.

3.3 Data Sources

Two phone surveys were conducted by the Center for Survey Research (CSR) at Virginia Tech: the National Homeowners Survey (Willis-Walton, 2006a) and the National Plumbers Survey (Willis-Walton, 2006b). A total of 780 completed homeowner survey responses and 880 completed plumbers' survey responses were gathered for the pinhole leak study as shown in Table 3.3.

Table 3.3 – Completed Telephone Surveys for Pinhole Leak Data Sample*

Region	Homeowners Survey	Plumbers Survey
Sarasota, Florida	109	36
Butler, Ohio	109	79
California	109	53
Rest of U.S.	453	712
Total	780	880

*Telephone survey funded through American Water Works Association Research Foundation, conducted by Virginia Tech Center for Survey Research (CSR), 2006.

The full sets of questions used in these surveys are presented in the appendix:

- Appendix 1 - National Homeowners Survey (Willis-Walton, 2006a)
- Appendix 2 - National Plumbers Survey (Willis-Walton, 2006b)

3.3.1. Phone Survey Methodology

Data for the homeowners' survey was collected by CSR staff members utilizing a Computer Assisted Telephone Interviewing (CATI) system for making telephone calls. All calls for the final phase of data collection (after pre-testing) were made during the period between September 30, 2006 and November 22, 2006 (Willis-Walton, 2006a).

Willis-Walton describes the phone number selection for the homeowners' survey as:

> "A random-digit dialing (RDD) sampling methodology was employed by the CSR for the administration of the homeowners' survey. Phone numbers included both listed and unlisted numbers. The surveys sampled more heavily in three hotspot regions: South – Sarasota, Florida; West – California; Midwest – Butler County Ohio." (Willis-Walton 2006a, p. 2).

Additionally, a survey was conducted of the nation's plumbers that asked among other questions: how often their firm repaired pinhole leaks; the location within the home and cost of pinhole leaks; the material most often repaired; their estimation on when a future leak would likely occur for a homeowner who chose to replace their plumbing (which was most often plastic). This survey was conducted by the Virginia Tech Center for Survey Research using the CATI system (after pre-testing) during the period between February 16, 2006 and April 04, 2006.

The identification of plumber's to survey was more complex than the random telephone number selection in the homeowners' survey. Willis-Walton describes their approach below:

> "A randomized list sampling technique was employed by the CSR for the administration of the survey. The CSR purchased access to InfoU.S.A./ReferenceU.S.A.™ business databases and then developed database search parameters to select records for plumbing businesses throughout the United States and in the geographic areas targeted for the study. Business SIC codes and yellow page headers were utilized to isolate all records under the general heading of "plumbing." Then records were grouped by the individual geographic areas targeted for the studies and then randomly selected from among the following sub-headings: plumbers, plumbing engineers, advanced plumbing, plumbing contractors, budget plumbing, and plumbing specialties. Cases for the United States sample were selected by the CSR using systematic randomization. Specifically, cases were selected randomly based on the total number of available records for the United States utilizing the eligible population as defined.
>
> The sampling design entailed a stratified sampling component in which areas identified by the Non-Uniform Corrosion in Copper Piping Assessment project team as having pinhole leaks were over-sampled, or over-represented in the sample. This stratification procedure ensured that not only would the survey yield nationally representative data from the cross-section of plumbers selected from the available records on the listing database, but that surveys would also be completed in disproportionately high numbers in targeted geographic areas deemed to be pinhole leak "hot spots." The four areas selected for disproportionate sampling were: South – Sarasota, Florida; West – California (entire state); Midwest – Butler and Hamilton County Ohio.
>
> A census of all available records in Sarasota, Florida and Butler County, Ohio were selected from the listing database by CSR for use in the study. Within Hamilton County, Ohio only the areas closest to Butler County were selected due to reports from the consulting engineers on the study that plumbers in this area were likely to have direct knowledge of the disproportionately high number of pinhole leaks being reported in adjacent areas." (Willis-Walton 2006b, p.2).

The randomly selected respondents to the surveys are assumed to represent the total U.S. pinhole leak population. This survey gathered information on homeowners' (detached single-family homes) pinhole leak expenses, damages, time spent dealing with leaks, and leak incident rates.

3.3.2. Survey Data Pinhole Leak Responses

Due to the nature of telephone surveying, a higher number of calls were made to ensure a large enough sample of completed surveys was collected. For example, to obtain the 780 homeowners and 880 plumbers response data-points used in this study, 2,789 and 2,763 calls had to be made to homeowners and plumbers, respectively. Below table 3.4 shows the response values for the homeowners and plumbers survey after excluding non-working numbers, hearing/language barriers, or residents not 18 years or older.

Table 3.4 – Total Calls Made for Survey Data Collection

Response Disposition	Homeowners Survey	Plumbers Survey
Reported No Leak	697	274
Reported Pinhole Leak	83	606
No Answer, Voicemail, > 12 dials	986	1,366
Refused Participation	1,023	517
Total Calls	2,789	2,763

For the homeowners' survey, out of 780 respondents who completed the survey 83 reported a pinhole leak while 697 had no pinhole leak. Of those 83 homeowners with at least one pinhole leak, 49 were in a hotspot region and 34 from the rest of the US.

For the plumbers' survey, out of the 880 completed surveys, 606 had experienced some work with pinhole leaks while 274 had never had work related to pinhole leaks. Of those 606 who had some work with at least one pinhole leak, 116 were in a hotspot region and 490 from the rest of the US.

Data from these two surveys provide information that will be used to generate the three major inputs to the EV model: probability of future leaks, average cost to repair or replace plumbing, and standard deviation of leak costs. Furthermore, the data on hotspots will be used to derive an EV cost frontier to test the hypothesis that risk premiums are higher within these higher risk regions.

3.4 Calculation Procedure

'Calculation Procedure' will describe the specific steps of calculating the three major inputs to the EV set (π_i, μ_i, and σ_i^2) using two phone surveys which gathered information on homeowner pinhole leak spending and plumbers' expert opinion on future likelihood for pinhole leaks.

Due to the low amount of data on reported cost available in the hotspots, these regions are combined into one group for a more robust estimate of mean and variance of cost, as well as for a more complete comparison of hotspot regions to the rest of the U.S. The rationale for combining hotspot regions is that hotspot regions face similar amounts of cost and should be comparable to each other, while the 'rest of the U.S.' group is distinctly different.

3.4.1. Null Response Imputation

For the Homeowners survey, whenever a question choice of DK, 'don't know', or RF, 'refused' was selected by the respondent, the regional average response in the survey for that question was substituted for that absent data as an imputation method.

3.4.2. Cost Derivation from Survey Data

The cost data available from the homeowners' survey provides information to compute the mean and variance of costs for repair and replacement by the two regions: hotspot and rest of the US. Survey data on cost was collected by asking respondents which range of values represented the costs they expended to repair pinhole leaks. This study used the midpoint value of each respondent's answer as described below.

3.4.2.1. Normalizing Survey Responses to Common Time Period

Responses to the survey indicated a year for the pinhole leak occurrence (Homeowner Survey Question #8). Assuming that the costs quoted by the homeowner in the remainder of the survey also occurred in that year, then the combination of all homeowner costs requires that nominal reported costs be converted to dollars of constant purchasing power. This procedure takes into account cost inflation over the years. This study used the Consumer Price Index Inflation Calculator (CPI, 2016) from the Bureau of Labor Statics to convert all reported costs to 2016 dollars. If the year of the first leak was reported 'unknown' by the homeowner then 2006 was used as the incident date and cost was then inflated to 2016. In the cases where the first year of leak was unknown but a time span of leak occurrences was reported, the reported time span was used to determine the initial year of leaks. For example, a homeowner did not recall what year the first leak occurred but reported their leaks happened over 10 years, then the first leak occurrence was assumed to be in 1996 (2006 – 10). The costs estimates provided by the homeowner were then inflated 20 years to be in 2016 dollars.

3.4.2.2. Normalizing Cost Given Variable Number of Leaks

Some homeowners reported their total costs for more than one leak. To normalize this cost, a cost per leak was calculated. (Homeowners Survey Question #9) Respondents reported number of leaks as a range: 1-2, 3-4, 5-6, 7-10, and more than 10. Midpoint number of leaks refers to the midpoint of the selected range. If respondents reported more than 10 leaks but did not give an exact number, the number was set at 12. If the respondent reported having pinhole leaks but did not know the amount, then 2.5 was used as this represents a conservative estimate between the first and second choice midpoints 1.5 and 3.5, respectively. This midpoint number of leaks is used in each of the cost components in the sections below.

3.4.2.3. Materials and Labor Cost

(Homeowner Survey Question #21) Respondents reported the amount of money spent on repairs as a range: less than \$100; \$100 to \$500; \$501 to \$1,000; \$1,001 to \$3,000; \$3,001 to \$5,000; and more than \$5,000. The midpoint of the selected range was used as the respondent's cost. If the homeowner selected more than \$5,000 then they provided a specific amount, which was used directly.

Equation 3.8 below shows the pipe repair costs per pinhole leak which is the survey midpoint for each respondent individual *i* times an inflation index (Appendix 3) to normalize costs to the current time value divided by the midpoint number of leaks from the survey which individual *i* selected in the survey.

Equation 3.8

$$\text{Repair Cost Per Leak}_{\text{i}} = \frac{\text{midpoint repair cost}_{\text{i}} * \text{inflation index}}{\text{midpoint \# leaks}_{\text{i}}}$$

The table below shows what the average repair cost per leak was for respondents in each region according to the survey responses.

Table 3.5 – Average Pipe Repair Costs per Leak from Survey Responses

Region	Average Pipe Repair Cost per Leak
Sarasota, FL	\$ 932
Butler, OH	\$ 185
California	\$ 395
Rest of US	\$ 292

3.4.2.4. Non-Pipe Damages Cost

Non-Pipe damage cost ((Homeowner Survey Question #23) is the midpoint of the range of damages selected by the respondent: less than \$100; \$100 to \$500; \$501 to \$1,000; \$1,001 to \$3,000; and \$3,001 to \$5,000. If less than \$100 was selected, cost was set at \$50. For more than \$5,000, the specific amount was used. There were no respondents who selected more than \$5,000 and did not specify an amount. If the respondent indicated there were non-pipe damage costs, but did not know the specific amount, then a regional average was used.

Equation 3.9 below shows the non-pipe repair damage costs per pinhole leak which is the survey midpoint for each respondent individual *i* times an inflation index (Appendix 3) to normalize costs to the current time value divided by the midpoint number of leaks from the survey which individual *i* selected in the survey.

Equation 3.9

$$Damage\ Cost\ Per\ Leak_i = \frac{midpoint\ damage\ cost_i * inflation\ index}{midpoint\ \#\ leaks_i}$$

The table below shows the average per leak damage costs to non-pipes, such as walls or floors, for respondents in each region according to the survey responses.

Table 3.6 – Average Non-Pipe Damage Costs per Leak from Survey Responses

Region	Average Damages Cost per Leak
Sarasota, FL	$ 963
Butler, OH	$ 454
California	$ 1,099
Rest of US	$ 48

3.4.2.5. Time Cost Spent Attending Pinhole Leaks

Time cost accounts for the value of time spent on attending to the repairs and fixing damages caused by leaks, which could otherwise be spent at work earning wages or other activities that have value. Time cost estimation combined a homeowner's reported hours spent on pinhole leaks and household income with BLS statistics on average workers per household to estimate an hourly cost of time per pinhole leak.

Hours spent dealing with leaks was reported by respondents to the homeowners' survey (Homeowner Survey Question #25). Respondents reported amount of time spent on leaks as a range: less than 10, 10-20, 21-40, 41-80, and more than 80. Midpoints of the indicated ranges were used to assign a specific number of hours. When respondents answered "more than 80 hours" were spent dealing with pinhole leaks, but did not give a specific number, the number of hours was set at 100. For respondents reporting less than 10 hours, an estimate of 5 hours was used.

The equation below shows total time in hours each survey individual *i* spent per leak on attending pinhole leak repairs.

Equation 3.10

$$Hours\ Spent\ Per\ Leak_i = \frac{midpoint\ total\ hours\ spent\ on\ leaks_i}{midpoint\ \#\ leaks_i}$$

The table below shows the actual average number of hours that people spent attending leaks according to the survey responses.

Table 3.7 – Average Hours Spent Repairing a Pinhole Leak from Survey Responses

Region	Average Hours Spent on Pinhole Leaks
Sarasota, FL	25.00
Butler, OH	7.50
California	37.50
Rest of US	23.18

Respondents selected one of the following ranges for household income (Homeowners Survey Question #37): less than $25,000, $25,000-$35,000, $35,000-$45,000, $45,000-$55,000, $55,000-$75,000, $75,000-$100,000, and more than $100,000. The midpoint of the selected range was used as family income. For Income "< $25,000" then $16,000 was used as the midpoint income. For respondents answering 'more than $100,000' for family income, income was set at $120,000. If respondents did not give a value for household income, income was set at the median income of the region based on Census estimates (U.S. Bureau of Census 2016), shown in the table below.

Table 3.8 – Median Income Used For Unreported Homeowner Income

Region	Census Median Income
Sarasota, FL	$ 52,036
Butler, OH	$ 58,890
California	$ 59,581
Rest of US	$ 53,281

To calculate an hourly value of time per household, this study used the total household income reported by respondents in the survey divided by an estimated number of hours worked per household in a year. The number of hours worked per household, which was not asked in the survey, was estimated using data from the Bureau of Labor Statistics (BLS) and US Census was used for the inputs in Equation 3.11 below.

Equation 3.11

$$Total\ Hrs\ per\ Household = Worked\ Hrs\ Per\ Person\ *\ (\#Workers\ Per\ House * \%\ Who\ Work)$$

The BLS reported that in 2015, the average total hours worked per day by "Employed persons who worked on an average day" for those age 15 years and over was 7.6 hours per day in a 7 day work week (BLS Average Hours Worked, 2015.), with an average of 8 hours on weekdays and 5.6 hours on weekends. The 7.6 hours per worker in a 7 day week is extrapolated to 2,766 hours a year (7 days a week * 52 weeks a year).

The US Census reported that the average number of adults per household, age 18 and over was 1.94 people in 2016 (US Census Households, 2016). Finally, using the BLS total number of full time employed workers, age 16 and over, in 2016 was 123,761,000 out of a total labor force of 153,007,000 (BLS Employed Workers, 2016). This means 81% of workers had full time jobs. In Table 3.9 below, these inputs are combined using Equation 3.11 to estimate the number of hours worked in a year for each household.

Table 3.9 – Estimated Hours Worked Per Year per Household

Input	Value
Number of Hours Worked Per Person - Per Day [1]	7.6 Hours
Number of Hours Worked Per Person - Per Year	2,766 Hours
Number of Adults per Household [2]	1.94 People
Percentage of Full-Time Employed Adults [3]	81%
Estimated Household Hours Worked Per Year	**4,341 Hours**

Finally, the time cost per leak of each respondent *i*, shown below in Equation 3.11, is measured as the household income divided by the average number of household hours worked per year, multiplied by the hours spent per leak (from Equation 3.10).

Equation 3.12

$$Time\ Cost\ Per\ Leak_i = \frac{Reported\ Household\ Income_i}{4{,}341\ Household\ Hours\ a\ Year} * \ Hours\ Spent\ Per\ Leak_i$$

The table below shows what the average time cost per leak was for respondents in each region according to the survey responses.

Table 3.10 – Average Time Costs per Leak from Survey Responses

Region	Average Time Cost per Leak
Sarasota, FL	$ 173
Butler, OH	$ 63
California	$ 210
Rest of US	$192

1 BLS Average Hours Worked, 2015. https://www.bls.gov/news.release/atus.t04.htm

2 US Census Households 2016. https://www.census.gov/hhes/families/data/cps2016AVG.html

3 BLS Employed Workers, 2016. https://www.bls.gov/cps/cpsaat08.htm

3.4.3. Probability Estimation

The probability distributions for the EV cost model are derived using survey data. The first is the plumbers survey which is used to calculate the probability of future leaks given pipe replacement ($\pi_{replace,t}$.) Since the EV model can use subjective probability based on expert opinion (Anderson and Dillon, p. 41), the plumbers are assumed to have more expert information than the homeowners do on probability of leaks in pipes after installation. In the plumbers' survey, they were asked specifically for their estimate on when a future leak would occur for homeowners who chose to replace their entire home plumbing with new pipes after the occurrence of a pinhole leak. Unfortunately, the plumbers were not asked a similar question about their expectation on a future pinhole leak for those homeowners who did not replace their entire pipe systems and only selected a simple fix. Therefore, to estimate $\pi_{repair,t}$, leak incident rates are derived from the homeowners' surveys.

3.4.3.1. Probability of Repair after Replacement

Plumbers were asked "On average, after replumbing, does it generally take six months, one year, two years, three years, four years, or five years or more before leaks begin to occur again?" (Plumbers Survey Question #12). If they specified any amount of years, their answers were coded as a 1, meaning a leak will occur within the lifetime of the pipe. If they said 'never', their answers were coded as a 0, interpreted as never to occur in the lifetime of the pipe material. The probability of a leak occurring is calculated as the plumbers' response rate for each time t:

Equation 3.13

$$\pi_{replace,t} = \frac{\sum_{i,t} Respondents\ with\ Leak_{i,t}}{Total\ Number\ of\ Survey\ Respondents}$$

3.4.3.2. Step-by-Step Procedure for Probability of Repair after Replacement

In this analysis, the reported probability curve was derived using smoothing to improve statistical quality as mentioned by Chavas. The five steps below demonstrate how the subjective probability curves were derived using the plumbers' survey data.

Step 1 – Response Rates were tallied between US and Hotspots

For the first step in this procedure, the plumbers' responses are tallied for question 12 in the plumbers' survey as the numerator of Equation 3.13 above. Table 3.11 below shows the results of this summary, where the total number of respondents who indicated that the next pinhole leak would be likely to occur in the specified number of years after a homeowner replaced all their plumbing with new ones.

Table 3.11 – Plumbers' Opinions of Next Leak Occurrence if Replaced Plumbing

Next Leak Will Occur in:	Hotspot Respondents	US Respondents
6 Months	1	7
1 Year	1	10
2 Years	1	1
3 Years	0	7
4 Years	4	6
5 Years	2	9
6 Years	3	2
7 Years	1	3
8 Years	0	1
10 Years	3	10
11 Years	0	1
12 Years	0	1
15 Years	0	8
20 Years	3	9
25 Years	0	1
27 Years	0	1
30 Years	1	4
40 Years	1	1
5 or More Years, but Not Specified	*2*	*18*
Never Again	55	289
Total Responses*	**78**	**389**

**Excluding plumbers who did not respond or indicated 'did not know'*

Step 2 – Distribute the 'More than 5 Years, but Not Specified'

Since a few plumbers gave a more generalized answer for when the next leak would likely occur with "5 or More Years, but Not Specified", these responses provide value but need to be assigned to the spread of responses. In this procedure, these responses were spread proportionally by the percentage of plumbers who provided a specific number of years for five or greater years to next leak.

For example, in the hotspot region there were 2 plumbers who indicated '5 or More Years, but not specified', meaning they believe a leak would definitely occur 5 years from now or afterward. In addition, 14 plumbers provided a specific year they expected the next pinhole leak to occur 5 years from now or afterward. Two plumbers indicated 5 years exactly (from Table 3.11 above), which represent 14.29% (2/14) of all respondents who indicated the next leak to be in '5 or more years'. So, of the two respondents who chose '5 or More Years, Unspecified', 0.3 would be applied to the Year 5 total (2 * 14.29% = 0.3). This amount is added to the original responses to be a new total of 2.3 respondents in the 5 years total for when the next leak will occur. Table 3.12 below shows the outcome of this process for all years of specifically reported years until the next pinhole leak.

Table 3.12 – Plumbers Opinion of Next Leak Occurrence if Replaced Plumbing with Distributed Response Rates '5 or More Years Unspecified'

Next Leak Will Occur in:	Hotspot Respondents	US Respondents
6 Months	1	7
1 Year	1	10
2 Years	1	1
3 Years	0	7
4 Years	4	6
5 Years	2.3	12.2
6 Years	3.4	2.7
7 Years	1.1	4.1
8 Years	0	1.4
10 Years	3.4	13.5
11 Years	0	1.4
12 Years	0	1.4
15 Years	0	10.8
20 Years	3.4	12.2
25 Years	0	1.4
27 Years	0	1.4
30 Years	1.1	5.4
40 Years	1.1	1.4
Never Again	55	289
Total Responses*	**78**	**389**

**Excluding plumbers who did not respond or indicated 'did not know'*

Step 3 – Group Counts into Intervals, Since Individual Years have Sparse Data

As mentioned in Section 2.1.4, to improve the statistical quality of a probability estimate (Chavas, p. 13), smoothing can be used. Since there were some missing years for the next likely pinhole leak per the plumbers' responses, the timeframe is not uniformly reported. This creates difficulty for measuring the expected cost and variance, which use a sum component for future cost for each year to the end of life of the pipe. To account for this non-uniformity, responses were grouped into more evenly distributed intervals, demonstrated in Table 3.13 below.

Table 3.13 – Grouped Plumbers Opinion of Next Leak Occurrence if Replaced Plumbing

Leak within	Hotspot Respondents	US Respondents
0 to 5 years	9.29	43.18
6 to 10 years	8.00	21.65
11 to 15 years	NULL	13.53
16 to 20 years	3.43	12.18
21 to 25 years	NULL	1.35
26 to 30 years	1.14	6.76
31 to 40 years	1.14	1.35
Never	55	289
Total Responses	**78**	**389**

**Excluding plumbers who did not respond or indicated 'did not know'*

Step 4 – Convert Response Counts to a Percentage and Impute Missing Values

Next, the response counts were converted to percentages using Equation 3.13, where the respondent total in each interval was divided by the total responses. For example, in hotspots the response rate for having a leak within the first 5 years after replacement is 11.90%. (9.29 / 78).

Not every time interval could have a percentage calculated for it based on response counts. There were two groups in Table 3.13 that had gaps in reported years from the plumbers: '11 to 15 years' and '21 to 25 years'. For additional smoothing, these NULL values were imputed as the halfway point between the preceding and subsequent response percentages. For example, the missing '11 to 15 years' likeliness of a leak becomes (10.26% + 4.4%)/2 = 7.33%. The results of this process are summarized in Table 3.14 below.

Table 3.14 – Percentage of Plumbers Response on Next Leak Occurrence for Replaced Plumbing with Imputed NULL Values

Leak within	Hotspot Response Rate	US Response Rate
0 to 5 years	11.9%	11.1%
6 to 10 years	10.26%	5.56%
11 to 15 years	7.33%	3.48%
16 to 20 years	4.4%	3.13%
21 to 25 years	2.93%	0.35%
26 to 30 years	1.47%	1.74%
31 to 40 years	1.47%	0.35%
Never	70.51%	74.29%

**Imputed values shown in red*

Step 5 – Distribute Leak Rates Evenly to Each Individual Year

The final step for the probability smoothing process is to evenly distribute the leak rate in each interval to an individual year. For example, within the first interval group for hotspots, '0 to 5 years' has an 11.9% response frequency which then would become 2.38% in each of the first five years (11.9%/5 = 2.38%). Below is a demonstration:

11.9% Cumulative Likelihood in 5 years:

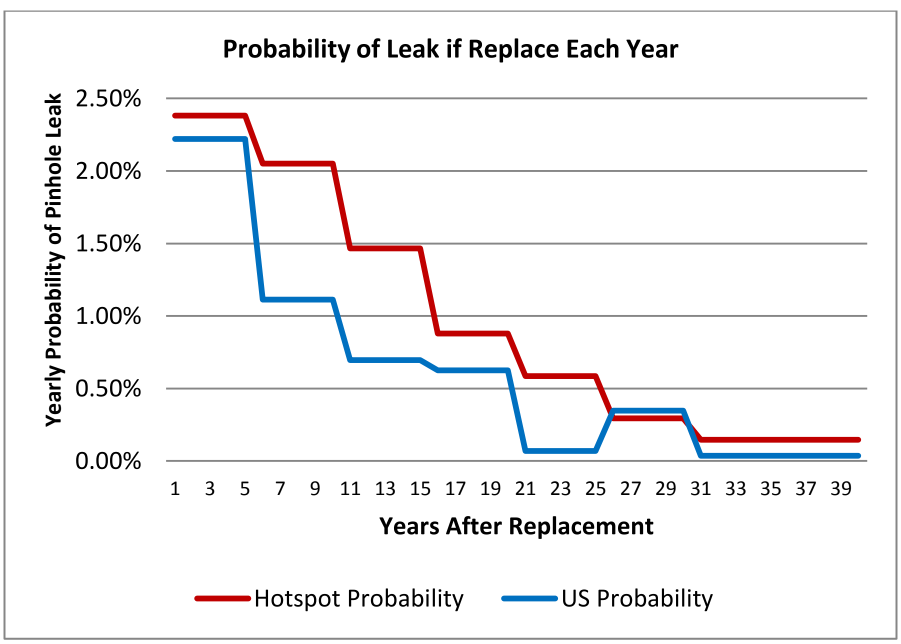
Leak within	Hotspot Response Rate
0 to 5 years	11.9%

Becomes 2.38% Each Year:

Leak in Year	Hotspot Probability
1	2.38%
2	2.38%
3	2.38%
4	2.38%
5	2.38%

Performing this operation for all response rates creates a stepwise looking probability curve for each region as shown in Figure 3.5 below, which plots the subjective probability of a leak occurring in each year after replacement of plumbing based on the expert opinion of plumbers. Although the hotspot rates are slightly higher than the US probability curve, as expected, both curves are downward sloping with declining probabilities, which is counterintuitive to the conceptual model developed.

Figure 3.5– Subjective Probability Distribution of Next Leak if Replacement



The reasoning for this downward probability curve is not known, one explanation for the declining probabilities is a view by the plumbers of pinhole leaks being a temporary condition that they do not expect to last for more than 15 years. Another explanation could be the wording of the question, which asked only when ‘the next’ leak would occur where the plumbers may expect leaks to continue in the future but were most likely to occur sooner rather than later, hence more responses in the first 5 years. A sensitivity analysis is performed later, in Section 4.9 that tests the impact of reinterpreting this question to having a “reoccurring” leak every x years. This would result in an increase in the probability over time, with more weight being given to years when the reoccurrence of leaks in earlier time periods would compound with responses in the later years.

Although there is no indication that pinhole leaks are a short-term problem, the EV cost model is still functional under a set of declining probabilities. It also accounts for the likelihood of multiple leaks in the future by using the probability in each time period multiplied by cost and summed up over the lifetime of the pipes, here 40 years.

3.4.3.3. Probability for Repair if Only Fixing Segment

To estimate the probability of future leaks after a repair of an individual leaking segment of pipe, $\pi_{repair,t}$, the homeowners survey data was used, since the plumbers’ were not asked about their opinion on when the next pinhole leak would occur after repair. Homeowners were asked “Approximately how many pinhole leak incidents have you had in your home? Would you say you’ve had pinhole leaks: 1 to 2, 3 to 4, 5 to 6, 7 to 10, or more than ten times?” (Homeowner Survey Question #9). The midpoint number of leaks reported by homeowners was used. If respondents reported more than 10 leaks but did not give an exact number, the number was set at 12. If the respondent reported having pinhole leaks but did not know the amount than 2.5 was used since this represents a conservative estimate between the first and second choice midpoints 1.5 and 3.5, respectively.

Homeowner response rates were measured to estimate the percentage of people affected by leaks. Respondents were split into two groups: the first were those who responded with closer to a ‘singular leak’ answer (Q9 choice A: ‘1 to 2 leaks’); the second were those with multiple leaks (Q9 all other responses with a leak indicated). This calculation is shown in the equation below:

Equation 3.14

$$Multiple\ Leaks\ Response\ Rate = \frac{\sum_{i,t} Respondents\ with\ Multiple\ Leaks_i}{Total\ Number\ of\ Survey\ Respondents}$$

This formula can also be applied to singular leaks and no leaks. Table 3.15 below shows the response rates for these different leak rate groupings. Hotspots did carry a higher likelihood of a leak for both singular and multiple leak respondents groups. Overall, the individuals in a hotspot region have a 4.9% chance of having multiple pinhole leaks, while 2.4% in the rest of the U.S. had a chance of multiple pinhole leaks.

Table 3.15 – Leak Incident Rates by Region

Number of Leaks	Hotspot	US
Respondents with a Single Leak (Between 1 and 2)	33 (10.1%)	20 (4.4%)
Respondents with Multiple Leaks (More Than 2)	16 (4.9%)	11 (2.4%)
Respondents with No Leaks	278 (85%)	419 (93.2%)
Total Respondents*	**327**	**450**

**3 respondents were dropped who reported a leak but did not indicate the number of leaks.*

Unlike in the plumbers' survey which asked the likelihood of a leak in a given year, the multiple leaks rate in Equation 3.14 accounts for leaks over all time periods. In order to control for the many years of leaks reported by the respondents, an annualized number of leaks must be calculated for those who experienced multiple leaks.

Homeowners also were asked "In approximately what year did you first have a pinhole leak or small hole in your drinking water pipes? (Homeowner Survey Question #8) Using this year of the first leak answered in this question by the homeowner up until the year of the survey in 2006, gives the length of exposure to pinhole leaks. If the homeowner did not know or provide a year of first leak, the observation was dropped from the probability estimation procedure. Combined with the number of multiple leaks reported by each homeowner, the leaks per year can be calculated for each individual *i* in the survey in Equation 3.15.

This calculation was only performed for respondents with multiple leaks. The calculation below represents a weighting factor to adjust leak response rate by region so that "repair choice" homeowners who risk a future leak aren't solely assessed on the probability of the next pinhole leak event, but also its severity in terms of the number of leaks that may show up with their next appearance.

Equation 3.15

$$Multiple\ Leaks\ per\ Year_i = \frac{Midpoint\ \#\ Leaks\ [for\ Multiple\ Leak\ Responses]}{Years\ of\ Leak\ Exposure}$$

For example, if a homeowner first experienced leaks in 2001, which is an exposure period of 5 years, with a total of 10 leaks during that time, then the leaks per year is 2 (10 leaks / 5 years). This homeowner multi-leak frequency was then averaged for respondents in the US and hotspot regions. The results of this leak severity weighting as shown below, indicate on a per year frequency the US has slightly less than one per year and hotspots slightly more than one per year.

Table 3.16 – Homeowner Multiple Leak Frequency

Region	Avg. Leaks Per Year
US	0.93
Hotspot	1.04

Multiple leak response rates as well as multiple leaks per year are used in estimating the probability of a future leak given repair, since homeowners selecting this strategy have already been exposed to at least one leak and are betting on a probability of having an additional leak in the future. Unlike homeowners who re-plumbed their home with a new material, repair owners have the same susceptibility to pinhole leaks in each year, ceteris paribus (e.g. water treatment and other conditions remain the same). Therefore, these probability inputs are held static over the 40-year time frame in the future cost estimate. Using these two inputs, the probability of a future leak given repair, can be calculated as:

Equation 3.16

$$\pi_{repair} = Multiple\ Leaks\ Response\ Rate * \ Average(Multiple\ Leaks\ per\ Year)$$

The calculation above estimates the probability for a future leak in the US given the repair strategy to be 2.3% (2.4% * 0.93) per year, while those in hotspots have a 5.1% (4.9% * 1.04) probability of having a leak in each year for a repair strategy.

3.4.4. Discount Rate for Future Costs

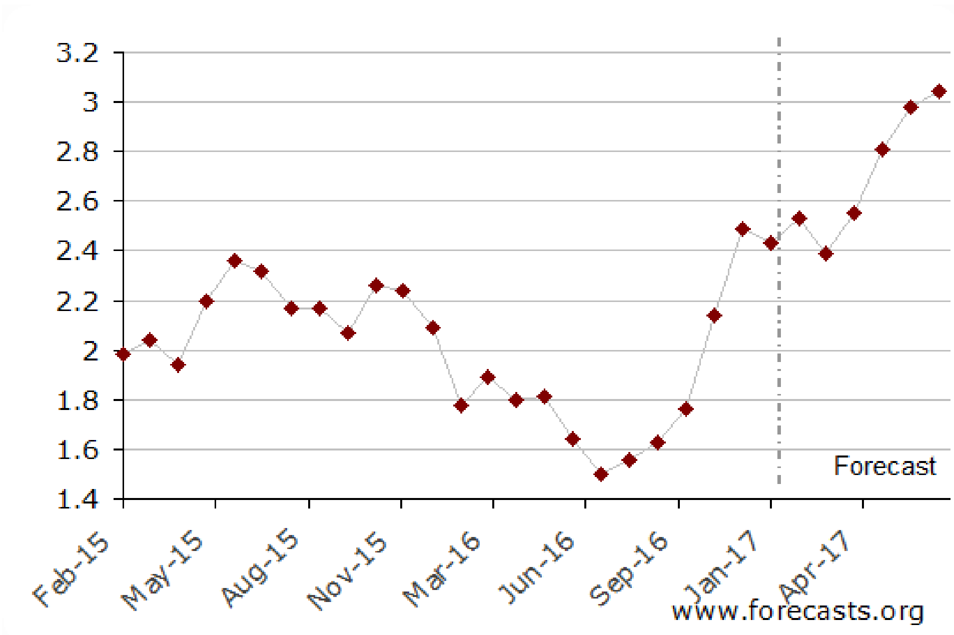
After the average cost per leak for repairs has been calculated for both the US and hotspots, it is then projected each year in the future before multiplying by the probability of the event happening. This cost is discounted by a risk-free rate as described in section 3.2.2:

$$\text{Real Risk Free Rate } (\mathrm{R_f}) = \frac{(1 + \text{nominal risk free rate})}{(1 + \text{inflation rate})} - 1$$

The nominal risk-free rate can be represented by a US treasury bill which is nearly risk-free. In Figure 3.6 below, the forecasted US treasury bond yield with 10 year maturity is projected to be at 3%. This is rate will be used as the nominal risk-free rate in the discount rate:

Nominal risk free rate = 3%

Figure 3.6 – Forecasted Percent Yield on U.S. 10-Year Treasury Securities Average by Month



(http://www.forecasts.org/10yrT.htm)

The next component in calculation of the risk-free discount rate is a forecasted inflation rate. A 2% long term rate is used in this study, which is the long-term projected goal of the Federal Open Market Committee which consists of twelve members including the seven members of the Board of Governors of the Federal Reserve System who oversee US monetary policy (Fed Reserve 2016). “On its latest meeting, in December 2016, the Federal Open Market Committee expressed an expectation that inflation in the US will rise to the long-term target of 2 percent over the medium term (in 2018-2019 years).

The Committee considers that a higher inflation rate is not consistent with the Federal Reserve’s mandate for maximum employment and price stability. Currently, US inflation is below this 2 percent target, even though it increased by about 1.1 percentage points from 0.1 percent in 2015 to around 1.2 percent in 2016.” (FOMC 2016).

Inflation rate = 2%

Therefore, the risk-free rate of pinhole leaks, shown in Equation 3.16, is 0.98%.

Equation 3.16

$$R_f = \frac{(1 + 0.03)}{(1 + 0.02)} - 1 = 0.98\%$$

Thus, the discount rate becomes:

Equation 3.17

$$Risk\ Free\ Discount\ Rate = \frac{1}{(1 + 0.98)^t}$$

This risk-free rate is used to discount the expected cost of an additional leak over a 40 year time period to be consistent with the range of the probability estimates provided by the plumbers in the plumbers survey.

3.4.5. Testing for EV Sufficient Conditions

In Section 2.2.2, three sufficient conditions for EV modeling were mentioned, of which one must hold one to justify the use of this modeling approach. Briefly, these conditions were:

1. Quadratic utility function of investors
2. Normality of the distributions specified by their expected values and variances
3. Asset choices have the same type of distribution but only vary in regard to location (mean) and scale (variance)

The first two conditions were noted to be quite restrictive (Robinson and Barry, p.6). Therefore, the third condition on location and scale will be tested to evaluate the appropriateness of the EV cost model for pinhole leaks since it is the least restrictive condition. To satisfy the LS condition, the distributions of observed cost data of each asset choice are compared and must have the same distribution but are allowed to differ in mean and variance.

To test the LS condition, Meyer and Rasche use the Kolmogorov-Smirnov (KS) multi-sample test which they “suggested as the best available alternative when examining for the location and scale condition” (Meyer and Rasche, p. 92). This KS test is measured by use of the D statistic, which is the “maximum difference between any pair of k empirical distribution functions (EDFs) formed from k sample” (Meyer and Rasche, p. 95).

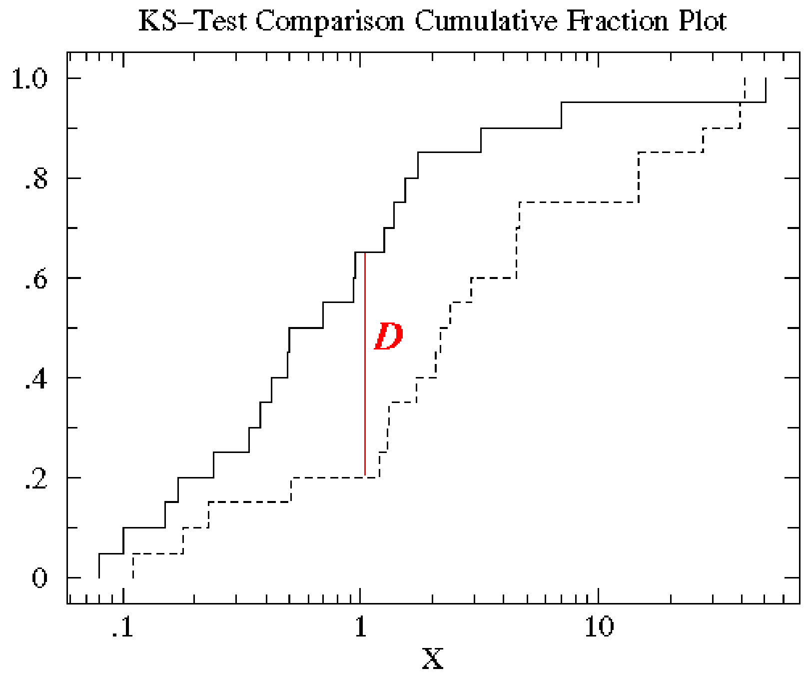
According to the National Institute of Standards and Technology, “some general purpose statistical software programs support the Kolmogorov-Smirnov goodness-of-fit test” (NIST - KS test, 2016). The Kolmogorov-Smirnov (KS) test statistic is defined (NIST – KS test, 2016) in Equation 3.18 below:

Equation 3.18

$$D = \max_{1 \le i \le N} \left(F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i) \right)$$

The D-statistic in the KS test will measure the maximum difference between two empirical distribution functions, which are the distribution functions associated with the empirical measure of the sample. This cumulative distribution function is a step function that jumps up by 1/n at each of the n data points (Kirkman, 1996). In Figure 3.7 below, the D-statistic, shown in red, is the largest difference between two cumulative distribution functions represented in the cumulative fraction plot (Kirkman, 1996).

Figure 3.7 – Example of KS D-Statistic Comparison



(Kirkman, 1996)

The null hypothesis of the KS test is that the two distributions are the same (NIST – KS Test, 2016). To meet the LS condition, the separation between the cost distribution for each asset choice in a cumulative fraction plot should have a D-statistic with a corresponding p-value that is <u>not</u> significantly different, in other words a high p-value at least > α=0.10. The p-value of the D-statistic can be determined by using a KS test statistics table, such as one shown by USF, by using the sample size N and the D-static value to identify the corresponding p-value (USF, 2017).

This paper utilizes an online software tool for the KS test, published by the physics department of the College of Saint Benedict and Saint John's University (Kirkman, 1996), which is an easy-to-use platform to input two data distributions and provides a simplistic summary page for interpreting the results of the test.

For the comparison of cost distributions between the repair and replace choices in the EV set, the KS test requires a minimum of 10 observations in each data set (Kirkman, 1996). When the homeowner survey data is stratified into US and hotspot regions, the quantity of US replacement observations does not meet this threshold, with only five homeowners indicating a replacement choice. Therefore, the repair and replacement datasets for the US and hotspots are combined into their respective strategies before administering the test. Since mean and variance differences are allowed under the LS condition, any shift in these statistics as a result of combining US and hotspot regions do not impact the KS test, where only the type of distribution is being measured. However, in order to normalize cost against a variable number of leaks, the cost per leak values are used in the repair and replacement distributions.

4. RESULTS

4.1 Overview

The methods described in this paper used a discrete choice EV cost methodology to determine risk premium estimates for pinhole leaks, both in high-leak incident 'hotspot' areas, as well as non-hotspots in the rest of the U.S. The two major options available to homeowners with pinhole leaks are to repair or replace their drinking water plumbing system, which can be categorized as a risk neutral or mildly risk averse strategy preference and a more risk-averse strategy preference, respectively. In a two-asset choice model, such as this one, the conservative lower bound risk premium for all homeowners who choose to replace is estimated to be $54,148,258 nationally. This is 9.6% of the national $563 million annual homeowner cost reported by Bosch and Sarver 2006.

Chapter 3 described how survey data were used in the estimation of the inputs for the EV cost model for both the US and pinhole leak hotspot regions. The survey data used in this study also confirm the existence of pinhole leak hotspots as reported in other studies. This is shown in Table 4.1 in terms of both number of respondents with leaks and the percentage out of the total number of respondents. Hotspot regions had a larger percentage of respondents with leaks, as well as a larger percentage of quantity of leaks per respondent; nearly double that of the rest of the US.

Table 4.1 – Proof of Hotspots: Leak Rates by Regional Group

Region	US	Hotspot
Respondents with No Leaks	419 (93.1%)	278 (85%)
Respondents with Leaks	31 (6.9%)	49 (15%)
Quantity of Leaks (% per respondent)	81.5 (18.1%)	121 (37.0%)
Total Respondents*	450	327

**3 respondents were dropped as reporting a leak but not indicating the amount*

4.2 Cost Distribution Results

Costs were measured as a combination of three factors: material and replacement of the pipe itself, non-pipe damages, and time costs spent handling pinhole leak problems. The variation of costs among homeowners created a distribution of cost. The mean and standard deviation of these costs were used as inputs in the EV cost model. The sections below show the results for the distribution of initial upfront costs to restore pipes and future repair costs.

4.2.1. Total Costs Distribution for Initial Cost

In Table 4.2 below, mean and standard deviation for the total cost of initial repairs is shown by each region and corresponding strategy. These values are used for the input in the initial cost component of the EV model calculation. The results show that the repair strategy in the rest of the U.S. has the lowest average cost and tightest standard deviation. The replacement strategy in hotspot regions had the highest average cost and widest standard deviation.

Table 4.2 – EV Inputs for Initial Costs

Average Initial Cost By Region / Repair Strategy	US, Repair	US, Replace	Hotspot, Repair	Hotspot, Replace
MEAN (μ_i)	$ 1,211	$ 2,129	$ 2,345	$ 5,378
Standard DEV (σ_i)	$ 1,278	$ 2,782	$ 2,405	$ 6,640

In Figures 4.1 A and 4.1 B, the distribution of costs is shown for the US and hotspots, which have been binned to more easily show the graphical shape of responses reported by homeowners (each respondent had reported a unique total cost value comprised of pipe damage, non-pipe damage, and time cost). Note that there were not many observations gathered on pinhole leak cost, just 83 out of 780 (approximately 10%), which also had to be split into regions.

Figure 4.1 A-US Cost Per Leak Distribution

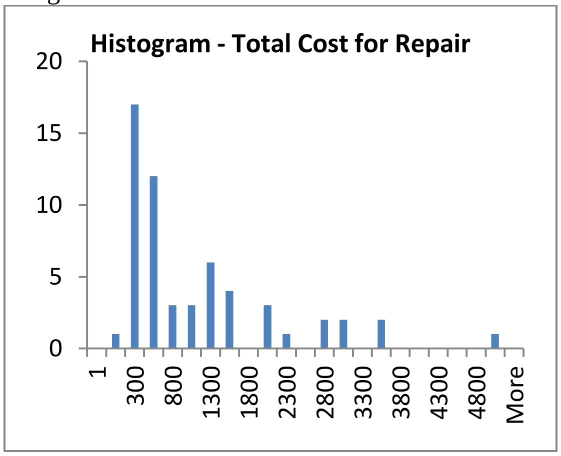
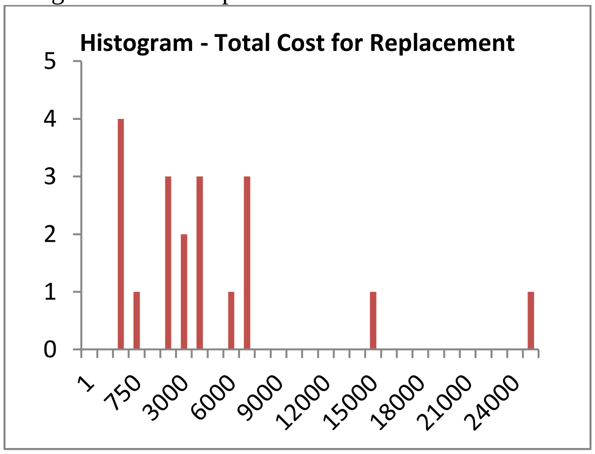


Figure 4.1 B-Hotspot Cost Per Leak Distribution



4.2.2. Cost per Leak for Future Cost

In Table 4.3 below, the mean and standard deviation for the cost per leak is shown by each region. These values are used as input for the EV model for future cost projections that are discounted and multiplied by the subjective probability of a leak. The results show that the repair strategy in the rest of the U.S. has a lower average cost per leak than hotspot regions.

Table 4.3 – EV Inputs for Future Repair Costs in Cash Flow

Average Cost Per Leak	US, Repair	Hotspot, Repair
MEAN (μ_i)	$ 623	$ 1,172
Standard DEV (σ_i)	$ 815	$ 1,083

Below in Figures 4.2 A and 4.2 B are the binned cost distributions for costs per leak by region.

Figure 4.2 A-US Cost Per Leak Distribution

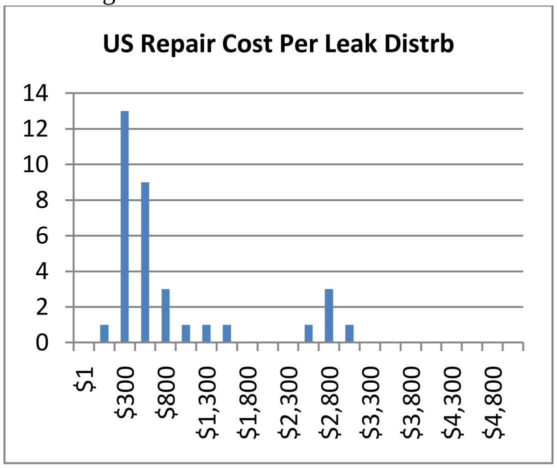
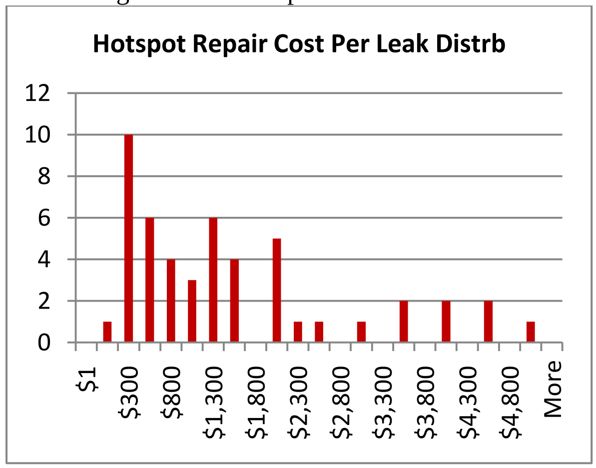


Figure 4.2 B-Hotspot Cost Per Leak Distribution



4.2.3. Testing for Location-Scale Condition

To evaluate the appropriateness of the EV cost model for pinhole leaks, the third condition for location and scale was used since it is the least restrictive condition. This condition was evaluated by calculating the D statistic in the KS test that measures the similarity of the distributions between two asset choices, as mentioned in Section 3.4.5. The repair and replacement datasets for the US and hotspots are combined into their respective strategies before administering the test to meet minimum data sample requirements. Below in Figures 4.3 A and 4.3 B are the binned costs distributions for costs per leak by repair strategy.

Figure 4.3 A-Repair Cost per Leak Distribution

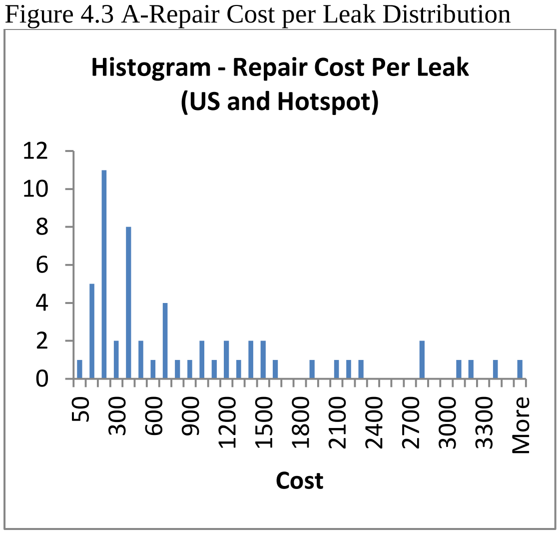
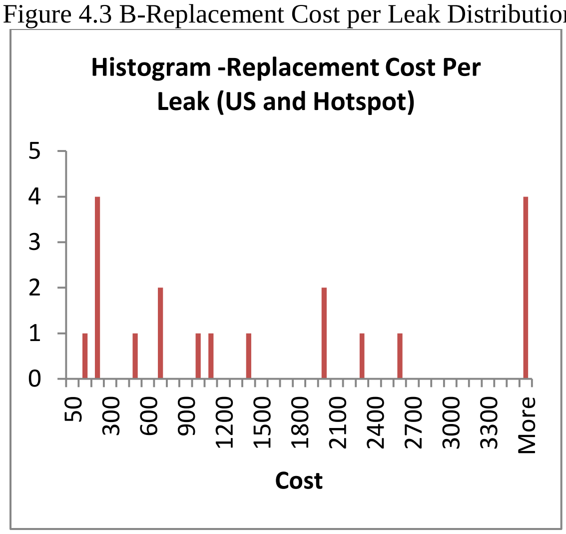


Figure 4.3 B-Replacement Cost per Leak Distribution



First, the LS condition looks for distributions that are equal except for location (mean) and scale (variance). To test for a difference in means (location), a two-sampled z test was performed. The z-test was selected since the distributions are most likely not normal given the shape of the histograms in Figures 4.3 A and B, whereas a t-test would require normal distributions. The results of this test are shown in Table 4.4 below. At the top of the table are brief summary statistics of the mean, variance, and number of observations for each set. The hypothesized mean difference was approximated to the difference in mean cost per leak (1,627 – 912 ≈ 700). The z values below and corresponding p-value (P(Z<=z)) for one of two tails measures how much separationthe distributions have given some overlap in cost amounts. The results for the two-tail test in the table below show a strong statistical difference (<0.001) between mean strategy costs, thus location difference.

Table 4.4 – Statistical Test for Differences in Cost Distribution by Repair Strategy

z-Test: Two Sample for Means	*Repair Cost Per Leak*	*Replace Cost Per Leak*
Mean	$ 912	$ 1,627
Known Variance	$ 991,496	$ 2,356,988
Observations	57	19
Hypothesized Mean Difference	$ 700	
z	-3.76	
P(Z<=z) one-tail	0.0001	
z Critical one-tail	1.64	
P(Z<=z) two-tail	**0.0002**	
z Critical two-tail	1.96	

Next, to measure the similarity in distribution between repair and replace strategy, the KS test was administered using an online tool published by the physics department of the College of Saint Benedict and Saint John's University (Kirkman, 1996) since it provides an easy-to-use platform for comparing two distributions.

The results of the KS test using the CSB/SJU software found (Data Reference: 63C0):

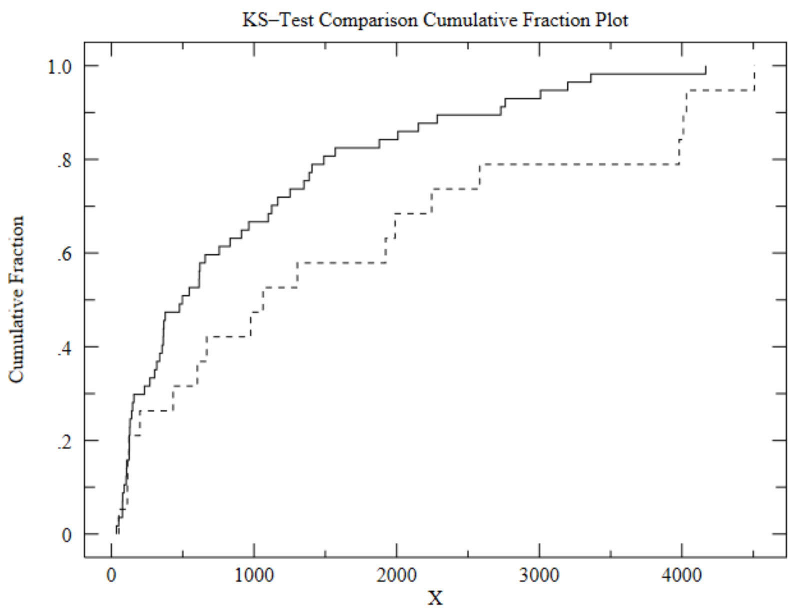
- The maximum difference between the cumulative distributions, D, is 0.2632 with a corresponding p-value of 0.237. Sample size takes on the lower of the two distributions set at N = 19.
- Repair Cost Distribution (Dataset 1):
    - KS says it's unlikely this data is normally distributed: P= 0.00 where the normal distribution has mean= 1359. and sdev= 1047.
    - KS finds the data is consistent with a log normal distribution: P= 0.56 where the log normal distribution has geometric mean= 451.9 and multiplicative sdev= 3.403
- Replacement Cost Distribution (Dataset 2):
    - KS finds the data is consistent with a normal distribution: P= 0.29 where the normal distribution has mean= 1858. and sdev= 1588.

- KS finds the data is consistent with a log normal distribution: P= 0.76 where the log normal distribution has geometric mean= 738.0 and multiplicative sdev= 4.893

The D-statistic above of 0.2632 and corresponding p-value of 0.237 indicate the null hypothesis of similar distributions cannot be rejected. Therefore, the LS condition is satisfied for the pinhole leak cost data when comparing the repair and replacement strategies. The analysis also indicated that the repair cost distribution was lognormal and did not satisfy the assumption for normality. However, the normality condition is not required given the LS condition is already satisfied for justification of the EV approach.

Finally, the CSB/SJU software provides graphical comparisons plots of the repair and replace distribution that show their close relationship that is not statistically significantly different, seen in Figure 4.4 below.

Figure 4.4 – Cumulative Fraction Plot between Repair and Replace Distributions of the KS Test



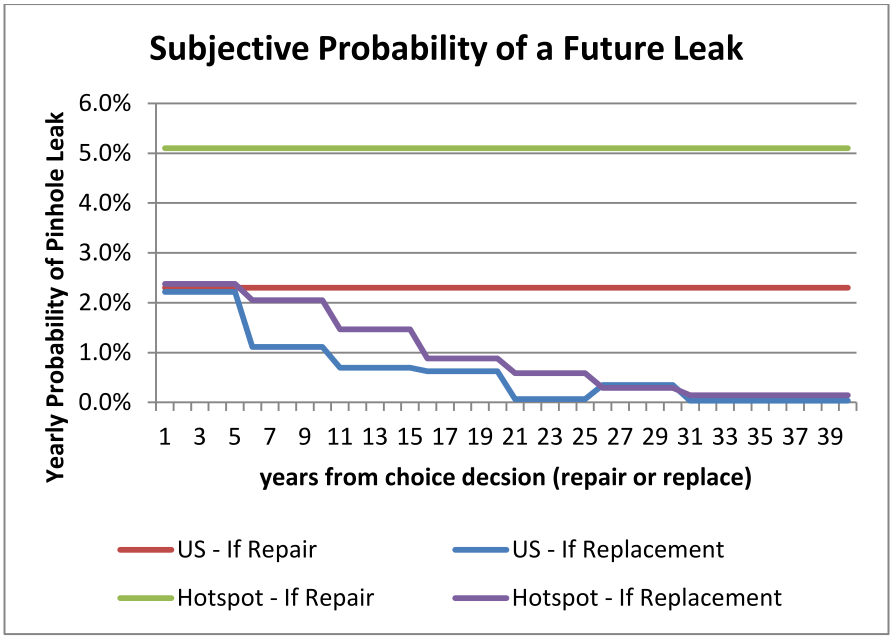
(CSB/SJU software: Analysis Results Data Reference 63C0)

4.3 Probability Curve Results

The figure below shows the relationship of the probability curves between each repair strategy and region. Repairing in a hotspot yields the riskiest probability at 5.3%, while replacing plumbing in either region significantly reduces the likelihood of pinhole leaks, with the "US replace plumbing" strategy having the lowest probability.

The initial repair probability of the US (the red line) has a similar probability to the replacement strategy for the first five years, but the benefits of pipe replacement eventually take over to reduce the chance of leaks in years 7 to 40.

Figure 4.5 – Probability Curves for Repair Strategy in EV Cost Model



4.4 EV Cost Calculation Results

The tables below contain the results of the total expected cost and variance, EV sets, for the US and hotspot regions. These values were produced by using the cost distributions and probability estimates derived from the homeowners and plumbers surveys.

In both regions, the expected cost of replacement is higher than that of repair, largely driven by the upfront costs to remove and install new piping material. However, we also see in both regions a significant reduction in the variance of cost for replacement. This lower variance reflects the lower probabilities of leaks that may give rise to structural damage, health issues, and other costs in the future.

Table 4.5 – EV Results for US

	EV Set - US	Repair Segment	Replace Plumbing
a	Initial Cost (mean)	$1,211	$2,129
b	Future Repair Cost * Prob	$473	$146
	Expected Cost (a + b)	$1,684	$2,275
	Variance Cost	$419,851	$142,995

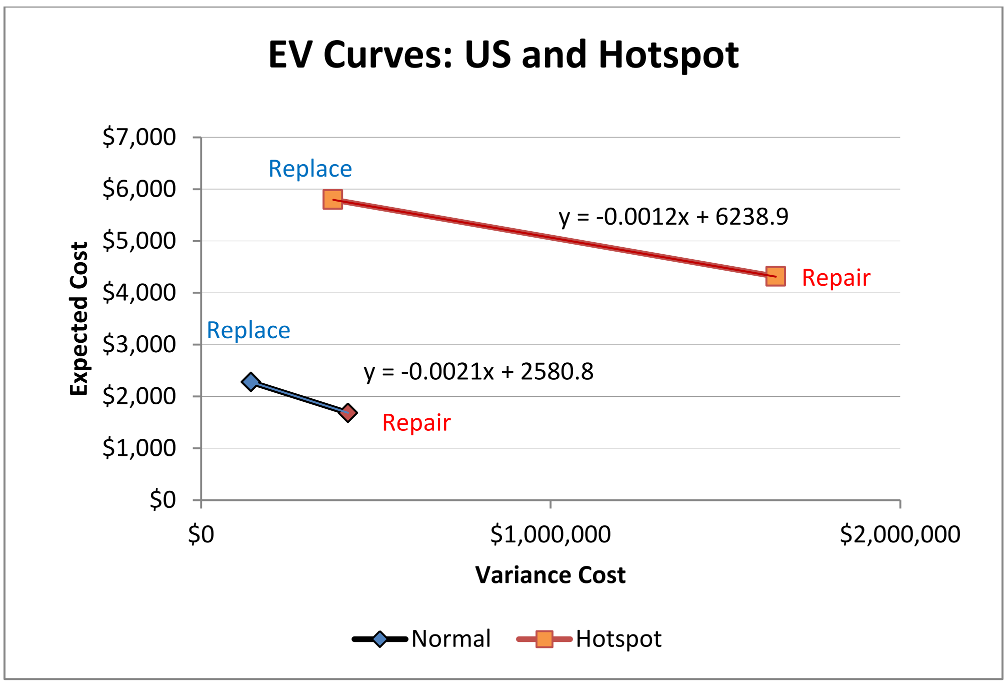
Table 4.6 – EV Results for Hotspot

	EV Set - Hotspot	Repair Segment	Replace Plumbing
a	Initial Upfront Cost (mean)	$2,345	$5,378
b	Future Repair Cost (mean) * Prob	$1,970	$418
	Expected Cost (a + b)	$4,314	$5,796
	Variance Cost	$1,644,098	$378,008

4.5 EV Cost Curves

The figure below plots the EV sets from Section 4.4 for the US and hotspot regions by repair strategy. The results show that the EV cost frontier formed the discrete choices available to homeowners in each region. The hotspot EV cost frontier appears as an upward shift to that of the US curve, which indicates the higher expected costs and variances due to the greater probability of a leak.

Figure 4.6 – EV Cost Curve Results for US and Hotspot Regions



4.6 Certainty Equivalent Estimation

The table below shows the linear function describing each region's EV curve. The intercept of this curve on the y-axis is the certainty equivalent, which represents the cost a homeowner is willing to pay to be risk-free of pinhole leaks. Hotspot owners have a higher cost they are willing to pay than that for the US, due to their higher expected costs whether repair or replacement option is selected.

Table 4.7 – EV Curve Regression Line Values

Equation for EV Curve	Slope(x)* Variance	Intercept (Yce)	Expected Values Repair	Replace
US	-0.0021	$2,580.80	$1,684	$2,275
Hotspot	-0.0012	$6,238.90	$4,314	$5,796

4.7 Risk Premiums

The risk premium, defined as Yce – E(x), was calculated for each region and repair strategy. As mentioned in Section 2.2.1, risk premiums for points on the discrete EV cost curve can take a range of values since different levels of homeowner risk aversion can reside on a point if the tangent of their utility curve is greater or less than the slope of the EV curve.

Because the discrete choice EV curve can be based on different levels of homeowner's preference for risk aversion, a range of risk premiums theoretically exists for each decision point. However, since the risk-preferences of the homeowners are not exactly known, the minimum risk premium value is calculated by extending the EV curve to its intersection with the y axis, which yields the certainty equivalent for the risky decision. The risk premium is estimated as the difference between the certainty equivalent and the expected cost of the replacement option. This also is the threshold value between the asset choices where less risk averse individuals who would seek a lower risk premium would switch to the repair option, which would also be chosen by risk neutral individuals. As mentioned before, since these two types of homeowners (modestly risk averse and risk neutral) cannot be distinguished based on the data, a risk premium of zero is assumed for all those choosing the repair strategy.

Table 4.8 below shows the results of the risk premium calculation for the replacement strategy. This is a conservative estimate, since more risk-averse homeowners would be willing to pay more, but no other asset choice exists with lower variance. The risk premium for the US is $305, while the hotspot regions have higher risk premiums of $442 indicating the amount they would be willing to pay to be risk free of pinhole leaks

Table 4.8 – Risk Premiums for EV Cost Curves

Region	Risk Premiums
US	$ 305
Hotspot	$ 442

4.8 Impact of Risk on National Pinhole Leak Cost

Homeowners in the United States, homeowners lose an estimated $563 million per year due to pinhole leaks (Bosch & Sarver 2006). However, this direct cost estimate did not account for the cost of risk to homeowners. In order to analyze the impact of risk and the number of national homeowners subject to the risk premiums in Table 4.8, an estimate of the number of homeowners choosing to replace is calculated.

The table below shows the breakdown of repair strategy choices by homeowners from the survey data. While most choose to repair, a higher percentage are opting to replace all of their plumbing after experiencing a pinhole leak.

Table 4.9 – Survey Results on Homeowner Repair Strategy Choice

Region	Pct. Who Indicated They Replaced Pipe
US	15%
Hotspot	29%

To extrapolate the risk premiums for pinhole leaks to a national level, these repair strategy percentages are applied to the number of homes estimated to experience a pinhole leak each year as presented by Bosch and Sarver (Bosch and Sarver 2006).

Table 4.10 – Estimated Number of Homes Experiencing Leaks Each Year

Total homes	Sarasota	Butler	Calif	Maryland*	Rest of US
Estimated number of homes with leaks per year	25,276	682	1,401	119,854	791,018

**Maryland is one of the hotspots and must be included in the national estimate*

Using the survey results on the percentage of homeowners choosing each repair strategy multiplied by the total number of homes experiencing a pinhole leak each year (Table 4.9* Table 4.10) yields the national approximate number of homeowners that choose each strategy.

Table 4.11– Estimated Number of Homes that Replaced Plumbing

Region	Est. Homes that Replaced
US	116,326
Hotspot	42,061

Next, multiplying the risk premium ranges for each strategy (Table 4.8) by the estimated number of homes to potentially elect that strategy (Table 4.11) results in an annualized risk premium amount. The repair strategy consists of risk neutral individuals to the weakly risk averse who have a risk premium of zero.

Table 4.12 – National Risk Premium Estimate

Region	Risk Premium Total
US	$ 35,536,751
Hotspot	$ 18,611,507
Total	**$ 54,148,258**

The total national risk premium for pinhole leaks is $54,148,258 (Table 4.12). This represents a conservative lower bound risk premium since the individual risk premiums in Table 4.8 represent the threshold value between risk neutral and risk averse. Some homeowners may have higher risk aversion levels, however in a two-asset choice model, their preference is not available, and so they would choose the option that offered the lowest variance, the replacement strategy.

Adjusting the $563 million annual 2006 homeowner cost reported by Bosch and Sarver to $692 Million in 2016 dollars, the national risk premium for pinhole leaks of $54 Million represents 7.8% of national cost homeowners would be willing to pay to avoid pinhole leaks.

4.9 Assessing Risk Aversion and Homeowner Strategy Selection

This paper conducted further analysis using the survey data to test whether homeowner strategy selection was based on risk preferences rather than other dominant factors such as pipe age or income. For those who opted for the risk averse strategy of replacement, it is important to analyze if their strategy selection was based on being able to more easily afford new pipes or if they selected to re-plumb on a view that their pipes had reached maturity and needed replacement rather than replacing due to the threat of additional leaks.

In terms of decision-making, the results found that 32% of homeowners in hotspot regions opt for the more expensive replacement strategy compared to 68% who opt for repairs. By comparison, just 16% in the rest of the U.S. opt for replacement versus 84% who opt for repairs (Homeowners Survey, Question 16). The reasoning behind their strategy selection was captured by the survey (Homeowners Survey, Question 17), which asked 'why' homeowners selected their strategy, which is shown in Table 5.1 below.

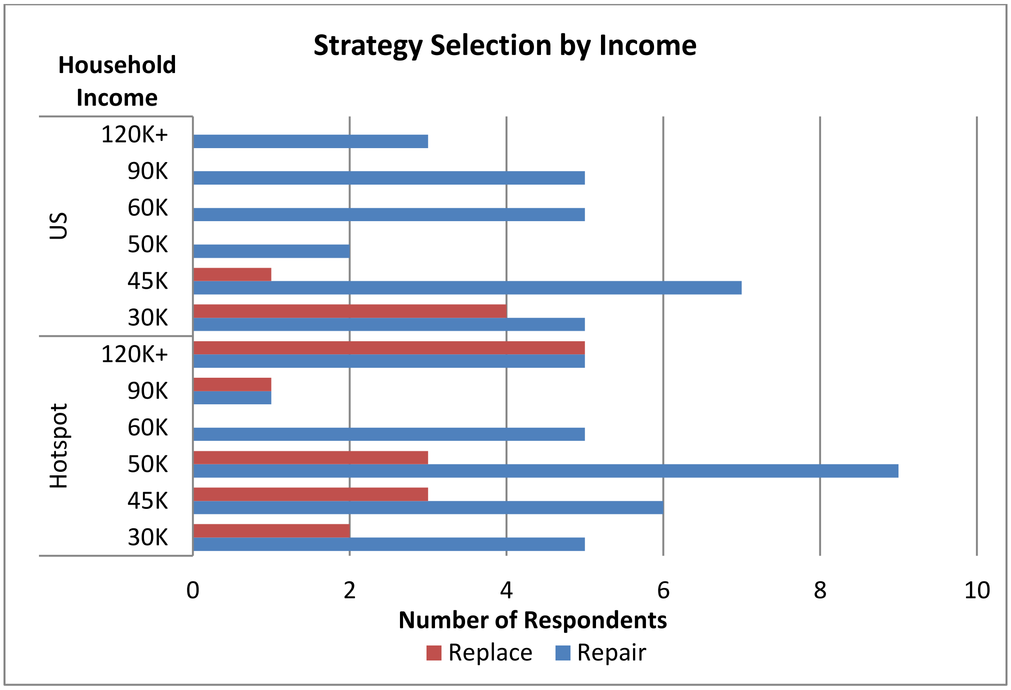
Table 4.13 – Count of Homeowners Indicating Reason for Strategy

Homeowner Reason for Strategy Selection (Q17)	US		Hotspot	
Strategy	Repair	Replace	Repair	Replace
Less Expensive	10	1	13	2
Less Time	1		2	
Less Disturbance	8		6	
Plumber Recommended	10	2	9	5
No Other Choice		1		4
Other (not mentioned by survey)	4	1	6	8
Grand Total	33	5	36	19

Homeowners' who chose the repair strategy, in both US and hotspots, indicated reasoning more closely related to risk aversion: 'less expensive', 'less time', 'less disturbance'. Alternatively, replacement strategists hardly indicated any of those reasons and instead favored the responses of 'no other choice' and 'other (not mentioned by survey'. Although their exact reason is not revealed by the answers, the homeowners who replaced clearly did not tend to the risk-averse ('less' expensive type) reason. Perhaps they could not indicate risk-aversion by the wording of the question. Another interesting response was the 'plumber recommended' choice. It is not clear from this answer what level risk-aversion preference the homeowners' had, however almost 30% of respondents selected this as their reasoning.

From an income perspective, an analysis found there was no monotonic relationship between higher levels of income and replacement selection in both hotspots and the rest of the U.S. Figure 4.7 shows the number of respondents in each region along with the level of reported household income. In this chart, replacement selection as a total percentage actually lean towards the lower income brackets, with 100% of U.S. replacers in the two lowest income categories and 57% of hotspot replacers in the three lowest income groups. Based on these results, risk-aversion seems more correlated with lower income. Perhaps lower income individuals are more affected by adverse cost events than higher income and thus tend to prefer "safer" strategies.

Figure 4.7 – Homeowner's Survey Strategy Selection by Income Level



Finally, this study looked at strategy selection in relation to the age of the pipe, where one might hypothesize that homeowners opt for replacement since their pipes had reached maturity and it was time to remove the old material and install brand new pipes. Homeowners were not asked in the survey about the age of their pipes, however they were asked the age of a home (Homeowners Survey – Question 1). The home age is not to be confused with their length of time the homeowners spent living in the home, since this value was obtained in a separate survey question (Homeowners Survey – Question 2). This study used home age as a proxy for pipe age, assuming most homes that were affected by pinhole leaks had copper pipes that were the original plumbing since copper material has a long life, sometimes up to 80 years.

An analysis found no relationship with replacement strategy selection and the home age, used as a proxy for the age of pipes. Figures 4.8 and 4.9 below plot the strategy selection of the hotspot and U.S. homeowners, respectively, and the reported age of their home. The charts show that replacement selection is not concentrated among older home ages, in fact some homeowners selected replacement in relatively new homes, like the one in 2003. Similarly, the pattern of repair is distributed among all ages and not concentrated into younger homes.

Figure 4.8 –Homeowner Survey Strategy Selection for Hotspots by Age of Pipe

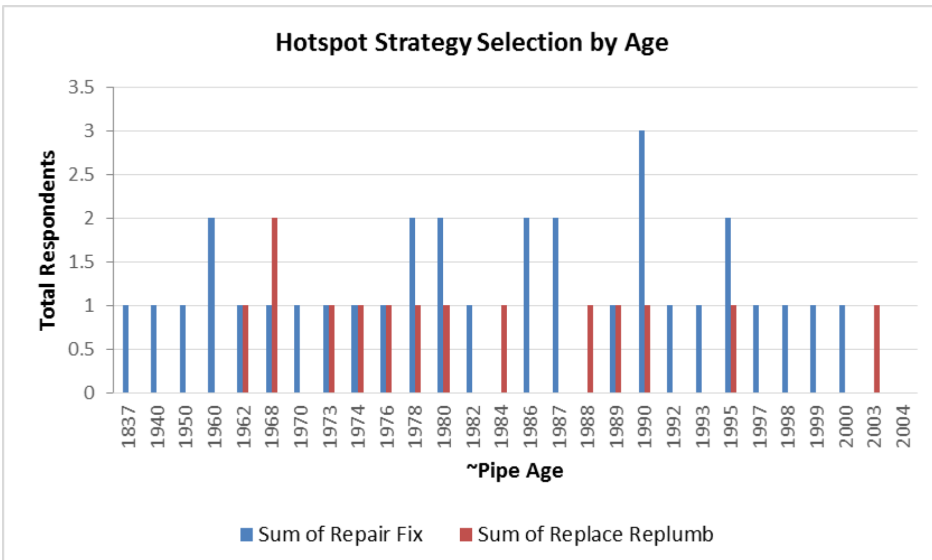
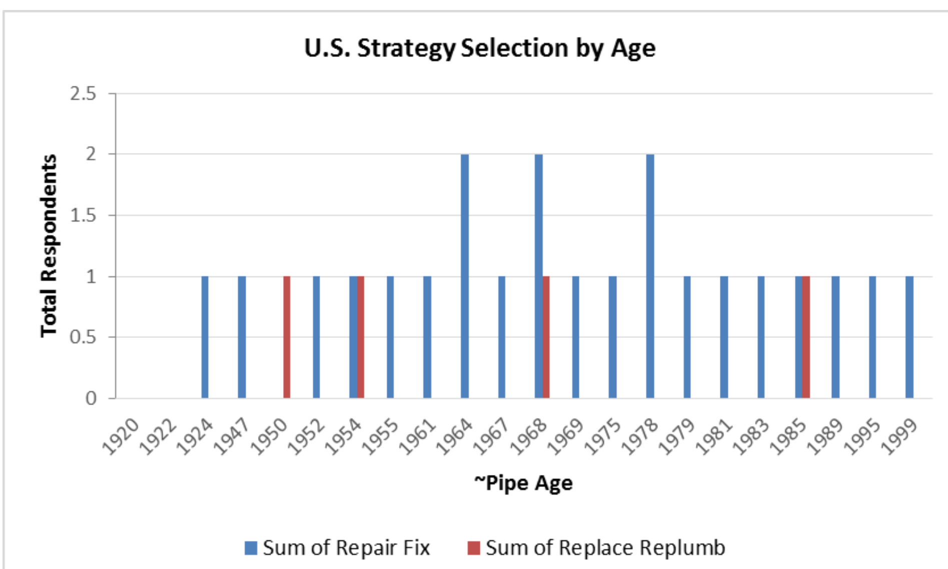


Figure 4.9 –Homeowner Survey Strategy Selection for U.S. by Age of Pipe



4.10 Model Performance

The EV cost model is sensitive to the value of the probability of leaks for repair or replace. Small changes in the probability of a future leak event have a large effect on cost since the probability estimate is applied to every time period when estimating the present value cash flow. If leak probabilities for repair exceed those of replacement up to a critical point, then the EV curve becomes flat or inverted in direction. When this happens, the expected cost for repair becomes equal to or greater than that of replacement and all risk averse and risk neutral individuals will prefer the replacement as the best option due to its lower variance.

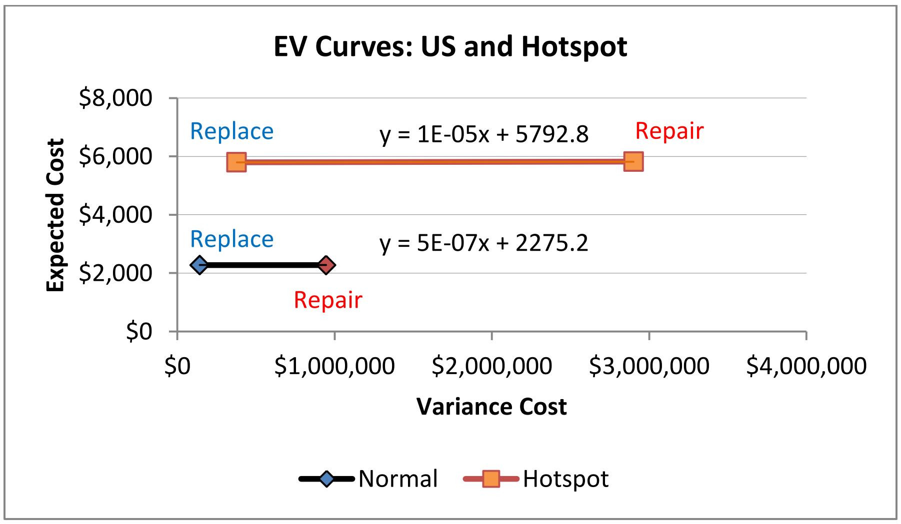
A sensitivity analysis on the repair probability, with all else being equal, found:

- With a +2.88% increase to the annual US repair probability to 5.18% likelihood of a pinhole leak each year, the EV curve flattens and all homeowners would prefer replacement over repair.

- With a +3.90% increase to the annual Hotspot repair probability to 9.00% likelihood of a pinhole leak each year, the EV curve flattens and all homeowners would prefer replacement over repair.

At these levels, the EV frontier becomes flat as demonstrated in Figure 5.1 below. In this scenario, replacement expected costs equal that of repair and all risk averse and risk neutral decision makers would choose to replace, as it is the lowest variance and equal or lowest expected cost. In order for the EV Cost model to perform under the conditions of this survey data, the repair probabilities must not exceed the values referenced above. An alternative set of survey data would have a different set of critical values for the model to be operational.

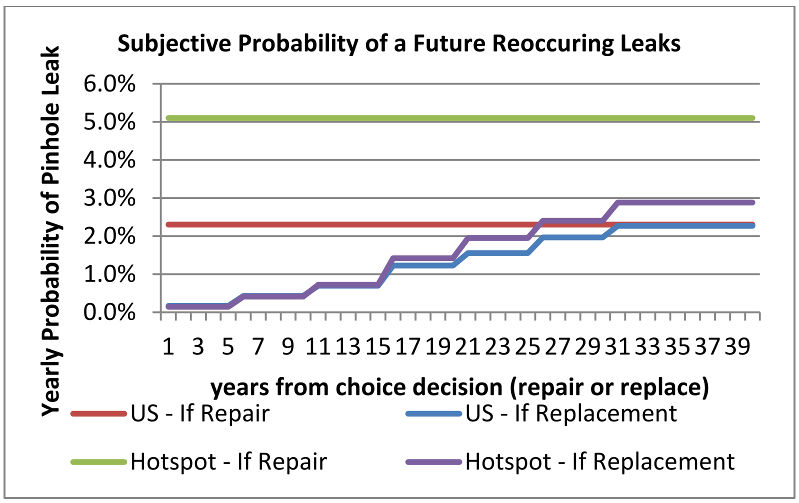
Figure 5.1 – Model Testing with Increased Repair Probability to the Critical Level



4.10.1. Sensitivity Analysis

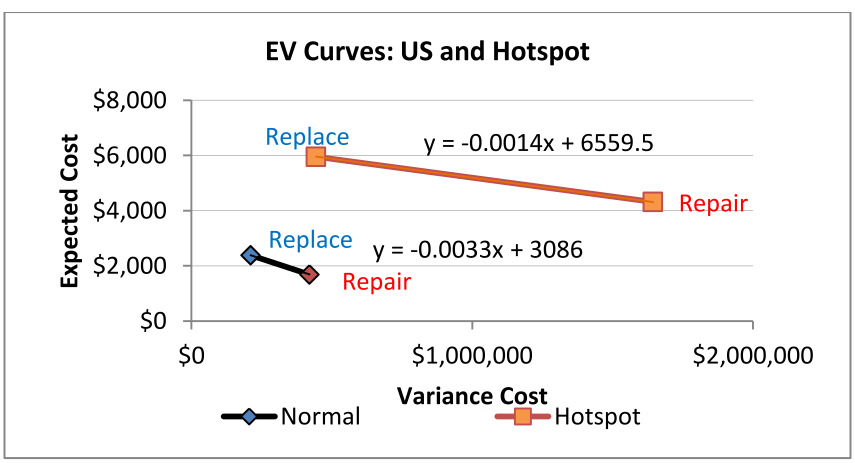
As mentioned in calculation procedures, Section 3.4.3.1 - Step 5, the probability curves for replacement were declining, which were counterintuitive to the conceptual model where the likelihood of a leak should increase with each passing year. These subjective probabilities are based on the plumbers' survey. If the question was reinterpreted to ask 'how often' would a homeowner have a leak after replacement, instead of only the 'next leak', then pinhole leak rates would be redistributed to later periods as a reoccurring event. The results of this conversion are shown in the probability curves in Figure 4.7 below. Note, the replacement probability curves are now step-wise increasing.

Figure 4.7 – Sensitivity Analysis of Reoccurring Replacement Probability



Increasing the later year probabilities of a leak for replacement has the effect of an upward shift in the expected cost of replacement. The EV curve in this scenario is shown in Figure 4.8. This results in a national risk premium of $107 Million, or 15% of total homeowner annual pinhole leak expenses, roughly double the original model results.

Figure 4.8 – Sensitivity Analysis Impact on EV Curves



5. Conclusions

Using a discrete choice EV cost model to measure the cost of risk for the national pinhole leak model provides insight into the risky choices homeowners undertake in terms of their plumbing systems. The data showed a downward sloping EV curve with an upward shift in the EV frontier for hotspot regions. The EV cost model was used to accomplish the objectives of the paper by assessing homeowner plumbing repair versus replacement decisions when faced with cost uncertainty and non-neutral risk preferences.

As stated in Chapter 1, the hypotheses for the objectives of this paper were to determine:

1. Based on the assumption that consumers are expected to behave as risk averse decision makers, it is expected that homeowner repair strategies will fit and EV cost framework where risk averse individuals' choice, *a*, represents an expected cost greater than those with a risk neutral, *n*, strategy, and the variance of the risk neutral option is greater than risk averse strategy for fixing pinhole leaks where:

    a. $E(cost_a) > E(cost_n)$ and

    b. $Var(cost_a) < Var(cost_n)$

2. Consumers in hotspot regions are expected to opt for more expensive replace versus repair decisions. This will be tested as a shift in the EV frontier for both risk averse *a* and risk neutral *n* such that:

    a. $E(cost_{a,\ hotspot}) > E(cost_{a,\ US})$ and

    b. $E(cost_{n,\ hotspot}) > E(cost_{n,\ US})$

The findings from the analysis results in Chapter 4 show that the repair and replace choices for remediating pinhole leaks conforms to the EV cost modeling framework, with a frontier that is downward sloping indicating a tradeoff between expected cost and variance of cost with an upward shift in the EV curve for hotspots.

For the US EV set, the expected cost for risk averse homeowners is the replacement strategy which is $E(cost_a) = \$2,275$. The risk neutral expected cost is that of the repair strategy $E(cost_n) = \$1,684$. This proves that hypothesis 1a, $E(cost_a) > E(cost_n)$, cannot be rejected.

In terms of variance, the US EV set found the risk averse replacement strategy variance of $Var(cost_a) = \$142,995$ and the risk neutral repair strategy variance $Var(cost_n) = \$419,851$. Thus hypothesis 1b, $Var(cost_a) < Var(cost_n)$, cannot be rejected.

When comparing the US to hotspot EV sets, the expected cost for risk averse homeowners is the replacement strategy which is $E(cost_{a,\ hotspot}) = \$5,796$. The expected cost for US risk averters mentioned above as the replacement strategy was $E(cost_{a,\ US}) = \$2,275$. Thus hypothesis 2a, $E(cost_{a,\ hotspot}) > E(cost_{a,\ US})$, cannot be rejected.

Finally, the hotpot EV set found the risk averse replacement strategy variance of $E(cost_{n,\ hotspot})$ = \$4,314 and the risk neutral repair strategy is that of the US above $E(cost_{n,\ US})$ = \$1,684. This proves hypothesis 2b, $E(cost_{n,\ hotspot}) > E(cost_{n,\ US})$, cannot be rejected.

Outcomes from testing these hypotheses reveal that higher expected cost and lower variance for the replacement decision demonstrate risk-averse preferences of the homeowners choosing the replacement strategy.

5.1 Recommendations

This study outlines what the expected costs and risks are to homeowners regarding pinhole leaks. One recommendation is for local water utilities to post information about the potential cost on their websites. This information would be beneficial to homeowner's and property owners for general awareness and financial planning. Armed with this information, it may be possible for a homeowner to save for a potential pinhole leak repair or pipe replacement as they do for other home assets like new roofing. This information could also be helpful to reduce anxiety about pinhole leaks. Some utilities, like the Washington Suburban Sanitation Commission in Maryland, readily share information about reported pinhole leaks on their website (WSSC, 2016).

Policy makers and water treatment utility managers can also gain valuable insight from this analysis. Another recommendation would be to implement local surveys to gather their residents' perceptions of pinhole leak risk. While this study focused on hotspots known at the time of the survey, there could be other regions with elevated costs and susceptibility to pinhole leaks.

Water treatment utility managers should consider the use of corrosion inhibitors for areas with elevated levels of pinhole leaks, as some already do (Bosch and Sarver, 2006). The use of corrosion inhibitors in the water line can reduce the chemical interactions with copper pipes that form pinhole leaks.

Policy makers should also consider the laws governing the liability of pinhole leaks. In almost every state, the homeowner is responsible for the damage incurred inside the home to their pipes. Due to the exogenous nature of pinhole leaks which affect some communities more than others due to local water chemistry, a utility should be required to perform periodic testing of their pipe network and preemptively identify neighborhoods that are susceptible using guidelines presented by Edwards (Edwards, 2005).

Finally, to provide more relief to affected communities, a governing body can enact a provision to collect funding through water utility bills or by local tax to provide rebates to residents on the repair of pinhole leaks. This may also help to reduce financial pressures on individuals within a community with high pinhole leak incident rates.

5.2 Limitations of the Study

5.2.1. Data Availability

One major limitation of this study is the limited amount of data on homeowner costs. While the total sample size of the survey at 780 seemed sufficient, segmenting the data into those with leaks as well as by region and repair strategy resulted in a small number of observations by category. If a future analysis were to be conducted using the methods described in this paper, a much larger data set should be gathered to ensure the accuracy of the results.

5.2.2. Selectivity Bias

A large number of homeowners indicated in Table 4.13 that they selected their strategy based on their plumber's advice. Perhaps many who chose to replace their plumbing were actually not risk averse but rather risk neutral and viewed the plumber's suggestion as the cheapest approach.

Another area of selection bias in the survey data comes from the refusal of participation. Homeowners usually with a negative experience from pinhole leaks, or plumbers with high revenues from these leaks, may be more apt to participate in the survey. Those who refused participation in the survey presumably had little exposure to pinhole leaks and were not inclined to invest time to complete the survey. There was a 37% and 19% participation refusal from homeowners and plumbers respectively. The survey results on leak incident rates may be skewed higher due to a potential bias.

5.2.3. Conservative Estimation of Cost

Due to the discrete choice methodology, the risk premiums estimated only reflect a lower bound indirect cost, since individuals with higher risk aversion (steeper utility curve tangents) have no other asset choice to select which reduces risk more than the replacement strategy. With more information available on homeowner risk preferences, relative risk aversion coefficients could be used, as those mentioned in Section 2.1.5, to measure risk premiums for homeowners with higher risk aversion.

Another limiting factor was that the likelihood of a future leak given replacement $\pi_{i,t}$ did not include a stochastic component where the probability is represented by a distribution of values in a specific period. This was due to the survey design that asked plumbers to give a single choice on the years to a next likely leak. Because of this limitation, the risk premium is assumed to be more conservatively estimated. If plumbers were asked about the incident likelihood for each future year, then the results could have produced a range of probabilities. If the probability ranges on the likelihood of a leak give replacement were available and an upper percentile value was used for $\pi_{i,t}$ in the calculation of expected cost and variance, then risk premiums might be higher in value.

5.3 Considerations for Future Studies

If more data were available at a regional and strategy selection level, these additional factors should be considered:

- Factor in additional direct costs, such as 'lost water', if this is possible to be measured by comparing increase in water meter bills

- Weighting homeowner perceptions on future leak risk by the length of time they have lived in a home. For example, do more years of self-observation for someone living in a home change their decision behavior?

- Consider the role of plumbers' recommendations on the decision to replace plumbing versus repair. Perhaps those who replace plumbing on the recommendation of their plumbers are actually risk neutral, but believe based on their plumbers' recommendations that future leak probabilities with a repair strategy are much higher than assumed in this study.

- Study the impact of pinhole leaks on the local economy, for example the shift in spending toward plumbing and home repair sectors and away from other industries like restaurants or retail.

- The probability estimate $\pi_{i,t}$, on the likelihood of an additional leak given replacement did not include a stochastic component as discussed in study limitations, Section 5.2.3. A future study could examine the results by treating this variable as a Bernoulli distribution to estimate probability ranges.

5.4 Research Applications

There are many potential applications for the use of discrete choice EV cost models. For similar homeowner-type decisions as pipe choice, there are repair and replace decisions with discrete asset choices for many of these other types of home and auto investments:

- Home appliances (HVAC's, dishwashers, water heaters, refrigerators)

- Window replacement

- Roof repair

- Solar panels vs traditional energy

- Automotive replacement (to fix your car or buy a new one)

For example, a homeowner may be deciding between a high-end dishwasher versus a low-end dishwasher. The high-end dishwasher, let's presume, is more expensive in its' upfront cost, but is more reliable and will last longer with few needed repairs. If the total expected cost for an item is equal to the initial cost plus future cost, then this high-end dishwasher would have a low variance in cost with a high expected cost. Alternatively, a low-end dishwasher is the least expensive upfront but is very unreliable, with the possibility of requiring many additional repairs and a high likelihood of needing to be entirely replaced sooner compared to a high end dishwasher. The low-end dishwasher would therefore have a high variance in costs, but a lower expected costs since it is cheaper up front while future repairs are discounted.

Furthermore, there are potential public health applications in which this methodology could be employed to measure the risk levels and premiums acceptable to the public when considering:

- Power plant type selection (not just operational costs, but public safety and risk of power outage or catastrophe)
- FDA drug side affects
- Corporate policy risk (decisions to pollute or cheat involving lower upfront costs but higher delayed costs if the offender is caught).

Power plants are a great example of risk-cost tradeoffs, particularly in the area of nuclear reactors. Typically, cost benefit analysis would look at the physical cost of constructing the plant itself against the energy production capability. Public concern over the construction of nuclear power plants clearly points to additional risk costs not being captured in the traditional cost benefit analysis, which might be shown more appropriately with an EV cost model.

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7. Appendix 1 –Homeowners' Survey Questions

Homeowner Pinhole Leak and Drinking Water Survey

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2006

Table 1. Call Dispositions For All Sample Records by Locality					
	Sarasota, Florida	Butler County, Ohio	California	Remainder of U.S.	Total
Total Initial Sample	1,001	786	965	3,414	6,166
Ineligible Sample:					
Sample member not a homeowner	120	72	93	422	707
Non-residential telephone number	79	44	81	309	513
Non-working telephone number (fax tones, out of service/disconnected numbers, automated disconnect services)	269	375	311	1,019	1,974
Hearing/language barrier	15	6	68	89	178
Report of no resident 18 years of age or older in household	0	1	0	4	5
Eligible Sample	518	288	412	1,571	2,789
Completed Interviews:					
Complete – No Pinhole Leaks Reported	86	97	95	419	697
Complete – Pinhole Leaks Reported	23	12	14	34	83
Non-respondents:					
Final disposition of no answer, busy, answering machine or callback after a minimum of ten attempts	208	87	156	535	986
Refusals	201	92	147	583	1,023

CALLING INFORMATION: Randomized Phone Number In Target Area

A) Hello, my name is _________________ and I'm calling as part of a research project funded by the American Water Works Association. We are conducting a study of homeowners across the nation to gather information about their experiences with the plumbing in their homes in order to help improve plumbing systems for citizens throughout the nation. Our research requires that I speak to an adult [AGE 18 OR OLDER] in your household. Would that be you?

[GO TO Q1] YES 1
NO 2

B) May I speak with that person?

[REPEAT FIRST THREE SENTENCES OF A, GO TO Q1] YES 1
NO 2

C) When may I call back to speak with (him/her)?

____

D) So that I will know whom to ask for, what is (his/her) name?

____

IF RESPONDENT OBJECTS: "We only need the person's first name, the last isn't necessary."

[REPEAT BACK FOR PRONUNCIATION IF NECESSARY,

TERMINATE CALL, AND CODE DISPOSITION]

Screener 1: **First, do you currently own a home?**

YES 1
NO [GO TO END1] 2
DK/RF [GO TO END1] 3

Screener 2: **Is your home a detached, single family residence?**

YES [GO TO Q1] 1
NO 2
DK/RF 3

End1: **I'm sorry, our study requires that I speak with owners of single family houses only. Thank you for your time.**

Q1. **In what year was your home built?**

YYYY
DK/RF 9999

Q2. **How long have you lived at this residence?**

IF LENGTH OF RESIDENCE IS < 1 YR: CODE AS "0."

YY
DK/RF 99

Q3. **Does the drinking water in your home come from a utility company or a private well?**

UTILITY 1
WELL 2
DK 3
RF 4

Q4. **How satisfied are you with the quality of the drinking water in your home? Would you say you are very satisfied, somewhat satisfied, somewhat dissatisfied, or not at all satisfied?**

VERY SATISFIED 1
SOMEWHAT SATISFIED 2
SOMEWHAT DISSATISFIED (Please specify why: ____________________________) 3
NOT AT ALL SATISFIED (Please specify why: ____________________________) 4
DK 5
RF 6

Q5. **What kind of drinking water pipes do you currently have in your home? Are they copper, iron, plastic or PVC, stainless steel, or made from another material?**

CHOOSE ALL THAT APPLY
COPPER 1
IRON 2
PLASTIC/PVC 3
STAINLESS STEEL 4
OTHER (Please specify: __________________) 5
DK 6
RF 7

Q6. **Have you ever had a small hole or pinhole leak in any of the drinking water pipes in your home?**

IF ASKED FOR ALTERNATE DEFINITION OF PINHOLE LEAK: "A pinhole leak is a small leak located directly on a water pipe, and may often be seen as a steady drip. A pinhole leak is not a dripping faucet or leaking toilet. "

YES [GO TO Q8] 1
NO 2
DK 3
RF 4

Q7. Have you ever had to repair or replace any of the drinking water pipes in your home?

YES (Please specify why repair/replacement was made: ________________________) 1
NO 2
DK 3
RF 4

GO TO Q27

Q8. In approximately what year did you first have a pinhole leak or small hole in your drinking water pipes?

YYYY
DK/RF 9999

Q9. Approximately how many pinhole leak incidents have you had in your home? Would you say you've had pinhole leaks 1 to 2, 3 to 4, 5 to 10, or more than ten times?

1-2 TIMES 1
3-4 TIMES 2
5-6 TIMES 3
7-10 TIMES 4
MORE THAN 10 TIMES (Please specify number ____ DK/RF 99) 5
DK 6
RF 7

Q10. Were the leaks in horizontal pipes, vertical pipes or in a 90 degree pipe bend?

CHOOSE ALL THAT APPLY
HORIZONTAL PIPE 1
VERTICAL PIPE 2
PIPE BEND 3
DK 4
RF 5

Q11. Were the leaks in cold water pipes, hot water pipes, or in hot water recirculation pipes?

CHOOSE ALL THAT APPLY
COLD 1
HOT 2
HOT WATER RECIRCULATION 3
DK 4
RF 5

Q12. What material was the pipe with the leaks made of? Was it copper, iron, plastic or PVC, stainless steel, or another material?

CHOOSE ALL THAT APPLY
COPPER 1
IRON 2
PLASTIC/PVC 3
STAINLESS STEEL 4
BRASS (Specify: leak around valve stem, brass cracked, or pinhole leak on the brass: ____________) 5
OTHER (Please specify: _________________) 6
DK 7

RF 8

Q13. Did the pinhole leaks occur underground, in your basement, or on the first floor or higher?

IF FIRST FLOOR OR HIGHER: "Please specify which floors of your home were affected by these leaks."

CHOOSE ALL THAT APPLY

UNDERGROUND 1
BASEMENT 2
FIRST FLOOR 3
SECOND FLOOR 4
THIRD FLOOR 5
FOURTH FLOOR/HIGHER 6
DK 7
RF 8

Q14. Who fixed your leak problems?

CHOOSE ALL THAT APPLY

HOUSEHOLD MEMBER 1
RELATIVE/FRIEND/NEIGHBOR 2
PROFESSIONAL PLUMBER/CONTRACTOR 3
OTHER (Please specify: ___________________________) 4
DK 5
RF 6

Q15. **In order to fix the leaks did you apply a clamp over the leak, replace only the leaking section of pipe, have all of your pipes internally coated with epoxy, or did you replace or replumb all of your drinking water pipes?**

CHOOSE ALL THAT APPLY

HAS NOT FIXED LEAKS YET [GO TO Q17] 1
CLAMP OVER LEAK 2
REPLACED ONLY LEAKING SECTION OF PIPE(S) 3
COATING/EPOXY 4
ENTIRELY REPLACED/REPLUMBED 5
DK 6
RF 7

Q16. **Why did you choose this strategy for fixing the leaks?**

CHOOSE ALL THAT APPLY

RECOMMENDED BY CONTRACTOR/PLUMBER 1
REQUIRED LESS DISTURBANCE TO WALLS/FLOORS/OTHER PARTS OF HOME 2
REQUIRED LESS OUT OF POCKET EXPENSE 3
REQUIRED LESS TIME TO DEAL WITH THE LEAKS 4
HAD TO DO THIS TO PREVENT LEAKS IN FUTURE/NO CHOICE 5
SAFETY CONCERNS 6
OTHER REASONS (Please specify: ______________________) 7
DK 8
RF 9

Q17. **Including any amount your insurance company may have paid, approximately how much did fixing all of the leaks cost? [IF Q15=1, CATI REPLACES TEXT AS "What do you estimate the cost will be for fixing this problem?"] Would you say less than $100, $101 to $500, $501 to $1,000, $1,001 to $3,000, $3001 to $5000, or more than $5,000?**

LESS THAN $100 1
$101 TO $500 2
$501 TO $1000 3
$1001 TO $3000 4
$3001 TO $5000 5
MORE THAN $5000 (Please specify amount: _____)DK/RF 99999 6
DK 7
RF 8

Q18. **Did the leaks cause the need for you to replace or repair anything else in your home such as flooring or walls?**

YES (Please describe other repairs/replacements: ________________) 1
NO 2
HAD DAMAGE BUT HAS NOT YET BEEN REPLACED (Please describe damage: ____________) 3
DK 4
RF 5

Q19. Including any amount your insurance company may have paid, approximately how much did these repairs cost? [IF Q18=3, CATI REPLACES TEXT AS "do you estimate these repairs will cost"] Would you say less than $100, $101 to $500, $501 to $1,000, $1,001 to $3,000, $3001 to $5000, or more than $5,000?

LESS THAN $100 1
$101 TO $500 2
$501 TO $1000 3
$1001 TO $3000 4
$3001 TO $5000 5
MORE THAN $5000 (Please specify amount: _____)DK/RF 99999 6
DK 7
RF 8

Q20. Do you have homeowner's insurance?

YES 1
NO [GO TO Q22] 2
DK [GO TO Q22] 3
RF [GO TO Q22] 4

Q21. Did your insurance ever pay for any of the costs associated with the leaks?

YES (Please specify the approximate percent of the total costs paid by your insurance ___, DK/RF 99) 1
NO 2
DK 3
RF 4

Q22. Would you say that your overall experience with these leaks was very stressful, somewhat stressful, not very stressful, or not at all stressful?

VERY STRESSFUL 1
SOMEWHAT STRESSFUL 2
NOT VERY STRESSFUL 3
NOT AT ALL STRESSFUL 4
DK 5
RF 6

Q23. About how many hours in total would you estimate you have spent dealing with the pinhole leak problems in your current home? Would you say you've spent less than 10 hours, 11 to 24 hours, 25 to 48 hours, 49 to 80 hours, or more than 80 hours?

LESS THAN 10 HOURS 1
11-20 HOURS 2
21-40 HOURS 3
41-80 HOURS 4
MORE THAN 80 HOURS (Please specify hours: ____) DK/RF 9999 5
DK 6
RF 7

Q24. Where did you turn to for information when you were trying to decide what to do about your leak problem?

CHOOSE ALL THAT APPLY
CONTRACTOR/PLUMBER 1
FAMILY/FRIENDS/NEIGHBORS 2
INTERNET 3
WATER UTILITY 4
TOWN/CITY/COUNTY AUTHORITIES 5
OTHER (Please specify: __________________) 6
DK 7
RF 8

Q25. [IF Q24=4, GO TO Q26] Have you ever reported your leak problem to your water utility?

YES 1
NO 2
DK 3
RF 4

Q26. What sources of information did you find most useful in dealing with your leak problem?

CHOOSE ALL THAT APPLY
CONTRACTOR/PLUMBER 1
FAMILY/FRIENDS/NEIGHBORS 2
INTERNET 3
WATER UTILITY 4
TOWN/CITY/COUNTY AUTHORITIES 5
OTHER (Please specify: __________________) 6
DK 7
RF 8

Q27. If you could choose any material for the drinking water pipes in your home, which material would you choose? Would it be copper, iron, plastic or PVC, stainless steel, or some other material?

CHOOSE ALL THAT APPLY
COPPER 1
IRON 2
PLASTIC/PVC 3
STAINLESS STEEL 4
OTHER (Please specify: _________________) 5
DK [GO TO Q29] 6
RF [GO TO Q29] 7

Q28. Why would you choose [CATI INSERTS "THIS MATERIAL/THESE MATERIALS"]?

____
____

Q29. If you ever had to replace all the plumbing in a home in which you were living, would you be willing to pay more for a pipe material that would remain leak free for the next 50 years? For reference, materials cost for re-plumbing an entire 2,000 square foot home might be 400 dollars for a standard grade of copper material. Would you be willing to pay [INSERT RANDOM VALUE] to ensure the material would remain leak free?

YES 1
NO 2
DK 3
RF 4

CATI WILL CYCLE THROUGH QUESTION UNTIL Q29=1, OR ALL VALUES HAVE BEEN READ. RANDOM VALUES ARE: "500 dollars, 600 dollars, 700 dollars, 1,200 dollars, 2,000 dollars, and 4,000 dollars."

Q30. [IF Q29.1 THROUGH Q29.7 >1, GO TO Q31] How certain are you that you would be willing to pay this much more for a pipe material that would remain leak free for the next 50 years? Would you say you are very certain, somewhat certain, not very certain, or not at all certain?

VERY CERTAIN 1
SOMEWHAT CERTAIN 2
NOT VERY CERTAIN 3
NOT AT ALL CERTAIN 4
DK 5
RF 6

Q31. Finally, just a few questions about you. In what year were you born?

19 __
DK/RF 1999

Q32. Do you consider yourself to be White, African American or Black, Asian, Hispanic or Latino, or a member of some other group?

WHITE 1
AFRICAN AMERICAN (BLACK) 2
ASIAN 3
HISPANIC (LATINO) 4
(SPECIFY:___________) OTHER 5
DK/RF 6

Q33. What is the highest level of formal education you have completed?

GRADE SCHOOL 1
SOME HIGH SCHOOL 2
HIGH SCHOOL GRAD [OR GED] 3
TRADE/VOC SCHOOL AFTER HS 4
SOME COLLEGE 5
COMPLETED COMMUNITY COLLEGE 6
FOUR YEAR COLLEGE/UNIVERSITY GRADUATE 7
GRADUATE SCHOOL/PROFESSIONAL SCHOOL 8
DK/RF 9

Q34. Counting yourself, how many people live in your household currently?

____
DK/RF 99

Q35. I'm going to read several income brackets to you. Please stop me when I get to the bracket that includes your best estimate of your total family income before taxes last year.

less than $25,000? 1
between $25,000 and less than $35,000? 2
between $35,000 and less than $45,000? 3
between $45,000 and less than $55,000? 4
between $55,000 and less than $75,000 5
between $75,000 and $100,000 6
over $100,000 7
DK/RF 8

IF Q6>1, GO TO END 2

Q36. Is there anything else that we have not already discussed that you would like to share about your experience with pinhole leaks?

Q37. You might be invited to participate in surveys about pinhole leaks at some point in the future. Would it be o.k. if someone called you in the future to learn more about your experiences with pinhole leaks?

YES 1
NO 2
DK/RF 3

Q38. GENDER

IF YOU CAN'T TELL THE GENDER OF THE RESPONDENT, ASK: "Just one more question: our survey requires that I ask if you are male or female."

MALE 1
FEMALE 2

END 2. Those are all of my questions. Thank you for your help with our study. Have a nice day/evening.

INTERVIEWER IF ASKED: "This study is being conducted …., If you have any additional questions about the purpose of the study, you can call X at XXXXXXX. Thank you again for your help with our study."

8. Appendix 2 - Plumbers Survey

Plumbers Survey: Examination of Pinhole Leaks in the United States and Targeted Geographic Areas

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Table 1. Call Dispositions For All Sample Records by Locality

	Sarasota, Florida	Butler County, Ohio	Hamilton County, Ohio	California	Remainder of U.S.	Total
Total Initial Sample	150	109	62	435	2,627	3,383
Ineligible Sample:						
Non-working telephone number (wrong number, permanent answering service, fax tones, out of service/disconnected numbers, automated disconnect services, call not returned to toll free number)	47	33	11	93	425	609
Hearing/language barrier	0	0	0	1	10	11
Eligible Sample	103	76	51	341	2,192	2,763
Completed Interviews:						
Complete – No Pinhole Leaks	13	5	10	24	222	274
Complete – Pinhole Leaks	23	13	25	55	490	606
Non-respondents:						
Final disposition of no answer, busy, answering machine or callback after a minimum of twelve attempts	38	30	14	196	1,088	1,366
Refusals	29	28	2	66	392	517

CSR VERSION 10 (FINAL)

CALLING INFORMATION: Known Respondent Phone Number In Target Area

A. Hello, may I speak with ___________________ ? My name is _________________ and I'm calling as part of a research project involving plumbers across the nation in order to gather information about their experiences with certain types of plumbing issues.

[GO TO Screener1] YES/CONTACT PERSON AVAILABLE 1

NO 2

B. May I speak with the person in your organization who is most knowledgeable about your company rates and total revenues?

[REPEAT FIRST THREE SENTENCES OF A, GO TO Q1] YES 1

NO 2

C. I will try calling (him/her) back at:

____

INTERVIEWER IF ASKED: "This study is being funded by the American Water Works Association Research Foundation. We are conducting a study of plumbers across the nation to gather information about their experiences with pinhole leaks in order to learn more about how pinhole leak problems can best be solved for consumers."

Screener 1: Does your firm ever do repairs to leaks in copper plumbing?
YES [GO TO R1] 1
NO 2
DK/RF 3
Screener 2: Why does your firm not repair leaks in copper plumbing?
____
End1: I'm sorry, our study is related to pinhole leaks in copper plumbing. Thank you for your time.

R1. Has your firm worked on detached single family homes in the past few years?
YES 1
NO [GO TO A1] 2
DK/RF [GO TO A1] 3
R2. Approximately how many service calls per year does your firm make on detached single family homes?
_____
DK/RF 9999
R3. On approximately how many of these service calls are repairs related to pinhole leaks performed?
_____
DK/RF 9999
IF R3=0, GO TO A1
R4. On approximately how many of these pinhole leak service calls were the leaks located by an organization other than yours?
____
DK 9999
IF R4=0|9999, GO TO R6
R5. On about how many of these service calls were the leaks temporarily repaired prior to your company working on them?
____
DK 9999

R6. Approximately how much total revenue for your company comes from jobs related to pinhole leak problems in single family homes each year?
____
DK/RF 9999999

R7. In general, how old are the pipes when the pinhole leaks first appear?
____ YEARS
DK/RF 999

R8. What is the material you use most often when replumbing a house?
COPPER 1
GALVANIZED/IRON 2
CPVC 3
PEX 4
OTHER (Please specify: __________________) 5
DK/RF 6
[IF R8>1, GO TO R10lab]
[IF R8=6, GO TO R11]

R9lab. For a 2,000 square foot, two-level house with two bathrooms and accessible pipes, what are

the approximate labor costs for a complete replumb using copper pipe?
LABOR (specify : _____) DK/RF 99999
IF COMBINED LABOR/MATERIALS PROVIDED, ENTER “0”.
IF R9lab=0, GO TO R9cmb

R9mat. For a 2,000 square foot, two-level house with two bathrooms and accessible pipes, what are the approximate material costs for a complete replumb using copper pipe?
MATERIALS (specify : _____) DK/RF 99999
GO TO R10lab

R9cmb. For a 2,000 square foot, two-level house with two bathrooms and accessible pipes, what are the approximate combined labor and material costs for a complete replumb using copper pipe?
COMBINED LABOR/MATERIALS (specify : _____) DK/RF 99999
[GO TO R11]

R10lab. For a 2,000 square foot, two-level house with two bathrooms and accessible pipes, what are the approximate labor costs for a complete replumb using [CATI INSERTS RESPONSE FROM R8]?
LABOR (specify : _____) DK/RF 99999
IF COMBINED LABOR/MATERIALS PROVIDED, ENTER “0”.
IF R10lab=0, GO TO R10cmb

R10mat. For a 2,000 square foot, two-level house with two bathrooms and accessible pipes, what are the approximate material costs for a complete replumb using [CATI INSERTS RESPONSE FROM R8]?
MATERIALS (specify : _____) DK/RF 99999
GO TO R11

R10cmb. For a 2,000 square foot, two-level house with two bathrooms and accessible pipes, what are the approximate combined labor and material costs for a complete replumb using [CATI INSERTS RESPONSE FROM R8]?
COMBINED LABOR/MATERIALS (specify : _____) DK/RF 99999

R11. In what rooms in the home do pinhole leaks occur most frequently?
CHOOSE ALL THAT APPLY
KITCHEN PIPES 1
BATHROOM PIPES 2
LAUNDRY PIPES 3
BASEMENT 4
OTHER (Please specify: ________________________) 5
DK/RF 6

R12. On average, after replumbing, does it generally take six months, one year, two years, three years, four years, or five years or more before leaks begin to occur again?
SIX MONTHS 1
ONE YEAR 2
TWO YEARS 3
THREE YEARS 4
FOUR YEARS 5
FIVE YEARS OR MORE (Please specify average number of years ___) 6
NEVER AGAIN/LEAKS DO NOT REAPPEAR 7
DK/RF 8

A1. Has your firm worked on multi-family apartment buildings in the past few years?
YES 1
NO [GO TO C1] 2
DK/RF [GO TO C1] 3
A2. Approximately how many service calls per year does your firm make on apartment buildings?

_____
DK/RF 9999

A3. On approximately how many of these service calls to apartment buildings are repairs related to pinhole leaks performed?

_____
DK/RF 9999
IF A3=0, GO TO C1
A4. On approximately how many of these pinhole leak service calls were the leaks located by an organization other than yours?

_____
DK/RF 9999
IF A4=0|9999, GO TO A6
A5. On about how many of these service calls were the leaks temporarily repaired prior to your company working on them?

____
DK 9999
A6. Approximately how much total revenue for your company comes from jobs related to pinhole leak problems in apartment buildings each year?

____
DK/RF 9999999

C1. Has your firm worked on commercial or public buildings in the past few years?
YES 1
NO [GO TO Q1] 2
DK/RF [GO TO Q1] 3

C2. Approximately how many service calls per year does your firm make on commercial or public buildings?

_____
DK/RF 9999

C3. On approximately how many of these commercial service calls are repairs related to pinhole leaks performed?

_____
DK/RF 9999
IF C3=0, GO TO Q1

C4. On approximately how many of these pinhole leak service calls were the leaks located by an organization other than yours?

____
DK 9999
IF C4=0|9999, GO TO C6

C5. On about how many of these service calls were the leaks temporarily repaired prior to your company working on them?

____

DK 9999

C6. Approximately how much total revenue for your company comes from jobs related to pinhole leak problems in commercial or public buildings each year?

____

DK/RF 9999999

Q1. Does your firm charge an hourly rate?
YES (Please specify rate: _____) DK/RF 999 1
NO 2
DK/RF 3
Q2. Including labor and materials, approximately how much revenue does your firm earn in a typical year for all plumbing-related work?

____

DK/RF 999999

Q3. Approximately what percentage of the single family homes in your area would you estimate have copper pipes? Would you say 25 percent or less, 26 to 50 percent, 51 to 75 percent, 76 to 90 percent, or more than 90 percent?
25% OR LESS 1
26-50% 2
51-75% 3
76-90% 4
MORE THAN 90% 5
DK 6
RF 7

Q4. Does this represent an increase, decrease, or no real change in the use of copper pipes in your area?
INCREASE (Why do you think this is occurring: ____________________) 1
DECREASE (Why do you think this is occurring: ____________________) 2
NO REAL CHANGE 3
DK 4
RF 5
CSR VERSION 10 (FINAL)
A7

Q5. Would you say that overall, pinhole leaks occur primarily in cold water pipes, hot water pipes, or about equally in both?
PRIMARILY COLD WATER PIPES 1
PRIMARILY HOT WATER PIPES (Are leaks seen in hot water recirculation pipes: ____) 2
ABOUT EQUALLY IN BOTH (Are leaks seen in hot water recirculation pipes: ____) 3
DK 4
RF 5

Q6. Would you say that pinhole leaks in copper plumbing in your service area occur mostly in vertical pipes, horizontal pipes, or at pipe joints?
VERTICAL PIPES 1
HORIZONTAL PIPES 2
PIPE JOINTS 3
OTHER (Please specify: ________________) 4
DK 5
RF 6

Q7. Do pinhole leaks in copper plumbing in your service area seem to occur mostly in or under the concrete slab, in the basement, on the first floor, or on the second floor or higher?
CHOOSE ALL THAT APPLY
IN/UNDER CONCRETE SLAB 1
IN BASEMENT 2
ON FIRST FLOOR 3
ON SECOND FLOOR/HIGHER 4
DK 5
RF 6

Q8. [IF SAMPREC= "Sarasota" SHOW "Just since September 2005",] Would you say the reports of pinhole leaks in your area have increased, decreased, or stayed about the same [IF SAMPREC_ "Sarasota" SHOW "in recent years"?]
INCREASED 1
DECREASED 2
STAYED ABOUT THE SAME 3
DK 4
RF 5

Q9. In your opinion, what is the main cause of pinhole leaks in copper plumbing in your area? Would you say the problem is due to high pressure, low pressure, chlorine, water velocity, soldering problems, erosion or corrosion, or some other cause?
CHOOSE ALL THAT APPLY
HIGH PRESSURE 1
LOW PRESSURE 2
CHLORINE 3
WATER VELOCITY 4
SOLDERING PROBLEMS 5
EROSION OR CORROSION 6
OTHER (Please specify: ___________________) 7
DK 8
RF 9

Q10. In general, do you usually recommend copper to your clients as the material to be used for complete replumbs?
YES 1
NO (Please specify why: ___________________________) [GO TO Q11] 2
DK [GO TO Q11] 3
RF [GO TO Q11] 4
Q10yes. Why do you usually recommend copper to your clients as the material to be used for complete replumbs?
CHOOSE ALL THAT APPLY
REQUIRED BY STATE/LOCALITY/CODE 1
EASE OF INSTALLATION 2
RESISTS CORROSION 3
PLUMBER ACCUSTOMED TO WORKING WITH COPPER 4
RELIABILITY/EASE OF MAINTENANCE 5
OTHER (Please specify: ____________________) 6
DK 7
RF 8

Q11. If you recommend entirely re-plumbing a residence or building, what factors are most

important in your decision to make this recommendation? Would you say it is the history of leaks in the neighborhood of the building, the number of leaks, the age of the plumbing system, or some other factors?
CHOOSE ALL THAT APPLY
LEAK HISTORY IN NEIGHBORHOOD 1
NUMBER OF LEAKS (Please specify number of leaks at which you recommend replumbing? _____) 2
AGE OF SYSTEM (Please specify age of system before you usually recommend replumbing? ____) 3
OTHER FACTOR(S): (Please specify: ___________________) 4
DK 5
RF 6

IF SAMPREC _ "Hamilton County" GO TO Q12

BC1. Are you aware of a pinhole leak problem occurring in the Butler County service area that includes Beckett Ridge and Princeton?
YES (Please describe problem: ______________________) 1
NO 2
DK/RF 3

BC2. How would you describe the frequency or amount of pinhole leaks in the Butler County service area compared to the pinhole leaks in the Northern Cincinnati areas such as New Burlington, Pleasant Run, Northgate, and College Hill?
BC3. Are there any particular areas or locations that you know of where copper pinhole leaks are a problem?
YES (Please name area(s) and describe problem(s): ______________________) 1
NO 2
DK/RF 3

Q12. Is there anything else you can tell me about pinhole leak repair incidents or costs in your area?
Q13. May I please have your name and job title for confirmation?
CHOOSE ALL THAT APPLY
NAME (Please specify: _________________) 1
JOB TITLE (Please specify: _____________________) 2

Q14. We might like to follow up with you for future research on pinhole leaks. Would you be willing to speak with us again in the future?
YES 1
NO 2
DK/RF 3

END 2. Those are all of my questions. Thank you for your help with our study. Have a nice day/evening.
INTERVIEWER IF ASKED: "This study is being funded by the American Water Works Association.
We are conducting a study of plumbers across the nation to gather information about their experiences with pinhole leaks in order to learn more about how pinhole leak problems can best be solved for consumers.
Thank you again for your help with our study."
INTERVIEWER PROMPT FOR SPECIFIC INFORMATION: Is there a difference? What is the specific difference? Does the respondent have ideas about why this difference exists? Anything else the respondent can tell us about leaks in these localities?

9. Appendix 3 – Inflation Index

Bureau of Labor Statics, as part of the Consumer Price Index, publishes an online calculator for converting dollars from one time period to another. In this study, costs reported in the past were converted to 2016 dollars. For example, $1 in 2005 is worth $1.23 in 2016.

The chart below plots the conversion of $1 dollar in each year into the 2016 dollar equivalent in the blue line. The gray line is an exponential smoothed curve to show the general trend of the inflation index for reference. The actual inflation index (blue line) was used in the study.