Two Issues in Premise Plumbing: Contamination Intrusion at Service Line and Choosing Alternative Plumbing Material

by

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ABSTRACT

Worldwide water distribution infrastructure system is old and deteriorating. A water system with its myriad appurtenances (including pumps, valves, and tanks) is susceptible to hydraulic transients resulting in high and low pressure waves alternatively passing through the network. While both low and high pressure events structurally tax the already weak system, there is copious evidence indicating intrusion of contaminants into the drinking water pipes from the pipe's exterior environment due to low pressure events associated with water hammer phenomenon. These contaminants enter into the drinking water as the home plumbing system is a passive recipient from the water main. While the major (municipal) system is readily recognized as a vast infrastructure system of nearly 1,409,800 km of piping within the United States, the minor (plumbing) system that is at least 5 to 10 times larger is generally not well analyzed. In this study, an experimental plumbing rig was designed and implemented that replicates the range of pressures encountered in actual minor water distribution systems.
This research addresses how a pressure transient triggered within a house and from municipal systems can impact the service line with a possible suction effect. Experimental results on low pressure events and the accompanying numerical modeling showed good agreement. The experiment also enabled visualization of the various pressure transient phenomena. It is demonstrated that hydraulic transients triggered from water mains result in low pressures events (up to -10 psig) in service lines which can allow possible intrusion of microbial and chemical contaminants at the service line. Structural integrity of service line and hydraulic integrity at water mains should be maintained to minimize any public health risks.

In the USA, about 90% of residential drinking water plumbing systems use copper pipes. Pinhole leaks in copper plumbing pipes have become a nationwide concern because these leaks cause property damage, lower property values, and result in possibility of adversely affecting homeowners' insurance coverage. In addition, resulting mold damage may cause health concerns. This research also addresses the concerns of the affected homeowners by enabling them to decide on whether to continue to repair or replace their plumbing system, the factors to be considered in a replacement decision, and the type of material to use for replacement. Plastic pipes such as PEX (cross-linked polyethylene), CPVC (Chlorinated Polyvinyl Chloride), and copper are considered in present analysis. Other alternatives include an epoxy coating technique on the existing piping systems, without the need to tear into walls. Multiple attributes of a plumbing system including cost (material plus labor charges), taste and odor impacts, potential for corrosion, longevity of the pipe system, fire retardance, convenience of installation or replacement, plumber or general contractor's opinions or expertise, and proven record in the market are considered. Attributes and material rankings are formalized within the framework of a preference elicitation tool namely AHP (Analytical Hierarchical Process). Surveys are conducted with selected homeowners in pinhole leak prone area in Southeastern US Community to observe their revealed and stated preferences. Participants' overall preference tradeoffs are reported in addition to comparing their revealed and stated preferences. Health effects, taste and odor of water turned out to be the most important factors from the survey. In real life, however, homeowners were not well aware of these safety issues related with plumbing materials. It is recommended that water professionals should work on bridging the gap between public perception and research results related to major and minor systems.

This Dissertation is dedicated to the memory of

Dr. G.V. Loganathan

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AUTHOR'S PREFACE

Both Themes I and II of dissertation are in extended manuscripts format that will be submitted to journals. The first Theme titled "Contamination Intrusion at Service Line" is prepared to be submitted to *Journal of American Water Works Association*. Theme II "Choosing Alternative Plumbing Material" is to *ASCE Journal of Water Resources Planning and Management* and *ASCE Journal of Infrastructure*.

The overall objectives of this dissertation are to better understand two important issues involved in premise plumbing systems. Public health issues and consumer concerns are addressed using experimental plumbing systems, numerical modeling, decision analysis, and by implementing surveys to real homeowners in home plumbing failure prone area.

Contamination Intrusion at Service Line

THEME I

Worldwide water distribution infrastructure system is old and deteriorating. A water system with its myriad appurtenances (including pumps and valves and tanks) is susceptible to hydraulic transients resulting in high and low pressure waves alternatively passing through the network. While both low and high pressure events structurally tax the already weak system, there is copious evidence indicating intrusion of contaminants into the drinking water pipes from the pipe's exterior environment due to low pressure events associated with water hammer phenomenon. These contaminants enter into the drinking water as the home plumbing system is a passive recipient from the water main. While the major (municipal) system is readily recognized as a vast infrastructure system of nearly 1,409,800 km of piping within the United States, the minor (plumbing) system that is at least 5 to 10 times larger is generally not well analyzed. In this study, an experimental plumbing rig was designed and implemented that replicates the range of pressures encountered in actual minor water distribution systems. This research addresses how a pressure transient triggered within a house and from municipal systems can impact the service line with a possible suction effect. Experimental results on low pressure events and the accompanying numerical modeling showed good agreement. The experiment also enabled visualization of the various pressure transient phenomena. It is demonstrated that hydraulic transients triggered from water mains result in low pressures events (up to -10 psig) in service lines which can allow possible intrusion of microbial and chemical contaminants at the service line. Structural integrity of service line and hydraulic integrity at water mains should be maintained to minimize any public health risks.

KEY WORDS: Contaminant Intrusion, Pressure Transients, Plumbing Systems, Water Hammer, Numerical Methods

1. Introduction

The growth in bottled water consumption, point of use water treatment (including various kinds of filters, distillation, ion exchange, and reverse osmosis) indicates citizens' concern regarding the quality of distributed water at the tap. Cost advantages of public water supply, higher maintenance problems related to the point of use devices and relative marginal improvement in water quality result in the municipal drinking water remaining as the top-ranked water supplier for maintaining established drinking water standards. It is widely believed that because a drinking water distribution system is pressurized, the water can only come out of the system. However, there is evidence that pump trips, opening and closing of fire hydrants, valve closures or malfunctioning, pipe break, and sudden change in demand and resonance can induce significant transients leading to low pressure events within a drinking water system. During such events a greater external pressure can lead to contamination intrusion through available openings. Tests of surrounding soil and pipe specimens from repair locations show the presence of pathogens. In 2000 alone 6,988 water systems affecting about 10.5 million people violated microbial drinking water standards in the US.

Le Chevallier et al. (2003) define intrusion as the specialized backflow situation in which nonpotable/contaminated water from the environment outside of the distribution piping flows into the pipe through leaking sections. Kirmeyer et al. (2001) and Friedman et al. (2004) provided comprehensive reviews and detailed discussions on the pathogen intrusion problems into the municipal drinking water systems. Kirmeyer et al. (2001) point out that water treatment facilities are the barrier against pathogens before the water enters the distribution systems. The barrier mechanisms include removal (inactivation) of pathogens, turbidity, organic matter to prevent biological regrowth in the distribution system, disinfection, treatment to maintain optimal contact time for Giardia – Cryptosporidium inactivation, and filter blockage of particle - contaminant carryover into the distribution system. Any breakthrough in this treatment plant barrier is considered high risk and probability of occurrence is also considered high. They also point out physical mechanisms grouped as *transitory contamination* due to low pressure propagation in the system drawing in contaminants from the exterior surroundings with a higher pressure; *cross connection* between potable water system and a source that can potentially introduce contaminants into the potable water; *pipe break, repair* and *installation* that expose the distribution system to the externalities as routes of entries. Storage facilities both covered and uncovered, purposeful contamination, growth and resuspension serve as additional sources for pathogen intrusion.

Transient high and low pressures can be triggered by pump on and off, pump trips due to power loss, opening and closing of fire hydrants, loss of tank connection, valve slams and malfunctioning, break in pipe, sudden change in demand and resonance. LeChevallier et al. (2003) provided pictures of an inundated air valve vault with an oily film first and in a short while, once a transient has passed through, the vault was completely drained allowing the contents to enter the distribution system. Another dramatic incident was displayed in Feeny (1999) [also see LeChevallier et al. (2003)] showing a cracked sewer pipe lying on top of a leaky water pipe. Kirmeyer et al. (2001) conducted soil and water quality tests at water main repair sites and found fecal coliform bacteria in 43% of the water samples and 50% of the soil samples. They conclude that waterborne pathogens are very common in the environment external to water distribution mains. Karim et al. (2003) reported bacteria and viruses in 66 soil and water samples collected next to drinking water pipelines in eight utilities in six states. They also found total coliform and fecal coliform bacteria in about 50% of the samples and 56% of the samples were positive for viruses providing evidence of human fecal contamination immediately exterior of the pipes.

Payment et al. (1991, 1997) conducted two epidemiology studies related to a drinking water distribution system located in the Montreal area and found people who consumed the tap water had increased levels of gastrointestinal illnesses. The data showed that people who lived away from the treatment plant had the highest risk of gastroenteritis. In their 2001 study, Kirmeyer et al. found the very same distribution system was extremely prone to negative pressures, with more than 90% of the nodes within the system drawing negative pressures under power outage scenarios. Another point of interest is that the system had a state of the art treatment plant; however, it had a vulnerable distribution system.

Friedman et al. (2004) focused on transitory low pressure propagation in the municipal system that typically uses 4 inch to 10 inch pipes. They documented intrusions of contaminants and low pressures of the order of negative 10 psi (gage). They also emphasize that the intruded contaminant is not re-extruded out of the pipe but a portion of it is carried downstream. Distribution mains downstream of pumps, high elevation areas, low static pressure zones, areas far away from overhead tanks, and segments of pipes upstream and downstream of active valves in high flow areas are the most susceptible for low or negative pressures. Locations with frequent leaks and breaks, high water table regions, flooded air vacuum valve vaults, and high risk cross connections have the highest potential for intrusion. Gullick et al. (2004) observed most surge events are the result of pump operations and outages. Novak (2005) provided experimental evidence for a 90 degree bent pipe with a pressure range of less than 10 psi and with a velocity of about 6 ft/sec contamination can be sucked into downstream of the 90 deg bent region of the pipe.

President's Commission on Critical Infrastructure Protection, under President Clinton (1997), designated three important attributes of drinking water infrastructure, namely, adequate quantities of water on demand, delivering water with sufficient pressure, and safety and high quality of the water. Since the terrorist events of September 11, 2001, water security at water infrastructure has received more attention than before. NRC (2006) categorized drinking water distribution system's integrity into the following components: i) *physical integrity* indicating the physical barrier between pipe externalities and inside the piping, ii) *hydraulic integrity* controlling right pressure, flow, water age, and capacity for providing fire flow, and iii) *water quality integrity* keeping high standard of water quality without any degradation. If any of the components fails to keep the good level of integrity, this will result in serious *public health risk*. This indicates that drinking water infrastructure bears significant operational and managerial responsibilities towards public health.

In order to emphasize the integral nature of contamination intrusion problem, real observations by the author are presented. Figure 1.1(a) shows a newly installed service line in Blacksburg, VA. The homeowner received the water bill of $500 for one month and he suspected the failure at service line because there was no leak inside the house (water meter was fine, too). He replaced old copper service line with PVC. As their service line was located within private property, the homeowner was fully responsible for repair/replace cost. Fortunately, the city took care of that month's water bill. Another example comes from Washington D.C. Due to public health risks associated with excessive lead level in water, WASA (Washing D.C. Water and Sewer Authority) is replacing lead service lines with copper lines only for public sections (as a part of lead service line replacement program); homeowners should take care of the sections within property line. The replacement cost is known to be at least $2,500 or more to replace 20' section. However, it is known that partial replacement entails disturbance of lead scales as it may cause galvanic corrosion at the remaining lead service line (located within property line) when coupled to new copper service line (Edwards, 2008). Figure 1.1 (b) shows a picture of replacing broken valves in Blacksburg, VA. If the crew is not very careful or the foreman or project manager is not very meticulous to check every detail, the finished part (connecting joint) can easily leak.

Figure 1.1 (a) Service line in front of Blacksburg high school; 2.1 (b) replacing broken valve in Blacksburg, VA

Leakage rates (water loss while transporting water from treatment plant to minor systems) in drinking water systems reaches 32 percent in some utilities which indicates high potential of contamination intrusion (Kirmeyer et al., 2001). It is emphasized that 6 billion gallons of treated water is disappearing during distribution (AWWA Water Loss control committee, 2003). According to AWWA (2005), the majority of water leaks occur at service lines, service fittings, and connections. Also, NRC (2006) noted that the lower total chlorine residuals, lack of dilution, and short detention time before potential consumption might increase the *potential health threat* to individual consumers if intrusions were to occur at service lines. Service line is known to be the weakest spot within drinking water infrastructure. To make matters worse, documentation of failure record is rare (because it is private property) so the prediction of the future failure using statistical analysis is difficult. Service line characteristics and specific objectives of *Theme I* are presented in Section 2.

2. Characteristics of Service Line and Plumbing Systems

America's water distribution infrastructure system is old and deteriorating. A water system with its myriad of appurtenances (including pumps, valves, and tanks) is susceptible to hydraulic transients resulting in high and low pressure waves alternatively passing through the network. The major municipal system is readily recognized as a vast infrastructure system of nearly 1,409,800 km of piping within the United States, the minor system (including service line) that is at least 5 to 10 times larger is generally not well addressed. It is noted that 21,239 km of new pipes are installed every year (only for major systems) to meet increasing population (Kirmeryer et al., 1994). In this section, we are explaining general characteristics of minor systems and service lines (diameter generally less than 2 inch) that connect the inner plumbing of house to the water main. Figure 1.2 shows the detailed schematic of the major/minor systems focusing on service line.

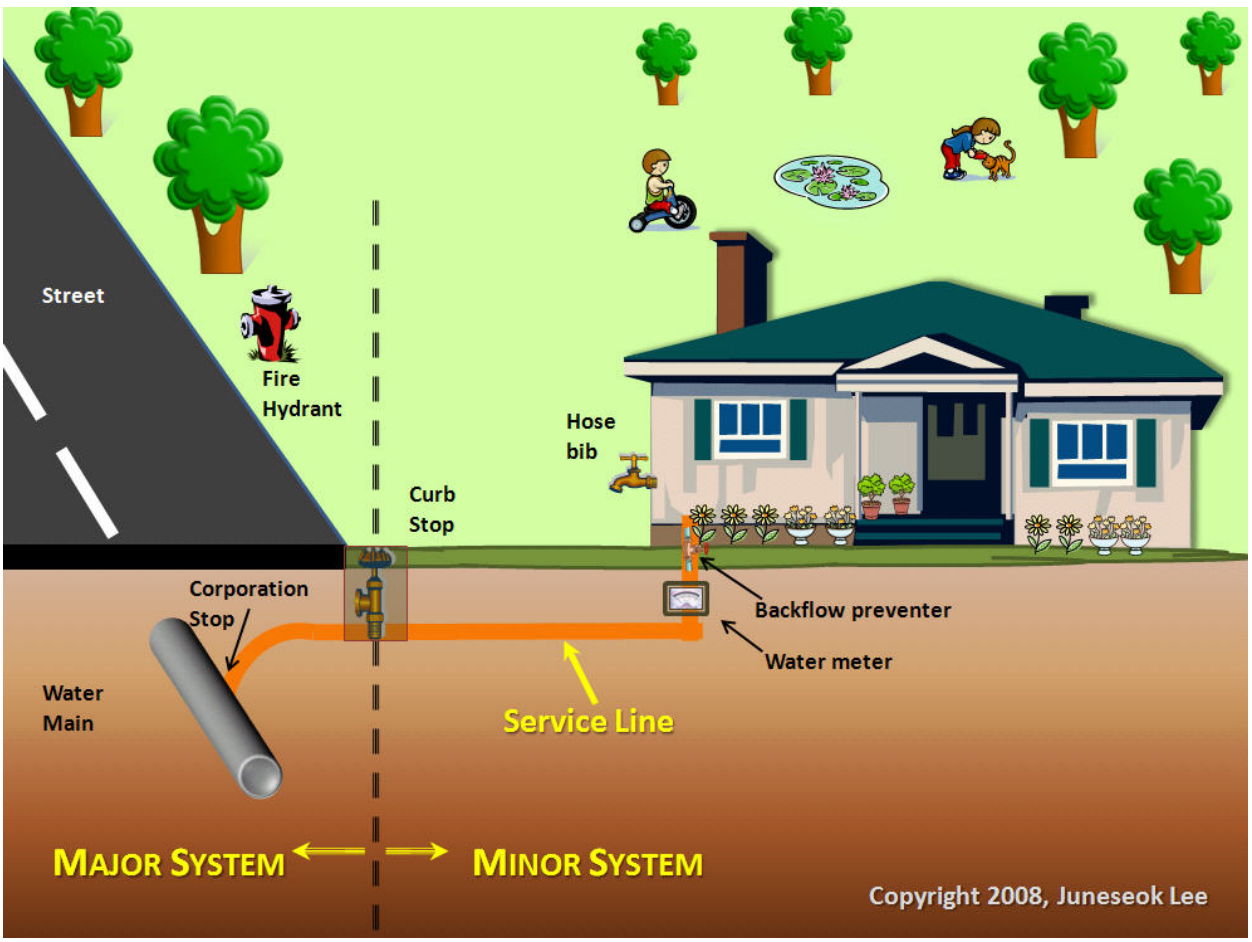


Figure 1.2 Schematic of service line

As indicated in Figure 1.2, curb stop is the dividing line between major/minor systems (including ownership demarcation). Water utilities and regulations are responsible for maintenance (e.g. physical condition, water quality, etc) up to curb stop. A major portion of service line and all of plumbing systems are homeowner's responsibility including water quality (Edwards, 2008). Regarding water quality test, lead and copper level are measured at consumer's tap water (within property line). Disinfectant residual and disinfection by-products (DBPs) are measured within distribution systems (NRC, 2006). Also, the proportion of waterborne disease outbreaks due to distribution systems is increasing. The major culprits are i) cross-connections and backsiphonage outbreaks associated with distribution systems and ii) pipe breaks and contamination of storage facilities. It is noted that outbreaks at premise plumbing level may not be easily recognized and reported compared to water main outbreaks. Water has long contact time with service line due to inherent nature of minor plumbing system which leads to low disinfectant residuals and consequently microbial re-growth and DBP formation (NRC, 2006).

As mentioned earlier, service lines are known to be the structurally weakest components in drinking water infrastructure systems. Excessive water loss, an unusually high water bill, or puddle at the front lawn may indicate service line failure. It is known that the leaks at the service line rarely go to upward direction so it is possible that the leaks go unnoticed for longer periods of time. Some utilities detected leak incidents lasting more than a month. For detecting water leaking at the service line, sonic and ultrasonic leak detectors are used for metallic service line. For plastic service lines, tracer gas or ground penetrating radar can be used to detect leaks. Service lines are susceptible to both internal and external corrosions. For external corrosion, soil corrosivity, stray electrical current, soil stability, bedding conditions, and temperature extreme could be important factors. Major causes of failures at service lines are i) contactors expose piping with backhoe or other mechanical equipment, ii) improper installation of fittings and pipes, and iii) supervising of installation is not done well. Hydraulic surges are also known to be another causes of failures. Piping material, material age, size, location, service pressure, flows, other hydraulic parameters will also dictate the generic characteristic of failure mechanisms. Due to structural stability and economic issues, replacing all components of the service line is known to be a better option than repairing the service line only; so proper installation practice and workmanship (from licensed workers with good training) under strict supervision with inspection is mandatory to maintain the physical integrity of the service lines (AWWARF, 2007). This way, the service line will have longer service life without having to spend unnecessary repair/rehabilitation/replacement cost. Installation techniques and procedures (laying, trenching, tapping, backfilling, protection methods) are included in AWWARF (2007).

Hydraulics of Major and Minor Systems

Edwards (2006) and Loganathan et al. (2005) described the comparison between major and minor system in detail. Drinking water is transported through major water systems to minor systems. Drinking water passes through corporation stop, curb stop, water meter, backflow preventer, bends, valves, junctions, and faucets, which cause significant amount of head losses. Major systems are pressurized to deliver the adequate quantity and pressure to consumers. So, the pressure and velocity distribution in a plumbing system is dictated by the pressure from the water main system.

The pressure and velocity in any pipe within minor systems are highly dependent on the street level pressure which is measured around corporation stop (see Figure 1.2). So, the street level pressure becomes a *boundary condition* for minor system. It is noted that the velocity head values are typically very small compared to the pressure and elevation heads. The street level pressure (P_{street}) can be expressed in terms of pressure (p_i), velocity (v_i) and elevation (h_i) of any pipe using the energy equation, when the *steady state is assumed*. The equation below shows the energy relation.

$$\frac{p_i}{\gamma_{water}} + \frac{v_i^2}{2g} + h_i + H_{Losses} = \frac{P_{street}}{\gamma_{water}} \qquad (1.1)$$

where, p_i is the pressure in any pipe (i) in home plumbing system, v_i is the velocity in pipe (i), h_i is the difference in elevation between the street level and the point of measurement, g is the acceleration due gravity, γ_{water} is the specific weight of water (considering constant density), H_{Losses} is the sum of minor and friction losses from the street level to the point of measurement. From equation (1.1), it is seen that velocity and pressure in home plumbing system is highly affected by any changes in the street level pressure (Ladd, 2005).

In water distribution systems, the pressure level changes with the high and low pressure zones according to the location of the pumping station or the elevation of that region. So, depending on the location of the house, the boundary condition will change markedly. In situations where the street main pressure is low or more energy is needed to raise the water in a tall building, a booster pump is used to supply additional head to the system. In addition, the street level pressure may drop significantly during peak hours due to simultaneous withdrawal, causing much lower velocities and pressures as compared to those in normal operation time. Fire flow situations can drastically drop the pressure in a house. Worthington (2006) received several noise reports from plumbing systems in Arizona. While no problems were found in minor systems, analysis of the nearby major water systems indicated that abrupt valve closure in the main system turned out to be causing noise problems at household level. This situation confirms that street level pressure becomes a critical boundary condition of pressure distribution in a residential house or building.

The typical plumbing system in a two story house is composed of fixtures including two hose bibs, two bathrooms, a dishwasher, a hot water heater, and a washing machine in the basement. Inside a typical house, there are three typical places where plumbing features go. They are kitchen, bathrooms, and laundry room. The other elements include the service line, which provides water to the house, the water meter, various other internal valves, tee junctions, and bends (Batterton, 2006).

The maximum pressure that the International Plumbing Code allows is 80 psi and usual steady state pressure for street level is 60-80 psig. Stein (1992) states, "water is distributed through street mains at pressures varying from about 50 psi at the main to about 70 psi". When factoring in losses associated with the water meter, hot water heater, fittings and friction, it would average 30 psig at the fixture. Novak (2005) has details on head loss calculations inside a house (for steady state). The minimum pressure should be 35 psig at the farthest point in the system, and at least 20 psig even in a fire flow situation. But the minimum pressure depends on the type of fixture installed within the house. For example, if the hydraulically most remote plumbing fixture in the system requires 15 psi, this will be the required minimum pressure. The individual elements of the plumbing system with minimum design flow and pressures are shown in Table 1. 1. Significant amount of energies (energy head) are dissipated through various bends, tees, and junctions in home plumbing. To supply adequately, minimum pressure should be satisfied.

There are two boundary conditions existing in plumbing water distribution systems. The first one is the *pressure available at the street main*. The second is at the *demand node*. As shown in Table 1.1, the minimum pressures are specified for each plumbing fixture. For conservative design, minimum available street main pressure is adopted. The street main pressure is the main source of energy for fluid to flow through a plumbing distribution network. The difference between the street main pressure and the required minimum fixture pressure defines the amount of acceptable *head loss* through the piping network. Smaller pipes will yield greater friction loss than a larger diameter pipe under the same operating conditions.

Table 1.1 Minimum design capacities at fixture supply pipe outlets (Woodson 2000)

FIXTURE	FLOW RATE (gpm)	PRESSURE (psi)
Bathtub	4	8
Bidet	2	4
Combination fixture	4	8
Dishwashing, residential	2.75	8
Drinking fountain	0.75	8
Laundry tray	4	8
Lavatory	2	8
Shower	3	8
Shower, temperature controlled	3	20
Sillcock, hose bibb	5	8
Sink, residential	2.5	8
Water closet, flushometer tank	1.6	15
Water closet, tank, close coupled	3	8
Water closet, tank, one piece	6	15

Plumbing distribution system demands are defined by the loads imposed by plumbing fixtures (i.e. toilets, showers, sinks, etc.), which are designed to operate at certain pressures. Because all fixtures operate under pressure, they are usually called "*pressure driven*". So, the basic requirement is to maintain a certain minimum pressure, p_{min}, to deliver the flow demand. This relationship is of the form, $Q = Kp^a$(for $p \le p_{min}$), and $Q = Q_{control}$ (for $p > p_{min}$); where, K = emitter coefficient (cfs/psi^{-a}), Q = flow (gpm, cfs), p = pressure (lb/ft^2, psi), a = exponent ~ 0.5, $Q_{control}$ = user controlled flow. Whenever p exceeds p_{min}, the pressure is capable of delivering more flow than actually needed (Ladd, 2005).

Just as the major system is susceptible to hydraulic transients, water hammer within the plumbing system can also induce transient pressure propagation. Water hammer is the destructive forces, pounding noises and vibration which develop in a piping system. Houten (2003) describes the noise problem in plumbing system along with control methods. When water hammer occurs, a high intensity pressure wave travels back through the pipe system until all the energies are dissipated. The common cause is the quick closing of the valves in plumbing system. It is known that the speed of the last 15% of the valve closure is directly related to the intensity of the surge pressure. The average flow velocity in plumbing system is 4~8 ft/sec. This destructive force may result in the following conditions: ruptured piping, leaking connections, weakened connections, pipe vibration and noise, damaged valves, damaged check valves, damaged water meters, damaged pressure regulators and gauges, damaged recording apparatus, loosened pipe hangers and supports, ruptured tanks and water heaters, premature failures of other equipment and devices (Plumbing & drainage institute, 1992). According to a survey of plumbers (Farooqi and Lee, 2006), most of the water hammer occurs from dishwashers and washing machines which are operated by mechanical solenoid valve. Plumbers recommend using water hammer arrestors or mitigate the problem by designing the velocities to not exceeding 4 feet per second (whereas the rest of the system is designed around 6 to 8 feet per second).

Piping Materials for Service Lines

According to AWWA 2002 Stats, 60.5% service line materials consist of copper followed by polyethylene (12.4%), galvanized steel (8.6%), PVC (6.3%), and remaining other materials including lead. Also, AWWARF (2008) performed surveys on twelve utilities in USA. Portland Water Utility (ME), Louisville Water Company (KY), Brown Deer Water utility (WI) are using copper for more than 90 % of the town's service lines. New materials including PEX and tri-layer pipes are emerging in service line application (AWWARF, 2008). It is known that copper pipe has high rated internal working pressure (for more detail, please refer to the Copper Tube Handbook by CDA). A nominal 1 inch schedule 40 PVC pipe has a burst pressure of 1,440 psig @73F, copper has a burst pressure ranging from 2,650 to 3,415 psig depending on the pipe type. It is known that service lines made from PVC can handle operating pressure above 100 psig (sustained pressure). Copper pipes do not become brittle or subject to fatigue failures but they can make noisy sound at high water velocities.

According to American Society of Mechanical Engineers Code for Pressure Piping (ASME B31), the allowable internal pressure for any copper tube in service is based on the formula:

$$P = \frac{2S(t_{min} - C)}{D_{max} - 0.8(t_{min} - C)} \qquad (1.2)$$

Where, P = allowable pressure (psi), S = maximum allowable pressure in tension (psi), t_{min}= wall thickness (minimum, inch), D_{max} = outside diameter (maximum, inch), and C = a constant. But for copper pipe, due to superior corrosion resistance, the B31 code permits the factor C to be zero and the equation reduces to: $P = \frac{2St_{\min}}{D_{\max} - 0.8t_{\min}}$. It is noted that the allowable pressure depends on the *service temperature and on the temper of the tube, whether it is drawn or annealed*. For nominal or standard size of each K, L, and M pipes, outside diameter is the same but inside diameters are different due to different thickness. K is the thicker than L and L is thicker than M pipe. According to outside diameter, thickness, and maximum allowable pressure in tension, the allowable pressure is determined using the above formula. The technical data for rated pressure, burst pressure, and thickness can be found in Copper Tube Handbook by CDA (2006). The pressures at which copper tube will actually burst are many times higher than rated working pressures which assure that tubes can withstand unpredictable pressure surges that can occur during the long service life of the system. For domestic use, designing copper tube water supply system is for determining the minimum tube size for each branch by considering following criteria (AWWA, 2004); available main pressure at street level, minimum pressure required at each fixture, static pressure losses due to height difference between service line and most distant fixture, demand at each fixture and total system, friction losses in the system (major and minor losses), and velocity limitations specified in the code.

There are several testing methods for pressure piping materials: i) sustained pressure test: select the test specimens at random and individual specimen is tested with water at the three controlled temperatures and pressures given in ASTM F 876, ii) burst pressure test: determine the minimum burst pressure with at least five specimens in accordance with ASTM Test Method D1599, iii) environmental stress cracking test: make a notch on the inside of the six randomly selected tubing walls in the axial direction, they apply burst pressure testing procedure, and iv) oxidative stability in potable chlorinated water application: in accordance with ASTM Test Method of F 2023, the extrapolated time to failure shall be determined.

The ASTM (American Society for Testing and Measurement) has developed minimum performance standards to determine PEX tubing's suitability for high temperature and pressure fluid distribution applications (ASTM F876). The values reported for performance standards at three different temperature and pressure ranges: 160 psi @73.4F, 100 psi @ 180 F, and 80 psi @ 200 F; Minimum Quick Burst Capability: 475 psi @ at 73.4°F, 210 psi @ 180°F, 180 psi @ 200°F; and Sustained Pressure Tests: 1000 Hrs. at 190 psi @ 180°F. According to PPFA (2002), water hammer pressure rise is ¼ times smaller than that of copper pipes. It is mentioned that water hammer arrestors are not necessary for PEX system. Table 1.2 is showing the maximum pressure rise (in psi) when stopping the given velocity.

Table 1.2 Hydraulic shock for different pipe type (maximum pressure rise in psi)

Velocity (fps)*	PEX	Copper
4	58	200
6	87	300
8	116	400
10	145	505

(* feet per second)

To the author's knowledge, no study has been conducted to examine hydraulic impacts at service line as a result of transients triggered from major and minor systems. Also, while it is known water hammer is common inside a home, *what pressures exist within the plumbing system is not clearly understood*. As minor system is a *passive recipient* from the water mains; if there is contamination at the service line, it is bound to enter into our tap water which poses *health risk issues*. The objectives of this research are to:

I. Design, construct, and implement an experimental plumbing system that replicates the range of pressures encountered in actual minor water distribution systems. The experimental plumbing system is used to:
   i. assess low pressure behavior at the service line to predict the potential for contamination intrusion from the surrounding soil or water.
   ii. measure pressure variations as the function of valve positions and sudden valve closing/opening with high sensitive pressure transducers and LabVIEW based DAQ systems.
   iii. evaluate the cavitation phenomenon through clear plastic pipe for steady and transient state.

II. Compare observed pressure values for the constructed plumbing system with those predicted by different numerical models including two commercial software (including Hammer and WHAMO) and author's MATLAB based program adopting explicit schemes to solve water hammer equations (continuity and momentum equations)

3. Experimental Plumbing System

Typical house connections to a municipal water main are shown in Figure 1.3. The average pressure in the main system is 70~ 80 psi and it dictates the pressure at each house level. Figure 1.4 displays a typical water distribution system for a single-story, single-family residential structure. According to Bhave (1991), "Plumbing distribution networks, especially for cold water lines, are usually branched-type systems. Branched networks are typically comprised of 'one source, one or more intermediate nodes, and one or more sinks which are plumbing fixtures'. There are no loops, or redundant nodes. This configuration provides only a single delivery path to each user point, that is, plumbing fixture. The direction of flow in all pipes is fixed. Steady state hydraulic analysis can be completed by starting at a node of known head (source node) and successively applying pipe head loss equations in concert with node continuity expressions".

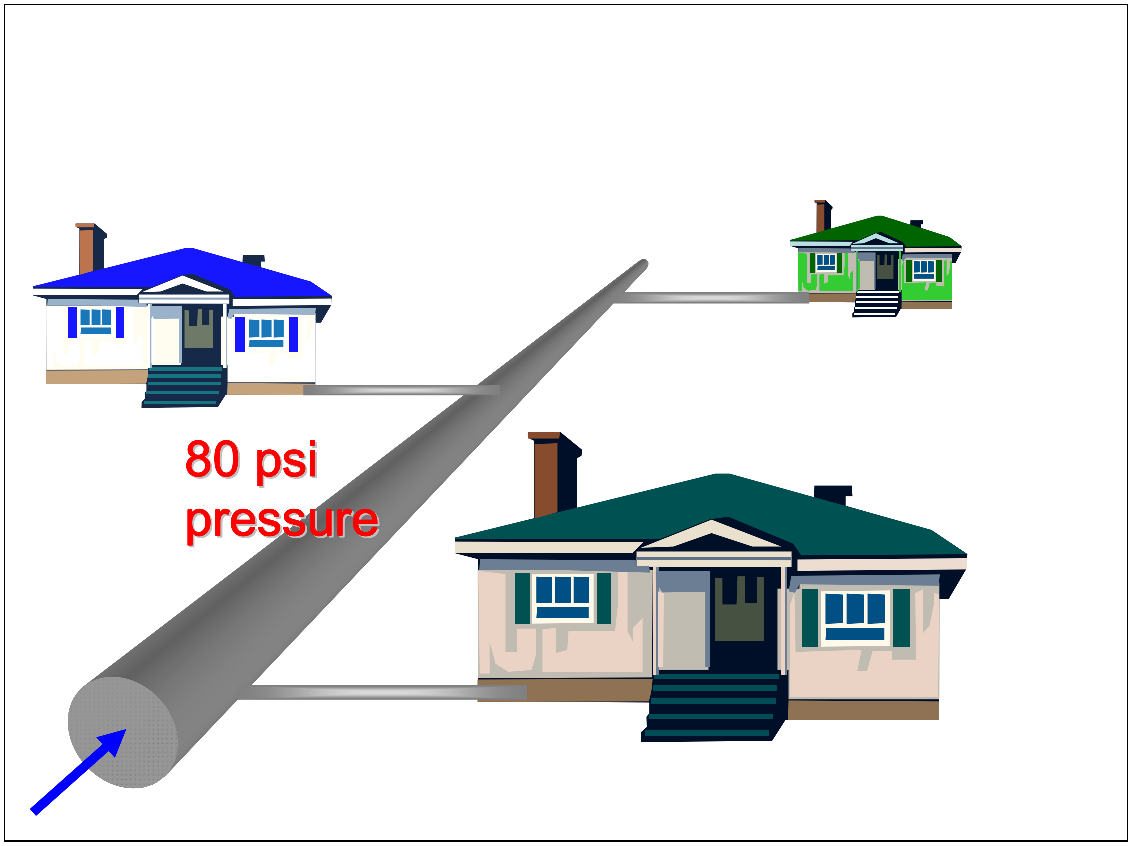


Figure 1.3 Municipal system and house connections

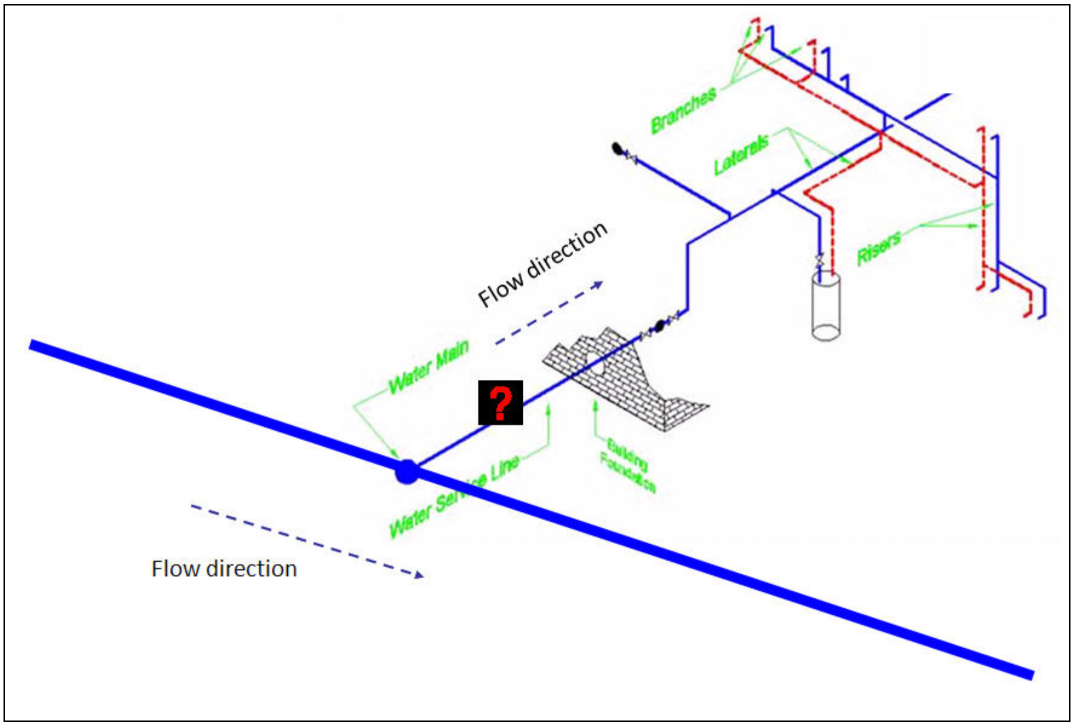


Figure 1.4 Branched system in a single residential house (Modified from Ladd (2005) with permission)

The main objective of the experiment is to measure pressures head variation at service line as the function of input parameters of boundary head, valve positions, and water hammer triggering mechanisms. An experimental rig is designed to mimic the range of street level pressures encountered in the real system to address

(*i*) how the low pressure wave moves through the plumbing system as the results of a street level transient and

(*ii*) how a transient triggered within a house can impact the service line with a possible suction effect.

Boyd (2004) conducted the intrusion experiment with simulated (major) drinking water distribution systems. In their experiment, however, pressure within pipe systems was maintained with pump; this causes lots of bubbles inside the piping system. Real plumbing system does not contain high volume of bubbles based on our observation. Also, the speed of sound under isothermal conditions for this mixture is known to be reduced to

$$a_m = \{\rho_m[\alpha / P + 1/(\rho_1 a_1^2)]\}^{-1/2} \tag{1.3}$$

where a_1 is the wave speed for single phase liquid (Martin, 1976). It is noted that the presence of free air reduces the effective bulk modulus of the liquid and acoustic wave speed. A change in void fraction to an order of 10^{-4} can reduce as pressure wave velocity as high as 30 %. It is known that air reduces the wave speed, peak pressures. Also it causes dissipation which attenuates the transient (Baasiri, 1983).

In our experiment, we are simulating real plumbing system by directly connecting to water main. Three scenarios, referred to as *Transient I, II, and III* (see Figure 1.5) that can trigger a transient in a service line are considered. Transient I: In this case, transients are triggered due to actions initiated from inside of the house (e.g., by shutting off the valve, shower heads, or automatic on/off of solenoid valve from laundry room). Transient II and III: In these cases, transient causing actions are initiated from the municipal water systems (e.g., pump trips, opening and closing of fire hydrants, valve closures, pipe break, sudden change in demand and resonance, and malfunctioning of valves). Depending on the flow direction in the system, there are two transients (i.e. transients II and III) which influence the pressure variation at the service line (see Figure 1.5).

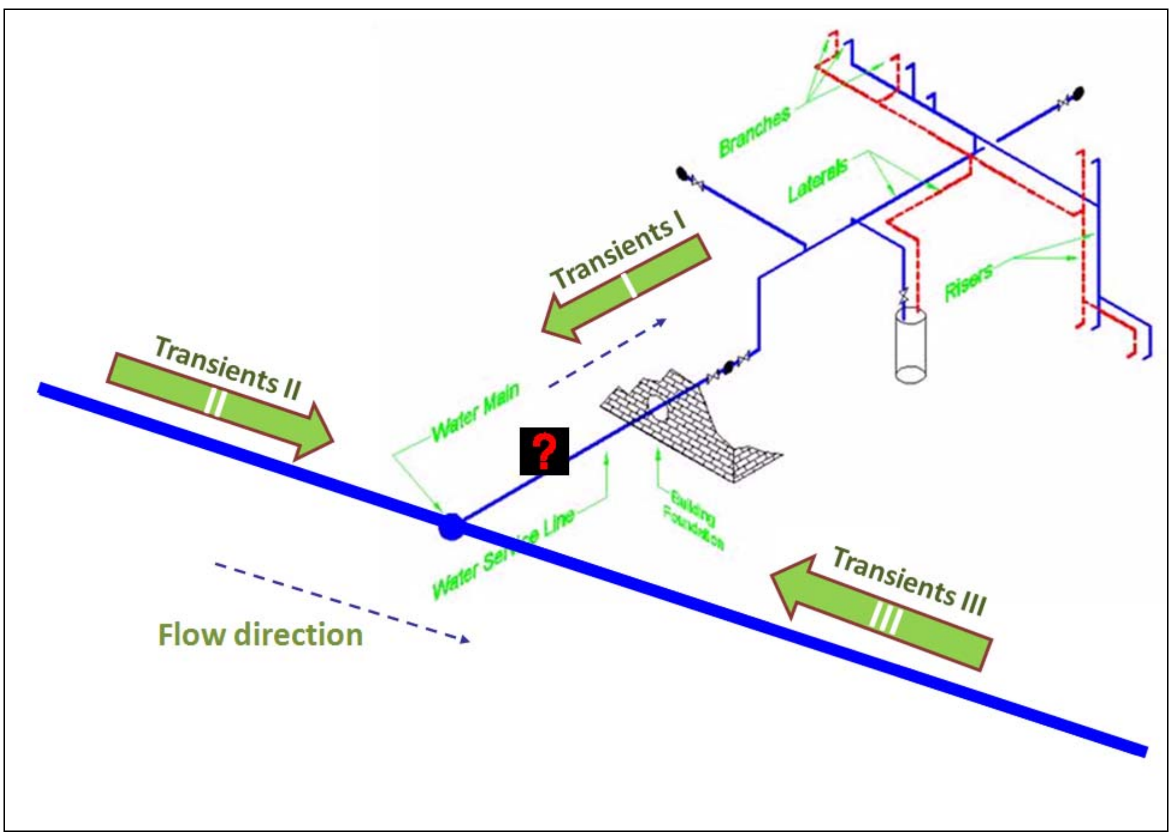


Figure 1.5 Scenarios of transients that can occur in drinking water distribution systems (modified from Ladd, 2005 with permission)

An experimental plumbing rig is built in the hydraulics lab of CEE department at Virginia Tech to simulate these proposed three scenarios. Detailed configuration of the rig is guided by current plumbing code and advice from the plumbers. Main line has 0.75" diameter and we used soldering instead of threaded appurtenances to mimic real home plumbing more closely. Dotted oval shape indicates the plumbing system inside house and solid line is for municipal water system outside of a house (see Figure 1.6). High sensitive sensors such as pressure transducers (with stainless steel diaphragm) and insertion type magnetic flowmeter were adopted to observe the spatial and temporal variation of the flow patterns. Table 1.3 gives specifications of the sensors employed including cost numbers. Three pressure transducers (P1, P2, and P3) and one flowmeter were installed at locations of interest (see Figure 1.6).

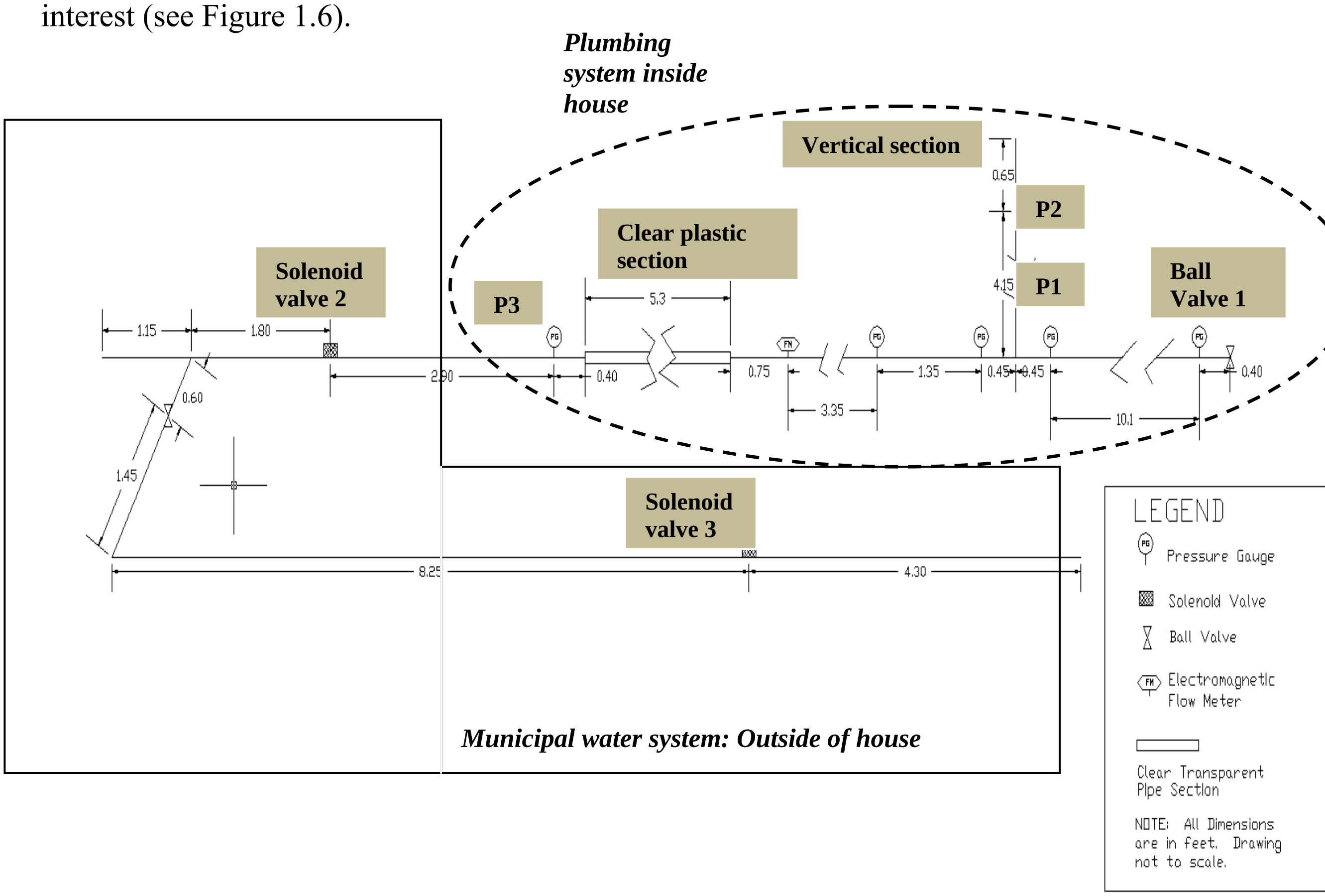


Figure 1.6 Schematic of the experimental plumbing system

The signals from the sensors were collected by LabVIEW based DAQ systems using sample and hold technique every 0.01 second so the data from multiple signals are acquired simultaneously. To visualize the phenomenon and study the specific nature of gaseous cavitation inside the piping system, a 5.3' section of clear plastic pipe was installed. We employed a high definition Video camera to capture the cavitation phenomenon for steady state and when water hammer hits. Figures 1.7 through 1.11 show the pictures of the experimental set up at various levels of details.

Table 1.3 Specification of the sensors

Apparatus	Specification	Cost
Dynamic Pressure Transducer	Output: ±5V, range: ± 500 psi, sensitivity: 10mV/psi, resolution: 10mpsi, frequency ≥ 500 kHz,	$729/each
Data Acquisition System and Modules	Sample and hold; NI 9233 4-Channel: 24-Bit, +/-5 V, 50 kS/s per channel; Analog Input Module; NI 9203 8-Channel: +/-20 mA, 200 kS/s, 16-Bit Analog Input Module	Total $2,700 including modules and chassis
Flow meter	Output: 4-20 mA, 3/4" fitting, Flow range: 0.15-16 fps, fluid: drinking water, no pressure drop, one-direction	$1,300 including power supply, meter, and fittings

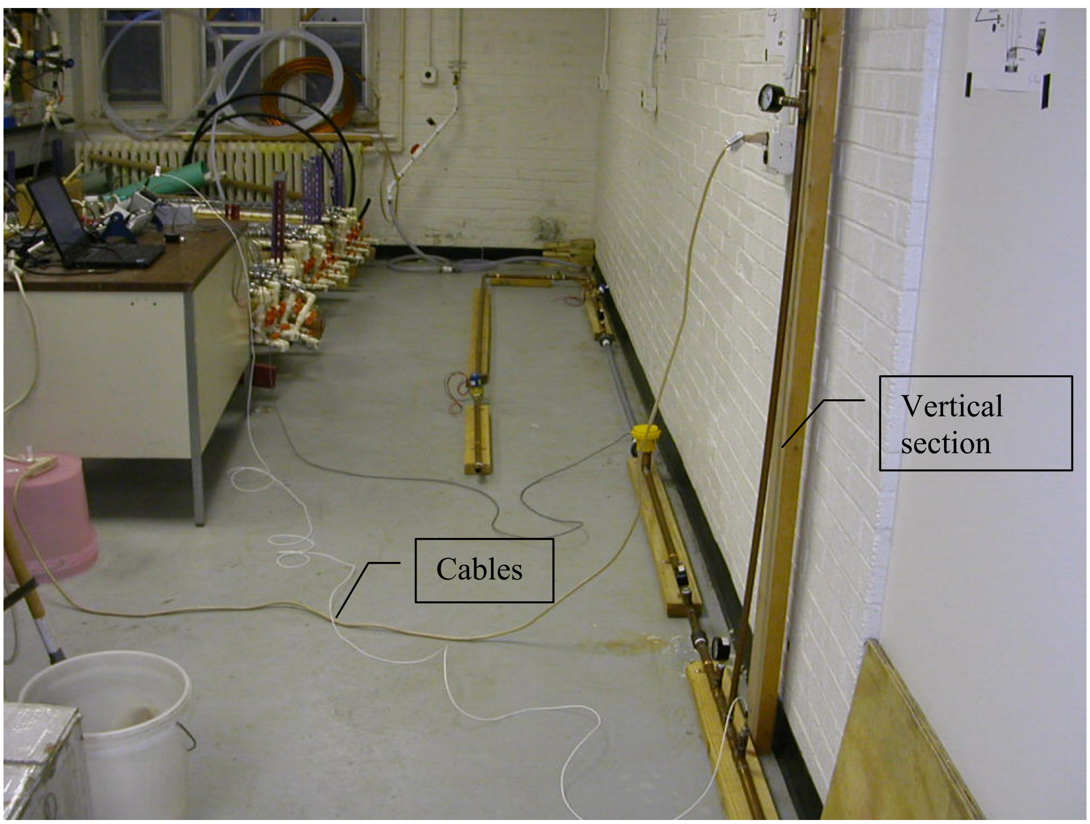


Figure 1.7 Experimental setup (pressure gages, vertical riser with dead end)

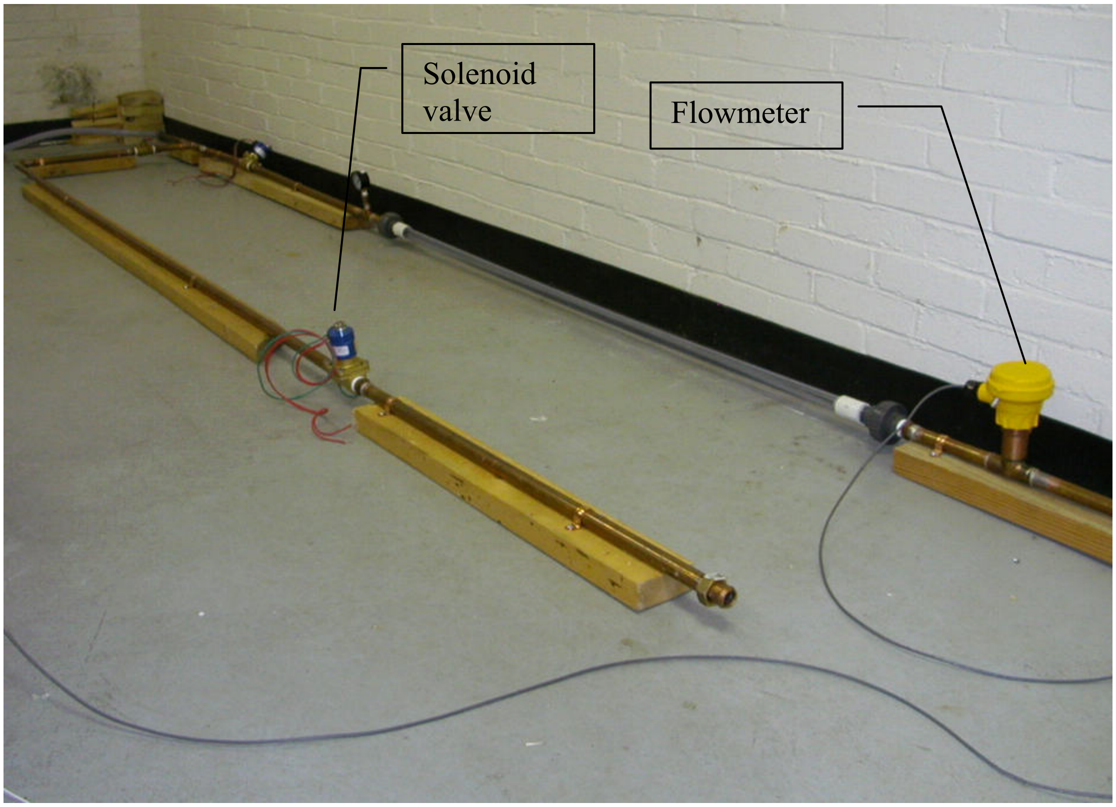


Figure 1.8 Flowmeter, clear plastic section, and solenoid valve

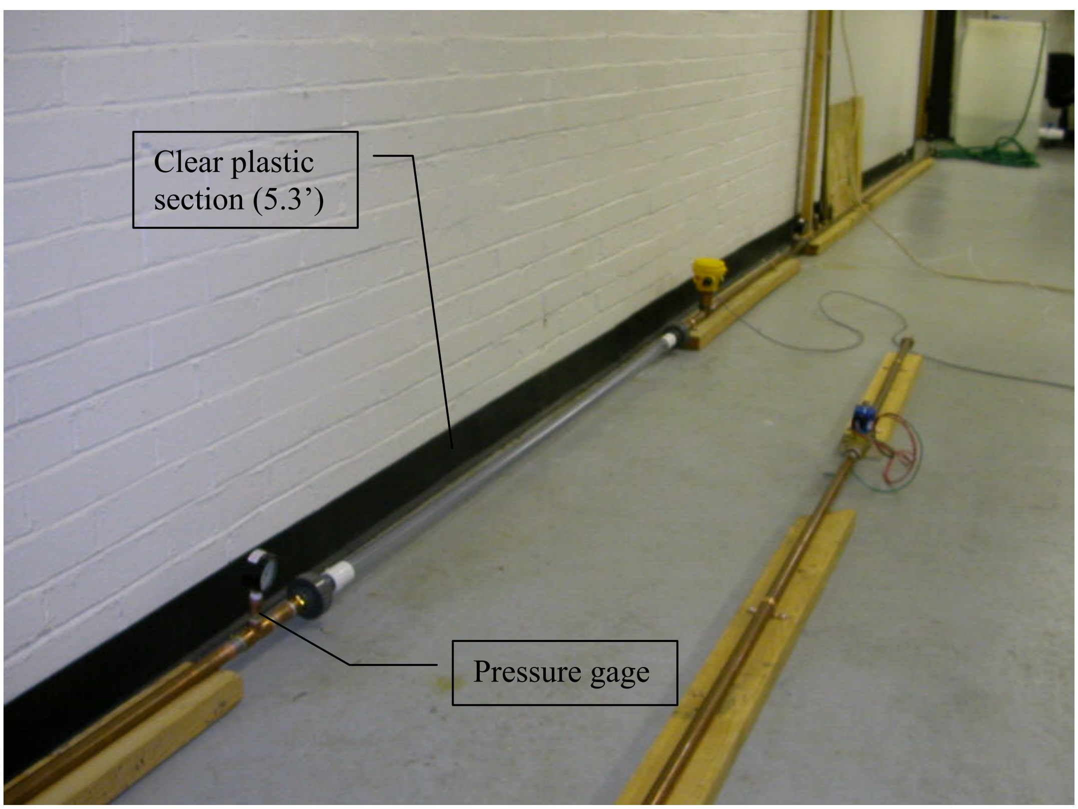


Figure 1.9 Experimental set up

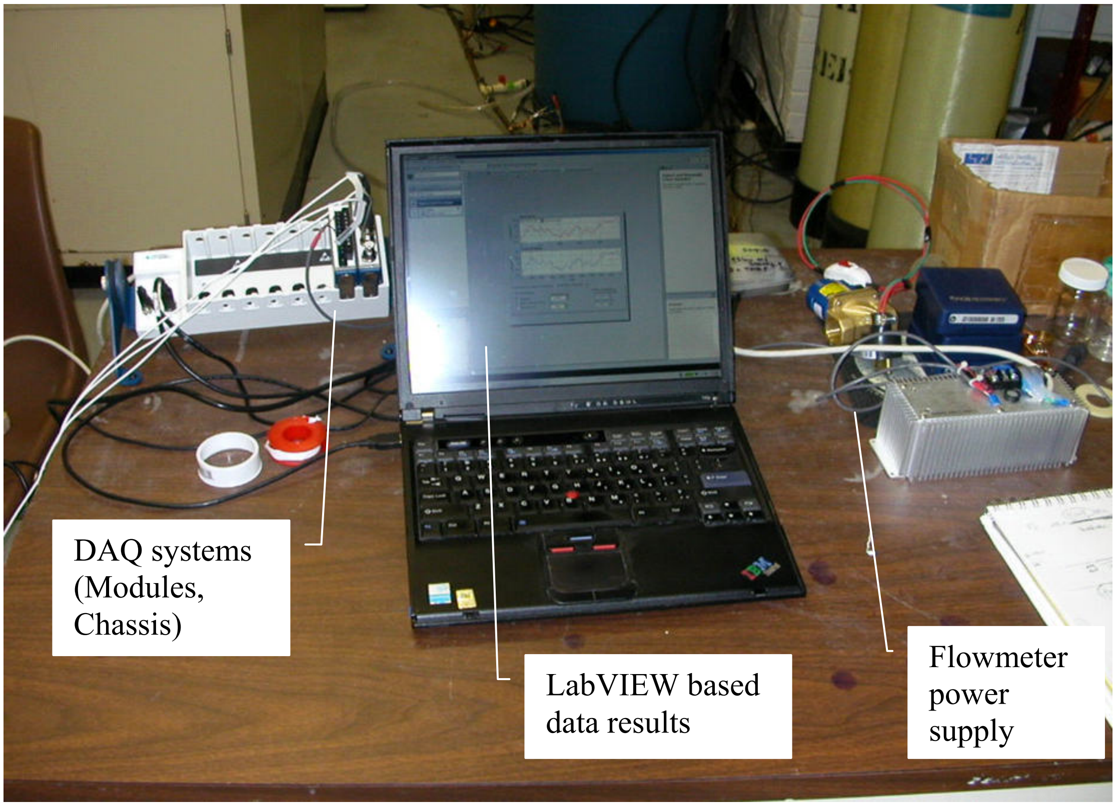


Figure 1.10 DAQ systems connection

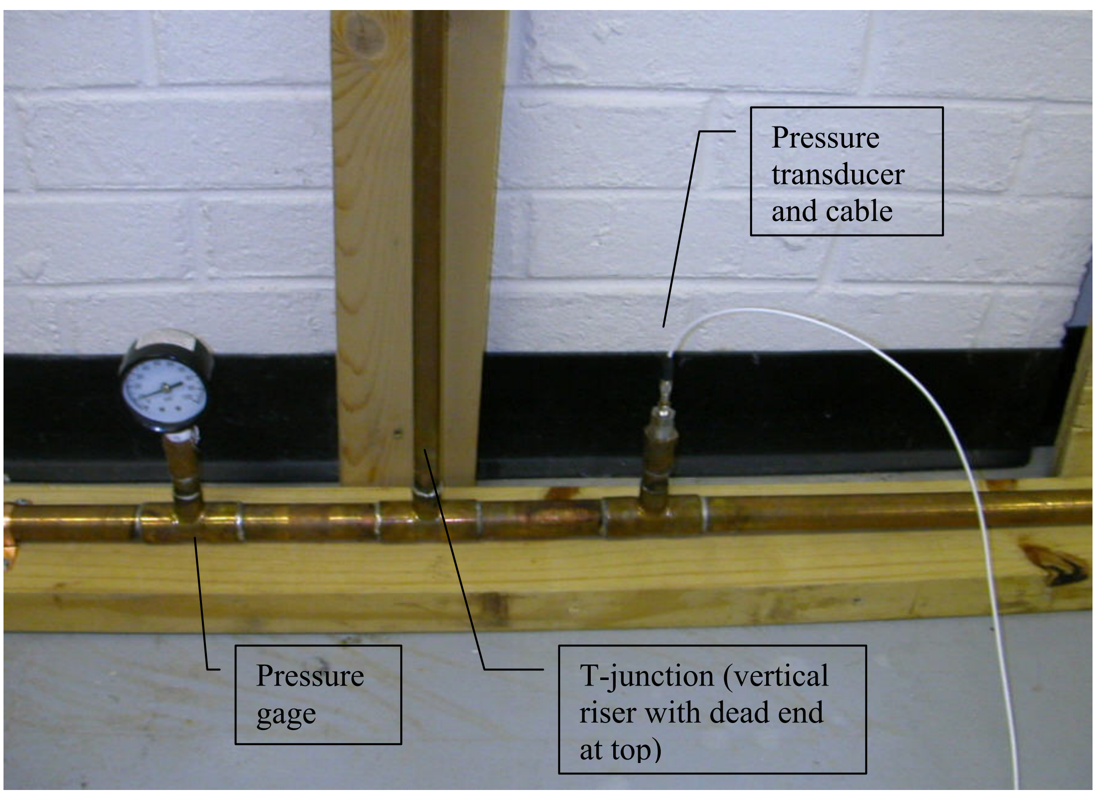
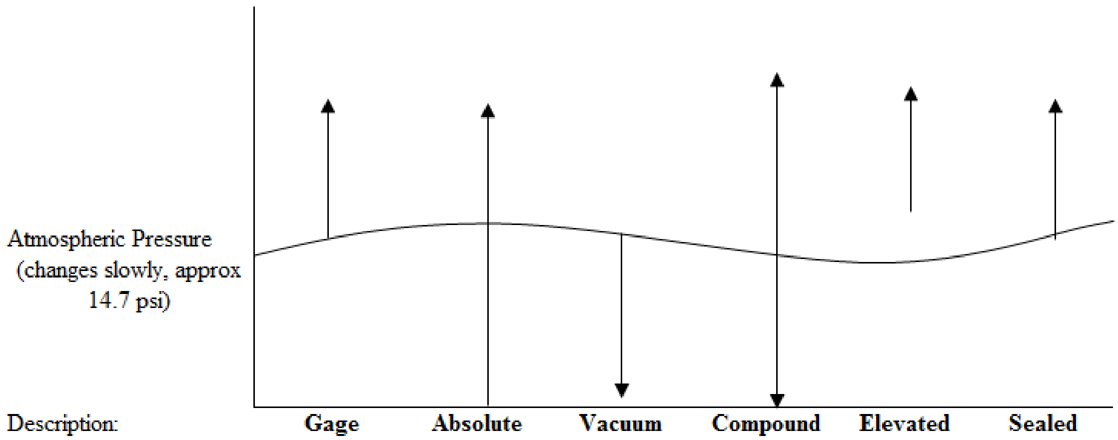


Figure 1.11 Pressure transducers and t-junction

The experiment involves pressure varying continuously over time over a range of -14.7 to over 250 psig (temperature range is 50 to 90 F [room temperature]). Water hammer occurs if a valve is suddenly closed (ball valve or solenoid valve) in a pipe system, and there is a sudden change in the velocity and pressure. As water hammer passes through the pipe, pressure measurements of the order of hundred readings per second capturing the maximum and minimum are required to visualize the pressure variation. The pressure continuously fluctuates until the transients die out. It was necessary to measure the pressures as they fluctuate continuously with time. To meet these requirements, we chose dynamic application sensors which means sudden change of properties. Water hammer shocks, acceleration, vibration, sound are examples of dynamic signals.

For dynamic applications, piezoelectric pressure sensors are known to be ideal as they are able to measure very high frequencies compared to strain gauge technology due to their stiffness. Stiffness also leads to fast response time. Piezo sensors offer a response time of less than 1 micro-second so there is no trouble making several hundred readings per second as long as sampling rate on the DAQ (Data Acquisition System) is high enough (Our DAQ system is able to collect maximum of 1M readings per second). However, piezoelectric sensors ignore the static pressure component. As such referencing the output to atmosphere or absolute is not possible. The sensor will show the pressure changes in relation to static pressure in the rig. In our application, the *baseline pressure* is the *water line's steady state pressure*. So, for the piezoelectric pressure sensor, instead of calling it gage pressure, it is really called a relative pressure measurement; *relative to the water line's steady state pressure*. For example, water line pressure is 30 psi; the 30 psig static water line pressure will read zero on a piezoelectric pressure sensor. A regular static sensor would read 30 psig. Then, when the water hammer hits, there will be a spike to 250 psi 'relative to 30 psig' and then a reflected pressure wave possibly down to -14.7 psi 'relative to 30 psig.' This -14.7 psi is relative to the static line pressure of 30 psig. For completeness, we are including the pressure reference for gage, absolute, vacuum, compound, elevated, and sealed in Figure 1.12.



	Gage	Absolute	Vacuum	Compound	Elevated	Sealed
Reference To:	Atmosphere Vented	Vacuum Sealed	Atmosphere Vented	Atmosphere Vented	Atmosphere or Vacuum	Atmosphere Sealed
Definition:	Units above Atmosphere	Units Above Full Vacuum	Units Below Atmosphere	Units above and below Atmosphere	Units above a selected zero	Units above a sealed reference

Differential Pressure (not shown): is the difference between two unknown pressures.

Figure 1.12 Pressure references (email correspondence from PCB Electronics with permission)

When a valve is closed and the water hammer occurs there is going to be some vibration in the rig. Nearly all of piezo sensors that we selected, are acceleration compensated; they have minimal response to the effects of vibration leaving just the pure pressure data. According to the manufacturer, other benefits are known to be excellent signal resolution, high frequency response, easy mounting and ground isolation (in case there is any electrical noise on the rig). We chose a piezo sensor that includes very high and low (±500 psig) range of pressure so the transducers are not damaged by water hammer's extreme shocks.

For flow rate, the flowmeter range is from 0.15 to 16 feet/sec. Sampling rate is maintained at 2 data per second. As it captures only one-direction, we could not capture the backflow phenomenon when the water hammer hits. Signals from flowmeter (4-20 m A) and transducers (± 5Volts) are imported to LabVIEW based DAQ systems. Regarding pressure, +5 volts correspond to +500 psi (relative pressure) and -5 volts to -500 psig (relative pressure). Linear interpolation holds for interpreting the pressure variations. All the data results are shown in Section 4.

4. Experimental Results

The experiment plumbing rig was connected to the water main in hydraulics lab to simulate a real household water supply situation (see Figure 1.7). The average static pressure was 80 ± 5 psi when all the valves were closed. It is opined that this fluctuation comes from water usage in nearby faucets or weak transients from the municipal systems. When the faucets were fully opened (flow rate is (37±5) liter/minute), however, the residual pressure was reduced to 40-45 psi in the system. The level of residual pressure could be controlled by maneuvering the valve at the water main. The valve was partially closed producing a residual pressure was 20-25 psig (flow rate is (20±4) liter/minute). Initially, the system is set in a steady state of 40 psig (residual pressure). Then the solenoid/ball valves were suddenly closed/ opened following three scenarios. The solenoid valve closing/opening time was known to be less than 0.3 seconds according to the manufacturer. The ball valve closing/opening time is believed to be less than 0.1 seconds after many times of operator's training.

Pressure Variation at Location P3 (Figure 1.6): Representing Service Line

The relative pressure variation at location P3 (representing service line; see Figure 1.6) are shown in Figures 1.14 through 1.19. Scenario I refers to the open/close at valve1; scenario II refers to open/close at valve 2; and scenario III is open/close at valve 3 (see Figures 1.6 and 1.13). It is noted that when we ran scenarios I and II, no water is flowing at branched sections (leading to valve 3) to have high residual pressure inside the systems.

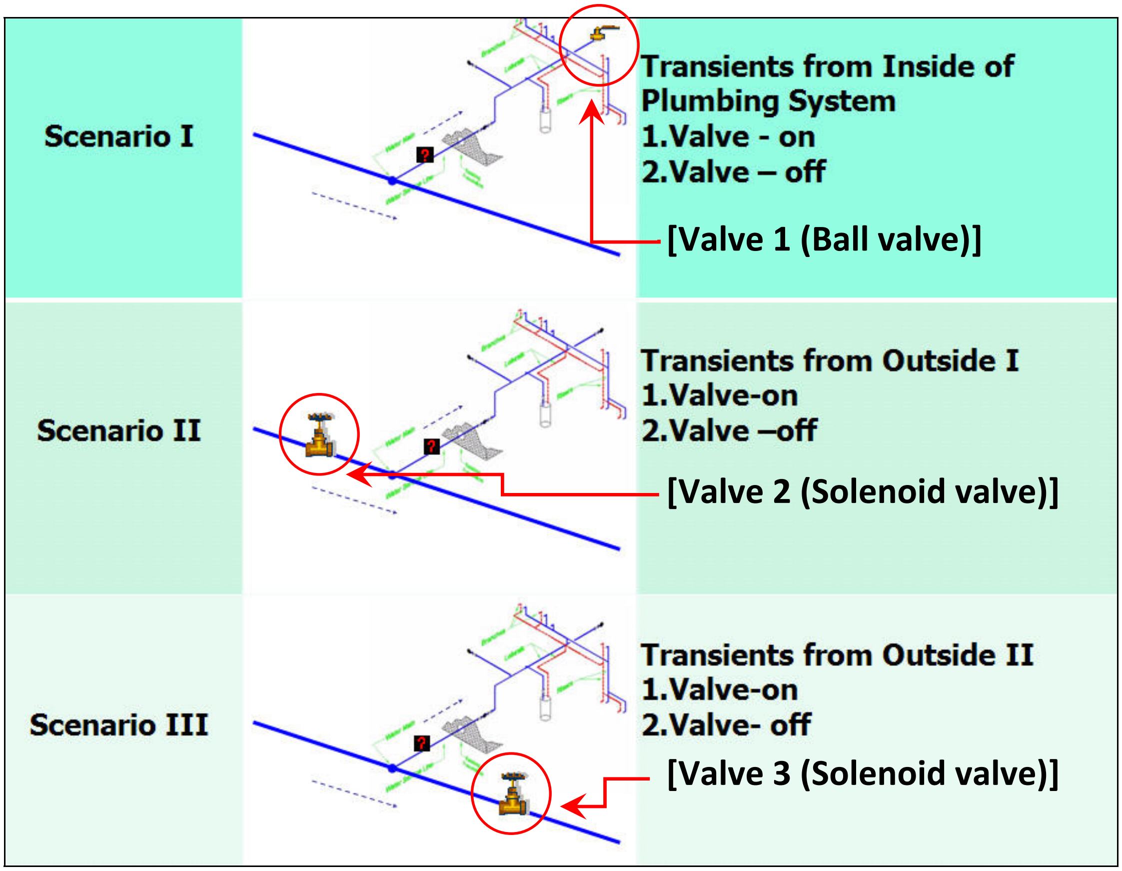


Figure 1.13 Scenarios of transients that can occur in drinking water distribution systems (modified from Ladd, 2005 with permission), refer to Figure 1.6 for valve numbering

When the valve 1 is suddenly closed (scenario representing *Transient I*), the pressure goes up to 70 psi (gage) from the steady state (see Figure 1.14). So, within fraction of a second, service line is going through (40+70=110) psig of pressure. This may result in *repetitive fatigue impact on service lines* due to constant on/off from inside the house. It is seen that water hammer from minor system is passing through the service line and goes out to water main systems because no reflection waves are observed. So water main should not be modeled as reservoir in hydraulic modeling. This will be covered in numerical modeling of Section 4. But when opened, it is causing -30 psig so 80 psig (static pressure) – 30 (instantaneous pressure change) = 50 psig; which is not creating low enough pressure to cause suction. Figure 1.15 is showing when residual pressure is around 20 psig. The trend is the same but the magnitude is smaller than fully opened case.

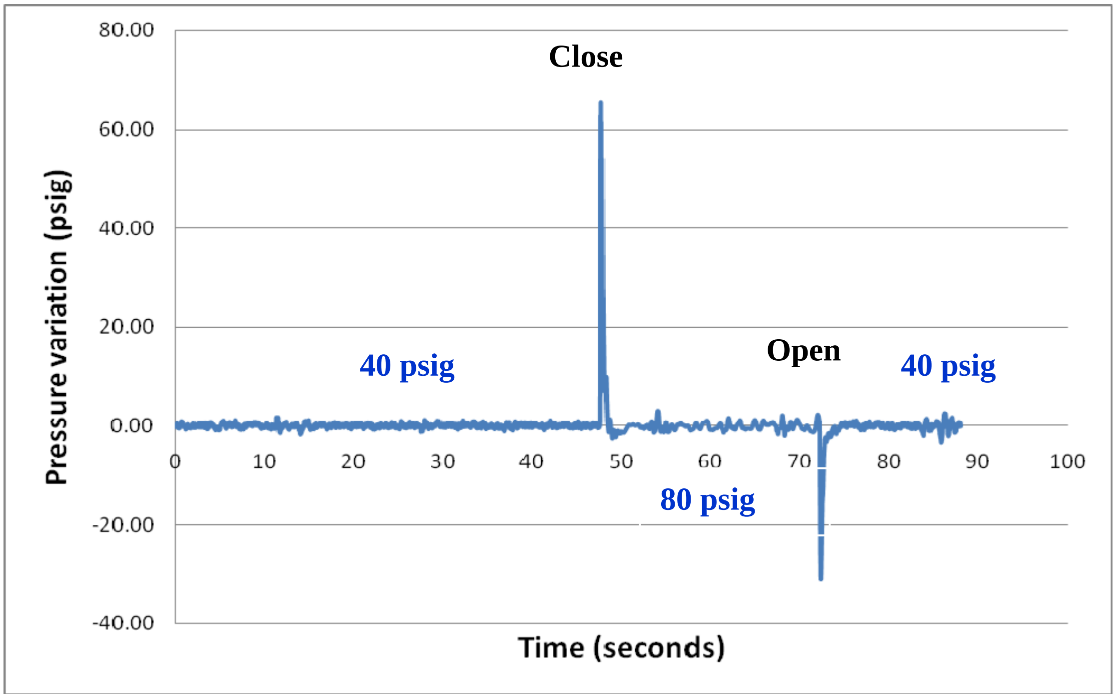


Figure 1.14 Pressure variation, scenario I, 40 psig residual pressure

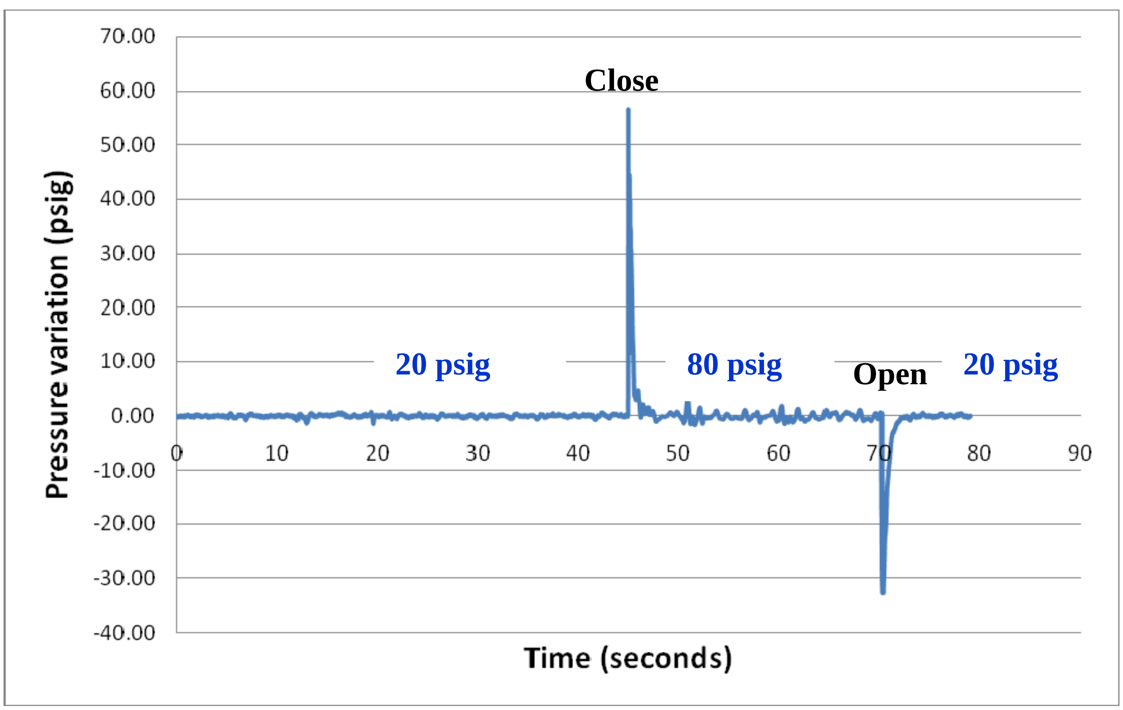


Figure 1.15 Pressure variation, scenario I, 20 psig residual pressure

Transient II scenario results are shown in Figures 1.16 and 1.17. After sudden closure, the pressure goes below 0 psig (around -10 psig) for a fraction of a second. It is noted that only *the first peak is guaranteed to be true in dynamic results*. The *second peaks onwards are residual wave actions that the sensor is tracking as it settles out to steady state (PCB, 2008)*. It is seen from that transient II is causing negative pressures (40 (steady state) – 50 (pressure variation) = -10 psig inside the system). Figure 1.17 is showing when residual pressure is around 20 psig. The trend is the same but the magnitude is smaller than fully opened case.

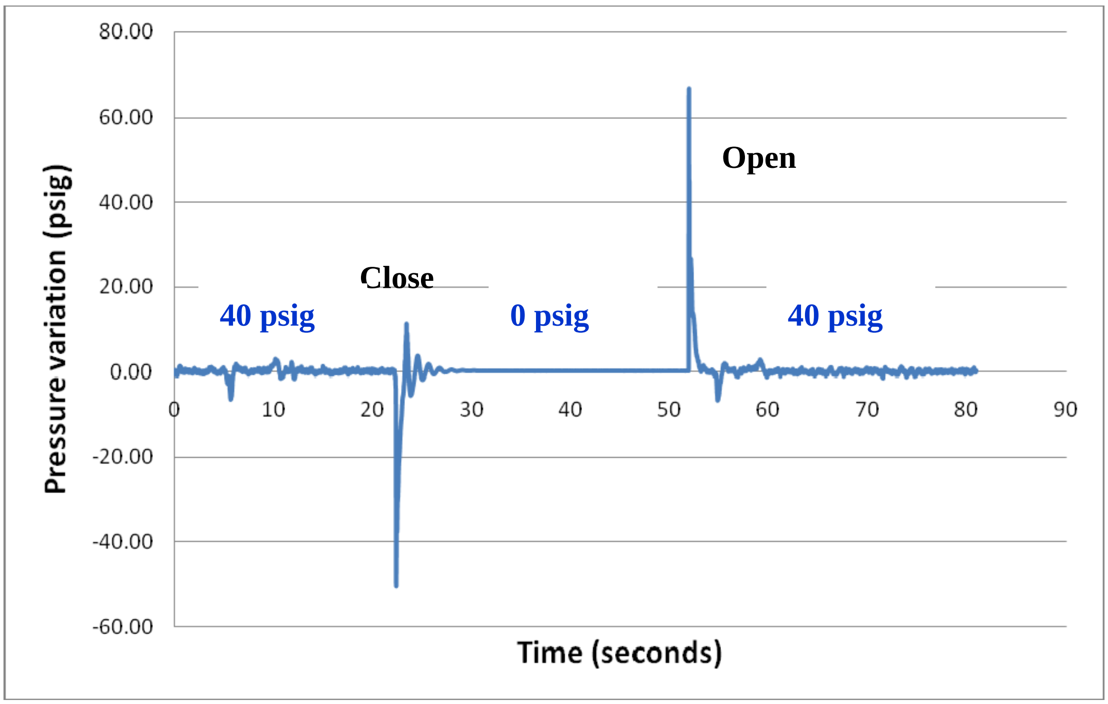


Figure 1.16 Pressure variation, scenario II, 40 psig residual pressure

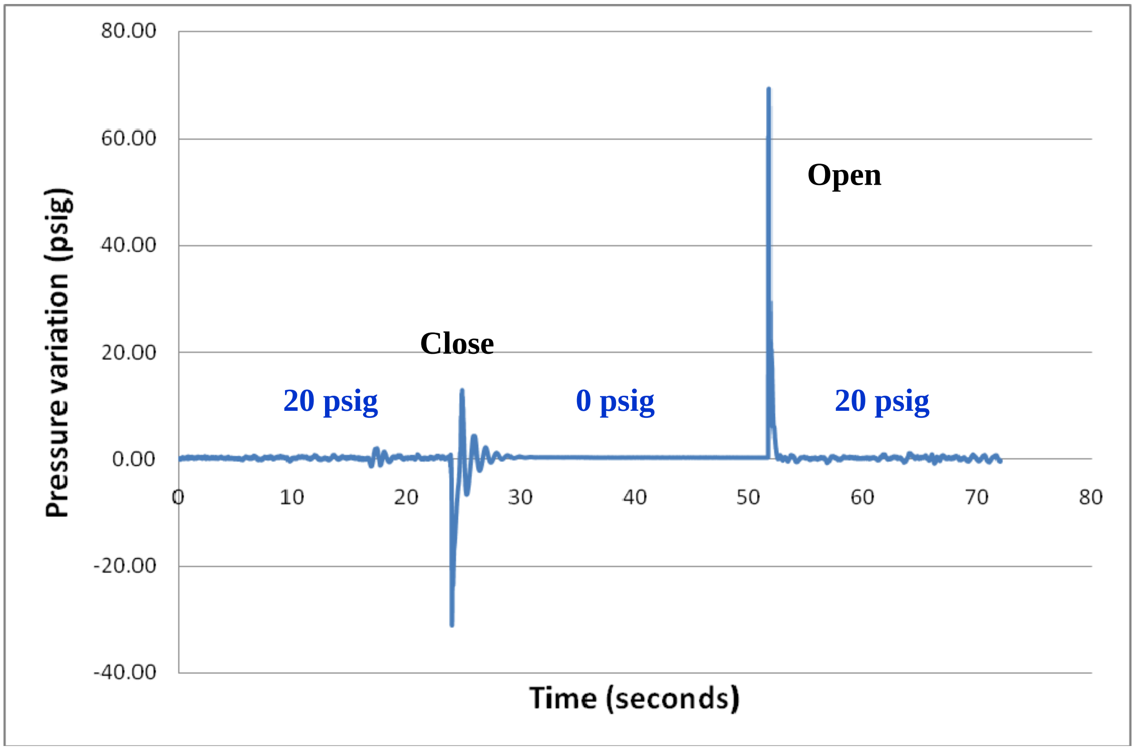


Figure 1.17 Pressure variation, scenario II, 20 psig residual pressure

In Figures 1.18 and 1.19, the pressure variation due to scenario III is shown. It is quite similar to scenario I but the magnitude of spikes is smaller due to smaller residual pressure. It is noted that water in the main line branch (leading to valve 1 and 2) are flowing during initial steady state.

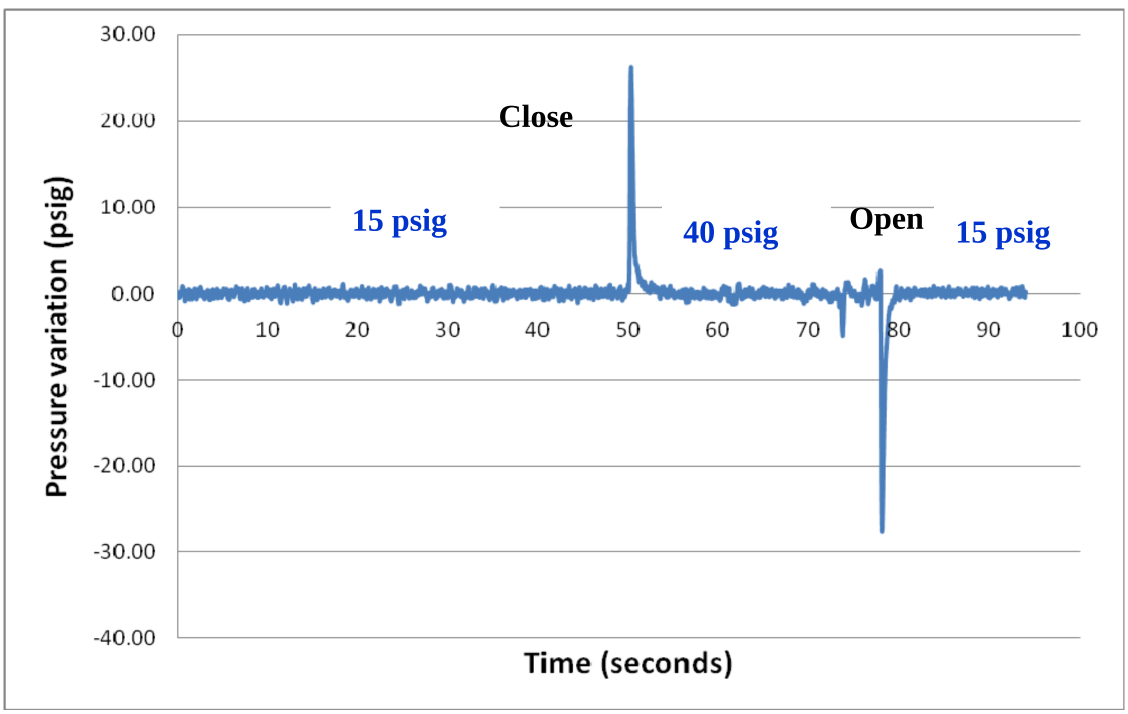


Figure 1.18 Pressure variation, scenario III, 15 psig residual pressure

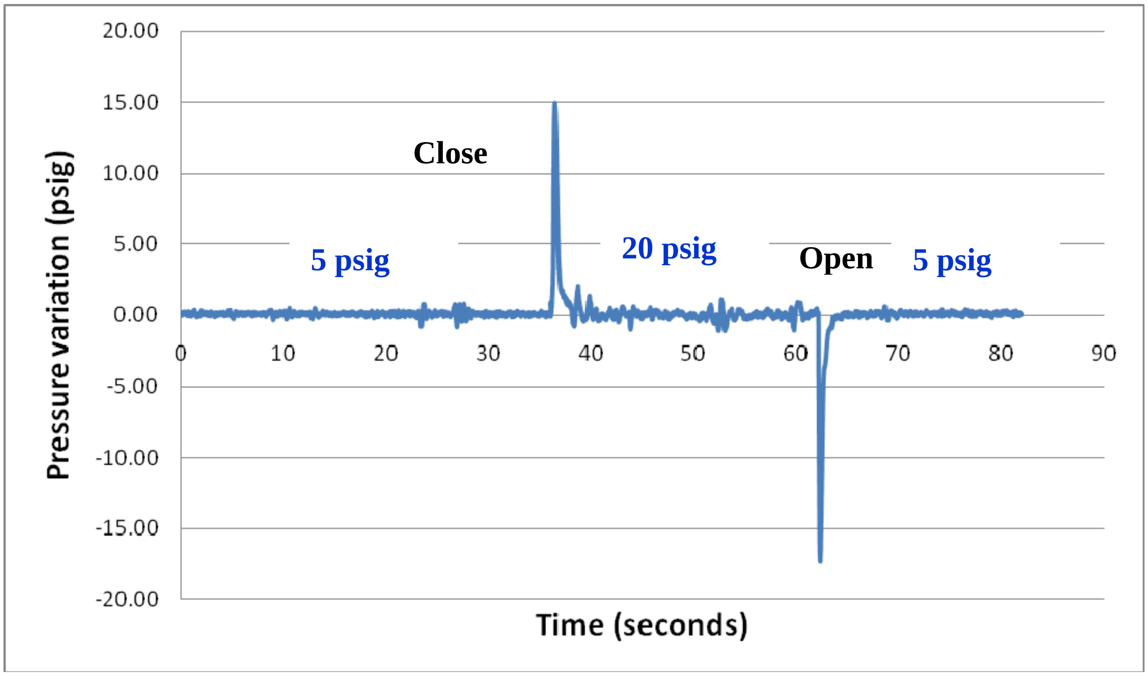


Figure 1.19 Pressure variation, scenario III, 5 psig residual pressure

At Vertical Section

We also measured pressure at vertical riser section *(with dead end)* as the water hammer is triggered (see Figure 1.6). Figures 1.20 through 1.22 are showing the pressure variation at vertical sections due to three scenarios. It is evident that scenario I is causing very high pressure (more than 100 psi variation, Figure 1.20) at vertical section. Triggered low pressure is also seen in Figure 1.21.

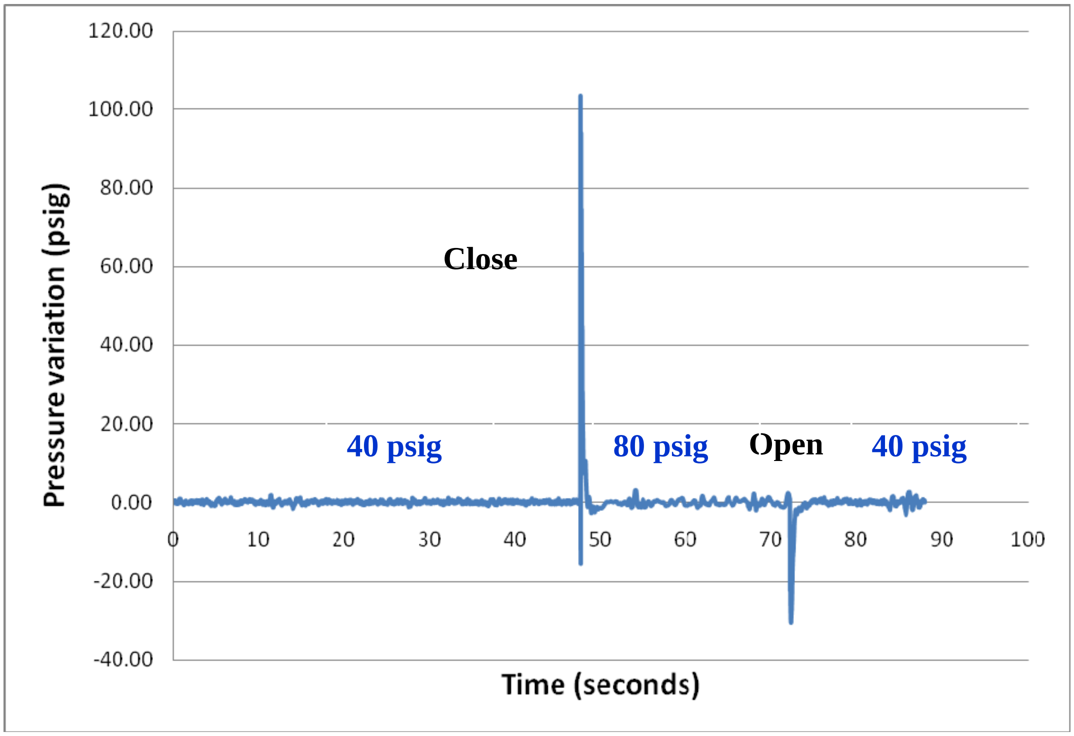


Figure 1.20 Pressure variation at vertical riser, scenario I, 40 psig residual pressure

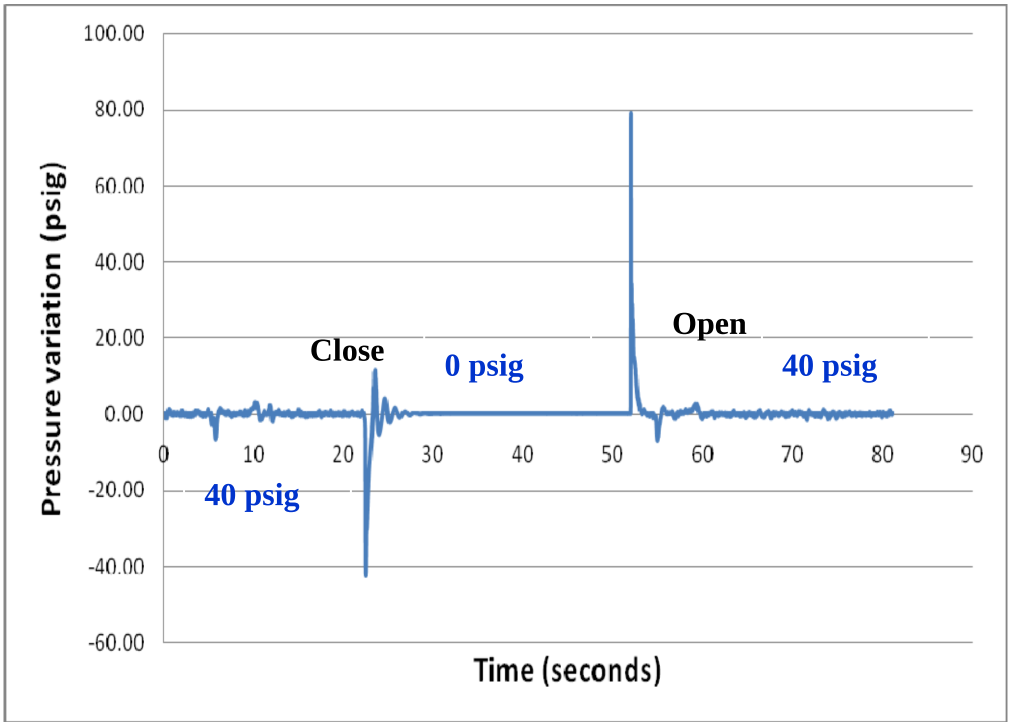


Figure 1.21 Pressure variation at vertical riser, scenario II, 40 psig residual pressure

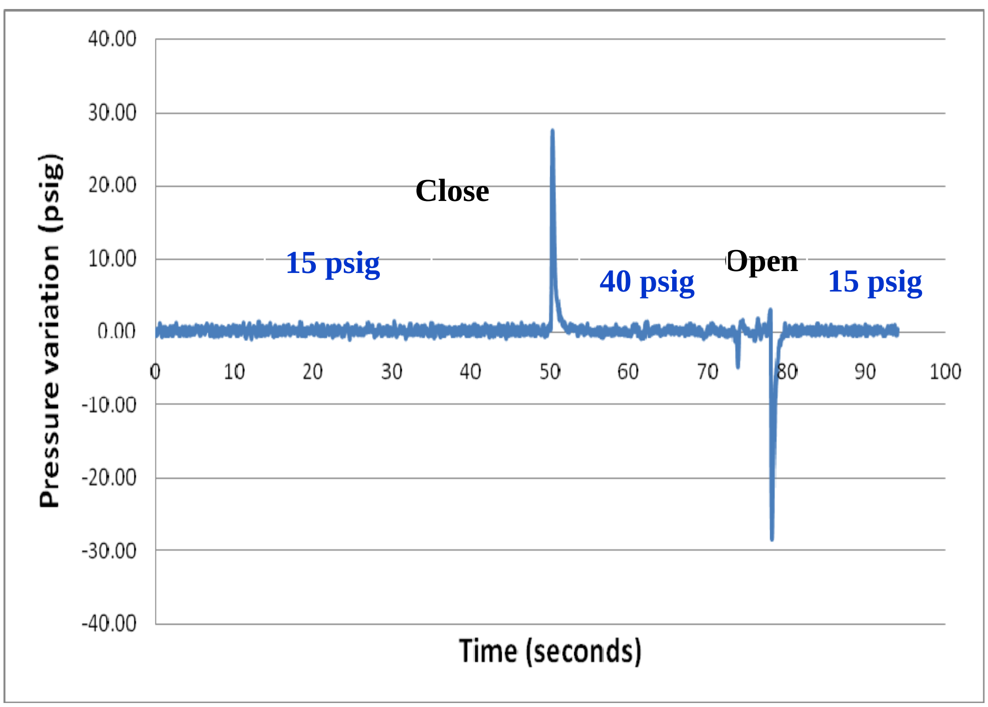


Figure 1.22 Pressure variation at vertical riser, scenario III, 15 psig residual pressure

A *t-junction that has vertical riser (pipe)* is handled numerically the same as any other junction and branch combination in terms of wave propagation by decomposing this entity into its constituent parts: a junction and several branches, one of which is vertical. In the specific case of a dead end, the sole boundary condition is that the flow is zero. Sometimes, this type of arrangement is inherently tricky because the top of the riser creates a "dead end" that is also at a higher elevation than the pipeline. According to Jung et al. (2007), dead-ends can amplify pressures up to two (2) times, depending on the topology. Their assertion that network simplifications that eliminate dead-ends from transient analysis are *invalid;* this assumes the modeler will only analyze the simplified network for transients. So, it is recommended to *check* key transient runs with all-pipes model (including dead-ends). From our experiment, we also observed higher pressure variation than the horizontal line (at service line section).

<u>Gaseous Cavitation</u>

When the pressure drops to -10 psig (above vaporous pressure values), gaseous bubbles forming in the clear plastic pipe section was observed; then the bubble disappeared within less than 1 second when pressure goes above gas saturation pressure (see Figures 1.16 and 1.23). The bubble formation time was very quick (less than 1 second) and this is *contrary to traditional theory of gaseous cavitation formation timing (2-3 seconds)*. It is noted that water hammer induced gaseous cavitation (from bulk liquid) was observed in this experiment and the formation time was very quick. Pre-existing gas nuclei that was existing on particles in the bulk solution seemed to grow to be the observed bubbles. Using HD video, consecutive phenomenon is captured every 0.033 second (30 frames per second). All pictures (in chronological order) are shown in Appendix I-D. It is observed that created bubble shape and numbers are near *random* but gas evolution and dissolution timing seem to be almost consistent (less than 1 second) as long as we control the water hammer triggering mechanism (valve closing time). As the clear plastic's diameter is ¾", rough size of the gaseous cavitation bubbles can be estimated.

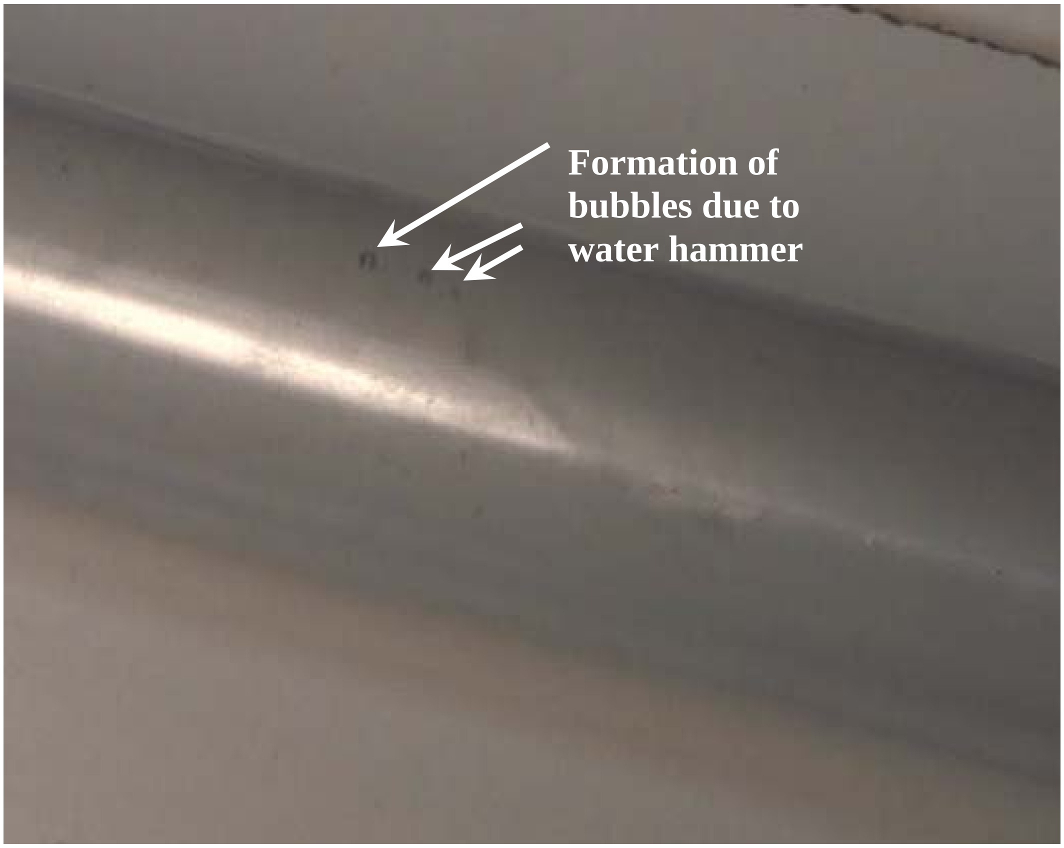


Figure 1.23 Water hammer induced gaseous cavitation (the pipe diameter is ¾")

The normal flow inside plumbing system is turbulent flow (the Reynolds number is 54,780 (diameter: 1", velocity: 8 ft/sec, water 60 F, absolute viscosity: $7.66*10^{-4}$ lb/ft sec). According to Scardina (2004, I), typical vapor pressures of water (10-40 ºC) is from 0.012 to 0.073 atmosphere; the total dissolved gas pressure of natural water is typically in the range from 0.8 to 1.2 atmosphere. When pressure drops below the saturation pressure of the constituent gases, bubbles comprised of dissolved gases are formed which is known as *gaseous cavitation*. When the pressure drops below vapor pressure, vapor cavities are created in liquid by phase transformation. In the following, theories on cavitation phenomenon are explained.

Gas Evolution from and Dissolution into a Liquid

According to Chang (1984), gas is the substance that is normally in the gaseous state at ordinary temperature and pressure while vapor is gaseous form of any substance that is liquid or a solid at normal temperatures and pressure. For water, the typical gas content of the bubbles is water vapor but the gaseous bubbles due to N_2, O_2, CO_2, Cl_2, and Ar can form (Novak, 2005). The gas release rate is proportional to supersaturation pressure, that is, the concentration difference drives the gas release rate: $\frac{dm}{dt} = \beta(c_s - c)$, m: gas mass c_s: dissolved gas concentration per unit volume at saturation, c is the observed dissolved gas concentration per unit volume, β is the gas transfer coefficient which includes the diffusion coefficient and the interfacial area for gas transfer per unit volume of liquid. Secondly, the gas release rate is related to the degree of underpressurization: $\frac{dm}{dt} = \beta S \frac{(p_s - p)}{RT} V_l$ where, S: Henry's constant, R: gas constant, T: absolute temperature and V_l is the unit volume of liquid (Zielke, 1990).

Solubility Based Equations

Vapor pressure is the pressure of a vapor in equilibrium with its non-vapor phases. At any given temperature, for a particular substance, there is partial pressure at which the gas of that substance is in dynamic equilibrium with its liquid or solid. This is called the vapor pressure of its liquid or solid state. Also, it indicates the evaporation rate of the liquid, which is the tendency of the molecules and atoms to escape from the liquid. So, when the vapor pressure of a liquid is higher at a given temperature, the boiling point is also low. For the vapor pressure of mixtures of gases in a liquid (single phase), Raoult's law governs the phenomenon. It states that the pressure of a single phase mixture is equal to the mole fraction weighted sum of the components' vapor pressure.

Henry's law governs gas distribution in water which is in equilibrium with the air. The solubility of a dissolved gas is directly proportional to the pressure on the fluid. The total dissolved gas pressure can be calculated by summing the partial pressures of gases and vapor pressure of the water.

$$\textit{Raoult's law: } y_i P = x_i P_i^0 \tag{1.4}$$

$$\textit{Henry's law: } y = \left(\frac{HV_s}{RT}\right)C = mC \tag{1.5}$$

Where y_i: mole fraction in gas phase, P: pressure, x_i: mole fraction in liquid phase, and P_i^0 : vapor pressure of pure liquid, y: gas-phase molar concentration, C: liquid phase molar concentration, H: Henry's constant, *m*: alternate form of Henry's constant, V_s: molar volume of the solution (L/mole), R: gas constant, and T: absolute temperature (K).

Diffusion

The dissolved gas from the bulk liquid diffuses into a bubble forming in tiny cracks and irregularities on surfaces.

$$\textit{Fick's first law } J_{diff} = -D\frac{dC}{dx} \tag{1.6}$$

$$\textit{Fick's second law } \frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{1.7}$$

where J: mass flux per unit area, D: molecular diffusion coefficient, and C: concentration. Drinking water in pipelines may contain a gaseous phase in the form of free bubbles suspended in the bulk solution or as nuclei adhering to or hidden in cracks on solid surfaces. Dissolved gas from the bulk liquid diffuses into a bubble forming in tiny cracks and irregularities on surfaces. The kinetic properties of the gases induce molecules of one gas gradually mix with molecules of another. Fick's first law governs the diffusion of molecules, that is, flux is proportional to the concentration gradient. A differential mass balance for flux in 1-Dimensional equation can be written $\frac{\partial C}{\partial t} = -\frac{\partial J}{\partial x}$ and this leads to Fick's second law, $\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$. The diffusion coefficient depends on the properties of diffusing substance [molar volume that dictates the mean free path in fluid and molecular mass] and properties of the fluid [viscosity, temperature, and pressure] Bubble can grow or shrink depending on the following factors: surface tension, ambient liquid pressure, vapor pressure of the liquid, and gas pressure inside the bubble. Also, large bubbles may be formed by coalescing of the two or more bubbles and free gas molecules entering the bubbles. But the observed bubble size was less than 0.1 mm.

Bubble Dynamics

According to Wiggert et al. (1979), the momentum equation for a small spherical bubble of radius R filled with vapor and gas and surrounded by a saturated flowing fluid is $p_g^* + p_v^* = p_l^* + \frac{2\sigma}{R}$, where p_g^* is the partial pressure of gas, p_l^* is the liquid pressure, σ is the coefficient of surface tension, and p_v is the vapor pressure. They neglected the viscous forces and assumed slow bubble growth in this equation (see Figure 1.24). The cavity size increases until the internal pressure is sufficient to offset the decreasing external pressure and surface tension. When this critical size is reached, cavity becomes unstable and expands explosively.

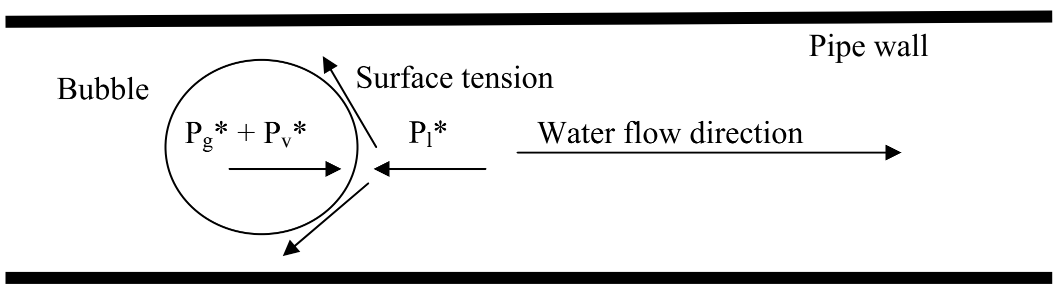


Figure 1.24 Bubble inside the pipe

It is known that maximum pressure from the bubble collapse is estimated to be at tens of thousands of psi and microjects (surrounding water rush into the bubble collapsed space) can move faster than sound wave speed (Konno et al., (2001), Siegenthaler (2000)). Also Chen (2002) observed the pipe failure due to bubbles. Observed gaseous cavitation due to water hammer may have implications of noise problems within plumbing systems which bears further research.

5. Numerical Models

Two major sources of drinking water are from surface water and ground water. The water quality can change due to the source of the raw water. Surface water sources are known to be more turbid and have more organic contaminants than ground waters due to urban pollutants that reach the surface water bodies with surface runoff. Ground waters on the other hand, have higher TDS (total dissolved solids) because of mineral pickup from soil and rocks. Ground waters may have dissolved gases like carbon dioxide [CO_2], ammonia [NH_3], hydrogen sulfide [H_2S] and sometimes iron and manganese (Tchobanoglous, 1985). At the treatment plant, disinfectant such as free chlorine, chloramines, ozone, ultra violet light, and chlorine dioxide is used to protect microbial contamination in drinking water distribution system (DWDS). Detectable disinfectant (0.2mg/l in case of free chlorine) residual is regulated to control regrowth of microorganisms, minimize microbial interactions with pipe wall biofilms, inactivate pathogens after primary disinfection, and prevent disease. Treatment plant also adds corrosion inhibitors (orthophosphate or polyphosphate) to prevent the corrosion of the water carrying pipes. The treated water is then pumped into the major water distribution system where it is transported through pipe network. It is also known that distribution system pipes can leach chemicals into water thus changing the water chemistry. So, water quality parameters are affected by the various pipe materials (Ductile iron or cast iron with or without lining, plastics, reinforced concrete, steel etc) including plumbing materials (Copper, PEX, CPVC etc). Additional important factors to change water quality can be biofilm re-growth, nitrification, internal corrosion, scale formation, flushing practice methods, and increasing water age. According to Farooqi (2006), water quality changes significantly due to the complexity of the factors during transportation of water. But the *dominant dissolved gases in drinking water from the faucets* are following the main composition in the air, namely, *nitrogen, oxygen, and carbon dioxide*. The composition changes according to temperature, season, and even day and night (Scardina, 2007).

In a liquid, gas may have two forms; dissolved and free gas. The dissolved gas is invisible in liquid and does not increase its volume and compressibility noticeably. But free gas (or '*entrained gas*') is dispersed in the liquid as bubbles that may make liquid look turbid. The liquid which is not completely degassed will usually contain some entrained air in the form of microscopic or submicroscopic bubbles either in the bulk of the liquid or near a solid contaminants or near the container wall. Fluid mixtures can be categorized into five phenomena [Shu, 2003]: 1) fully degassed fluid, 2) fully degassed liquid with vapor, 3) liquid with dissolved gas, 4) liquid with dissolved and free gas, 5) liquid with dissolved gas, free gas, and vapor. Vaporous cavitation can show 2) or 5). The cavity may become so large as to fill the entire or partial section of the pipe (known as *air pocket*) and divide the liquid into two columns in vertical pipes or pipes with steep slopes which is known as *column separation*. In horizontal pipes or mild slopes, however, a thin cavity aggregated to the top of the pipe and extends over a long distance in the pipe [i.e. *cavitating flow*]. So, the vapor cavities may be physically dispersed homogeneously or collected into a single or multiple void spaces, or a combination of the two phenomenon. For gaseous cavitation, 4) can be seen. Free gas is distributed throughout the liquid in a homogeneous mix or lumped as pockets of free gas, trapped along the pipe wall, in pipe joints, in surface roughness, and crevices.

According to Wallis (1969), the most widely used models (when free gas exists) are homogeneous model, separated models, and drift flux model. For a two phase or two component mixture one dimensional flow model, six equations are required to represent the conservation of mass, momentum, and energy of each phase. To describe the interaction between each phase, additional formulations are required. One or more of the conservation equations are formulated for the mixture rather than individual phases so simplified governing equations are established. Drift flux considers only velocity difference between the two phases. Separated model includes all of the equations mentioned above. If there is not a significant difference in velocities of the both phases, homogeneous models can be applied to bubbly mixture models. For homogeneous model, two components are treated as a single pseudo-fluid with averaged fluid properties.

The analysis of plumbing systems differs markedly from the analysis of municipal systems. It is a typical practice to treat the flow in municipal systems as steady flow and the continuity and energy equations are solved for head (H) and flow (Q); however, in plumbing systems because the demands last for hardly a few minutes transient analysis is more appropriate and the continuity and momentum equations are solved. As mentioned, the water hammer is a transient flow phenomenon introduced in pipe flow systems by suddenly obstructing the flow. As a consequence, there is a pressure rise and fall and the pattern is repeated until the transients decay.

In the preliminary phase of this study, we proposed the continuity and momentum equations for a two phase mixture having a low void fraction and insignificant slip. We made several assumptions when using the equations given here: 1) fluid mixture is homogenous, bubbly, two-component nature. 2) Difference in pressure across a bubble surface can be neglected, and 3) There is no momentum exchange between each phase; no slip between each phase.

$$\textit{Continuity equation: } \frac{\partial P}{\partial t} + \rho_m a_m^2 \frac{\partial V}{\partial x} = 0 \tag{1.8}$$

$$\textit{Momentum equation: } \frac{\partial V}{\partial t} + \frac{1}{\rho_m}\frac{\partial P}{\partial x} + \frac{f}{2D} V\,|V| = 0 \tag{1.9}$$

Where ρ_m : mixture density and a_m : wave speed of the mixture. In addition, we also considered the additional gas release volume when the pressure drops below saturation pressure. So, when the pressure is below saturation pressure, fractional volume of free bubble has to be adjusted. As the gas release rate is proportional to the degree of underpressurization.

$$\frac{dm}{dt} = \beta S \frac{(p_s - p)}{RT} V_l \tag{1.10}$$

where, β : gas transfer coefficient which includes the diffusion coefficient and the interfacial area for gas transfer per unit volume of liquid , S: Henry's constant, R: gas constant, T: absolute temperature , and V_l is the unit volume of liquid.

After what we observed the real phenomenon through clear plastic pipes, the liquid was solid single phase liquid instead of homogeneous mixture. So, we are solving for classical water hammer equations [Chaudhry, 2007]. For completeness, we present the water hammer equations here as:

$$\text{Continuity equation: } \frac{\partial p}{\partial t} + V\frac{\partial p}{\partial x} + c^2 \rho \frac{\partial V}{\partial x} = 0 \tag{1.11}$$

$$\text{Momentum equation: } \frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\sin\alpha + \frac{f}{2D} V|V| = 0 \tag{1.12}$$

in which: p = pressure, V = velocity, c = wave speed, ρ = density, g = acceleration due to gravity,

α = angle of inclination of pipe, f = friction factor, D = diameter, x = spatial dimension, t = time. These equations are solved for a pipe network that incorporates suitable interior boundary conditions for appurtenances such as valves and junctions of several pipes and external boundary conditions for service line, tanks, and faucets. The solution of these equations yields the pressure, p(x, t) and velocity, V(x, t) as functions of x and t with x – dimension is taken along the length of the pipe. The pressure can be high positive and negative and the velocity can be negative indicating flow reversal.

For a transient flow analysis, Joukowski equation is the famous fundamental theory that is still used as a rough check for head calculation

$$\Delta H = -\frac{a}{g} \cdot \Delta V \tag{1. 13}$$

where a: pressure wave speed, g: gravitational acceleration, and V is the velocity. The assumptions of the model are: i) no friction in the pipe and ii) no wave reflections in the system. That is, there is no interaction between devices or boundary conditions in the system. Karney (1990) presents several counter examples for Joukowski's equation when applying it to Network analysis. Also, Jung et al. (2007) review the current guidelines in transient related AWWA publications and provides some warnings for simplified analysis which is based on Joukowski's equation.

To the author's knowledge there is no specific computer package available for solving plumbing system networks. However, there are a few commercial packages and packages from the US Army corps of Engineers (WHAMO, Water hammer and mass oscillation) and Bentley (Hammer) that can solve the transient flow in pipes. WHAMO and Hammer is designed for hydropower and water distribution systems to analyze transients induced by pumps, turbines, and turbine pumps involving valves, governors, reservoirs and surge tanks. In this study we adopted WHAMO and Hammer to solve for pressure and flow patterns in small diameter pipe networks involving valves, faucets, and vertical t-junctions. In the following we provide an overview of the Numerical schemes that each software is employing.

The governing equations (Equations 1.11 and 1.12) are nonlinear hyperbolic PDE. A closed form solution is not available and the coefficients are all constant. Numerical methods should be used to solve these governing equations. WHAMO is using *implicit finite difference method*. The unknown dependent variables at a section at the end of time step are expressed in terms of the unknown values of the dependent variables at the near nodes. The implicit method replaces the partial derivatives with finite differences and provides a set of equations that can then be solved simultaneously. According to Fitzgerald and Van Blaricum, (1998), implicit method is unconditionally stable so large time steps can be used. But it is necessary to solve a large number of non-linear equations simultaneously as this method is for large systems. The WHAMO uses the implicit finite-difference technique but converts its equations to a linear form before it solves the set of equations.

Hammer is using *Method of Characteristics (MOC)* for solving the governing equations. MOC is known to be accurate and informative means to solve water hammer problems considering friction and gravity within any pipe and minor losses concentrated at various pipe joints (Shin et al., 1975). But the use of MOC is usually limited by the formation of the shock waves due to the steepening of compression waves as the need to incorporate the shock equations as the internal boundary conditions in the characteristics grid (Padmanabahn, 1978). For hyperbolic systems, it means the solutions follow certain characteristic pathways which is the wave speed. It entails converting the two partial differential equations to ordinary differential equations then solving using an explicit finite difference method. One drawback to the method of characteristics is that the time step must be small to satisfy the Courant condition for stability.

Additionally, we adopted *explicit scheme using MATLAB coding* for the solution of the water hammer equations. The solution of these equations yields the pressure, H(x, t) and velocity, Q(x, t) as functions of x and t with x – dimension is taken along the length of the pipe. We are adopting second-order explicit model for the analysis of single liquid transient flows. It is known that higher order schemes reproduce sharper shocks compared to the first order methods. McCormack's method is one of second order (both in space and time) explicit methods. The results obtained from McCormack's method are known to be perfectly satisfactory to for many flow applications (Anderson, 1995). This scheme is composed of predictor and corrector step.

One-sided FDMs are used for the spatial derivatives in each of these steps. First, forward Finite Difference (FD) is used in the predictor and backward FD is used in the corrector part. Alternatively, backward FD is adopted in the predictor and forward FD is used in the corrector part. Each alternative takes turns as time step increases. Also, this method is stable if $a_m \Delta t \le \Delta x$. See the formulations below. *: predicted values, i: space node and j: time level. The values of H and Q are assumed to be known at all nodes at time j level. We are solving for time (j+1) level (see Figure 1.25).

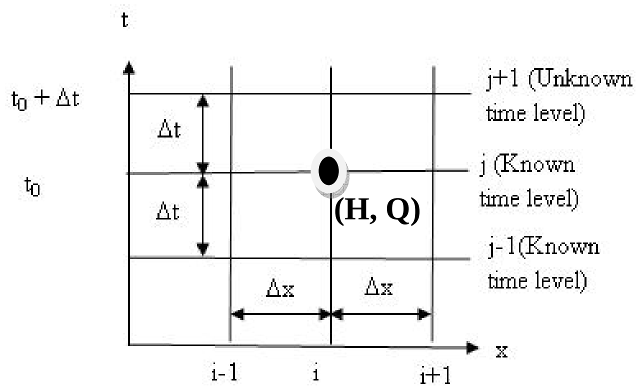


Figure 1.25 Explicit scheme

In alternative 1, predictor part

$$H_i^* = H_i^j - \frac{\Delta t}{\Delta x}\frac{a^2}{gA}(Q_{i+1}^j - Q_i^j),$$

$$Q_i^* = Q_i^j - \frac{\Delta t}{\Delta x} gA(H_{i+1}^j - H_i^j) - RQ_i^j \left|Q_i^j\right| \cdot \Delta t, \text{ (i=1,2,…,n)} \tag{1.14}$$

Corrector part

$$H_i^{j+1} = \frac{1}{2}(H_i^j + H_i^* - \frac{\Delta t}{\Delta x}\frac{a^2}{gA}(Q_i^* - Q_{i-1}^*)),$$

$$Q_i^{j+1} = \frac{1}{2}(Q_i^j + Q_i^* - \frac{\Delta t}{\Delta x} gA(H_i^* - H_{i-1}^*) - RQ_i^* \left|Q_i^*\right| \cdot \Delta t), \text{ (i=2,…,n+1)} \tag{1.15}$$

In alternative 2, the predictor and corrector parts are:

Predictor part

$$H_i^* = H_i^j - \frac{\Delta t}{\Delta x}\frac{a^2}{gA}(Q_i^j - Q_{i-1}^j)\,,$$

$$Q_i^* = Q_i^j - \frac{\Delta t}{\Delta x} gA(H_i^j - H_{i-1}^j) - RQ_i^j \left|Q_i^j\right| \cdot \Delta t \text{ , (i=2,…,n+1)} \qquad (1.16)$$

Corrector part

$$H_i^{j+1} = \frac{1}{2}(H_i^j + H_i^* - \frac{\Delta t}{\Delta x}\frac{a^2}{gA}(Q_{i+1}^* - Q_i^*))\,,$$

$$Q_i^{j+1} = \frac{1}{2}(Q_i^j + Q_i^* - \frac{\Delta t}{\Delta x} gA(H_{i+1}^* - H_i^*) - RQ_i^* \left|Q_i^*\right| \cdot \Delta t) \text{ , (i=1,2,…,n)} \qquad (1.17)$$

<u>Boundary conditions</u>

<u>Characteristic boundaries</u>

From the governing equation,

$$\begin{aligned} &\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \\ &\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + RQ\,|\,Q\,| = 0 \end{aligned} \qquad (1.18\text{ a, b})$$

Multiplying equation 1.18 (a) by η and adding it to the equation 1.18 (b), then we have

$$(\frac{\partial H}{\partial t} + \eta gA\frac{\partial H}{\partial x}) + \eta(\frac{\partial Q}{\partial t} + \frac{a^2}{\eta gA}\frac{\partial Q}{\partial x}) + \eta RQ\,|\,Q\,| = 0$$

$$\text{Let, } \eta gA = \frac{dx}{dt} = \frac{a^2}{\eta gA}\text{ , so } \eta = \pm\frac{a}{gA} \qquad (1.19)$$

When $\lambda^+ = \dfrac{dx}{dt} = a$, C+: $(\dfrac{\partial H}{\partial t} + \lambda^+ \dfrac{\partial H^+}{\partial x}) + \dfrac{a}{gA}(\dfrac{\partial Q}{\partial t} + \lambda^+ \dfrac{\partial Q^+}{\partial x}) + \dfrac{aR}{gA}Q\,|\,Q\,| = 0$ (1.20)

When $\lambda^- = \dfrac{dx}{dt} = -a$, C-: $(\dfrac{\partial H}{\partial t} + \lambda^- \dfrac{\partial H^-}{\partial x}) - \dfrac{a}{gA}(\dfrac{\partial Q}{\partial t} + \lambda^- \dfrac{\partial Q^-}{\partial x}) - \dfrac{aR}{gA}Q\,|\,Q\,| = 0$, (1.21)

At the boundary conditions, equations are solved with the condition imposed by the boundary. The characteristic of the boundary condition is shown in Figure 1.26. For the upstream boundary, C- characteristic line is valid and C+ is for downstream. These boundaries are used to depict the complete behavior of the fluid under transient condition. Each boundary condition is solved independently of interior points' calculation and other end of the boundary.

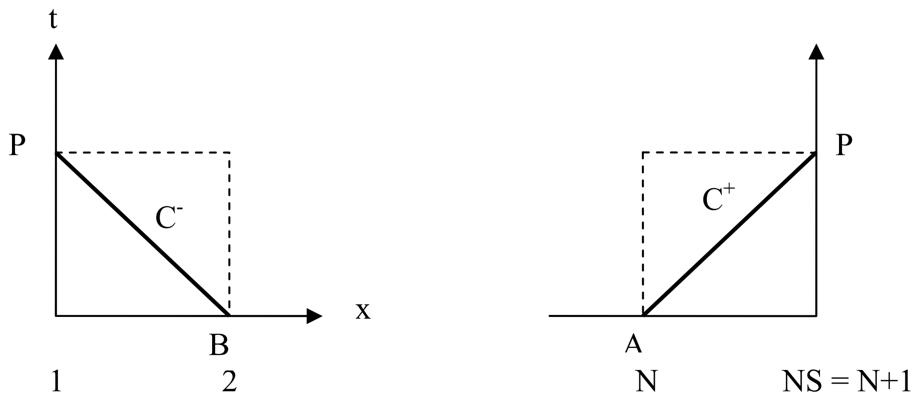


Figure 1.26 Boundary characteristic (upstream and downstream)

Reservoir

During a short-period transient event, the hydraulic grade line elevation of the upstream reservoir is assumed to be constant.

$$H_1 = H_R \tag{1.22}$$

Where H_R: hydraulic grade line above the reference datum, H_1: head value at the upstream section at point P. With C- equation and H_1=H_R, the velocity can be obtained at the boundary. So, H, and Q, are obtained for next time level (j+1).

Dead end

When the pipeline contains a dead end at the downstream end of a pipe, Q_{NS}=0 and H_{NS} is determined from compatibility equation.

General junction

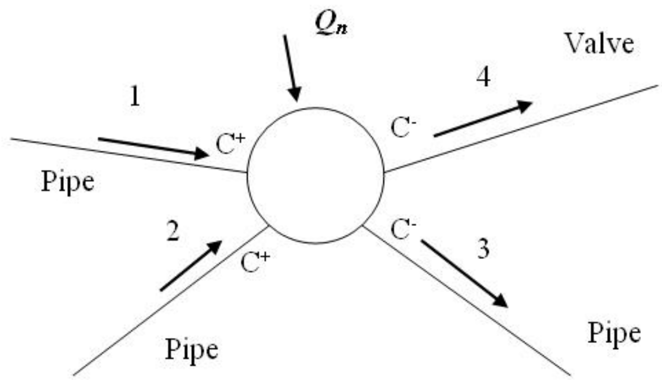


Figure 1.27 General junction

Figure 1.27 is showing a general junction with pipeline, non-pipeline elements (valve), and nodal inflow. A continuity equation can be written at the junction. At any instant, the sum of the inflow is zero.

$$\sum Q_{in} = \sum Q_p + \sum Q_e + Q_n = 0 \tag{1.23}$$

Where, $\sum Q_{in}$: sum of the inflow (added to zero at any instant), $\sum Q_e$: sum of all instantaneous non-pipe flows, $\sum Q_p$: sum of all instantaneous pipe flows, and Q_n: a nodal flow. When minor losses are neglected at the junction, the energy equation can be written for each element at the junction.

$$H = H_{1,\,NS} = H_{2,\,NS} = H_{3,1} = H_{4,1} \tag{1.24}$$

Using the compatibility equations, $Q_{1,NS}$, $Q_{2,NS}$, $Q_{3,1}$, and $Q_{4,1}$ are obtained.

Valve

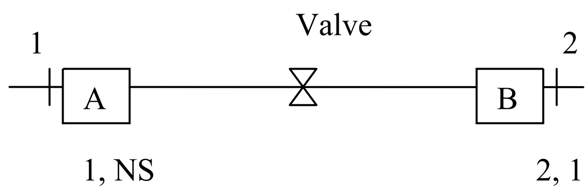


Figure 1.28 Valve located in-line

Figure 1.28 is showing the valve located between two pipelines where A and B showing the interconnecting junctions on both sides of the valve. It is assumed that the inertia effects are neglected in steady state orifice equation and volume of fluid stored inside the valve is constant. For positive flow, $H_{1,NS} = H_A$ and $H_{2,1}=H_B$.

The orifice equation is

$$Q_{1,NS} = Q_{2,1} = Q_v = \frac{Q_0 \tau}{\sqrt{H_0}} \sqrt{H_A - H_B} \tag{1.25}$$

where, H_0: steady state HGL drop across the valve with flow of Q_0 ($\tau = \frac{C_d A_G}{(C_d A_G)_0} = \sqrt{\frac{K_0}{K}} = 1$: dimensionless valve opening).

When combined with compatibility equation, Q_v can be obtained. Also, for reversal flows,

$$Q_{1,NS} = Q_{2,1} = Q_v = -\frac{Q_0 \tau}{\sqrt{H_0}} \sqrt{H_A - H_B} \tag{1.26}$$

Combined with the compatibility equation, Q_v can be obtained.

Convergence and Stability

Discretization error

U(x, t) is the exact solution of the PDE and u(x, t) is the exact solution of the finite difference equation. Then, (U-u) is called *discretization error*. This is introduced when replacing the PDE to finite difference approximation.

Truncation error

$F_i^j(u) = 0$ is the finite difference equation at grid point iΔx and jΔt, where i and j: number of the grid points in the x and t direction. Substituting the exact solution of PDE U(x, t) into finite difference approximation equation, then $F_i^j(U)$ is the local truncation error at (iΔx, jΔt).

Consistency

FDM is said to be consistent when the truncation error tends to zero as Δx and Δt approach zero.

Convergence

FDM is said to be convergent as exact solution of FDM u approaches to exact solution of PDE U, as both Δx and Δt approach zero. It is difficult to directly prove the convergence. But FDM is convergent if the scheme is proved to be consistent and stable.

Stability

When the computations are performed to an infinite number of significant figures (decimal digits), the solution u (x, t) of the FDM will be exact. But even in computers nowadays, round-off errors are introduced at each time step. So, the numerical solution we obtain is different from the exact solution. There are cases that round off errors are amplified, decrease or stay the same. The scheme is said to be stable when the amplification of the round off errors are bounded for all sections as time goes infinity. Unstable schemes result in very rapidly growing error in a few time steps. So, stability conditions have to be satisfied.

CFL (Courant Friedrich Lewy) stability condition

$\Delta x \geq a\Delta t$, the courant number is defined as $C_N = \dfrac{a}{\Delta x / \Delta t} = \dfrac{a\Delta t}{\Delta x}$ and $C_N \leq 1$.

This stability criterion applies only to linear equations (when the friction term is small). Even if the CFL condition is met, the scheme may become unstable: when the friction term is large (large friction factor, large time step, large change in discharge, or small conduit diameter: according to the friction loss equation). The stability of the FDM may be done using von Neumann theory. In this approach, errors are expressed in a Fourier series at an instant of time (for linear equations). The scheme is said to be stable if the errors decay as time increases.

In the following, pseudo code is shown (Figure 1.29) and one simple example is included to compare each numerical result. Finally, numerical results are compared with the experimental results.

```
# Supply initial data
old =0;
new=1;
time=0;
TIME_MAX entered by the user;

Loop on m from 0 to M         % set initial data
V(old,m)=u0(x(m));
End of loop on m

Loop for time <TIME_MAX
        Time=time+k           % time being computed
        n_time=n_time+1
        v(new,0)=beta(time)           % set boundary conditions
        loop on m from 1 to M-1
                v(new,m)=…. % McCormack scheme
        End of loop on m
        v(new, M)=v(new,M-1)         % apply boundary condition

        old=new               % reset for the next time step
        new=mod(n_time,2)
end of loop on time
```

Figure 1.29 Pseudo code for McCormack Scheme (MATLAB)

Example I

For the given schematics, compare the pressure transient behavior when we shut the valve instantaneously (closing time=0 at t=0): Explicit Scheme (McCormack's Scheme), Implicit Scheme (WHAMO), and Method of Characteristics (Hammer).

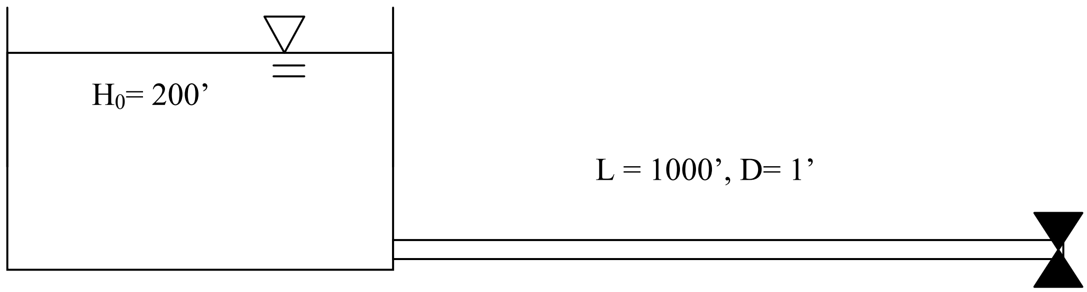


Figure 1.30 Reservoir problem

Given

Darcy Weisbach friction coefficient=0.02

Time step=0.02 sec

Distance step=100'

Flow rate =19.5 cfs

Find: pressure variation at x=500' (from the valve; at the center of the pipe)

Solution

WHAMO and Hammer were run separately and imported into MS Excel for graphing. Similarly, MATLAB program was run with explicit scheme code and imported to Excel (see Figure 1.31). All numerical results are showing very similar first peak values but implicit methods (WHAMO) seems to be converging faster than Explicit and MOC schemes. MOC and Explicit methods are showing relatively similar results. Programming codes for Explicit scheme and WHAMO are shown in Appendix I-A. Hammer can be run in a use-friendly graphic interface without programming code.

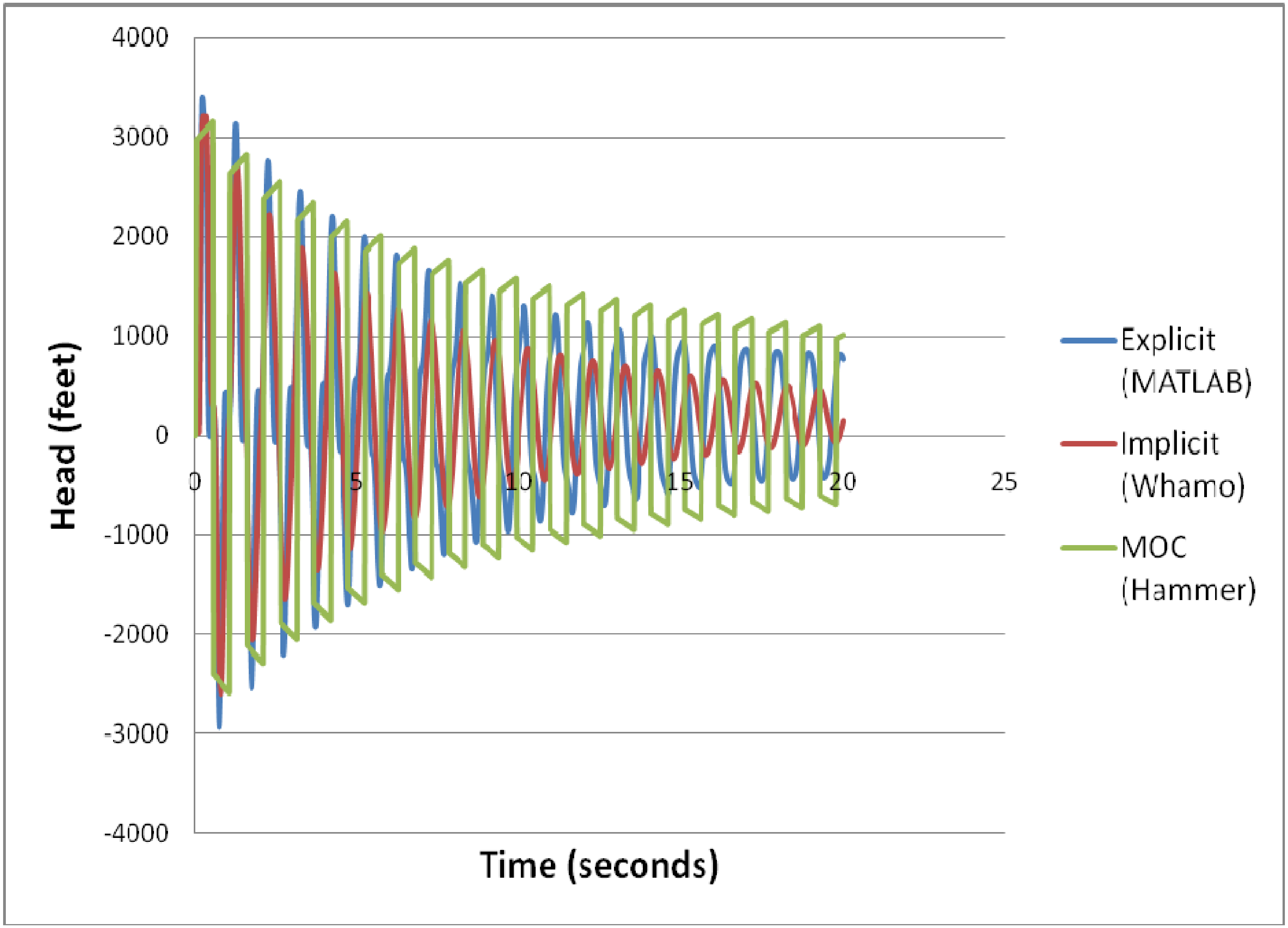


Figure 1.31 Reservoir results comparison

<u>Example II: Simulating Scenario II by Triggering Water Hammer from municipal systems [sudden closure]</u>

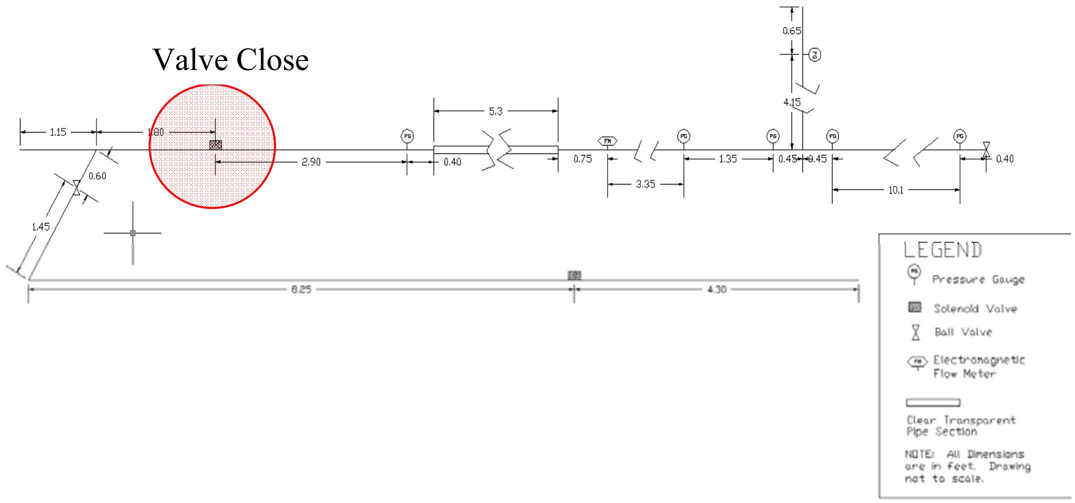


Figure 1.32 Scenario II schematic

The flow rate is 40 lpm (0.023543 cfs) and the observed pressure values are shown in Figure 1.33. When we suddenly close the valve, the lowest pressure at service line is -10 psig (40-50=-10 psig). As mentioned in Section 2, only *the first peak is guaranteed to be true in dynamic results*. The *second peaks onwards are residual wave actions that the sensor is tracking as it settles out to steady state (PCB, 2008)*. So, we are presenting simulated numerical results separately in Figure 1.33. Wave speed and valve closing time were calibrated. All three results are showing similar behavior and the lowest pressure values are near -10 psig (see Figure 1.34). Programming codes for MATLAB based explicit scheme and WHAMO are included in Appendix I-B.

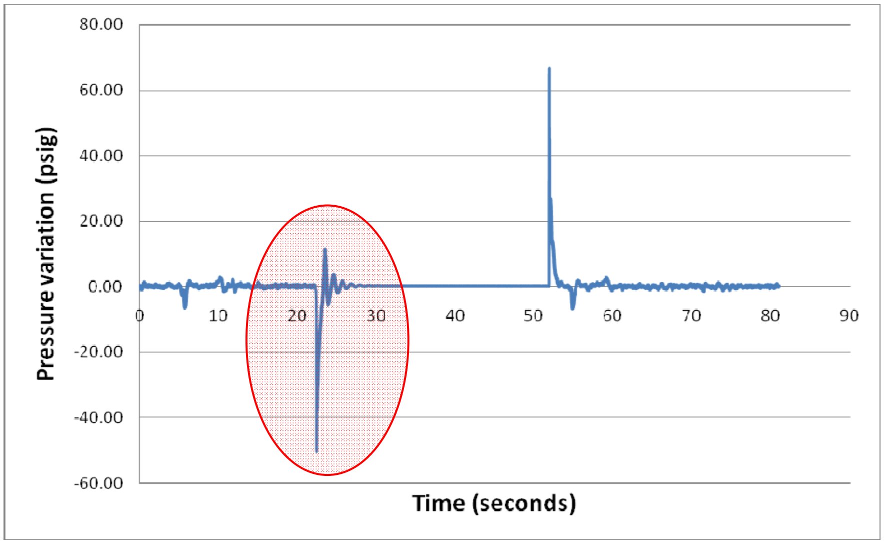


Figure 1.33 Observation values of scenario II

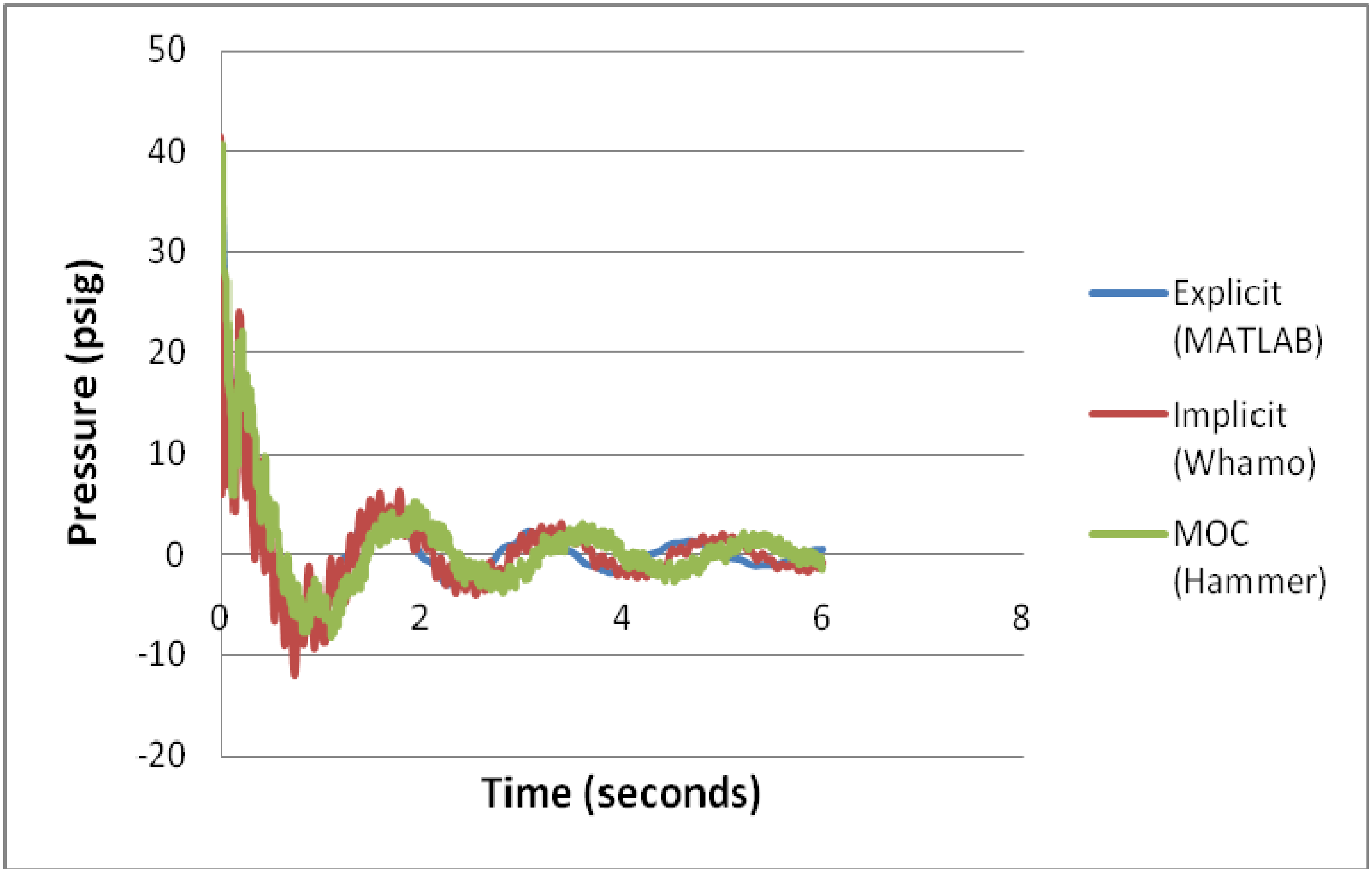


Figure 1.34 Comparison of numerical models

<u>Example III: Simulting Scenario I by Triggering Water hammer from within a house [sudden closure]</u>

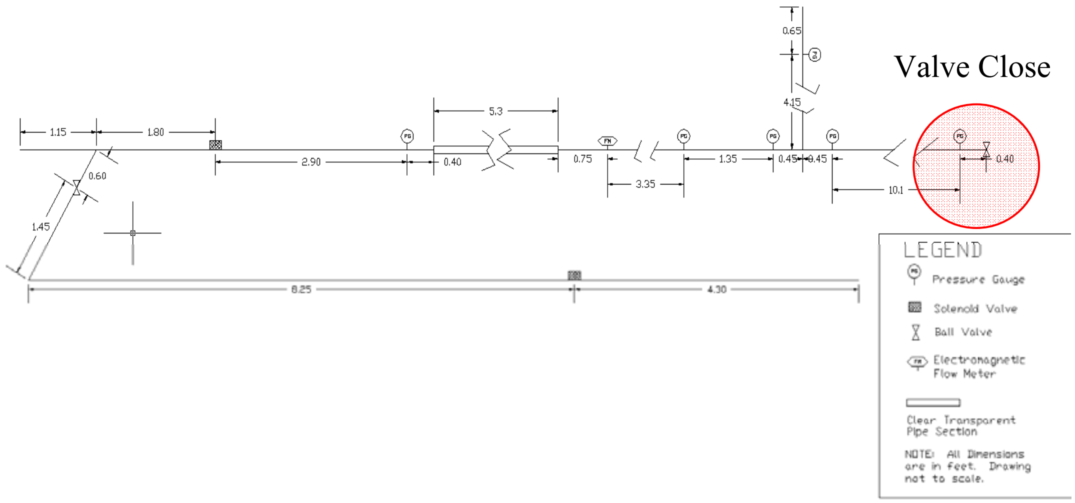


Figure 1.35 Scenario I schematic

As WHAMO and Hammer do not allow the user to enter different boundary and intial values at reservoir, only the numerical results from explicit scheme (using Matlab coding) is shown in Figure 1.37. We are modeling the main water system as reservoir which has constant head values. But in reality (Figure 1.37), the high pressure wave is passing through the service line and goes out to water mains; no reflected waves are observed. Observed first peak values show by and large similar trend when compared to simulated first peak. The programming codes for explicit scheme and WHAMO are shown in Appendix I-C.

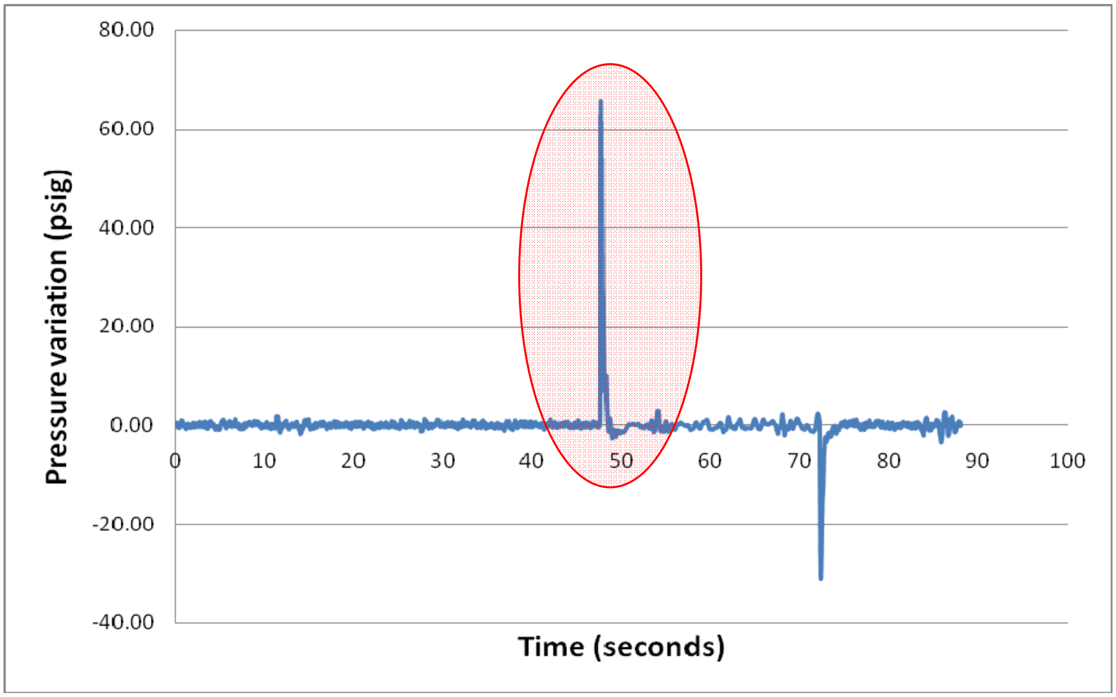


Figure 1.36 Observation values of scenario I

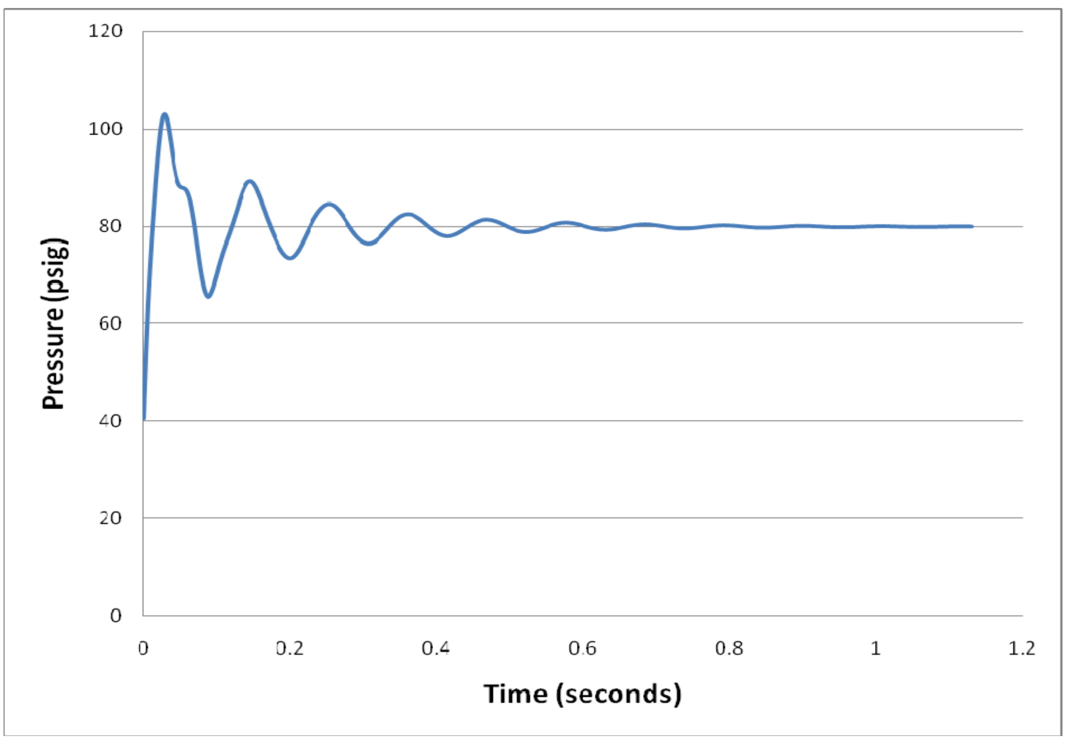


Figure 1.37 Simulated values of scenario I by MATLAB

6. Conclusions, Recommendations, and Future Research

Pressure variations at the service line corresponding to typical street level pressures encountered in a real water supply system are examined in this research. This study was specifically developed for a typical one or two story house (1800-2200 square foot; water hammer impacts from inside house applies *only to cold water line*) plumbing system which includes 150- 250 feet of pipes. Major findings of this research are following.

1. Experimental plumbing system that mimics real service line and minor system was successfully constructed in the lab. Pressure variations were captured 100 times per second with high sensitive sensors and LabVIEW based DAQ systems.

2. As a result of a street level transient, low pressure wave (up to -10 psig for fraction of a second) can propagated to the experimental service line. This pressure drop would be sufficient to induce potential contamination intrusion at service line.

3. A transient triggered within a house (due to sudden valve closure) structurally tax the experimental service line but did not have a possible suction effect. If an actual service line is not strong enough, then this may cause constant fatigue effects and may result in bursting.

4. Vertical sections with dead ends have higher pressure variation (up to 110 psig variation) when the transients were triggered from inside the house. This may be related to the noise effect at home but bears further examination.

5. Gaseous cavitation was observed due to water hammer induced low pressure (as a result of street level transient); also found that bubble formation timing due to gaseous cavitation can be less than 1 second. This is quite contrary to the previous theories of 2-3 seconds. This phenomenon has practical implications of implosion or gaseous impingement that is known to erode protective scales on the wall.

6. Experimental values on pressure variations are compared with various numerical methods' outcomes (Hammer, WHAMO, and MATLAB based program coding) and they

showed a reasonably good agreement after calibrating pressure wave speed. This is single liquid phase state so classic water hammer equations seem to work well.

7. In the plumbing, pressure wave triggered from inside the house was not reflected back from the major water systems; instead it passed through the major systems. So, major water systems should not be regarded as a reservoir (i.e. as boundary condition) when modeling transient flow impact from within a house.

It is demonstrated that hydraulic transients in water mains have high potential to result in sufficiently low pressures at service lines to allow possible intrusion of microbial and chemical contaminants. It is recommended that this new knowledge should be broadly disseminated to homeowners, water utility personnel, homebuilders, and public health officials. Specifically, *physical integrity of service line* and *hydraulic integrity at water main* should be maintained with utmost efforts to protect any possible human health risk involved with service line. Appropriate outreach programs targeted at educating public regarding these issues should be developed.

i) Physical integrity at service lines: All service line construction and installation activities should be performed under strict supervision with a good workmanship (professional license including good quality training). All the appurtenances at the service line (including piping materials, fittings, joints, and valves) should meet correct pressure ratings and corrosion susceptibility for specific environment. Leak should be checked after installation and leak detection be performed on a regular basis (especially home plumbing system is older than 25 years old). We specifically chose 25 years as this is the recommended home plumbing replacement time in pinhole leak prone area in D.C. once they had leak incidents in their plumbing systems (Loganathan and Lee, 2005). Also, service line condition should be inspected when purchasing a house. For water utilities, it is recommended to maintain a good quality database (e.g. GIS) for service lines including failure data, soil condition, pipe materials, installation date, and any repair/replacement history so future leaks can be predicted. The integrity of service line can only be maintained with careful planning, management, and knowledge of the environmental conditions where the line is buried.

ii) Hydraulic integrity at major systems: As mentioned, hydraulic transients from major systems dictate the pressure variation at service lines. At utility level, it is recommended to use surge protection devices to protect any negative pressures and high pressures (pipe bursting due to high pressure spike); this will include training or hiring transient flow analyst who can identify the weak spots. State or federal regulation may consider tax incentives that voluntarily take the initiatives.

iii) Public perception: Water professionals and policy makers should work on *bridging the gap between public perception and research results*. This can be done through broad education on water quality, public health risk, and drinking water infrastructures. Public education will help homeowner's increased awareness of 'not much known but could be serious problems' due to the unique characteristics at the service lines which can certainly magnify the public health risks. Education can be done through *education outreach from research universities* to K-12 including high school and middle school teachers. Official website (from government agency or utilities) should include this information for homeowners. Regular public newsletter or small handbook will also be helpful.

Additionally, service line should also be able to deliver water without any quality deterioration. In this vein, new water sampling methods may need to be included which considers possible intrusion events at distribution systems. Paradigm shift of ownership issues can be considered. For example, Seoul Government of South Korea is planning to include minor systems as part of public assets (Park, 2006). Some utilities in UK, decided to be responsible for the entire service line (except plumbing system inside the house) to resolve water leakage issues (AWWARF, 2007). These will lead to a safer design not only within the house but also better maintenance practices for the municipal system.

This work has several implications for future research. First, pressure, which is the intrinsic nature of plumbing system, has several implications. It was observed that low pressure inside the plumbing system causes degasification of water known as 'gaseous cavitation' which may lead to gaseous impingement or cavity formation. High velocity (related with pressure) can also cause localized wearing of protective scale on the wall which is known as 'erosion corrosion'. It is known that if a corrosion pit is initiated due to water quality, high pressure and velocity can aggravate and dominate pit growth. Second, longevity comparison of PEX or CPVC pipes versus copper in water hammer situation will be interesting. The energy loss will be different for each pipe and water hammer response and scale growth will show completely different behavior. Current hypothesis of the author is that PEX will not withstand frequent water hammer situations but it bears further examinations. Third, vertical section with dead end at the top is shown to be experiencing up to 120 psi pressure variation in this experiment. This may have implications on sound problems within home plumbing. This also needs further examinations. Fourth, induced high pressures can also lead to pipe bursting or early failure at weak spots (e.g., joints in PEX pipe systems, soldered locations in copper pipes, or couplings made up of different materials). Lastly, the temperature will have significant impact on hot water piping materials. This may govern the conditions for scale formation and may cause degasification of water, decrease in pH which may worsen the condition of copper pipes. Combination of constant pressure taxation may degrade the conditions. The results of this study should be helpful in identifying the physical parameters that may be responsible for causing copper failures in home plumbing; knowing that hydraulic and physical parameters are synergistic to produce adverse effects to existing plumbing materials.

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Choosing Alternative Plumbing Material

THEME II

In the USA, about 90% of residential drinking water plumbing systems use copper pipes. Pinhole leaks in copper plumbing pipes have become a nationwide concern because these leaks cause property damage, lower property values, and result in possibility of adversely affecting homeowners' insurance coverage. In addition, resulting mold damage may cause health concerns. This research also addresses the concerns of the affected homeowners by enabling them to decide on whether to continue to repair or replace their plumbing system, the factors to be considered in a replacement decision, and the type of material to use for replacement. Plastic pipes such as PEX (cross-linked polyethylene), CPVC (Chlorinated Polyvinyl Chloride), and copper are considered in present analysis. Other alternatives include an epoxy coating technique on the existing piping systems, without the need to tear into walls. Multiple attributes of a plumbing system including cost (material plus labor charges), taste and odor impacts, potential for corrosion, longevity of the pipe system, fire retardance, convenience of installation or replacement, plumber or general contractor's opinions or expertise, and proven record in the market are considered. Attributes and material rankings are formalized within the framework of the preference elicitation tools namely AHP (Analytical Hierarchical Process). Surveys are conducted with selected homeowners in pinhole leak prone area in Southeastern US Community to observe their revealed and stated preferences. Participants' overall preference tradeoffs are reported in addition to comparing their revealed and stated preferences. Health effects, taste and odor of water turned out to be the most important factors from the survey. In real life, however, homeowners were not well aware of these safety issues related with plumbing materials. It is recommended that water professionals should work on bridging the gap between public perception and research results related to major and minor systems.
Keywords: AHP (Analytical Hierarchical Process), Preference Tradeoffs, Plumbing Systems

1. **Introduction**

In drinking water distribution, a major system is defined as the main water distribution system that brings drinking water from treatment plant to house level while a minor system is the plumbing system that carries the water within a property line including service line (Loganathan and Lee, 2005). Consider the overall drinking water transportation system shown in Figure 2.1. Home plumbing systems (i.e. minor systems) can be regarded as *passive recipients* of supplied water from the municipal system.

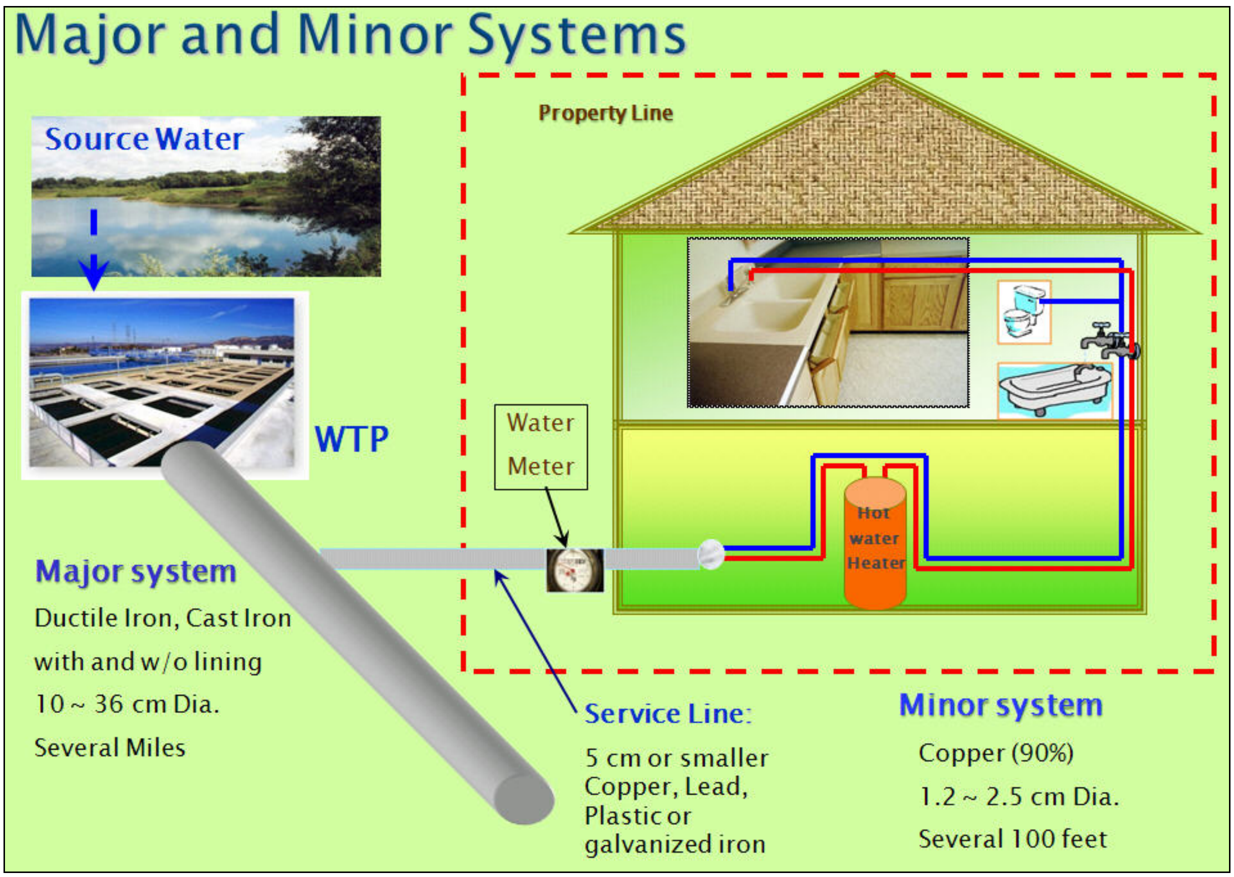


Figure 2.1 Overall aspect of drinking water transportation

Edwards (2007) and Loganathan and Lee (2005) note that the major systems within the US are composed of nearly 1.5 million km of piping. They also contain detailed tables to compare various characteristics of major and minor systems. Important (physical and chemical) aspects of both systems are covered in *THEME I* of this dissertation. Major systems have been the primary focus of research since these systems represent a large portion of public infrastructure and assets. However, minor systems, which are privately owned, and are at least 5 or 10 times larger than major systems have not been well addressed so far.

Recently, increased pinhole leaks in domestic copper plumbing pipes have been observed. The distribution of nationwide pinhole leaks in years 2000 through 2004 is shown in Figure 2. 2 (data provided for copper pipes and obtained from Copper Development Association and Plumbing Expert surveys; non-copper plumbing materials were not assessed). Although pinhole leaks are a nationwide problem, there are several areas in selected states (California, Florida, Maryland, and Ohio) which showed higher frequencies of leak incidents. In *THEME II*, *homeowner's overall decision framework* is described when they experience frequent leak incidents in passive/ minor systems.

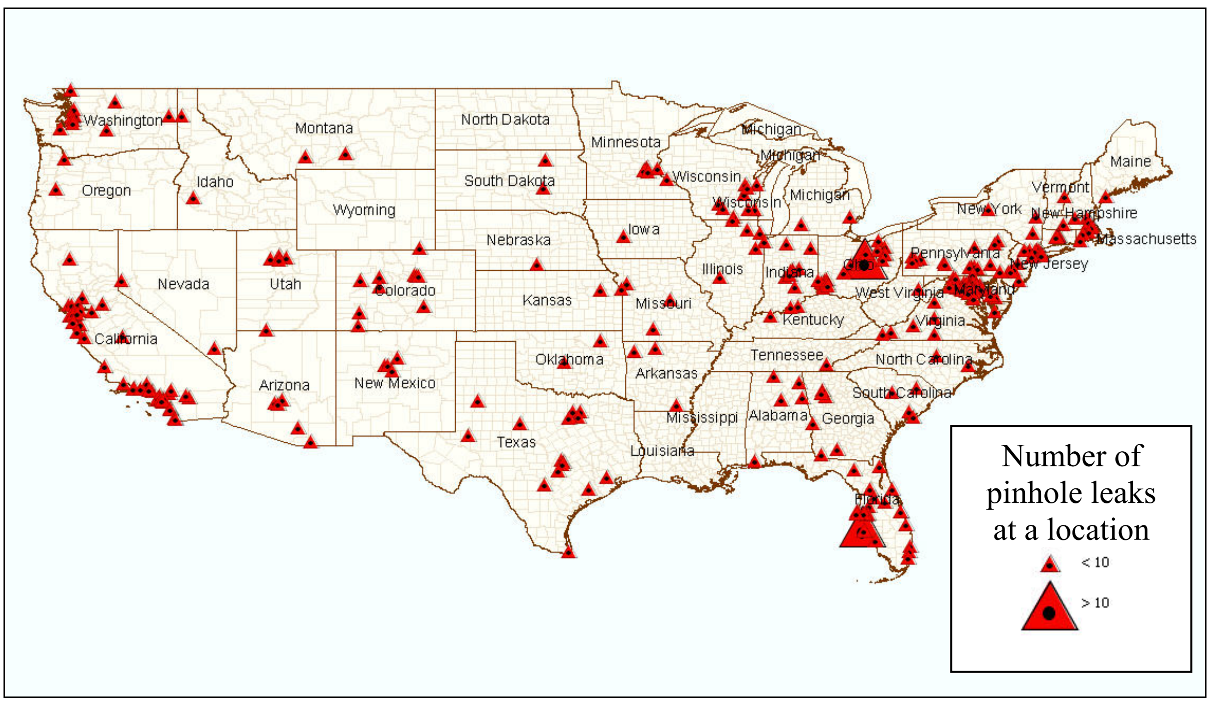


Figure 2.2 Nationwide distribution of locations reporting pinhole leaks in years 2000 through 2004. Map is based on 447 reported leaks over a 5 year period (2000-2004). According to U.S. 2000 census data there were 115 million housing units in the US. Thus the data in the above map represents failures occurring about one out of 257,000 US. homes over 5 years.

Municipalities or private water companies manage major water distribution systems and management (including operation and maintenance) costs are distributed among all subscribing homeowners. However, when there is a leak incident in a house, the homeowners cover the repair/replacement cost of a home plumbing system as it is private property. The homeowners are typically faced with the following issues when a leak occurs: water damage and repair cost, service disruption, possible lowering of home value, and potential health consequences resulting from brown mold growth on the surface of walls, floors, and ceilings. Mold can cause allergic reactions including irritation of eyes, skin, and throat. Copper corrosion can also result in higher copper concentrations in drinking water than allowed by EPA (1.3 mg/l). The excessive amount of copper can cause health problems such as nausea, vomiting, diarrhea, and stomach cramps (EPA, 2006). Repairs associated with plumbing failure can take up to several weeks as the repairs extend beyond replacing the part of failed pipe to repairing all related damage to the house. The extensive repairs may cost households thousands of dollars. In many cases, the property insurance policy does not cover damages resulting from leaks and households are forced to cover the expenses by themselves. In addition to the financial and time costs, households experience emotional stress due to dealing with these problems (Kleczyk and Bosch (2006), Lee and Loganathan (2006)).

An additional problem associated with leaks is that the plumbing system is generally hidden within the wall/drywall and the damages are revealed only after a leak occurs. A proactive monitoring system requires home inspections accessing certain critical locations deemed prone to corrosion; however, such accessibility is not currently available without major disruption of the building structure. Water utilities and homeowners in areas with high rates of pinhole leaks consider additional treatment to water in terms of corrosion inhibition (by phosphate addition), use of different plumbing materials such as plastics (CPVC, PEX) and stainless steel, as well as coating the interior of the existing pipe systems.

The growth in bottled water consumption, point of use water treatment including various kinds of filters, distillation, ion exchange, and reverse osmosis indicate citizens' concerns regarding the quality of drinking water. However, utilizing alternative water sources such as a well or bottled water can introduce other water-related issues. Bottled water is typically expensive and does not address the issue of home use of water for bathing, cleaning, and other domestic activities. The quality of the bottled water has been brought into question regarding its source and the shelf life from processing to consumption. Dual systems supplying potable and non-potable water require the maintenance of two networks and are expensive. Point of use treatment alternative requires separate installation and maintenance costs. These alternatives have different life times, impacts and health risks, which make homeowner's decision complicated.

The public perceptions of risk and reaction to hazards, while hard to measure, play a fundamental role in consumers' drinking water decisions. Objective risks are based on relative frequencies of occurrences obtained from historical or experimental studies. Perceived or subjective risk involves personal or subjective judgment and is a function of confidence (Slovic and Weber 2002). Home plumbing decisions that may affect drinking water risks include choice of when to repair or replace a minor system as well as the type of material to use in replacement. When informed about the attributes of each plumbing material alternative, consumers can decide on the alternative most preferable to them based on the preference tradeoffs among plumbing materials' attributes. Multiattribute utility models (Keeney and Raiffa, 1992) can be adopted to maximize the preference level of consumers. The decision of choosing an appropriate plumbing material can be based on various attributes of materials such as cost (material cost plus labor and installation cost), health effects, corrosion susceptibility, strength, property real estate values, and behavior in the case of a fire. On the other hand, the perception of risk for plumbing materials can be quantified through the assessment of the willingness-to-pay (WTP) for a corrosion free plumbing material or improvement in the performance of existing plumbing material. The estimate of WTP reflects socioeconomic characteristics and previous experiences of individual households (Champ et al., 2003).

The rest of this theme is organized as follows. In Section 2, general characteristics of plumbing materials are described. Various surveys to assess risk and costs of pinhole leak problems are discussed in Section 3. The information provides more insight into the socioeconomic impact of leaks on the affected homeowners. Although plumbing is a necessity for the public health, very little research has focused on consumer decisions related to plumbing. Economically sustainable optimal replacement time of home plumbing system is explained in Section 4. This is defined as *Phase I: optimal replacement time* of the decision framework that homeowners should follow when replacing their plumbing system. Section 5 describes *Phase II: choosing alternative plumbing materials*. Three preference elicitation tools are introduced to evaluate plumbing alternatives: AHP (Analytical Hierarchical Process), CA (Conjoint Analysis), and CV (Contingent Valuation). These tools are implemented to a pinhole leak prone southeastern US community. Survey results are reported in Section 6. Section 7 addresses the conclusions and research implications.

2. Alternative Plumbing Materials

According to Marshutz' survey (2000), copper accounts for 90% of plumbing installed in new homes, followed by PEX (cross linked polyethylene) at 7%, and CPVC (chlorinated polyvinyl chloride) at 2%. A telephone survey (Farooqi and Lee, 2005) observed that the share of plastic pipe in plumbing industry is increasing due to ease in installation and lower material cost. Polybutylene (PB) was introduced in the 1970's to about six million homes in the United States (http://accuspec.biz/PB Plumbing.htm). However, PB is no longer used for home plumbing system due to leak problems which resulted in several lawsuits against PB manufacturers. The consumer Plumbing Recovery Center offered a free replacement of entire plumbing system for those who had installed PB (http://www.pbpipe.com/index1.htm). Galvanized iron pipes are still used but their usage is not high especially in residential area. These pipes have potential to build up rust over a period of time. This rusting causes loss of hydraulic conductivity and leaching of rust particles resulting in *red water* problems.

Woodson (1999), an author with extensive plumbing experience, selected consumers' plumbing material alternatives as copper, CPVC, and PEX. It is noted that copper pipes generally performed well in plumbing except where there are major pinhole leak problems. From a replacement perspective, copper can be regarded as *defender* and other materials can be viewed as *challenger* in hotspot areas (considering that copper accounts for 90% of plumbing installed in new homes within US). According to Edwards (2005), there are various causes of pinhole leaks (in copper pipes) such as i) water chemistry (high pH, sufficient chlorine, and presence of aluminium solids), ii) SRB (sulfate reducing bacteria) or MIC (Microbiologically influenced corrosion) which certain bacteria that produce metabolic byproducts can create localized failure on pipe surface, and iii) erosion corrosion due to high velocity, pressure, induced negative pressure, cavitation, or gas bubbles). Farooqi (2006) describes detailed mechanisms of copper pipe failures.

Consumer's decisions on plumbing material selection are dictated by various factors (see Figure 2.3). First, the regulations and standards of the federal, state, and local governments have major impacts. These regulations influence plumbers, material producers, insurance companies, and water utility companies; consequently, consumers are influenced by all of the above stakeholders. For example, PEX use has been approved in most states, except California and Massachusetts. In some parts of Florida, the use of copper pipe is less preferred due to the seriousness of pinhole leak problems. In new homes, the general contractors may decide the material. When high rates of pinhole leaks were observed in the D.C. area, the water utility company responded accordingly by adding corrosion inhibitors. Expert advice from plumbers and general contractors will influence homeowner's decisions. Also, insurance companies have access to CLUE reports (Comprehensive Loss Underwriting Report) which form a comprehensive database of personal property information relating to insurance claims on private property. This database contains personal information on the insured, the name of the insurance company involved, the policy number, the claim number, the accident, as well as the amount paid out to the customer. When a customer calls the insurance company for an inquiry of home plumbing issues, their call history is recorded on the CLUE report. Therefore, customers may have difficulty in purchasing home insurance next time or renewing (www.franscona.com/resource/jag403clue.htm, March 2008). In the following, general characteristics of available plumbing alternatives are elaborated.

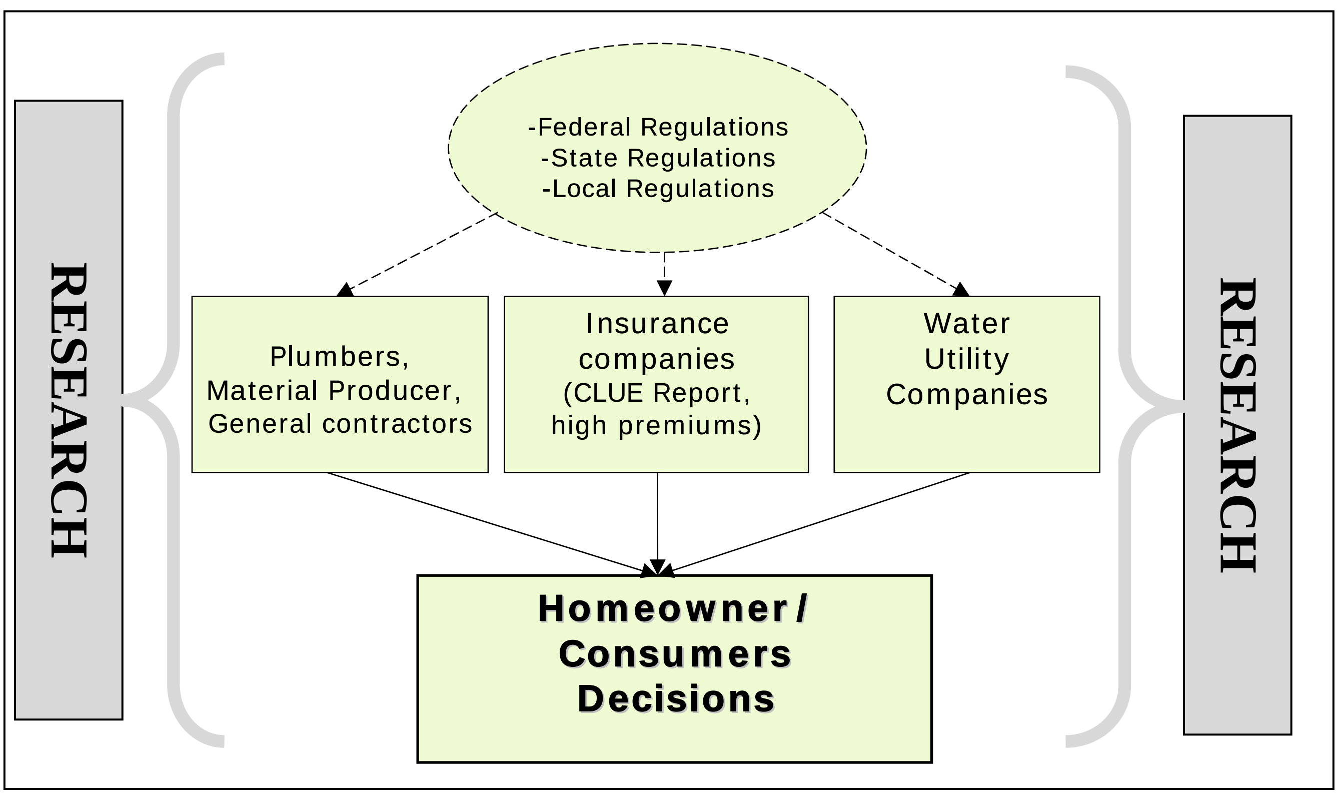


Figure 2.3 Stakeholder relations

Farooqi and Lee (2005) conducted a survey of plumbers in the USA. The result indicate that plumbers do the plumbing repairs on an hourly basis, but they do not fixing the dry wall so the homeowner has to work with a separate general contractor. The labor rate for plumbing repairs varies between $ 45 and $ 75 per hour. The replacement cost of plumbing system including labor and materials are shown in Table 2.1. These statistics are from the national telephone survey (Willis-Walton, 2006) cited by plumber respondents for 2,000 square feet, two level house.

Table 2.1 Replacement cost of household plumbing system including labor and materials for 2,000 square feet house

Cost parameters	Replacement cost in US $		
	Copper (n=207*)	CPVC (n=45*)	PEX (n=74*)
Median	4,000	3,500	3,450
Mean	5,680	4,240	3,654
Min	700	800	750
Max	50,000	15,000	12,000

(*number of respondents per material)

Copper is the most widely used material in residential and commercial plumbing. The advantages of using copper include affordability, fire resistance, little health hazards, and durability. However, due to pinhole leak incidents in hotspot areas, consumers may prefer plastic pipes. Concerns with copper pipes also include metallic taste especially with long stagnation periods and increased consumption of residual disinfectant by the pipe walls (Cuppet et al., 2006). High levels of copper can cause nausea, vomiting, and diarrhea (http://www.atsdr.cdc.gov/toxprofiles/tp132.html, accessed on March 2008). If experiencing elevated copper levels in drinking water, it may be likely that lead levels are also elevated if the plumbing system in home or apartment contains lead solder joints, lead service lines, or brass fixtures. Since lead and copper enter drinking water under similar conditions, it’s advisable to test for lead when testing for copper. Also, there’s a metallic taste in drinking water before copper levels are high enough to cause adverse health effects. Customer’s taste complaints may be the sign of copper corrosion, taste threshold may be lower than EPA’s secondary drinking water standards. The USEPA lead copper rule (1991) regulates the concentration of copper in drinking water to a maximum contaminant limit of 1.3 mg/L.

PEX (polyethylene cross linked) pipes are more flexible pipes than metal pipes. These pipes require different plumbing design than traditional branch and main arrangement. PEX plumbing systems require individual pipe lengths for every fixture which is connected to a common manifold and thus result in an increase in the number of pipes and the total pipe length. But due to lower unit price of PEX, the overall cost almost equals the cost of plumbing with other plastic pipe. The main advantage is that each pipe is free of joints (which requires soldering) and therefore less prone to leak. The use of PEX has raised some concerns regarding possible leaching of MTBE (methyl tert butyl ether) and ETBE (ethyl tert-butyl ether) into drinking water, increased odors (Durand and Dietrich, 2007), and its ability to withstand fire (http://www.prnewswire.com/cgi-bin/stories.pl?ACCT=109&STORY=/www/story/11-18-2004/0002464315&EDATE, accessed on March 2008). It has been reported that the PEX pipe may become stiff in cold weather and may be difficult to use. PEX use has been approved in all the states with California and Massachusetts requiring acceptance by jurisdiction (Toolbase News, http://www.toolbase.org/pdf/techinv/homerunplumbingsystems_techspec.pdf, accessed on March 2008). Like all potable water materials, PEX pipes comply with the health requirements set by NSF/ANSI-61 for potable water supply (http://www.nsf.org/consumer/plumbing/index.asp, accessed on March 2008).

It is known that CPVC pipes may become brittle when exposed to the sunlight over an extended time period. The concerns with CPVC pipes include possible microbial growth, cracking in the event of an earthquake, plastic taste and melting in the event of fire. The solvents used to join fittings and pipe may contain volatile organic compounds (VOCs), require proper ventilation during installation, and can cause odor problems (http://www.builderswebsource.com/techbriefs/cpvccopper.htm#Benefits%20CPVC accessed on 10/29/2006). CPVC pipes manufactured to the stringent ANSI/NSF-61 standards have been approved for potable water use by all the national plumbing codes (http://www.nsf.org/consumer/plumbing/index.asp, accessed on March 2008). The CPVC pipe itself, however, has a low odor potential (Heim and Dietrich, 2007).

Stainless steel pipes are mainly used in industrial applications. Stainless steel provides excellent resistance to corrosion due to the presence of 18% chromium and 8% nickel (Roberge, 2000). The stainless steel is, however, expensive. Because of the cost, its use is limited to specialized industries for conveying chemicals or other similar applications. A concern with stainless steel pipes is the possible leaching of chromium. The stainless steel pipe is approved for use in United States, and complies with NSF/ANSI-61 health requirements (http://www.nsf.org/business/newsroom/press_release.asp?p_id=12241, accessed on March 2008).

3. Previous Studies

In this section, major findings of four surveys that were conducted at Virginia Tech (Kleczyk et al., 2005, Farooqi and Lee, 2005, Willis-Walton, 2006, Bosch et al., 2006) are reported.

First, a mail survey was sent to the Maryland suburbs of Washington D.C. in July 2004. The objective of the survey was to observe the pinhole leak occurrence rate and financial, time, and emotional costs. Washington Suburban Sanitary Commission (WSSC) has been collecting pinhole data from the affected homeowners (WSSC, 2004). GIS (Geographic Information System) analysis revealed that homes located near two water treatment plants have a higher degree of leak incidents (Loganathan and Lee, 2005). A total of 5,009 surveys were sent to Maryland residents and 1,128 respondents returned the surveys.

After weighting responses to account for disproportionate sampling in areas known for high leaks, an estimated 36% of respondents in detached homes and 21% of respondents in apartments or condominiums reported having experienced one or more leaks in their current dwellings. Nearly 30% of respondents with pinhole leaks reported expenditures of at least $500 for repairing leaks and collateral damages. Ten respondents cited spending more than $10,000 in repairs. These repair costs involve fixing ceilings, walls, and floors. In addition, some homeowners had to move out of their houses during the renovation process, which raised the total damage cost. Several respondents commented on the loss of invaluable personal belongings such as family photos, clothes, and inherited furniture. In addition, 70% of the respondents who had pinhole leaks spent at least 10 hours dealing with pinhole leaks and damages. More than half of the respondents felt very stressed regarding this problem and 'aggravated or worried' about the possibility of leaks in the future. Kleczyk and Bosch (2006) concluded that overall anxiety was increased due to i) lack of adequate knowledge and information on the causality of pinhole leaks, ii) lack of sufficient advice or assistance from local water utility, local government, and insurance companies, and iii) full financial responsibility borne by the homeowner.

Farooqi and Lee (2005) conducted telephone surveys of plumbers in nine cities, namely New Orleans (LA), Wilmington (DE), Jackson (MS), Manchester (NH), Bismarck (ND), Austin (TX), Columbus

(OH), Detroit (MI) and Memphis (TN). These cities were not included in the most recent Copper Development Association failure reports (2000-2004). The plumbers were contacted by a random selection from the telephone directory yellow pages. The survey was conducted from July 7th 2005 through August 8th 2005. Priority questions included the frequency of pinhole leaks, possible causes of the pinhole leaks and cost of repair, cost of replumbing, and process of repair and pipe materials. A total of two hundred forty-two calls were attempted, and fifty-five calls were successful (22% success rate). Out of fifty-five plumbers surveyed, 86% acknowledged pinhole leaks were a problem. Twenty-two responded with a definite yes about the existence of the pinhole leaks; twenty-five stated that it is not a common problem; and eight stated that the problem does not exist. The survey results support the occurrence of pinhole leaks as a nationally widespread problem. Among the causes enumerated by the plumbers, the most cited reasons include the age of the plumbing, weak spots in pipe, well water, and soldering flux.

A nationwide telephone survey (Scardina et. al, 2007) was conducted to gain an understanding of the leak cost to owners of homes, apartment dwellings, and commercial buildings and homeowner's Willingness to Pay (WTP) for materials guaranteed to remain leak-free for 50 years. Surveyed communities included geographic regions in the East, Southeast, Midwest, and West as well as the U.S. in general. Homeowners' reported time and out-of-pocket costs and plumbers' estimates of revenues from pinhole leak repairs became the basis for calculating leak costs. The estimated cost of pinhole leaks and pinhole leak prevention cost (within US) is nearly $930 million per year (Scardina et al, 2007). More than 50% is related to single-family homes while multi-family apartment dwellings and commercial buildings account for around 20%. In single-family homes, 50% of the cost is allocated to repairs, 30% to homeowners' time spent on the repairs, and the remainder is for property damage. For those who have had leaks before, the mean willingness to pay for leak-free materials was $1,130 and for those who had not experienced leaks, the mean willingness to pay for leak-free materials was $1,007. Six percent of respondents were willing to pay a premium of at least $4,000 (Kleczyk et al., 2006). Major findings through these surveys are i) 8% of respondents had experienced one or more leaks in their current houses, ii) some hotspots are experiencing over 20% of respondents one or more leaks, iii) plumbing failure incidents are economically (including time) very stressful to homeowners. Over 50% of respondents spent more than $100 on repairs with estimates as high as $12,000. One fourth of respondents with leaks suffered collateral damages. Also, respondents with leaks indicated that they did not report the problem to the utilities.

Bosch et al. (2006) surveyed water utilities and found out that almost 60% of utilities who responded are adding corrosion inhibitors. They are doing this to i) protect main and service lines, ii) to comply with the lead and copper rule, and iii) to give protection to residential customers. The cost per customer per year was found to vary from $ 0.1 to almost 6. This number includes buying inhibitors as well as labor and equipment cost of administering to the water; however this figure does not include costs of removal at the wastewater treatment plant (removing phosphate is roughly equal to the cost of purchasing chemical).

4. Decision Phase I: Optimal Replacement Time of Plumbing System

In this section, the overall decision framework is established for homeowners who are experiencing frequent plumbing failure incidents (see Figure 2.4). When consumers are experiencing leak incidents repeatedly, they need to make a rational decision whether to continue to repair or to replace the system with a reliable alternative. As shown in Figure 2.4, phase I refers to the optimal replacement time and phase II refers to choosing the right material with available information. Once homeowners decided to replace, they will want to maximize the degree of satisfaction (utility values) in making a decision; homeowners should consider in terms of diverse attributes such as cost, convenience of installation, reliability of the system, behavior at the high temperatures, health impacts, resale values, guaranteed warranty, and taste and odor of the drinking water due to different material use.

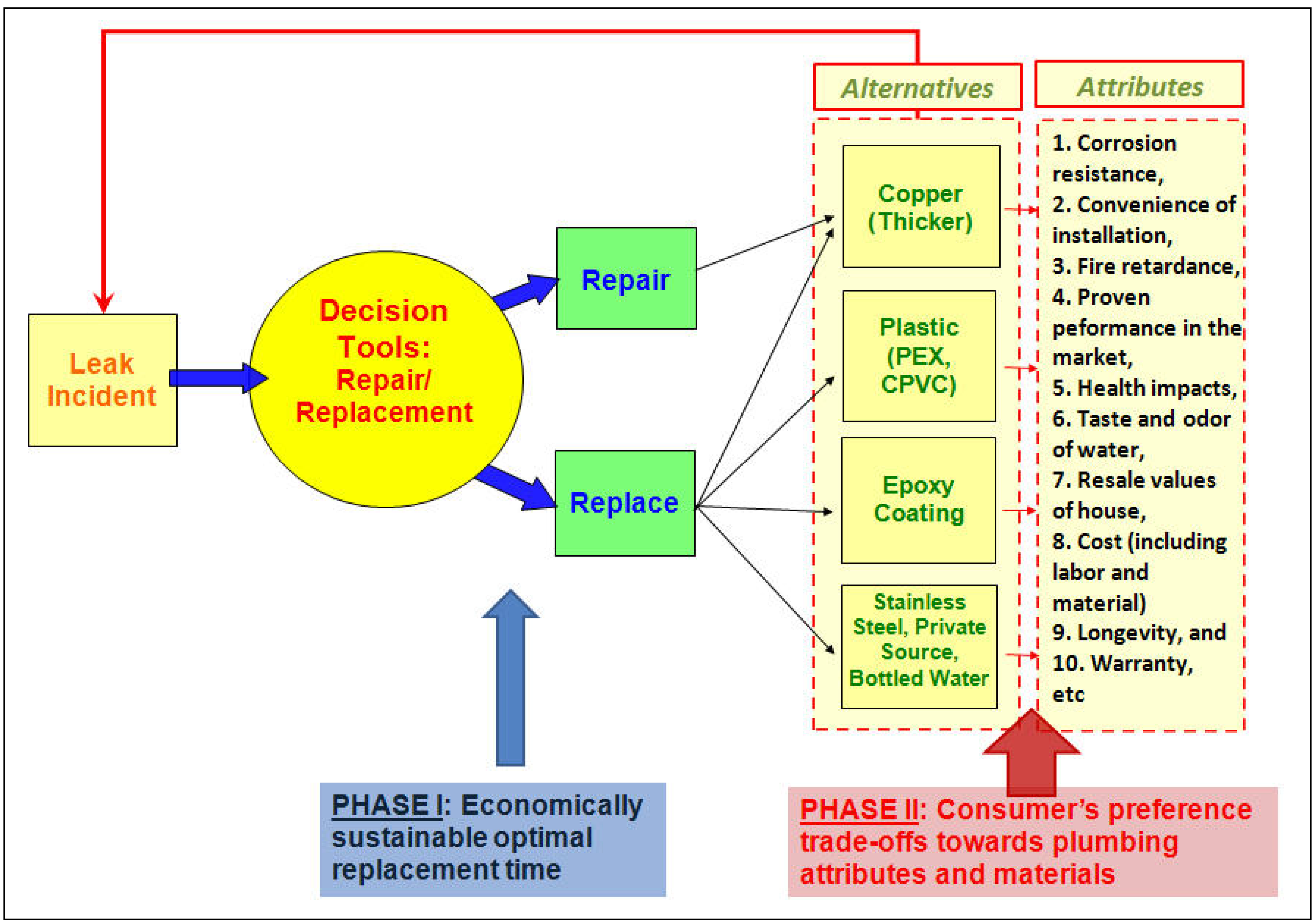


Figure 2.4 Overall decision framework

Decision of Repair/Replacement

A repairable asset is assumed to be in continual use; however, after paying for repairs, the system can be restored to either a better state, about the same, or worse. A simple numeric example illustrates this idea. The net loss to the homeowner from a pinhole leak would be repair/replacement cost plus the value lost [R+ (W_0-W_1)], where W_0: initial value of the plumbing system, W_1: value after leak incidents with a repair/replacement, and R: repair/replacement cost. This construct can be applied for 'n' repairs accounting for proper discount. The optimal replacement time can be obtained by minimizing the total discounted loss over n repairs versus the loss of replacing the system. *Failure times, costs, and consumer preferences* are required for a development of repair/replacement criterion. Repair costs vary from $500 to several thousands of dollars; whereas replacement cost ranges between $6,500 – 16,000 depending on the alternative selection and size of the house (Martin et al., 2007). In the US, replacement will often involve removal of dry walls to gain access to the pipes, which is a time consuming intrusive process. Recently, a new technology has been introduced to inject epoxy into the existing piping systems, without the need to tear into walls; however, it is relatively new in the market and bears further examination.

The following formulation can be utilized in which the contribution of costs towards present worth after replacement is assumed negligible (also see Shamir and Howard, 1979 and Kleiner et al., 1998). At the time of the n^{th} leak, a decision has to be made whether to replace the plumbing system at a cost of F_n or to repair it at a cost of C_n. The scenario also implies that for the previous (n - 1) leaks only repairs have been performed. If we assume that the plumbing system will be replaced (C_n included in the sum should be adjusted for F_n when necessary) at the time of n^{th} leak, t_n, we can write the present worth of the total cost of the pipe as:

$$T_n = \sum_{i=1}^{n} \left\{ \frac{C_i}{(1+r)^{t_i}} \right\} + \frac{F_n}{(1+r)^{t_n}} \qquad (2.1)$$

in which: r = discount rate, t_i = time of i^{th} leak measured from the installation year (year), C_i = repair cost of i^{th} break, F_n = replacement cost at time t_n, T_n = total cost at time '0' (present worth). When the system is new, it tends to experience very few leaks; whereas an old system experiences more leaks under the same conditions. Therefore, the combination of varying time interval between leaks (accelerated leak incidents towards the end of life cycle), relatively smaller repair cost, and a generally large replacement cost leads to the existence of a 'U' shaped present worth of the total cost curve over time (see Figure 2.5). The *accelerated replacement* refers to replacing the plumbing system well in advance of the optimal replacement time. *Delayed replacement* ideally includes all the consequences of neglecting repairs or just performing repairs amounting to paying penalties to compensate for high replacement cost.

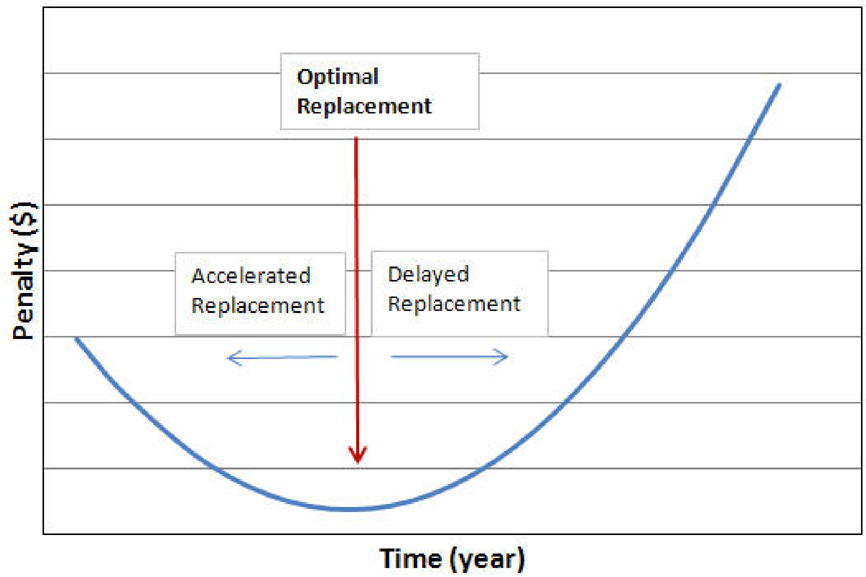


Figure 2.5 Present worth of the total cost curve

Following Loganathan et al. (2005), the point of minimum total cost in eq. (2.1) occurs at the time when the inequality

$$t_{n+1} - t_n < \frac{\ln\left(\frac{C_{n+1}}{F_n} + \frac{F_{n+1}}{F_n}\right)}{\ln(1+r)} \qquad (2.\ 2)$$

is satisfied for the first time in which: C_n = repair cost at n^{th} leak and F_n = replacement cost, r = discount rate, and t_{n+1} = time for $(n+1)^{th}$ leak, t_n = time for $(n)^{th}$ leak. Using the above constructs, Loganathan and Lee (2005) developed a non-data intensive decision model for determining economically optimal replacement time. They synthesized the leak arrival pattern with a built leak rate model. Optimal replacement time calculated to be about 22 years (after installation) for WSSC service area. High quality databases geared to specific areas experiencing pinhole leaks could help inform homeowners' repair or replacement decisions.

5. Decision Phase II: Preference Trade-offs Towards Plumbing Materials

Analysis presented in this section guides homeowners to decide on the alternative plumbing material (Figure 2.4) taking into account material attributes including cost (material plus labor charges), taste and odor of the water, potential for corrosion, longevity of the pipe system, fire retardance, convenience of installation or replacement, plumber or general contractor's opinions or expertise, and proven record in the market. For example, typical concerns regarding use of plastic pipes (PEX, CPVC) include pipe strength, fire hazard, final disposal, reaction to chlorine, taste and odor, and health effects (Woodson, 2004, Dietrich et. al , 2006). Stainless steel is considered less susceptible to corrosion; however, its price is generally considered high for home plumbing compared to the other materials and the market share is low. As mentioned, copper accounts for 90% of homes in US, followed by PEX (cross linked polyethylene) at 7%, and CPVC (chlorinated polyvinyl chloride) at 2%. Telephone surveys of plumbers (Farooqi and Lee, 2005) tend to show an increased use of plastic pipes due to easier handling in installation and lower material cost.

In this study, three preference elicitation tools for *choosing alternative plumbing material* are considered: CA (Conjoint Analysis), CV (Contingent Valuation) (Champ et al., 2003), and AHP (Analytical Hierarchical Processes) (Saaty, 1980; 1990). CA and CV have been primarily adopted in marketing and economics research. They are based on utility theory and therefore decision maker's Willingness to Pay (WTP) values can be estimated. The approaches assume that individuals are able to rank bundles of goods in terms of preferences or desirability. Preference ordering or desire of individual is a fundamental assumption in economics. AHP is a multiattribute preference elicitation method that allows for examining tradeoffs among attributes for a given level of utility. AHP and CA can be compared as both consider multiple attributes of the plumbing system. The relative importance (i.e. part-worth values) of each attribute is estimated. Preference elicitation tools can be applied to plumbing purchasing decisions to assess homeowners' preferences towards different materials and more importantly their valuation of the different attributes.

First, a survey was administered to 135 students in Civil and Environmental Engineering at Virginia Tech to gauge preferences for plumbing materials. Based on the comments from engineering students, survey modules were improved for better readability, clear formats, and comfortable time to finish the survey. Updated surveys (in mail survey format) were sent to selected homeowners of pinhole leak prone area in Southeastern community. Two-phase surveys were systematically implemented to i) better understand their concerns and ii) compare preference elicitation tools. Survey design and methodology will be covered in Section 5.2 through 5.3. In the following section, formal methodologies (i.e. AHP, CA, and CV) are discussed.

5.1 Preference Elicitation Tools

5.1.1 Analytical Hierarchical Process (AHP)

Generally, comparing several attributes of a product simultaneously is a complicated procedure. Assessing pair-wise preferences enables the decision maker to concentrate judgment on a pair of elements with respect to a single property without thinking about other properties or elements [Saaty (1990)]. So this unique mechanism of AHP helps the decision makers to concentrate on their decision more carefully. Elicited preferences may be based on the standards already established in memory through a person's experience or education. Of course, this caution should be advised to all three methods (AHP, CA, and CV). Strength of the AHP is that it is applicable to the measurement of intangible criteria along with tangible ones through ratio scales and rooted in rigorous mathematical procedures. The process includes the following steps:

Step1 [Identify and present the attributes in hierarchical structure]: Decomposing a complex problem into hierarchical structure is helpful to have detailed understanding of the problem. It is easier to have a big picture by integrating each piece of information. Figure 2.6 shows a schematic that lists various attributes of three plumbing materials. The available alternatives are Materials A, B, and C. The 7 attributes, listed in the middle, are based on the comments from faculties and graduate students from civil and environmental engineering, Economics, and Food and Science department. These groups have extensive knowledge and experience on the nature of plumbing issues. For plumbing material selection the following seven attributes are considered in engineering student survey.

- Price—includes cost of materials and labor for installation and repair;
- Corrosion resistance—dependability of material to remain free of corrosion;
- Fire retardance—ability of material to remain functional at high temperatures and not to cause additional dangers such as toxic fumes;

- Health effects—ability of material to remain inert in delivering water without threatening human health;
- Longevity—length of time material remains functional;
- Resale value of home— people's preference for a particular material including aesthetics as reflected in home resale value;
- Taste and odor—ability of material to deliver water without imparting odor or taste.

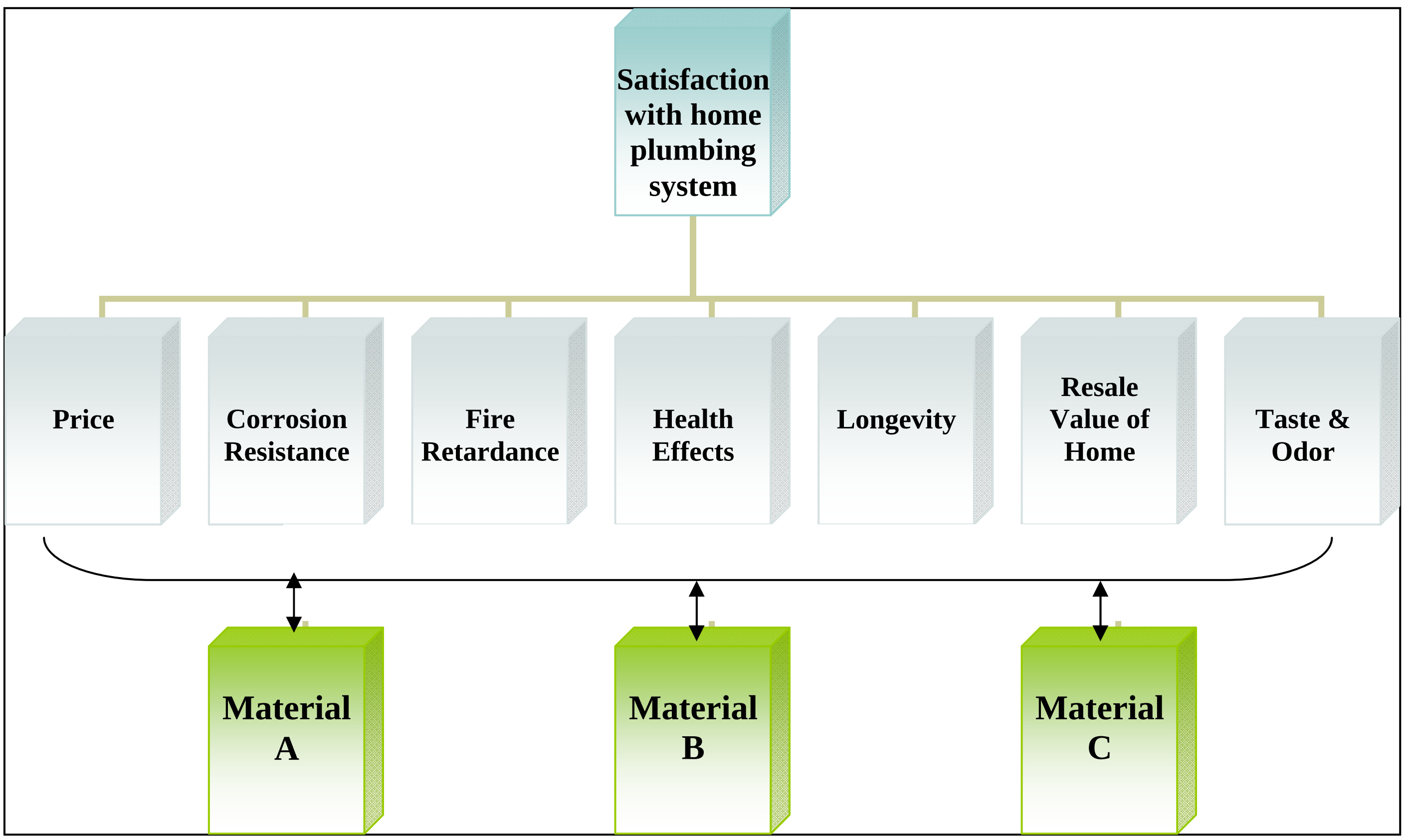


Figure 2.6 Plumbing Material Selections

Step 2 [Use the standard preference table]: A scale (1-9) of pair-wise preference weights is given in Table 2.2 (Saaty, 1980).

Table 2.2 Standard numerical scores

Preference Level	Numerical score, a(i,j) 1-9 scale
Equally preferred	1
Equally to moderately preferred	2
Moderately preferred	3
Moderately to strongly preferred	4
Strongly preferred	5
Strongly to very strongly preferred	6
Very strongly preferred	7
Very strongly to extremely preferred	8
Extremely preferred	9

Step 3 [Develop the pair-wise preference matrix]: In AHP, instead of directly assessing the weight for attribute, i, the relative weight $a_{ij} = \frac{w_i}{w_j}$ between attribute i and j is assessed. As shown in Tables 2.3 and 2.4, each participant is asked to fill in a 7x7 attribute matrix of pair-wise preferential weights.

Table 2.3 Pair-wise preference weight matrix

	Attribute 1	Attribute 2	…	Attribute n
Attribute 1	$\frac{w_1}{w_1}$	$\frac{w_1}{w_2}$	…	$\frac{w_1}{w_n}$
Attribute 2	$\frac{w_2}{w_1}$	$\frac{w_2}{w_2}$	…	$\frac{w_2}{w_n}$
…	…	…	…	…
Attribute n	$\frac{w_n}{w_1}$	$\frac{w_n}{w_2}$	…	$\frac{w_n}{w_n}$
Sum	$\frac{X}{w_1}$	$\frac{X}{w_2}$	…	$\frac{X}{w_n}$

in which: $X = (w_1+w_2+\ldots+ w_n)$.

From the pair-wise preference matrix, we observe the following.

$$\begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \begin{Bmatrix} w_1 \\ w_2 \\ \cdots \\ w_n \end{Bmatrix} = n \begin{Bmatrix} w_1 \\ w_2 \\ \cdots \\ w_n \end{Bmatrix} = n\{\mathbf{w}\}$$

in which: = {**w**} = required global preference vector (of weights). Table 2.4 is a reciprocal matrix in that the off diagonal elements are reciprocals of each other, Numerical score, a(i,j) =

$$\frac{weight\ for\ criterion, i, w_i}{weight\ for\ criterion, j, w_j} = \frac{1}{a(j,i)}$$

An example is shown in Table 2.4. In row H and column R, the entry of 8 implies that health effects are very strongly to extremely preferred in comparison to resale value of home in the ratio of 8:1. Row H for health effects overwhelms all other attributes with the entries staying well above 1. In row P and column C, the cell value of 0.2 indicates corrosion resistance is strongly preferred to price in the ratio of 5:1.

Table 2.4 Example pair-wise preference weight matrix

	P	C	F	H	L	R	T
P	1	0.20	0.25	0.14	0.20	0.50	0.33
C	5	1	5	0.33	1	6	1
F	4	0.20	1	0.17	0.33	1	0.25
H	7	3	6	1	4	8	3
L	5	1	3	0.25	1	2	0.33
R	2	0.17	1	0.13	0.50	1	0.50
T	3	1	4	0.33	3	2	1
Sum	27.00	6.57	20.25	2.35	10.03	20.50	6.42

(P: price, C: corrosion resistance, F: fire retardance, H: health effects, L: longevity, R: resale value of home, and T: taste and odor)

Step 4[Evaluate the re-scaled pair-wise preference matrix]: A rescaled preference matrix is generated by dividing each column entry in Table 2.4 by that column's sum yielding Table 2.5. The last column "Avg" contains average values for each row and shows the ranking of the attributes. Table 2.6 shows the ordered relative ranking of the attributes.

Table 2.5 Rescaled pair-wise weight matrix

	Relative importance of each attribute							
Attrib.	P	C	F	H	L	R	T	Avg.
P	0.04	0.03	0.01	0.06	0.02	0.02	0.05	0.03
C	0.19	0.15	0.25	0.14	0.10	0.29	0.16	0.18
F	0.15	0.03	0.05	0.07	0.03	0.05	0.04	0.06
H	0.26	0.46	0.30	0.43	0.40	0.39	0.47	0.38
L	0.19	0.15	0.15	0.11	0.10	0.10	0.05	0.12
R	0.07	0.03	0.05	0.05	0.05	0.05	0.08	0.05
T	0.11	0.15	0.20	0.14	0.30	0.10	0.16	0.17
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 2.6 Relative ranking of attributes

Attribute	Weight	Rank
Health Effects	0.38	1
Corrosion resistance	0.18	2
Taste and odor	0.17	3
Longevity	0.12	4
Fire resistance	0.06	5
Resale value	0.05	6
Price	0.03	7

Step 5[Evaluate preferences]: For each attribute, a pair-wise weight matrix and the associated rescaled matrix for three pipe materials A, B, and C are obtained (Table 2.7). Results for price attribute which only includes the prices of the material are shown as Table 2.8. The right 3 columns show the rescaled matrix in which the weights sum to 1. The procedure is iterated for other attributes for the three materials. The results are shown in Table 2.9 as the 3 x 7 matrix. The final ranking of the 3 materials is obtained by using the average ranking for the three materials for price, corrosion resistance, fire retardance, health effects, longevity, resale value of home, taste and odor and the average ranking of the criteria themselves from Table 2.5. The respective matrix and the vector are given in Tables 2.9 and 2.10.

Table 2.7 – Attributes for Drinking Water Pipe Materials

	Pipe Material A	**Pipe Material B**	**Pipe Material C**
Corrosion Resistance	May corrode under select conditions	Not susceptible to corrosion	Resists corrosion and oxidation
Fire Retardance	Can withstand temperatures up to 2,000 degrees Fahrenheit without melting and emitting toxic fumes	May melt and emit toxic fumes at temperatures above 180~200 degrees Fahrenheit	Can withstand temperatures up to 2,000 degrees Fahrenheit without melting and emitting toxic fumes
Effects on Resale Value of Home	May increase resale value of a home	May have a negative effect on the resale value of a home compared to other plumbing materials	May increase the resale value of a home
Taste / Odor	Compounds released from this material in drinking water plumbing may give a bitter or metallic taste or odor to the water	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water	No effects on taste and odor of drinking water have been found
Health Effects	Compounds from plumbing made of this material that are released into drinking water, and exceed EPA standards, may cause vomiting, diarrhea, stomach cramps, and nausea	Compounds from plumbing made of this material that are released into drinking water may lead to microbial growth in water	No adverse effects on health have been found
Longevity	Plumbing made of this material have a 50-year manufacturer's warranty	Some types of plumbing made of this material have 10-year manufacturer's warranty	Plumbing made of this material has a long life span
Price (in year 2005)	Price for ½'' diameter pipe: $6.48 Price for ¾'' diameter pipe: $10.04	Price for ½'' diameter pipe: $2.84 Price for ¾'' diameter pipe: $4.67	Price for ½'' diameter pipe: $19.46 Price for ¾'' diameter pipe: $30.11

Table 2.8 Pair-wise matrix and the rescaled matrix for the attribute Price

Material	A	B	C	Material	A	B	C	Avg.
A	1.00	0.33	2.00	A	0.22	0.20	0.33	0.25
B	3.00	1.00	3.00	B	0.67	0.60	0.50	0.59
C	0.50	0.33	1.00	C	0.11	0.20	0.17	0.16
Sum	4.50	1.67	6.00	Sum	1.00	1.00	1.00	1.00

Table 2.9 Average ranking for the materials

Material	P	C	F	H	L	R	T
A	0.25	0.16	0.44	0.33	0.25	0.30	0.25
B	0.59	0.30	0.11	0.26	0.25	0.16	0.25
C	0.16	0.54	0.44	0.41	0.50	0.54	0.50

(P: price, C: corrosion resistance, F: fire retardance, H: health effects, L: longevity, R: resale value of home, and T: taste and odor)

Table 2.10 Attribute preference vector

Attribute	Average
P	0.03
C	0.18
F	0.06
H	0.38
L	0.12
R	0.05
T	0.17

Multiplying the above pipe material preference matrix (Table 2.9) and the attribute preference vector (last column of Table 2.5 shown in Table 2.10) yields a final preference matrix that is shown in Table 2.11.

Table 2.11 Final preference matrix

Material	Preference
A	0.28
B	0.26
C	0.46

Based on the highest relative preference score of 0.46, Material C obtains a rank of 1, followed by Material A for a rank of 2, and B with a rank of 3. The consistency check for the material related matrices and average relative criteria preference vector are performed following Saaty (1980) and is discussed in next step. Participants are advised to reassess the pair-wise weights if the consistency check failed.

Step 6[Perform consistency check]: The calculated maximum eigenvalue in Table 2.3 λ_{max} = n, where n: number of attributes. If the actual eigenvalue is different from n, there are inconsistencies in the weight assignments. Saaty (1980) defines a consistency index as C.I. = $\frac{\lambda_{\max} - n}{n-1}$. Based on a large number of randomly simulated outcomes, Saaty (1980) suggests that if the ratio of C.I. to R.I. (Random Index given in Table 2.12) is less than 0.1 [i.e. $\frac{C.I.}{R.I.} < 0.1$], the weights should be taken as consistent. Table 2.12 contains the R.I. values calculated from randomly generated weights as a function of the pair-wise matrix size (number of criteria). Saaty (1980) originally assessed consistency by finding the eigenvalues and eigenvectors of the matrix; however, in this paper, we adopt a simplified approach which utilizes the rescaled pair-wise preference matrix [A_{norm}] (Table 2.13 obtained from Table 2.3).

Table 2.12 Random Index (RI)

Matrix Size	1	2	3	4	5	6	7	8	9
R.I.	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45
Matrix Size	10	11	12	13	14	15			
R.I.	1.49	1.51	1.48	1.56	1.57	1.59			

Table 2.13 Rescaled pair-wise preference matrix [A_{norm}]

	Attribute 1	Attribute 2	…	Attribute n	Average
Attribute 1	$\frac{w_1}{X}$	$\frac{w_1}{X}$	…	$\frac{w_1}{X}$	Ave($\frac{w_1}{X}$)
Attribute 2	$\frac{w_2}{X}$	$\frac{w_2}{X}$	…	$\frac{w_2}{X}$	Ave($\frac{w_2}{X}$)
…	…	…	…	…	…
Attribute n	$\frac{w_n}{X}$	$\frac{w_n}{X}$	…	$\frac{w_n}{X}$	Ave($\frac{w_n}{X}$)
Sum	1	1		1	

in which: $X = (w_1+w_2 + \ldots + w_n)$.

If the weights are consistent, all columns of [A_{norm}] should be identical. Also, note the rescaled columns sum to 1 forming a stochastic matrix in the sense that probabilities sum to 1. Such a matrix has a maximum eigenvalue of 1. The last column of Table 2.14 is the relative preference vector between criteria 1, 2, and n obtained by averaging the columns of the rescaled pair-wise matrix. We multiply Step 2 pair-wise preference weight matrix with the relative preference criteria vector from the last column of Table 2.13 as shown in Tables 2.14, 2.15, and 2.16.

Table 2.14 Pair-wise preference weight matrix

Attribute 1	Attribute 2	…	Attribute n
$\frac{w_1}{w_1}$	$\frac{w_1}{w_2}$	…	$\frac{w_1}{w_n}$
$\frac{w_2}{w_1}$	$\frac{w_2}{w_2}$	…	$\frac{w_2}{w_n}$
…	…	…	…
$\frac{w_n}{w_1}$	$\frac{w_n}{w_2}$	…	$\frac{w_n}{w_n}$

Table 2.15 Relative preference criteria vector

Average
$\text{Ave}(\frac{w_1}{X})$
$\text{Ave}(\frac{w_2}{X})$
…
$\text{Ave}(\frac{w_n}{X})$

Table 2.16 Product of preference weight matrix and preference criteria vector

Product
$[(\frac{w_1}{w_1})\text{Ave}(\frac{w_1}{X})+(\frac{w_1}{w_2})\ \text{Ave}(\frac{w_2}{X})+\ldots+(\frac{w_1}{w_n})\ \text{Ave}(\frac{w_n}{X})]$
$[(\frac{w_2}{w_1})\text{Ave}(\frac{w_1}{X})+(\frac{w_2}{w_2})\ \text{Ave}(\frac{w_2}{X})+\ldots+(\frac{w_2}{w_n})\ \text{Ave}(\frac{w_n}{X})]$
…
$[(\frac{w_n}{w_1})\text{Ave}(\frac{w_1}{X})+(\frac{w_n}{w_2})\ \text{Ave}(\frac{w_2}{X})+\ldots+(\frac{w_n}{w_n})\ \text{Ave}(\frac{w_n}{X})]$

The ratio of each entry of product column to respective average column is obtained by dividing each entry of the product column (Table 2.17) by the respective entry of the average column to yield (Table 2.18).

Table 2.17 Ratio of each entry of product column to respective average column

Ratio = $\frac{Product}{Average}$
$\frac{[\frac{w_1}{w_1}\cdot Ave(\frac{w_1}{X})+\frac{w_1}{w_2}\cdot Ave(\frac{w_2}{X})+...+\frac{w_1}{w_n}\cdot Ave(\frac{w_n}{X})]}{Ave(\frac{w_1}{X})}$
$\frac{[\frac{w_2}{w_1}\cdot Ave(\frac{w_1}{X})+\frac{w_2}{w_2}\cdot Ave(\frac{w_2}{X})+...+\frac{w_2}{w_n}\cdot Ave(\frac{w_n}{X})]}{Ave(\frac{w_2}{X})}$
…
$\frac{[\frac{w_n}{w_1}\cdot Ave(\frac{w_1}{X})+\frac{w_n}{w_2}\cdot Ave(\frac{w_2}{X})+...+\frac{w_n}{w_n}\cdot Ave(\frac{w_n}{X})]}{Ave(\frac{w_n}{X})}$
Sum of ratios ≈ n^2

We divide the sum of ratios, which is around n^2 by n to obtain A.R. (average ratio), which should be close to n. The Consistency Index (C.I.) is $\frac{[A.R.-n]}{(n-1)}$. The C.I. is checked against the permissible limit ($\frac{C.I.}{R.I.}$ < 0.1) to accept the AHP results. If it fails, the pair-wise weights should be re-assessed.

5.1.2 Conjoint Analysis (CA)

Conjoint analysis (CA) is for analyzing the effects of levels of independent or predictor variables (also known as attributes or factors) on a dependent variables. A specific combination of levels of the attributes is called a stimulus, treatment, or alternative. For example 3- distinct levels for each of 4- attributes will yield (3*3*3*3) stimuli. Consideration of the totality of the 81 stimuli is called a 'full factorial' design. Typically a subset of the stimuli known as a 'fractional factorial' design will be analyzed. Decision makers or respondents react to a set of profile descriptions (i.e. stimuli) and the utility (part-worth values) associated with each level of each factor is determined. Large part worth utility means the significant or most preferred levels of the attribute. Likewise, small part worth utility means the least preferred attributes. Different methodologies have been proposed to increase the prediction capacity as a preference elicitation tools. In this section, the most representative CA methodologies are explained.

Consider 2 attributes of a car, namely, engine power and available room (see Table 2.18). The attribute engine power has 2-levels namely max and standard. The available room has 3-levels large, sedan, and sport. Table 2.18 shows this data. Rank 1 is assigned by a respondent for the most preferred and rank 6 in the least preferred. A rating scale may also be used in which 10 in the most preferred and 1 is the least preferred. The ratings are shown within parameters. A choice model requires the respondent to select one stimulus from a choice set. In Table 2.18, respondent 1 has chosen stimulus 3 and respondent 2 has chosen stimulus 1. In the following, we are explaining CA in a stepwise manner.

Table 2.18 Stimuli descriptions and respondent rankings

Stimulus	**Engine Power**	**Room**	**Respondent 1**	**Respondent 2**
1	Max	Large	3 (8)	1 (10)
2	Max	Sedan	2 (9)	3 (8)
3	Max	Sport	1 (10)	5 (6)
4	Standard	Large	6 (7)	2 (9)
5	Standard	Sedan	5 (6)	4 (7)
6	Standard	Sport	4 (5)	6 (5)

Step 0 [Data collection methods]

Full profile approach utilizes the complete combinations of the factors. It is giving realistic description of the situation or product description by defining the levels of each of the attributes and possibly the respondent can consider the environmental correlation between attributes. The primary advantage of this approach is that all main and interaction effects are independent. In multiple regression, main effects are estimated parameter for each level of attribute whereas interaction effects are estimated parameters for the cross product of two or more independent variables.

Step 1 [Stimulus set construction]

Fractional factorial design is used to reduce the number of stimulus to a manageable size for the respondent. Usually, full factorial experiments require many runs which make the respondents easily exhausted. But fractional factorial design adequately chooses fraction of the treatment combinations required for the complete factorial experiments to be run (ASQC Glossary & Tables, 1983). For example, for a two level and six attributes, $2^6 = 64$ runs are required for full factorial design. This is referred to as L^n design, L denotes the number of levels and n is the number of attributes. But properly chosen fractional factorial enable analysts to study variables in a relatively limited number of tests (say, 8, 16, or 32 runs) while keeping the experiment design both *balanced and orthogonal*. Balanced means the combination treatment (i.e. stimulus) has the same number of element observations and orthogonal design whose levels of different attributes must be independent from each other (the corresponding columns of the array have to be uncorrelated). According to Orme (2002), the attributes have to be independent from each other when the additive utility model is used and the level should be mutually exclusive. For more details, refer to Montgomery (1991).

Step 2 [Presenting the stimulus]: Verbal description, Paragraph description, and pictorial model representations can be used. Pictorial approaches are known to be the most effective methods when individual level parameters are to be estimated.

*Step 3 [Dependent variable's measurement scale]***:** A measurement scale for the dependent variable (i.e. the respondent's response to the stimulus or combination treatment) can be classified as *nonmetric* and *metric*. Nonmetric means paired comparison or rank order; metric includes rating scales assuming interval scale properties. The measurement can be overall preference or most likelihood of purchase. Potentially, metric has more information in the scales but the accuracy may decrease as the number of stimuli gets larger.

Step 4 [Estimation of part-worth values]

We are explaining three methodologies to estimate the importance of each attribute (i.e. part worth values,β): 1) rating scale, 2) choice model, and 3) ranking scale. For the case studies, we applied rating scale and choice probability model.

1) Rating Scale

Decision makers make judgments about the magnitude of utility (Y_i values) presented to them in attribute-based questions. In table 2.19, stimulus 3 is rated as 10 by respondent 1 and 6 by respondent 2. These values represent the magnitude of utility (Y_i values). It is assumed that the utilities of each respondent are transformed to the rating scales. Ordinary Least Square (OLS) regression is adopted due to the simplicity of the data analysis. In OLS, the errors in this model are treated as additive nuisance parameters whereas random utility model has structurally significant interpretation (this is explained in choice based models).

General linear model

We have a sample of n stimuli denoted by Y_i corresponding X_{ji} denoting the level of attribute j in the ith stimulus. Assuming linear relationship between Y_i and the k-1 X_{ji} for j = 2,…, k and i = 1,2, …, n, we can write

$$Y_i = \beta_1 + \beta_2 X_{2i} + ... + \beta_k X_{ki} + u_i \qquad (2.3)$$

The unknowns are β coefficients (part-worth utilities) and disturbance u. The n equations can be set up as a matrix form to obtain estimates of the unknowns (Johnston 1972).

$$\mathbf{y = X\beta + u} \qquad (2.4)$$

$$\text{where, y} = \begin{bmatrix} Y_1 \\ Y_2 \\ ... \\ Y_n \end{bmatrix}, \text{X} = \begin{bmatrix} 1 & X_{21} & ... & X_{k1} \\ 1 & X_{22} & ... & X_{k2} \\ ... & ... & ... & ... \\ 1 & X_{2n} & ... & X_{kn} \end{bmatrix}, \boldsymbol{\beta} = \begin{bmatrix} \beta_1 \\ \beta_2 \\ ... \\ \beta_n \end{bmatrix}, \text{and u} = \begin{bmatrix} u_1 \\ u_2 \\ ... \\ u_n \end{bmatrix}$$

Using least square estimation, values of β can be estimated. Let $\hat{\beta} = \{\hat{\beta}_1 \quad \hat{\beta}_2 \quad ... \quad \hat{\beta}_k\}$ which means the column vector estimating **β.** We can write as y = $X\hat{\beta} + e$, where e denotes the column vector of n residuals (y- $X\hat{\beta}$). So, the sum of squared residuals is $\sum_{i=1}^{n} e_i^2 = e'e = (y - X\hat{\beta})'(y - X\hat{\beta})$. We differentiate to get the value of $\hat{\beta}$ that minimizes the sum of squared residuals.

$\frac{\partial}{\partial \hat{\beta}}(e'e) = -2X'y + 2X'X\hat{\beta} = 0$. So, $\hat{\beta}$ is estimated as $\hat{\beta} = (X'X)^{-1}X'y$.

2) Choice-based Model

Conjoint Analysis has been popularly used by many disciplines, but concerns arose regarding its application. For example, the high rating of the alternative does not necessarily mean that consumers will choose that option. To address these issues, a discrete choice theory was introduced using Random Utility Modeling (RUM); the probability that person 'n' chooses option 'i' from a set of options given to that particular person C_n is designated by

$$P[i|C_n]=P[(V_{in} + \varepsilon_{in}) > (V_{in} + \varepsilon_{in})] \text{ for all } j\neq i \in C_n, \qquad (2.5)$$

in which: $U_{in} = V_{in} + \varepsilon_{in}$ is the random utility made up of the systematic explainable component V_{in} and ε_{in} the random component (Champ et al., 2003).

$$V_{in} = \sum_k \beta_k x_{kin} + \beta_p P_{in} + \varepsilon_{in} \qquad (2.6)$$

where x_{kin} is attribute k in profile V_{in}, β_k is the preference parameter associated with attribute k, and β_p is the parameter on profile cost. According to Champ et al. (2003), the individual choice is assumed to be deterministic, however, the researcher does not have all information about each individual and therefore, the error term represents the uncertainty in the final choice. The parameter estimates (β) are defined as marginal utilities of attributes ($\beta_k = \frac{\partial U}{\partial x_k}$) and marginal utility of money (β_p). As a result, the marginal rate of substitution (MRS) between any two attributes k and m is defined as the ratio of two parameter estimates:

$$\text{MRS} = \frac{\beta_k}{\beta_m} \qquad (2.7)$$

MRS can be explained on the surface of indifference curve. For completeness, a concept of indifference curve is presented.

Indifference Curve

An indifference curve is a graph where each point on the curve, consumers have the same level of utility (satisfaction level); consumers have no preference for one bundle over another. This theory is derived from ordinal utility theory that individuals can always rank two bundles according to their order of preferences.

When we take the total derivative of U(x, y) at point (x_0, y_0),

$$dU\,(x_0, y_0) = \frac{\partial U(x_0, y_0)}{\partial x}dx + \frac{\partial U(x_0, y_0)}{\partial y}dy \qquad (2.8)$$

The indifference curve that is passing through (x_0, y_0) should render the same amount of utility; $U(x_0, y_0)$. Mathematically speaking, *$dU(x_0, y_0)$ should be zero.* From above equation, we can write as

$$\frac{dx}{dy} = -\frac{\dfrac{\partial U(x_0, y_0)}{\partial y}}{\dfrac{\partial U(x_0, y_0)}{\partial x}} \qquad (2.9)$$

On the indifference curve, this equation indicates the slope at point (x_0, y_0). Also, this is the *marginal rate of substitution (MRS)* between attributes x and y.

Probability Modeling

The probability of a consumer choosing an alternative *i* from a set of attribute level combinations *choice set C* is defined as:

$$P(i|C) = P(U_i > U_j) = P(v_i + e_i > v_j + e_j), \text{ for all } j \in C \qquad (2.10)$$

where C contains all competing alternatives. When errors are independently and identically distributed (IID) following a type I extreme value (Gumbel) distribution and preferences are homogenous and errors have the same scale parameter, the multinomial logit model can be applied.

$$P\,(i|C) = \frac{\exp(\mu v_i)}{\sum_{(j \in C)} \exp(\mu v_i)} \qquad (2.11)$$

where, μ is the scale parameter. Multinomial logit models are frequently employed to model relationship between a polytomous response variable and a set of regressor variables. Generalized logit models and conditional logit models can be used. In a conditional logit model, choice is determined only by the characteristics of the alternatives whereas for a generalized logit model, an individual who make the choice becomes main unit of analysis (explanatory variables contain individual characteristics). Here, we are focusing on conditional logit model.

When an additively separable specification of utility and μ=1 is assumed, the probability of choosing profile *i* from the set *C* is defined as follows

$$P(i|C) = \frac{\exp(\sum_{k=1}[\beta_k x_{ik}] + \beta_p p_i)}{\sum_{(j\in C)}\exp(\sum_{k=1}[\beta_k x_{jk}] + \beta_p p_j))} \quad (2.12)$$

If N represents the sample size and individual choice is defined as

$$y_{in} = \begin{cases} 1 \text{ if respondent n chose profile i} \\ 0 \text{ otherwise} \end{cases}$$

then the likelihood function is

$$L = \Pi_{n=1}^{N}\Pi_{i\in C}P_n(i)^{y_{in}} \quad (2.13)$$

After logarithmic transformation, the multinomial logit model is estimated by solving for the values of β's that maximize the log-likelihood function.

$$\ln L = \sum_{n=1}^{N}\sum_{i\in C} y_{in}((\sum_{k=1}^{l}\beta_k x_{ikn} + \beta_p p_{in}) - \ln\sum_{j\in C}(\sum_{k=1}^{l}\beta_k x_{jkn} + \beta_p p_{jn}) \quad (2.14)$$

We are assuming that the joint probability density function depends on the βs. Also, the sampled data is representative of the population and β will most likely cause the observed data to occur. So, we formed an estimate for the unknown parameters β as a function of these observed data samples. The point estimation is to pick a one dimensional statistics that estimates β in optimal point. So, the value of β that maximize the probability density function is the most likely value for β (Papoulis et al, 2002).

This model relates paired comparison data to a choice probability model assuming the paired comparisons are probabilistically independent. Each consumer is asked to choose one combination from each of several different choice sets; he/she chooses one combination of attribute levels maximizing the magnitude of utilities. The attributes of the product that define the choices are called choice attributes to distinguish them from other attributes that may be of interest but do not contribute to the final choices.

3) Ranking Scale

Decision makers rank a set of profiles from most to least preferred choices provided to them. The ranking scale provides analysts the most preferred alternative and all other alternatives in ordinal manner. The sequence of choices from the decision maker can be considered as the joint probability for ranking alternatives from the choice sets. Assuming that the most preferred profile is chosen first and second rank is chosen next time, the formulation is

$$Pr\ [\text{j ranked } 1^{st}, \text{k ranked } 2^{nd} \ldots \text{J ranked last}] = Pr\ (j|\ j, k, l, \ldots, J) \cdot \ldots \cdot P(J\text{-}1|\ J\text{-}1, J) \quad (2.15)$$

Rank-ordered logit model can be employed for a given ranking. It can be formulated as a function of the probability of the utility of alternative *j* being greater than that of alternative *k*, the utility of *k* being greater than that of *l*, and so on (Champ et. al, 2003).

$$P(U_j > U_k > \ldots > U_J) = \prod_{j=1}^{J-1} \left(\frac{\exp[\mu(\sum_{m=1}^{l} \beta_m x_{jm} + \beta_p p_j)]}{\sum_{i=j}^{J} \exp[\mu(\sum_{m=1}^{l} \beta_m x_{im} + \beta_p p_i)]} \right) \quad (2.16)$$

in which, $\sum_{m=1}^{l} (\beta_m x_{jm} + \beta_p P_j)$ refers to the sum over m = 1,2,…, l attributes. It is known that parameter estimates may lack stability and reliability as ranking practice is more demanding exercise for the participants so get confused or fatigued as they proceed through the survey.

5.1.3 Contingent Valuation (CV)

CV is a survey based method frequently used for estimating economic values on environmental goods and services not bought and sold in the market place. As these goods are not routinely traded in the market, actual costs/sales information is seldom available. So, CV involves directly asking people how much they would be willing to pay for specific environmental services. A randomly selected group is provided with some hypothetical issues 'X' and asked a question or a sequence of questions. "What is your Willingness to Pay (WTP) for X or "Would you favor spending $y for X, yes or no?" the follow up questions are for eliciting the detailed WTP. The first questions is an example of '*open ended format*' and the latter question is '*closed-ended*' format which the respondents are asked whether they would be willing to pay a particular amount for improvement of 'X'. Like CA, CV is classified as '*stated preference*' method as it directly asks people to state their values to hypothetical questions as opposed to '*revealed preference*' data which are on actual decision and outcomes (Champ et al., 2003).

The WTP obtained from the sample population is then extrapolated across the entire affected population (often taking into account socioeconomic factors such as income and education level) and then used as the dependent variable in a regression model. The validity and reliability of the CV has been debated for a long time because the application process is complicated and lengthy. For example, the results of CV surveys are often highly sensitive to what people believe they are being asked to value. The CV studies are also highly demanding for the respondents who are asked to compare reductions/increases in services to the effects of monetary changes. As a result, unless the CV survey is carefully designed and executed, the results may be significantly biased and the sensitivity of the estimated WTP to the magnitude of the good in question will fail the validity of CV estimates (Carson, 2000).

As mentioned, the main objective of CV is to obtain WTP from the respondents. The estimation methods are closely related with the fundamental theories of WTP. So, fundamental theories of WTP are presented before explaining CV procedures.

<u>Theoretical background on WTP</u>: According to Champ et al (2003), people have preferences both for non-market and market goods. It is assumed that individual is able to rank the bundles of goods in terms

of preferences or desirability. Preference ordering or desire of the individual is the fundamental element of economic theory. Using utility function, we can represent the preferences as below.

$$U(X^A, Q^A) \qquad (2.17)$$

Where *X*: vector of all levels for n market goods that individual chooses, *Q*; the vector of all levels for the k non-market goods. For each bundle of goods *(X, Q)*, a single number is assigned from utility function. CA and CV can be compared in the sense that both are rooted from utility based models.

When someone is purchasing market goods within one's income y, he or she is maximizing the utility subjected to a rationed level of the non-market goods. We can formulate this situation as typical optimization problem.

$$\text{Maximize U (X, Q)} \qquad (2.18)$$

$$\text{Subject to } P \cdot X \leq y \text{ , } Q = Q^0$$

P is the vector of the price for n market goods. We are solving for *X* that depends on *y* (level of income), *P* (prices of market goods), and *Q* (level of the rationed nonmarket goods); that is, the vector of optimal demands for each market good can be written as $X^*=X(P, Q, y)$. The *indirect utility function* can be derived by plugging in a set of optimal demands into the utility function; $U(X^*, Q) = v(P, Q, y)$. Through the demand functions, the demand quantity of goods is given at a given price vector and income level. We can interpret this at marginal value curves as the goods consumption occurs up to the point where marginal benefits equal marginal costs.

Willingness to pay (WTP) or Hicksian compensating variation is defined as below.

$$v(p^0, Q^0, y - c) = v(p^1, Q^1, y) \qquad (2.19)$$

where *v*: indirect utility function, p: price of the good or service, Q: quality of the good or service, with Q^0 current quality and $Q^0 > Q^1$ where condition 1 denotes deteriorating quality if the protection program is not implemented and c is the WTP to maintain the indirect utility the same. CV study measures the quality or quantity change of the goods to be valued. This model is evaluating the level of the utility difference from the current condition and the condition when new policy is implemented. In this formulation, the policy is to maintain the current status, so $Q^0 > Q^1$. In order to keep the current (better) environment, one should pay amount of c (WTP) from his or her income. That utility is the same as when the environment gets worse; but the total income is higher by c. Keeping more money to one's own pocket, one should tolerate the worsened environmental condition that may impose. Step-by-step procedures are following.

Step 0 [Define the valuation problem: identify the quantity or quality change to be valued]: What services are being valued and who are the relevant population should be determined.

*Step 1 [Decision about the survey]***:** The second step is to make preliminary decisions about the survey itself, including but not limited to whether it will be conducted by mail, phone or in person, how large the sample size will be, who will be surveyed.

Step 2 [Survey Design]: The next step is the actual survey design. This is the most important and difficult part of the process. It is accomplished in several steps. The survey design process usually starts with initial interviews and/or focus groups with the types of people who will be receiving the final survey. In the initial focus groups, the researchers would ask general questions, including questions about public understanding of the issues related to the site, whether they are familiar with the site and its wildlife, whether and how they value this site and the habitat services it provides. In later focus groups, the questions would get more detailed and specific, to help develop specific questions for the survey, as well as decide what kind of background information is needed and how to present it.

<u>Deriving WTP values using different questionnaire formats:</u> The most common formats of surveys are 1) open ended questions, 2) the payment card method, and 3) dichotomous choice questions. Sequential bids are also available but the results are easily biased by the starting point (Boyd, 2006). Here, we are considering open ended, payment card method, and dichotomous choice questions and the detailed analysis methodology is provided in *Step 4*.

*Step 3 [Survey implementation]***:** The next step is the actual survey implementation. The first task is to select the survey sample. Ideally, the sample should be a randomly selected sample of the relevant population, using standard statistical sampling methods. They would then use a standard repeat-mailing and reminder method, in order to get the greatest possible response rate for the survey. Telephone surveys can be carried out in a similar way, with a certain number of calls to try to reach the selected respondents.

Step 4[Compilation and analysis of the results]: The next step is to compile, analyze and report the results. The data must be entered and analyzed using statistical techniques appropriate for the type of question. Methodologies for three different types of survey questionnaire are explained below.

1) Open ended questions

In the open ended question format, respondents are asked to state their highest amount of money they are willing to pay if the policy is implemented. But Loomis (1988) mentions that this is not really the way that respondents make decisions in real market where the price is specified first then the respondents make decision whether they will purchase or not. Also, there may be a problem of non-response.

Typically, arithmetic mean is adopted to calculate WTP.

$$\bar{x} = \frac{\sum_{i}^{n} x_i}{n} \qquad (2.20)$$

Where, x_i: open-ended response for the i^{th} respondent, n: the number of respondents, x_i corresponds to individual WTP which corresponds to *c* in the indirect utility function or the Hicksian compensation.

2) Payment-card data analysis

The payment card method is to show various cards that contain specific amounts of bids and ask them to choose the largest amount they are willing to pay. But the problem is the range of values used on the payment card, anchoring effects (the final bid at the end of the iterations are significantly influenced by the starting bid given to the respondents), and size of intervals displayed on the card.

Respondents' true value (c_i) is located in the interval ($\$B_{li}$, $\$B_{ui}$) where l: nearest lower bid that respondent i circled, u: nearest upper bid amount on payment card. So, the true value can be expressed as

$$\log c_i = z_i^{'}\beta + \varepsilon_i \qquad (2.21)$$

Where ε_i: random error which is assumed to be normally distributed with mean 0 and standard deviation of σ. z_i: vector of variables that explain variation in responses to the valuation questions, and β: vector of coefficients to be estimated. The probability that c_i is between the interval on the payment card that respondent i chose is

$$\Pr(c_i \subseteq (\$B_{li}, \$B_{ui})) = \Pr((\log \$B_{li} - z_i^{'}\beta)/\sigma) < t_i < \Pr((\log \$B_{ui} - z_i^{'}\beta)/\sigma) \qquad (2.22)$$

where t_i:standard normal variable. The joint probability density function for n independent observations can be interpreted as a likelihood function defined over the unknown parameters β and σ : Log likelihood function for a sample size n can be written as,

$$\log L(\beta, \sigma \mid \$B_{li}, \$B_{ui}, z_i) = \sum_{i=1}^{n} \log[\phi(\$B_{ui}) - \phi(\$B_{li})] \qquad (2.23)$$

where ϕ: normal cumulative distribution function. By estimating the coefficient parameter $\hat{\beta}$, WTP can be derived. It should be noted that exp (z_i'β) will be the median of the distribution c rather than mean as it is following log-normal distribution (Cameron, 1987). The mean for the untransformed c can be obtained as below by scaling the median by an estimated constant $\exp(\frac{\hat{\sigma}^2}{2})$.

$$E(\log c) = z'\hat{\beta} \text{ or } E(c) = \exp(z'\hat{\beta})\exp(\frac{\hat{\sigma}^2}{2}) \qquad (2.24)$$

Mean WTP is the most relevant welfare measure with regard to cost-benefit analysis but median WTP is sometimes the preferred measure, too (Hanemann 1984). As known, mean is very sensitive to the outliers and this may results in poor WTP curve from logistic regression. But median WTP may not be a valid estimate of the average amount that people are willing to pay unless the distribution is symmetric.

3) Dichotomous choice data analysis

In dichotomous choice question, respondents are asked to answer ‘yes’ or ‘no’ to the amount of money whether they are willing to pay for the new policy. It is simply the take it or leave it. The initial amount asked to the respondents varies. From Buckland (1999), CV method using dichotomous choice is considered to be the most promising approach to perform the welfare measures such as WTP

As offered amount is varying across the respondents, the yes/no responses convey information about σ (Cameron 1987).

$$\begin{aligned}\Pr(YES_i) &= \Pr(\log c_i > \log \$B_i) = \Pr(\frac{u_i}{\sigma} > \frac{\log \$B_i - z'\beta}{\sigma}) \\ &= 1 - \phi(\frac{\log \$B_i - z_i'\beta}{\sigma})\end{aligned} \quad (2.25)$$

So, the log likelihood function is

$$\log L = \sum_{i=1}^{n} \{I_i \log[1 - \phi(\frac{\log \$B_i - z_i'\beta}{\sigma})] + (1 - I_i)\log[\phi(\frac{\log \$B_i - z_i'\beta}{\sigma})]\} \quad (2.26)$$

where $I_i = \begin{cases} 1 \text{ if respondent answered yes,} \\ 0 \text{ if respondent answered no.} \end{cases}$

The mean and median calculation follows payment-card data methods.

Step 5 [Use of the results]: From the analysis, the researchers can estimate the average value for an individual or household in the sample, and extrapolate this to the relevant population in order to calculate the total benefits from the site.

In this section, different preference elicitation tools were discussed in step-wise manner. They have been widely adopted in marketing (CA), decision analysis (AHP), and non-market valuations (CV). In collaboration with a faculty and graduate students from the Agricultural and Economics Department at Virginia Tech, we are applying these preference elicitation tools to empirical surveys (sections 5.2 and 5.3) to gage homeowner's preferences towards plumbing materials and attributes. In this dissertation, however, the focus is on AHP. We will be able to compare the results from each method as a future research. Theoretical backgrounds are explained in next section to further understand these methods.

5.1.4 Discussions on Theories

In this section, we are comparing three preference elicitation tools. Both AHP and CA are based on attributes; so both methods have largely been applied to multiattribute optimization problem. In this sense, AHP and CA can be compared. On the other hand, CV and CA have same root as utility-based models. So, CV and CA can be compared. So, CA has both attribute based and utility based characteristics. Figure 2.7 is showing the overall relationships (Boyle, 2007).

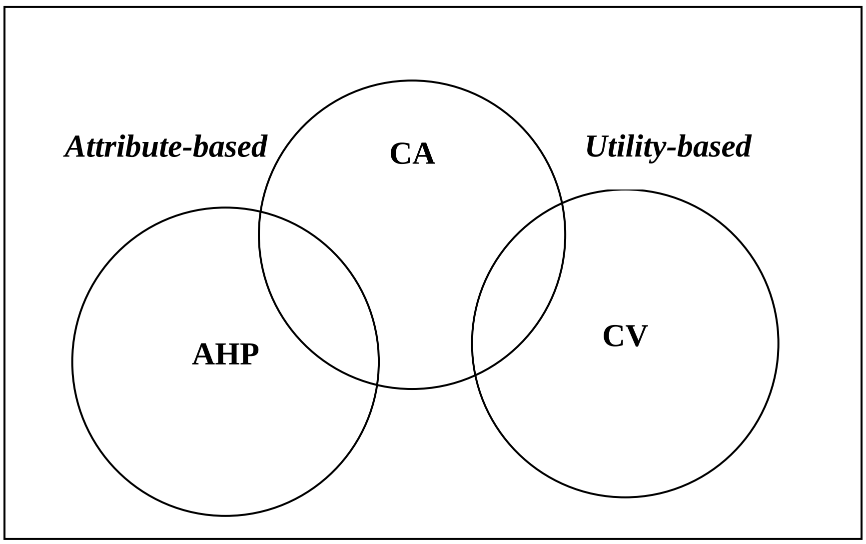


Figure 2.7 Relationships between each method

As explained, CA uses additive part-worth utility model and AHP is using the weighted additive utility model. The distinct difference between CA and AHP is the analysis procedure. CA obtains the part-worth utilities from the stimulus response. In this sense, CA is *decompositional approach*. In other words, CA estimates the structure of the consumer's preferences once the assessment of the stimulus is specified for levels of different attributes. On the other hand, AHP starts from lower level of attributes and aggregate the values into final ranking of each attribute or goods; so this is *compositional approach*. The total utility of an alternative is computed by an additive value function summing up the weighted utilities of its attribute levels. The CA respondent's input is usually ordinal or interval scales (for dependent variable) and AHP users input the ratio scale (say, w_i/w_j). In other words, respondents are filling in the matrix with their degree of preference for one over the other (w_i/w_j); on the other hand, CA analysts calculate the part-worth values (β) from the rating scales for the stimulus. In this sense, the MRS (Marginal Rate of Substitution: the two attribute k and m defined as the ration of two parameter estimates) from CA parallels the weight that AHP users fill in (see Figure 2.8). According to Scholl et. al (2005), AHP can have 7-8 alternatives or attributes levels while CA can have up to 6 attributes with 2-4 levels. AHP require many simple comparison questions whereas the number of questions for CA is relatively small but the questions are relatively more complex.

	Attrb. 1	**Attrb. 2**	**…**	**Attrb. n**
Attrb. 1	$\frac{w_1}{w_1}$	$\frac{w_1}{w_2}$	…	$\frac{w_1}{w_n}$
Attrb. 2	$\frac{w_2}{w_1}$	$\frac{w_2}{w_2}$	…	$\frac{w_2}{w_n}$
…	…	…	…	…
Attrb. n	$\frac{w_n}{w_1}$	$\frac{w_n}{w_2}$	…	$\frac{w_n}{w_n}$

AHP

$$Y_i = \beta_1 + \beta_2 X_{2i} + \ldots + \beta_k X_{ki} + u_i$$

$$\text{MRS} = \frac{\beta_k}{\beta_m}$$

CA

Figure 2.8 Comparison of AHP and CA

Comparing several attributes simultaneously is complicated. AHP is comparing only two attributes at a time without thinking about other factors. So this mechanism helps the decision maker to concentrate on their decision more carefully. But it should be noted that elicited preferences may be based on the standards already established in memory through a person's experience or education. Of course, this caution should be advised to all three methods (AHP, CV, and CA). Also, there is a consistency check in AHP. If the consistency check fails, the respondents are usually advised to do the procedure again even though AHP take into account the difficulty of giving precise preference judgments. This might be a lengthy procedure for both analysts and decision makers when the consistency fails.

To compare the CA and CV, it is necessary that both methods have the specific formats to convey the same information. Also, Random Utility Model (RUM) model should be used. Below formulation follows Stevens et al. (2000). CA is formulated for the rating scale that asks respondents to rate the current situation and after the implementation of the policy.

$$R_1=h(U_1), \text{ and } R_0=h(U0),$$

R_1 and R_0: respondent's ratings, h: transformation functions. Then, utility difference dV can be written as $dV = R_1 - R_0 = U(D_1, Y-N) - U(D_0, Y) + e_1 - e_0$, where D_0: vector of attributes for the status quo situation, D_1: vector of attributes of goods, and e: random variable,

To be compatible with CA, dichotomous choice model of CV is employed. We can express the value of utility when amount \$N is spent, $U_1 = U(D_1, Y-N) + e_1$. The utility when \$ N is not spent is $U_0 = U(D_0, Y) + e_0$. So, when the respondents decided to pay, the utility for U_1 should be larger or equal to U_0, that is, $U_1 \geq U_0$. Utility difference can be written as $dU = U_1 - U_0$. So, $dU = U(D_1, Y-N) - U(D_0, Y) + e_1 - e_0$, where the utility is assumed to be linear, additive, and independent with income and attributes. The WTP probability is Pr=G (dU), where G is the probability function for the random component $e_1 - e_0$. Assuming logit probability function for G, WTP probability can be written as $\Pr = \frac{1}{1+e^{-dU}}$. Median WTP for the improvement which is $D_1 - D_0$ can be obtained when $dU=0$; this point is the *indifference point* where there is 50% chance that individual will pay the amount. With the formulation above, Hicksian surplus estimates (WTP or c value) are provided for both CA and CV, so they can be compared from utility point of view.

There are few previous studies comparing CA and CV, but empirical studies have shown that WTP estimates are markedly different (Boxall et al., 1996, Magat et al., 1988, and Stevens et al., 2000). It is generally agreed that CA is offering more conceptual advantages to respondents than CV (especially in environmental program valuations) (Boxall et al., 1996), but CA should also be approached with caution. More research is needed to fill these gaps.

5.2 Application of AHP Surveys to Engineering Students

AHP surveys were administered to civil engineering sophomore and junior students at Virginia Tech during November 2006. This survey module is attached in Appendix II-A. To provide motivation for the survey, we gave a 20-minute presentation regarding drinking water infrastructure problems from both engineering and economics viewpoints. The names of the materials were not disclosed in the survey to prevent students' previous experience with their plumbing materials from biasing their preferences for attributes and materials. It is noted that almost none of the students own their homes, so the results may not reflect the true decisions of homeowners.

A total of 135 students took the AHP survey of which 19 surveys were incomplete so 116 surveys were analyzed. Among 116 surveys, 26 students passed strict consistency test [CI/RI < 0.1]. If we relax strict consistency ratio to 0.15, another 25 students passed the less restrictive test. Here it is assumed that 51 students' results are reliable. Table 2.19 contains the attribute ranking for 10 sampled students who passed the consistency test (among 51 students). The last column (Avg. 51) indicates 51 students' average ranking of the attributes. Students rank health effects the highest, followed by taste and odor, corrosion resistance, longevity, and price. Resale value and fire resistance ranked lowest on the list. The final ranking of the materials A, B, and C is shown in Table 2.20. All 10 students rated Material C highest.

Table 2.19 Students ranking of attributes

Student Number / Attribute	Importance of attributes for each student										Average of 51 students
	3	6	13	26	33	45	46	49	52	55	
P	0.03	0.04	0.04	0.04	0.03	0.11	0.04	0.07	0.03	0.04	**0.06**
C	0.07	0.06	0.09	0.17	0.08	0.06	0.24	0.05	0.10	0.10	**0.11**
F	0.08	0.22	0.04	0.06	0.03	0.04	0.09	0.02	0.07	0.07	**0.07**
H	0.37	0.39	0.31	0.32	0.35	0.33	0.28	0.41	0.44	0.39	**0.36**
L	0.11	0.17	0.15	0.19	0.14	0.07	0.27	0.11	0.10	0.11	**0.12**
R	0.11	0.09	0.06	0.11	0.13	0.05	0.03	0.09	0.07	0.13	**0.09**
T	0.23	0.03	0.32	0.10	0.25	0.33	0.05	0.25	0.19	0.16	**0.18**

(P: price, C: corrosion resistance, F: fire retardance, H: health effects, L: longevity, R: resale value of home, and T: taste and odor)

Table 2.20 Final ranking of the materials

Student Number / Materials	Importance of materials for each student										Average of 51 students
	3	6	13	26	33	45	46	49	52	55	
A	0.26	0.30	0.14	0.29	0.13	0.18	0.24	0.20	0.16	0.20	0.22
B	0.19	0.21	0.20	0.20	0.15	0.32	0.13	0.18	0.25	0.21	0.24
C	0.55	0.49	0.66	0.51	0.72	0.50	0.63	0.63	0.59	0.59	0.54

Out of 51 students who passed the consistency test, 43 students' results revealed that health impacts is their top-priority attribute followed by taste and odor (4 students), price (2 students), corrosion resistance (1 student), and resale values of home (1 student). The overall average rankings of attributes from 51 students show that health effects, taste and odor, longevity, and corrosion resistance are the dominant factors. In addition, 45 students (out of 51 students who passed consistency test) chose material C as their first options followed by Material B (4 students) and Material A (2 students). Table 2.8 contains the plumbing material information that we provided to the students. These results indicate that health, and taste and odor may be surrogates for the purity of water that dominates preferences for a plumbing material. The manner and the type of information provided to the participants are important in preference changes.

To check the validity of AHP, we adopted the reference methods in the survey. At the end of the survey, we asked students to directly rank each material. Comparing their direct selection and AHP results (i.e. reference methods), 33 out of 51 students' first material choices were the same. The correlation coefficient between AHP-computed rank and direct selection showed that for 19 students the correlation coefficient was 1, which indicates complete matching between direct and AHP ranks. Twenty students got a coefficient of 0.5, which means 2 out of 3 materials were identically ranked. As the problem becomes more complex, pair-wise type preference elicitation tools should be beneficial in making a rational decision.

5. 3 Homeowner Survey of Pinhole Leak Prone Area

Based on the experience gained from engineering student's survey, a mail survey was developed for selected homeowners in a Southeastern community which had experienced unusually high rate of pinhole leak incidents in their community. Copper pinhole leak experts in Virginia Tech (Drs. Scardina and Edwards) had been working for these communities and we were introduced to the representatives of the community for our research. Engineering student survey instruments were updated to fit their particular circumstances. This survey module is geared towards real homeowner groups who will have higher motivation in selecting survey alternatives compared to students. We had several field trips to the community and had meetings with pinhole leak committee composed of 4 homeowners with extensive knowledge and experience on these issues and Property Owner Association (POA). We learned about homeowners' attitudes and experiences regarding drinking water and overall home plumbing system. Also, we tried to learn more about consumer concerns related to their home drinking water and water supply system in pipe failure prone area. More details on methodology and survey design are explained in the following sections.

5.3.1 Background

The southeastern community was founded in 1980's and approximately 4,700 acres in size and is close a river. There are about 3,300 homes including condos and apartments; and a total of 6,600 residents. Most of the residents are retired people. The first copper-pipe home plumbing failure occurred in 2001. Water quality changes turned out to be the culprit for high rates of leaks. Even 6 year-old houses have suffered leaks. Ninety-five percent of the leaks were in cold water pipes and builders used copper pipes from the same suppliers. In this community, water is provided through two utilities.

In year 2006, there was a switch from Utility 1 to Utility 2. The switch caused problems mainly because of the differences in water qualities such as chlorine level, hardness, and pH. Detailed information on water quality can be found in Scardina and Edwards (2007). Contrary to affected home plumbing systems (minor systems), utilities' major system did not have a leak problem because they are using different piping materials (mainly iron pipes). According to the recommendations from Drs. Scardina and Edwards from Virginia Tech, Utility 2 added corrosion inhibitor (phosphate) to water treating process (after April of 2006); and the number of newly reported leaks has decreased so far (Martin et al., 2007).

The affected homeowners in this community had three alternatives i) repairing the leak, ii) doing a complete replacement of existing plumbing system, and iii) coating the existing pipe system with epoxy. When they make a decision, they had to balance the risk of possible future leaks that might cause another damages to homes and personal belongings vs. the cost of a replumb or relining. So, their information sources were from other homeowners or plumbers who have had leaks recently and experienced repair, epoxy coating, or replumbed with other alternatives (PEX, CPVC). As mentioned, utilities took actions by adding corrosion inhibitors to reduce the leaks at home. If a certain period of warranty from replumbing or epoxy coating is guaranteed, their decision was based on the *cost* in addition to the repair of collateral damages to the home and furnishings due to replumb or relining operations.

Some community residents have been taking several additional actions such as i) *preventive replumbing*, which was even done by those who did not experience any leaks in their houses (after seeing what happened to their neighbors), ii) applied epoxy coating with or without leak experiences, iii) inline injection of phosphate (corrosion inhibitor) into home water systems, and iv) water softener or water conditioning systems.

5.3.2 Methodology and Survey Design

A *two-phase survey approach* was used to understand *homeowner's concerns, attitudes, and experiences* in pinhole leak prone area regarding drinking water and home plumbing system. In phase I, the survey instrument was designed to gather a wide variety of information about the nature of pinhole leaks, costs in addressing the problems, and their experiences in dealing with the problems. Socioeconomic data were included at the end of the survey. Also, Conjoint Analysis and Contingent Valuation problems (1 problem each) were included to compare the nature of preference elicitation tools. Specifically, 1st phase survey module includes items such as pipe materials, failed locations, whether they repair/replaced the systems, what alternatives they chose after a leak incident, and any preventive actions (if they had taken any). Time spent to deal with these issues, level of stress, level of concern for future possible leaks were also included in the module.

In Phase II, the focus was mainly on comparing AHP and CA. To reduce the sequence bias, half of the surveys had CA questions first and the other half of the survey had AHP questions first. The decision making processes (replacing plumbing systems) of residents' coping with leak incidents are compared with real decisions from Phase I survey. Survey designs are explained in next section. As mentioned, engineering student surveys were used as a pre-test to asses the time, length, difficulty, and contents which are required to complete all surveys. The survey modules excluded the bias from previous personal experiences. The surveys themselves could be administered in mail format. In addition, the instrument was pre-tested with a property owner association in the affected community, and 3 faculty members from Civil Engineering in Virginia Tech who have extensive knowledge and experiences.

Revealed Preference Survey

A mail survey was implemented to the community residents in July 2007. Selected total sample size that we could contact by regular mail was 1,600. We followed the standard mail survey techniques (Dillman, 2000). The basic steps are;

Step i) questionnaire survey is included in the mail with postage-paid return envelope,

Step ii) send a reminder card, and

Step iii) for those who had not responded to the first survey, send a second copy of the survey.

We received total of 1,047 responses (65% response rate). Usual successful response rate in survey is known to be around 20-25% (Boyle, 2007). This unusually high response rate shows that community residents are interested and serious regarding these issues. The 1st phase survey module is attached in Appendix II-B.

Stated Preference Survey

In the second phase of the survey, AHP and CA were applied to those who were willing to be contacted again. As mentioned, only AHP results are reported in this dissertation. CA work is conducted by a Ph.D. student in Agricultural and Economics Department. The survey module is included in Appendix II-C. To average out any bias, 6 different sets of randomized surveys were used.

From Phase I, we received 1,047 respondents and 400 respondents were willing to be contacted again for further questionnaire. Using the similar steps (Dillman, 200), we sent 400 surveys and received 250 surveys back (63%). In this phase, we wanted to understand homeowner's decision making process in the choices of home drinking water plumbing systems and materials. As emphasized earlier, plumbing materials have various important implications for costs, reliability, aesthetics, taste and odor, and health impacts of drinking water. The main purpose of the survey was to elicit preferences for home drinking water plumbing attributes and materials. In engineering student survey, we used 7 different attributes namely, costs (labor + material), reliability, aesthetics, taste and odor, and health impacts and three plumbing materials; Copper, Plastic, and Stainless Steel. To be more realistic to the respondents in the community, the listed attributes and alternative materials were changed. The maximum attribute number of 7 was in order not to confuse or put mental burden on the respondents. After personal communications with the homeowner association committees and pinhole leak experts, we developed the most important and relevant criteria; corrosion, taste and odor of drinking water, health effects, convenience of installation, proven performance in the market, cost (labor + material), and manufacture warranty. Also we considered materials copper, PEX, and Epoxy Coating which corresponds to their existing real alternatives. The given information is shown in Table 2.21. Material A, B, and C corresponds to Epoxy coating, PEX, and copper respectively. The material names were not disclosed so the respondents are not biased by their previous experiences.

- Corrosion resistance—ability of the material to resist corrosion.
- Taste/odor—effect of the material on the taste or odor of drinking water.
- Health—possible health effects of the material on those who consume drinking water.
- Convenience of installation—ease of installing the plumbing material in the home.
- Proven performance in market—time the plumbing material has been successfully used in the market.
- Cost (material and labor)—material and labor cost to install the plumbing material in the home.
- Warranty—length of time the plumbing material is guaranteed against failure.

Table 2.21 Updated messages for Southeastern US community survey module

	Material A	Material B	Material C
Corrosion Resistance	Corrosion proof	Corrosion proof	Some risk of corrosion
Taste / Odor	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water.	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water.	Compounds released from this material in drinking water plumbing may give a bitter or metallic taste or odor to the water.
Health Effects	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may lead to microbial growth in water. Microbial growth may cause severe illness.	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may lead to microbial growth in water. Microbial growth may cause severe illness.	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may cause vomiting, diarrhea, stomach cramps, and nausea.
Convenience of Installation	No need to tear into the wall and/or floor. Installation takes around 4 days.	Need to tear into some sections of wall for installation. Installation takes 5-6 days.	Need to tear into the wall and/or floor to replace the existing system. 7-9 days required for installation.
Proven Performance in Market	Less than 10 years in the market.	Less than 20 years in the market.	More than 50 years in the market.
Cost (labor + material)	\$9,000 ~ 14,000 depending on the size of house.	\$6,500 ~ 13,000 depending on the size of house.	\$9,000 ~ 16,000 depending on the size of house.
Warranty	Warranty is 15 years for the material.	Warranty is 10 years for the material.	50 years manufacturer's warranty. Some exceptions apply, e.g. warranty reduces to one year if compounds in water corrode pipes.

Instead of following standard numerical scores, a shortened version of score values was adopted (see Table 2.22) so as not to confuse the community residents, detailed mathematical approaches were avoided. Also, in engineering student survey, AHP problem was presented in a matrix form but in the community survey, a simple comparison format was used so they can easily choose their pair-wise preference levels. This applies to both attribute and material comparison.

Table 2.22 Standard numerical scores

Preference Level	Score
Equally preferred	1
Moderately preferred	3
Strongly preferred	5
Very strongly preferred	7
Extremely preferred	9

Cost (material + labor)					Health			
9	7	5	3	1	3	5	7	9
Convenience of installation					Taste/Odor			
9	7	5	3	1	3	5	7	9

V. Convenience of installation
The following question asks you to compare three options for convenience of installation.

Option A	No need to tear into the wall and/or floor. Installation takes around 4 days.
Option B	Need to tear into some sections of wall for installation. Installation takes 5-6 days.
Option C	Need to tear into the wall and/or floor to replace the existing system. 7-9 days required for installation.

Comparison (a) Please circle the number to show your preference for option A or B.

Option A					Option B			
9	7	5	3	1	3	5	7	9

Comparison (b) Please circle the number to show your preference for option B or C

Option B					Option C			
9	7	5	3	1	3	5	7	9

Comparison (c) Please circle the number to show your preference for option C or A

Option C					Option A			
9	7	5	3	1	3	5	7	9

Figure 2.9 Example of AHP questionnaire in updated survey module

5.3.3 Results

Revealed Preferences for Community Residents

In this section, important aspects of survey results relevant to the scope of this study are included. For complete survey results, refer to Bosch et al. (2008). Out of 1,047 respondents, 212 respondents (20%) reported incidents of pinhole leaks in their potable plumbing systems; 780 respondents (74%) reported no experience of leak incidents in their houses; and 32 respondents (3.2%) reported do not know. One hundred and twenty eight respondents (60%) of the respondents with leaks had experienced 1 or 2 leaks; 47 respondents (22%) had 3 or 4 leaks; and 33 respondents (15%) reported more than 5 leak incidents.

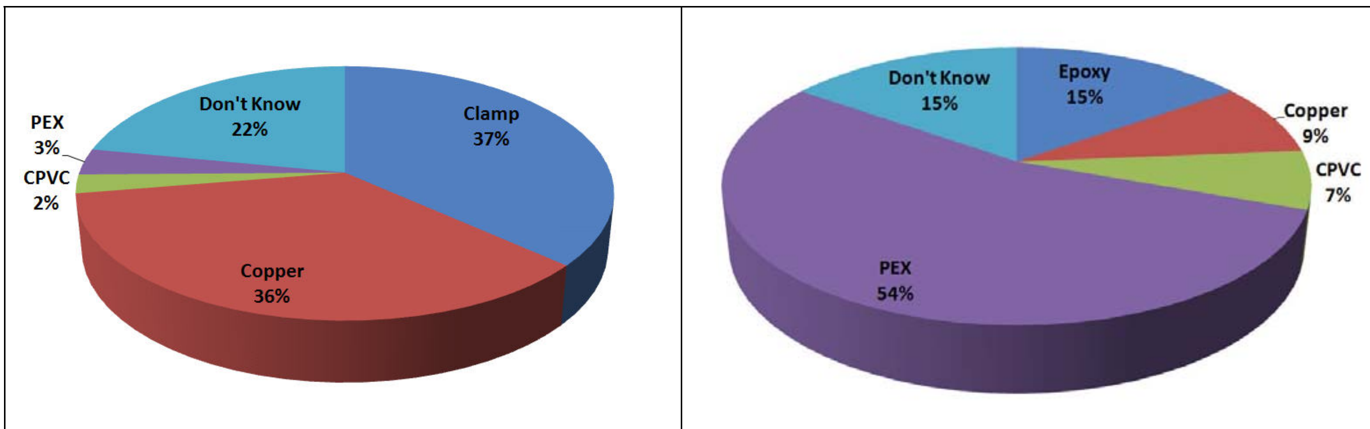
Seventy-seven respondents repaired the leak using a clamp (Table 2.23). It is likely that a clamp was used initially before leaking sections were replaced or replumbed for the whole house. One hundred thirty-three respondents repaired the leak by replacing the leaking pipe section. Copper was most often used. Fifty respondents repaired the leak by *replumbing the entire house*. PEX was most often used (32 respondents) for replumbing followed by Epoxy coating (9 respondents). Five respondents replumbed with copper (same or thicker pipes) and 4 respondents did replumb with CPVC.

Table 2.24 lists the cost of repairing pinhole leaks. Twenty-nine percent of respondents with leaks reported that the expense of repairing pinhole leaks was less than $100; while 30% reported expenses between $100 and $500; and 37% reported more than $500 in expenses for pinhole leak repairs. Seven respondents reported more than $10,000 in costs of repairs. This figure possibly includes replumbing the whole house. Property damage cost due to pinhole leaks are shown in Table 2.25. Ninety-two percent of respondents with leaks reported having to repair property damage caused by leaks in addition to the expense of repairing leaks. Forty percent of respondents with damage reported less than $100 of damage while 49% had over $100 in damage. Twelve respondents had over $5,000 in property damage.

Table 2.23 Method of Leak Repair

Repair method	Number of observations	Percent[a]
Clamp over leak	77	7
Replaced leaking pipe section with copper	75	35
Replaced leaking pipe section with CPVC	5	2
Replaced leaking pipe section with PEX	7	3
Replaced leaking pipe section-material not specified	46	22
Applied coating of Epoxy to all plumbing	9	4
Replumbed with copper	5	2
Replumbed with CPVC	4	2
Replumbed with PEX	32	15
Replumbed-material not specified	9	4
Other	7	1
Don't know	3	1
Total	279	129

[a]Multiple choices per respondent were accepted. Percent = number reported divided by the total number of respondents with leaks (212).



(a) Repaired only failed sections
[out of 210 households]

(b) Replumbed whole plumbing system
[out of 59 households]

Figure 2.10 (a) Revealed preferences for those who repaired (b) Revealed preferences for those who replumbed

Table 2.24 Costs of Repairing Pinhole Leaks

Amount	Number of observations	Percent[a]
Less than $100	61	29
$100 to $500	64	30
$501 to $1,000	14	7
$1,001 to $3,000	11	5
$3,001 to $5,000	20	9
$5,001 to $10,000	28	13
$10,001 to $20,000	6	3
More than $20,000	1	0
Do not know	3	1
Missing/not reported	4	2
Total	212	99

Table 2.25 Costs of Repairing Property Damage from Pinhole Leaks

Amount	Number of observations	Percent[a]
Less than $100	85	40
$100 to $500	47	22
$501 to $1,000	16	8
$1,001 to $3,000	18	8
$3,001 to $5,000	10	5
$5,001 to $10,000	12	6
More than $10,000	0	0
Do not know	8	4
No property damage	16	8
Total	212	101
[a]Totals do not sum to 100 due to rounding.		

In Table 2.26, prevention device is shown for respondents with pinhole leaks and without pinhole leak experiences. Thirty-five percent of respondents with leaks and 20% of respondents without leaks use some type of pinhole leak prevention strategy. It is clear that those who experienced leaks are more prone to invest in prevention devices to prevent possible future leaks. Preventive replumbing turned out to be the most dominant among those with leaks. In contrast, water softener/conditioner was the most common strategy used by those without leaks, which was used by 9% of those respondents.

In Table 2.27, water treatment usage for purposes other than corrosion prevention is shown. About 63 % of respondents use refrigerator filter for purposes other than pinhole leak prevention followed by thirty-two percent of respondents who purchase drinking water. The most common reasons given for using water treatment devices are to improve taste or smell of drinking water (mentioned by 45% of respondents) and to improve safety of drinking water (mentioned by 33% of respondents).

Table 2.26 Use of Pinhole Leak Prevention Devices

	Respondents with pinhole leaks[a]		Respondents without pinhole leaks[b]	
	Number	Percent	Number	Percent
Preventive replumbing	28	13	16	2
Preventive epoxy injection	8	4	4	0
Phosphate injection	12	6	26	3
Water softener/water conditioner	11	5	79	9
Copper Knight	5	2	12	1
Other	19	9	64	8
None used	134	63	644	77
Missing/not reported	4	2	29	3
Total	295	139	874	105

[a]Multiple choices per respondent were accepted. Percent = number reported divided by the total number of respondents with leaks (212).
[b] Percent = number reported divided by the total number of respondents without leaks (835).

Table 2.27 Use of Water Treatment for Purposes other than Corrosion Prevention

	Number	Percent [a]
Filter for entire home	133	16
Refrigerator filter	523	63
Water softener/water conditioner	66	8
Pitcher or bottle to filter water	136	16
Purchased drinking water	265	32
Filter on faucet or under kitchen sink	117	14
Ultra violet (UV) system	2	0
Other	25	3
None used	249	30
Missing/not reported	19	2
Total	1,535	184

[a]Multiple choices per respondent were accepted. Percent = number reported divided by the total number of respondents (1,047).

Stated Preferences (AHP results) for Community Residents

Among 250 surveys received, 133 respondents passed the consistency test (CI/RI of 0.2). As was done for engineering student survey, these 133 results are assumed to be reliable. Mean attribute results for 133 respondents (from AHP) are shown in Figure 2.11. These values are parallel to the part-worth values in CA. It is seen that health effect and taste/ odor are the two important factors in deciding on the plumbing materials. Corrosion resistance and proven performance in the market constitute the next set of important attributes. Cost and convenience of installation seems to be the least important factor. It is interesting to see that cost is not highly dominant factor for homeowners. This is partly due to the similar cost ranges listed in the given information. In real life, cost figure may become major factors if there is a large difference among alternatives.

To see the preference difference between those who have leak experiences and no experiences, 133 respondents' are broken down into two groups; with leaks (28 respondents) and without leak experiences (105 respondents). As seen in Figures 2.12 (a) and (b), there is little difference in between each group. Majority of respondents regarded health and taste of odor as their major decision factors.

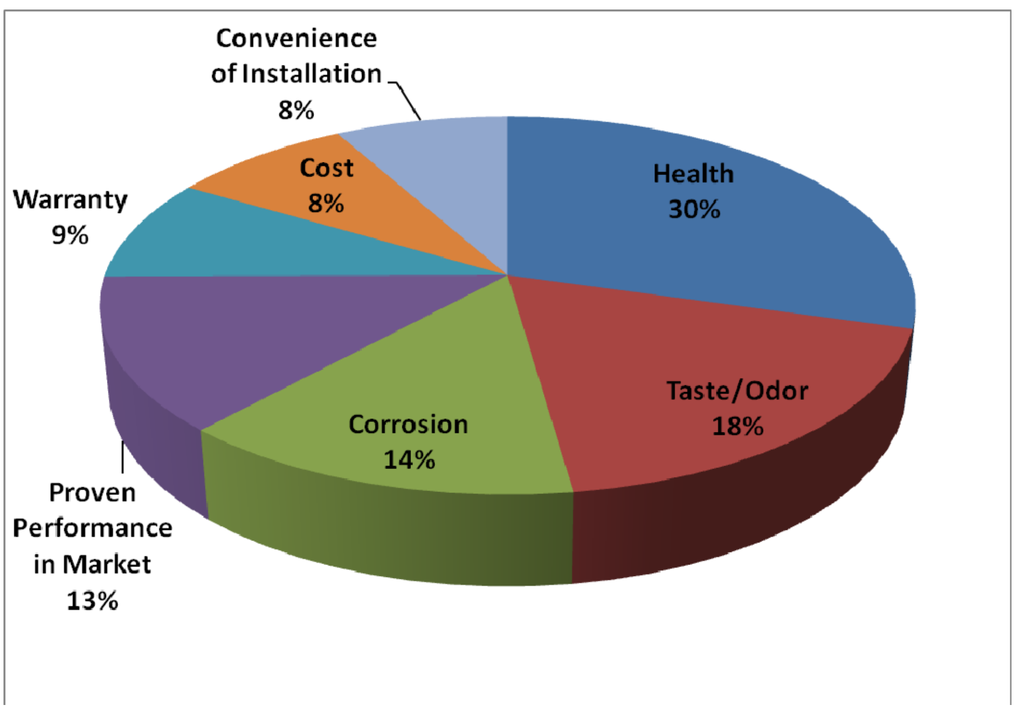


Figure 2.11 Importance of attributes from AHP (average stated preferences for 133 respondents)

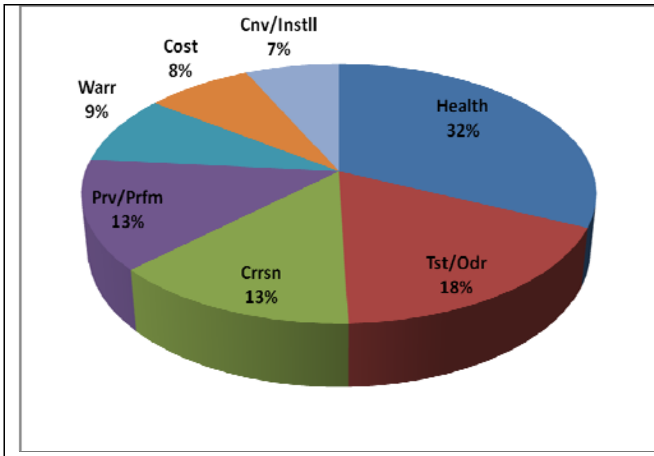
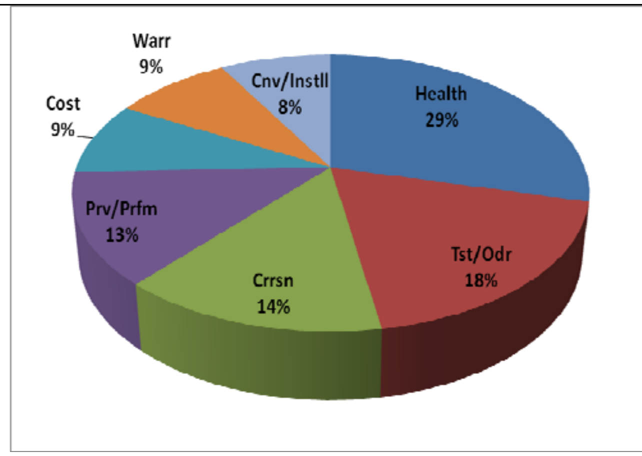
	
Importance of attributes from AHP with Leak experiences (28 respondents)	**Importance of attributes from AHP without leak experience (105 people)**

Figure 2.12 (a) Importance of attributes from AHP with leak experience (b) Importance of attributes from AHP without leak experience

Table 2.28 includes the final material ranking for those who passed the consistency test. We used modal values for 130 respondents. Most of the respondents chose Material A followed by B and C.

Table 2.28 Material ranking

Material	Rank
A (Epoxy coating)	1
B (PEX)	2
C (Copper)	3

5.3.4 Comparison between Revealed Preferences and Stated Preferences

Among 250 returned surveys, 133 respondents are turned out to be the reliable data set (CI/RI of 0.2). Hundred and twenty data sets are unfinished or finished but consistency test failed. To compare revealed and stated preferences, we link 133 respondents' AHP results with revealed preferences surveys. Out of 133 respondents, we found out that 28 households had experienced pinhole leak incidents. Hundred and five households had not experienced any leak incidents in their plumbing system. For 28 households who had experienced leak incidents, their original pipe materials were all copper before they had any leaks.

Among 28 homeowners, 7 households did replumb their whole plumbing systems and 21 households repaired the failed section with clamp (3 households), copper (7 households), or not specified (10 households) in the surveys. Table 2.29 shows the real actions and AHP results for those who replumbed after leak incidents. For example, respondent # 1,310 replumbed with Epoxy coating in real life; and AHP result (revealed preferences; 3rd column) is Epoxy coating. Their real actions are corresponding to the AHP's decision results. Likewise, respondent1,301's real replumb choice was PEX and AHP decision result are matching. However, 1,322's AHP results are Epoxy; real actions were with thicker copper pipes. Forty three percent of respondents are corresponding (revealed preferences are the same as stated) and 57% are not (see Figure 1.12).

Table 2.29 Preference of those who replumbed after leak incidents

Respondent Number	Revealed preferences (Real actions)	Stated preferences (AHP)
1,301*	PEX	PEX
1,310	Epoxy coating	Epoxy coating
1,314	Epoxy coating	Epoxy coating
1,322	Thicker copper	Epoxy coating
1,295	Copper	PEX
1,127	PEX	Epoxy coating
1,730	PEX	Epoxy coating

*highlighted part indicates indivdiduals who had same revealed and stated preferences

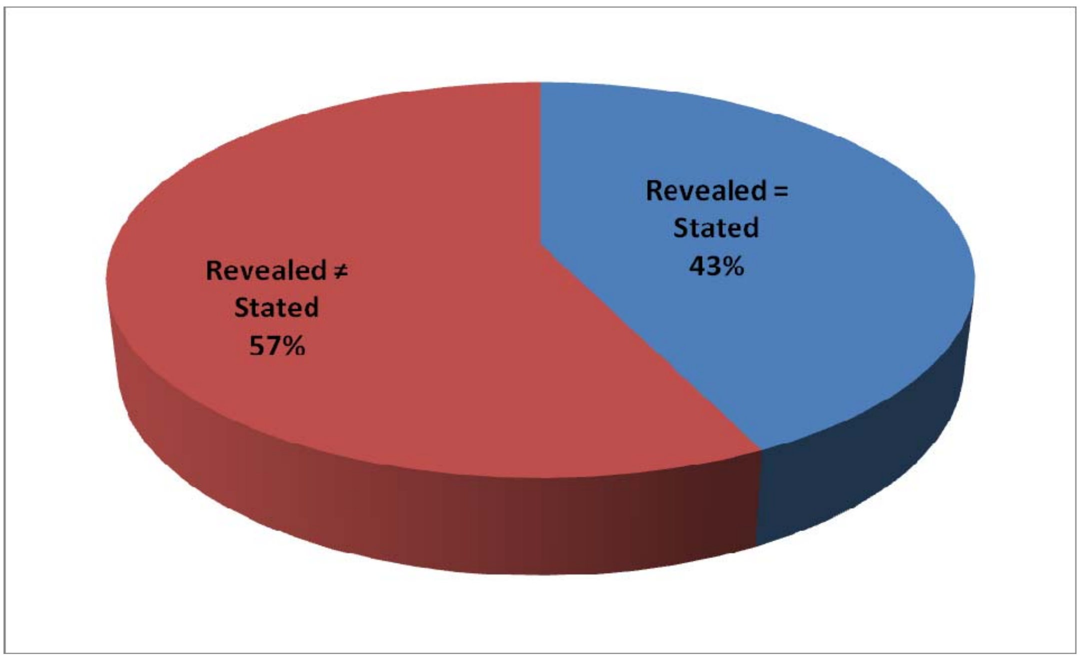


Figure 2.13 Proportion of corresponding stated and revealed preferences (n=7)

Selecting alternative plumbing material is subjective to homeowners' perception and preferences. So, the final selection will change from one homeowner to another. According to AHP results, *health effects and taste and odor of water turned out to be the dominant factors for homeowners*. Some homeowners showed preference for one material, but they chose another option in real life. It is highly likely that their decisions are influenced by the amount information they could access. For example, southeastern community A residents seem to think corrosion resistance as the only criteria when choosing an alternative plumbing material. Even though safety issues (health, taste and odor) turned out to be the most important in the stated preferences, homeowners were not well aware of these issues related with plumbing materials in real life. Due to limitations in the number of attributes in AHP, we could only include the most important 7 attributes in the survey. There should be other attributes that will affect consumer's decisions such as attractive marketing strategies, special discount offers or purchase incentives and advise from others (plumbers, consultants, architects, neighbors etc). In addition, higher number of sample size will show better comparison between revealed and stated preferences.

6. Conclusions and Future Research

An increasing rate of pinhole leaks is causing concerns for homeowners, water utilities, and policymakers. Results from the various surveys administered by Virginia Tech researchers provided insights into the socioeconomic impacts of pinhole leaks on individual households. The total costs associated with pipe failures could be as high as $25,000 in addition to the cost of homeowners' time, and mental stress resulting from frequent leaks. While copper has remained a relatively inert carrier of water, pinhole leaks resulting from corrosion have forced consumers to consider alternatives including other plumbing materials or lining the interior of the pipes with epoxy. Water utilities have also responded through use of corrosion inhibitors such as phosphate.

A two-phase plumbing decision model was completed including optimal repair or replacement timing and choice of plumbing material. Plumbing replacement is suggested 22 years or 4^{th} leak after installation for affected Washington D.C. Area (Loganathan and Lee, 2005). Good quality data on leak incidences and costs would help improve the model for homeowners' decision-making. Choosing alternative plumbing material is subjective to homeowners' perception and choice. In real life, numerous factors will influence homeowner's preference changes in selection of a particular pipe material. These factors encompass a spectrum of issues including durability, affordability, resistance to corrosion, taste and odor of water, safety issues against possible health hazards, fire resistance, serviceability during extreme weather conditions, cost, added value to house/ dwelling unit, willingness to pay, willingness to take risk, magnitude and type of risk, consumers' perception, past experience, and to some extent the local regulations and neighborhood's experience.

In this study, cost, corrosion resistance, reliability, taste and odor of water, health effects, warranty, and proven performance in the market were considered for analyzing homeowners' decision on choosing plumbing material. Formal preference elicitation methodologies (AHP in this study) were applied for considering various attributes involved in home plumbing. The magnitude of consumers' preferences towards plumbing attributes and materials are quantified in pinhole leak prone area (Southeastern US community A). The response rates for both revealed and stated preference survey were over 60%. This very high rate of response rate reflects their keen interest in these issues. We found out that health and taste and odor considerations dominate the consumer choice. These results indicate that health, and taste and odor may be substitute attributes for the purity of water that dominates preferences for a plumbing material. Reliability of material seems to be highly related to mental stress; the residents are very concerned about removing the dry wall to replace a failed pipe without a guarantee that another leak will not spring in the future. We also found out that there is very little difference in stated preferences towards plumbing attributes for those who had leak experiences and without leak experiences in their plumbing systems. The manner and the type of information provided to the participants are important in preference changes.

When comparing revealed and stated preferences, we also observed the difference in realism vs. idealism; people respond one way in stated preferences but "behave differently" in real life choice. It is highly likely that their decisions are influenced by the amount information they could access. Even though safety issues (health, taste and odor) turned out to be the most important in the stated preferences, homeowners were not well aware of these issues related with plumbing materials in real life.

As a future research, it should be interesting to compare the results of the preference elicitation tools (CA, CV, and AHP) with the actual actions taken in choosing plumbing systems and materials. Through this research, homeowners will be able to make better informed decisions in selecting alternative plumbing materials. Water professionals, policy makers, water utilities should work on bridging the gap between public perception and research results. The results of these surveys can help fill the information gap about pinhole leaks among policy experts and water utilities who are dealing with this problem. This information will be helpful for advising policy experts and utility companies on ways to deal with pinhole leaks.

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APPENDIX I -A

RESERVOIR PROBLEM

```
%THIS PROGRAM IS FOR SOLVING RESERVOIR-VALVE PROBLEM USING MATLAB(EXAMPLE 1
IN THEME I)

clear all;

delT=0.02;     %time step
h=100;
M=1000/h;

t_final = input('Enter end of time in seconds:       ');
time_step_N = t_final/delT;

a =4000; %FT/SEC celerity
A = 0.785398; %FT2 area of pipe: PI/4*D^2, D=1'
g =32.2; %FT/sec2 gravitational acceleration
f=0.02; %darcy-weisbach friction coeff.
D=1;% FT; Diameter of the conduit

AA=delT*(a^2)/(h*g*A);%constant AA
BB=delT*g*A/h;% constant BB
CN=a*delT/h; % Courant Number should be less than 1
R= f/(2*D*A);


Hold=zeros(1,M+1);
Qold=zeros(1,M+1);


for m=1:M+1 %set initial data
    Hold(m)=200-(20)*(m-1);
    Qold(m)=19.5;
end

Hstar=zeros(1,M+1);
Qstar=zeros(1,M+1);
Hnew=zeros(1,M+1);
Qnew=zeros(1,M+1);

% CP = Qold(M)+g*A/a*Hold(M)-R*delT*Qold(M)*abs(Qold(M));
% CN = Qold(2)-g*A/a*Hold(2)-R*delT*Qold(2)*abs(Qold(2));
% CA = g*A/a;

%------------------------------ McCommas Scheme-------------

for j=1:time_step_N %time step


CP = Qold(M)+g*A/a*Hold(M)-R*delT*Qold(M)*abs(Qold(M));
CN = Qold(2)-g*A/a*Hold(2)-R*delT*Qold(2)*abs(Qold(2));
CA = g*A/a;
```

```
    alterna=mod(j,2);

    if alterna==1

         for i=1:M
             Hstar(i)=Hold(i)-AA*(Qold(i+1)-Qold(i));
             Qstar(i)=Qold(i)-BB*(Hold(i+1)-Hold(i))-
R*abs(Qold(i))*Qold(i)*delT;
         end

         for i=2:M
             Hnew(i)=0.5*(Hold(i)+Hstar(i)-AA*(Qstar(i)-Qstar(i-1)));
             Qnew(i)=0.5*(Qold(i)+Qstar(i)-BB*(Hstar(i)-Hstar(i-1))-
R*abs(Qstar(i))*Qstar(i)*delT);
         end

            Hnew(1)=200; %set the left B.C.
            Qnew(M+1)= 0; %set the right B.C.
            Qnew(1)=CN +CA*Hnew(1);   %set the left B.C.
            Hnew(M+1)= CP/CA; %set the right B.C.

    else

        for i=2:M+1
             Hstar(i)=Hold(i)-AA*(Qold(i)-Qold(i-1));
             Qstar(i)=Qold(i)-BB*(Hold(i)-Hold(i-1))-
R*abs(Qold(i))*Qold(i)*delT;
        end

        for i=2:M
             Hnew(i)=0.5*(Hold(i)+Hstar(i)-AA*(Qstar(i+1)-Qstar(i)));
             Qnew(i)=0.5*(Qold(i)+Qstar(i)-BB*(Hstar(i+1)-Hstar(i))-
R*abs(Qstar(i))*Qstar(i)*delT);
        end

            Hnew(1)=200; %set the left B.C.
            Qnew(M+1)= 0; %set the right B.C.
            Qnew(1)=CN +CA*Hnew(1);   %set the left B.C.
            Hnew(M+1)= CP/CA; %set the right B.C.

    end

%      for mm=1:(time_step_N)+1
%      time(mm)=mm*delT;
%      end
%
%      figure (1)
%      plot(time,Hnew(1),'-g',time,Hnew(10),'-r', time, Hnew(21),'-r')

H1(j)=Hnew(4);
H5(j)=Hnew(5);
H10(j)=Hnew(6);
```

```
AAA=[H1;H5;H10];

    for kk=1:M+1
        Hold(kk)=Hnew(kk);
        Qold(kk)=Qnew(kk);
    end

end
```

```
 WHAMO
%THIS PROGRAM IS FOR SOLVING RESERVOIR-VALVE PROBLEM USING WHAMO(EXAMPLE 1 IN
THEME I)

Joukowski comparison
c Hammer-Whamo comparison

  SYSTEM
  EL HW AT 100
  EL C1 LINK 100 1
  JUNC AT 1
  EL C2 LINK 1 2
  JUNC AT 2
  EL V1 LINK 2 200
  EL TW AT 200

  NODE 100 ELEV 200
  NODE 1 ELEV 0
  NODE 2 ELEV 0
  NODE 200 ELEV 0
  FINISH

  RESE ID HW ELEV 200.0 FINI
  RESE ID TW ELEV 0 FINI

  COND ID C1 LENGTH 500.0 DIAM 1.0 FRICT 0.02 CELE 4000.0
  numseg 5 FINI

  COND ID C2 LENGTH 500.0 DIAM 1.0 FRICT 0.02 CELE 4000.0
  numseg 5 FINI

  VALVE ID V1 TYPE 1 DIAM 1.0 VSCHED 1 FINI

  VCHAR TYPE 1 GATE 100. 0. 0.
  HDCOEF 1.0 100000000. 10000000000. FINI

  schedule
  vsched 1 T 0.0 G 100. T 0.0001 G 0.0
  fini

  HISTORY
  NODE 100 Q HEAD PSI
  NODE 1 Q HEAD PSI
  NODE 2 Q HEAD PSI
  NODE 200 Q HEAD PSI
  ELEM C1 Q
  DECIMAL 3
  FINI

  PLOT
  NODE 100 Q HEAD PSI
  NODE 1 Q HEAD PSI
  NODE 2 Q HEAD PSI
  NODE 200 Q HEAD PSI
  ELEM C1 Q HEAD PSI
  FINI
```

```
DISPLAY ALL FINI
SNAPSHOT TIME 0.0 FINI

CONTROL
DTCOMP 0.02 DTOUT 0.02 TMAX 50.
FINI

GO
GOODBYE
```

APPENDIX I -B

SCENARIO II

```
%THIS PROGRAM IS FOR SOLVING SCENARIO II PROBLEM USING MATLAB (EXAMPLE 2 IN
THEME I)

clear all;

g =32.2; %FT/sec2 gravitational acceleration

t_final = input('Enter end of time in seconds:       ');


%%********************EVERY M IS WRITTEN IN M1************
%*******CAUTTION!!!****************************************
%==================PIPE CHARACTERISTICS=====================


delT1=0.001;
delT2=0.001;
delT3=0.001;     %time step

time_step_N1 = t_final/delT1;
time_step_N2 = t_final/delT2;
time_step_N3 = t_final/delT3;

h1=5;
h2=5;
h3=5; % in feet; distance step

M1=20/h1; %number of sections M's
M2=5/h2;
M3=60/h3;

a1 =200; %FT/s celerity
a2 =200;
a3 =200;

A1 = 0.0031; %FT2 area of pipe
A2 = 0.0031;
A3 = 0.0031;

f1=0.1; %darcy-weisbach friction coeff.
f2=0.1;
f3=0.1;

D1=0.063;% in feet; Diameter of the conduit
D2=0.063;
D3=0.063;

AA1=delT1*((a1)^2)/(h1*g*A1);%constant AA
AA2=delT2*((a2)^2)/(h2*g*A2);
AA3=delT3*((a3)^2)/(h3*g*A3);
```

```
BB1=delT1*g*A1/h1;% constant BB
BB2=delT2*g*A2/h2;
BB3=delT3*g*A3/h3;

CNumber1=a1*delT1/h1; % Courant Number should be less than 1
CNumber2=a2*delT2/h2;
CNumber3=a3*delT3/h3;

R1= f1/(2*D1*A1);
R2= f2/(2*D2*A2);
R3= f3/(2*D3*A3);

Hold1=zeros(1,M1+1);% preallocation for Hold
Qold1=zeros(1,M1+1);

Hold2=zeros(1,M2+1);
Qold2=zeros(1,M2+1);

Hold3=zeros(1,M3+1);
Qold3=zeros(1,M3+1);

%---CAUTION!!-----%TIME IS CONSTANT FOR EVERY PIPE!!!=========
for m=1:M1+1 %set initial data

    Qold1(m)=0.023;
    Hold1(m)=100-6.25*(m-1);
end

for m=1:M2+1
    Qold2(m)=0;
    Hold2(m)=75+6.25*(m-1);
end

for m=1:M3+1
    Qold3(m)=0.023;
    Hold3(m)=75-6.25*(m-1);
end
%---------------------

Hstar1=zeros(1,M1+1); % preallocation for Hstar
Qstar1=zeros(1,M1+1);

Hstar2=zeros(1,M2+1);
Qstar2=zeros(1,M2+1);

Hstar3=zeros(1,M3+1);
Qstar3=zeros(1,M3+1);

%---------------------

Hnew1=zeros(1,M1+1); %preallocation for Hnew
Qnew1=zeros(1,M1+1);

Hnew2=zeros(1,M2+1);
```

```
Qnew2=zeros(1,M2+1);

Hnew3=zeros(1,M3+1);
Qnew3=zeros(1,M3+1);

%-------------------Preallocation for Hs: Head values according to time at a
certain location-----------

    H1=zeros(1,time_step_N1);
    H5=zeros(1,time_step_N1);
    H11=zeros(1,time_step_N1);
    H15=zeros(1,time_step_N1);
    H21=zeros(1,time_step_N1);

    HH1=zeros(1,time_step_N2);
    HH5=zeros(1,time_step_N2);
    HH10=zeros(1,time_step_N2);
    HH15=zeros(1,time_step_N2);
    HH21=zeros(1,time_step_N2);

    HHH1=zeros(1,time_step_N3);
    HHH5=zeros(1,time_step_N3);
    HHH10=zeros(1,time_step_N3);
    HHH15=zeros(1,time_step_N3);
    HHH21=zeros(1,time_step_N3);

%-------TIMESTEP IS THE SAME!!!--------- McCommas Scheme---------------------
-----




 for j=1:time_step_N1 %time step


        CP1 = Qold1(M1)+g*A1/a1*Hold1(M1)-R1*delT1*Qold1(M1)*abs(Qold1(M1));
        CN1= Qold1(2)-g*A1/a1*Hold1(2)-R1*delT1*Qold1(2)*abs(Qold1(2));
        CA1= g*A1/a1;

        CP2= Qold2(M2)+g*A2/a2*Hold2(M2)-R2*delT2*Qold2(M2)*abs(Qold2(M2));
        CN2= Qold2(2)-g*A2/a2*Hold2(2)-R2*delT2*Qold2(2)*abs(Qold2(2));
        CA2= g*A2/a2;

        CP3= Qold3(M3)+g*A3/a3*Hold3(M3)-R3*delT3*Qold3(M3)*abs(Qold3(M3));
        CN3= Qold3(2)-g*A3/a3*Hold3(2)-R3*delT3*Qold3(2)*abs(Qold3(2));
        CA3= g*A3/a3;

   alterna=mod(j,2);

    if alterna==1

         for i=1:M1
```

```
            Hstar1(i)=Hold1(i)-AA1*(Qold1(i+1)-Qold1(i));
            Qstar1(i)=Qold1(i)-BB1*(Hold1(i+1)-Hold1(i))-
R1*abs(Qold1(i))*Qold1(i)*delT1;
        end

        for i=1:M2
            Hstar2(i)=Hold2(i)-AA2*(Qold2(i+1)-Qold2(i));
            Qstar2(i)=Qold2(i)-BB2*(Hold2(i+1)-Hold2(i))-
R2*abs(Qold2(i))*Qold2(i)*delT2;
        end

        for i=1:M3
            Hstar3(i)=Hold3(i)-AA3*(Qold3(i+1)-Qold3(i));
            Qstar3(i)=Qold3(i)-BB3*(Hold3(i+1)-Hold3(i))-
R3*abs(Qold3(i))*Qold3(i)*delT3;

        end

        for i=2:M1

            Hnew1(i)=0.5*(Hold1(i)+Hstar1(i)-AA1*(Qstar1(i)-Qstar1(i-1)));
            Qnew1(i)=0.5*(Qold1(i)+Qstar1(i)-BB1*(Hstar1(i)-Hstar1(i-1))-
R1*abs(Qstar1(i))*Qstar1(i)*delT1);
        end

        for i=2:M2
            Hnew2(i)=0.5*(Hold2(i)+Hstar2(i)-AA2*(Qstar2(i)-Qstar2(i-1)));
            Qnew2(i)=0.5*(Qold2(i)+Qstar2(i)-BB2*(Hstar2(i)-Hstar2(i-1))-
R2*abs(Qstar2(i))*Qstar2(i)*delT2);
        end

        for i=2:M3
            Hnew3(i)=0.5*(Hold3(i)+Hstar3(i)-AA3*(Qstar3(i)-Qstar3(i-1)));
            Qnew3(i)=0.5*(Qold3(i)+Qstar3(i)-BB3*(Hstar3(i)-Hstar3(i-1))-
R3*abs(Qstar3(i))*Qstar3(i)*delT3);

        end

      %%%%%BOUNDARY CONDITION

        % PIPE 1 B.C.
           Hnew1(1)= -CN1/CA1; %set the left B.C.
           Qnew1(1)= 0;

           Hnew1(M1+1)= (CP1-CN2-CN3)/(CA1+CA2+CA3);
           Qnew1(M1+1)= CP1-CA1*Hnew1(M1+1);

         % PIPE 2 B.C.: VERTICAL SECTION!!
           Qnew2(M2+1)=0; %set the right B.C.
           Hnew2(M2+1)=CP2/CA2 ;

           Hnew2(1)=(CP1-CN2-CN3)/(CA1+CA2+CA3);
           Qnew2(1)= CN2+CA2*Hnew2(1);
```

```
          % PIPE 3 B.C.
            Qnew3(M3+1)= CP3; %set the right B.C.
            Hnew3(M3+1)= 0;

            Hnew3(1)=(CP1-CN2-CN3)/(CA1+CA2+CA3);
            Qnew3(1)= CN3+CA3*Hnew3(1);


    else

        for i=2:M1+1

             Hstar1(i)=Hold1(i)-AA1*(Qold1(i)-Qold1(i-1));
             Qstar1(i)=Qold1(i)-BB1*(Hold1(i)-Hold1(i-1))-
R1*abs(Qold1(i))*Qold1(i)*delT1;
        end

        for i=2:M2+1
             Hstar2(i)=Hold2(i)-AA2*(Qold2(i)-Qold2(i-1));
             Qstar2(i)=Qold2(i)-BB2*(Hold2(i)-Hold2(i-1))-
R2*abs(Qold2(i))*Qold2(i)*delT2;
        end

        for i=2:M3+1
             Hstar3(i)=Hold3(i)-AA3*(Qold3(i)-Qold3(i-1));
             Qstar3(i)=Qold3(i)-BB3*(Hold3(i)-Hold3(i-1))-
R3*abs(Qold3(i))*Qold3(i)*delT3;

        end

        for i=2:M1

             Hnew1(i)=0.5*(Hold1(i)+Hstar1(i)-AA1*(Qstar1(i+1)-Qstar1(i)));
             Qnew1(i)=0.5*(Qold1(i)+Qstar1(i)-BB1*(Hstar1(i+1)-Hstar1(i))-
R1*abs(Qstar1(i))*Qstar1(i)*delT1);
        end

        for i=2:M2
             Hnew2(i)=0.5*(Hold2(i)+Hstar2(i)-AA2*(Qstar2(i+1)-Qstar2(i)));
             Qnew2(i)=0.5*(Qold2(i)+Qstar2(i)-BB2*(Hstar2(i+1)-Hstar2(i))-
R2*abs(Qstar2(i))*Qstar2(i)*delT2);
        end

        for i=2:M3
             Hnew3(i)=0.5*(Hold3(i)+Hstar3(i)-AA3*(Qstar3(i+1)-Qstar3(i)));
             Qnew3(i)=0.5*(Qold3(i)+Qstar3(i)-BB3*(Hstar3(i+1)-Hstar3(i))-
R3*abs(Qstar3(i))*Qstar3(i)*delT3);

        end
```

```
     %%%%%BOUNDARY CONDITION

       % PIPE 1 B.C.
          Hnew1(1)= -CN1/CA1; %set the left B.C.
          Qnew1(1)= 0;

          Hnew1(M1+1)= (CP1-CN2-CN3)/(CA1+CA2+CA3);
          Qnew1(M1+1)= CP1-CA1*Hnew1(M1+1);

        % PIPE 2 B.C.: VERTICAL SECTION!!
          Qnew2(M2+1)=0; %set the right B.C.
          Hnew2(M2+1)=CP2/CA2 ;

          Hnew2(1)=(CP1-CN2-CN3)/(CA1+CA2+CA3);
          Qnew2(1)= CN2+CA2*Hnew2(1);



        % PIPE 3 B.C.
          Qnew3(M3+1)= CP3; %set the right B.C.
          Hnew3(M3+1)= 0;

          Hnew3(1)=(CP1-CN2-CN3)/(CA1+CA2+CA3);
          Qnew3(1)= CN3+CA3*Hnew3(1);


  end

%     for mm=1:(time_step_N)+1
%     time(mm)=mm*delT;
%     end
%
%     figure (1)
%     plot(time,Hnew(1),'-g',time,Hnew(10),'-r', time, Hnew(21),'-r')

          H1(j)=Hnew1(1);
          H5(j)=Hnew1(2);
          H11(j)=Hnew1(4);
%           H15(j)=Hnew1(15);
%           H21(j)=Hnew1(21);

          HH1(j)=Hnew2(1);
          HH5(j)=Hnew2(1);
          HH10(j)=Hnew2(2);
%           HH15(j)=Hnew2(15);
%           HH21(j)=Hnew2(21);

          HHH1(j)=Hnew3(1);
          HHH5(j)=Hnew3(2);
          HHH10(j)=Hnew3(10);
%           HHH15(j)=Hnew3(15);
%           HHH21(j)=Hnew3(21);

          AAA1=[H1;H5;H11];
```

```
            AAA2=[HH1;HH5;HH10];
            AAA3=[HHH1;HHH5;HHH10];

    for kk=1:M1+1

        Hold1(kk)=Hnew1(kk);
        Qold1(kk)=Qnew1(kk);
    end

    for kk=1:M2+1
        Hold2(kk)=Hnew2(kk);
        Qold2(kk)=Qnew2(kk);
    end

    for kk=1:M3+1
        Hold3(kk)=Hnew3(kk);
        Qold3(kk)=Qnew3(kk);
    end
end
```

```
 Joukowski comparison
%THIS PROGRAM IS FOR SOLVING SCENARIO II PROBLEM USING WHAMO (EXAMPLE 2 IN
THEME I)

c Hammer-Whamo comparison

  SYSTEM
  EL HW AT 100
  EL C1 LINK 100 1
  JUNC AT 1
  EL V1 LINK 1 2
  JUNC AT 2
  EL C2 LINK 2 3
  JUNC AT 3
  EL C3 LINK 3 99
  JUNC AT 99
  EL C4 LINK 99 5
  EL FBC1 AT 5
  EL C99 LINK 99 4
  JUNC AT 4
  EL C5 LINK 4 6
  JUNC AT 6
  EL V2 LINK 6 7
  JUNC AT 7
  EL C6 LINK 7 200
  EL TW AT 200

  NODE 100 ELEV 100.0
  NODE 1 ELEV 0.0
  NODE 2 ELEV 0.0
  NODE 3 ELEV 0.0
  NODE 4 ELEV 0.0
  NODE 6 ELEV 0.0
  NODE 7 ELEV 0.0
  NODE 99 ELEV 0.0
  NODE 200 ELEV 0
  FINISH


  RESE ID HW ELEV 100.0 FINI
  RESE ID TW ELEV 0 FINI

  COND ID C1 LENGTH 1.0 DIAM 0.063 FRICT 0.1 CELE 200.0
  numseg 1 FINI

  COND ID C2 LENGTH 1.0 DIAM 0.063 FRICT 0.1 CELE 200.0
  numseg 1 FINI

  COND ID C3 LENGTH 16.0 DIAM 0.063 FRICT 0.1 CELE 200.0
  numseg 4 FINI

  COND ID C4 LENGTH 5.0 DIAM 0.063 FRICT 0.1 CELE 200.0
  numseg 2 FINI

  COND ID C5 LENGTH 10.0 DIAM 0.063 FRICT 0.1 CELE 200.0
  numseg 5 FINI
```

```
COND ID C6 LENGTH 50.0 DIAM 0.063 FRICT 0.1 CELE 200.0
numseg 20 FINI

COND ID C99 DUMMY DIAM .063 CELE 200.0 FRIC .1 FINI

FLOWBC ID FBC1 Q .0 fini



VALVE ID V1 TYPE 1 DIAM 0.063 VSCHED 1 FINI

VCHAR TYPE 1 GATE 100. 0. 0.
DISCOEF 1.0  0. 0. FINI

schedule
vsched 1 T 0.0 G 100. T 0.001 G 0.0 T 10.0 G 0.0
FINISH

VALVE ID V2 TYPE 2 DIAM 0.063 VSCHED 2 FINI

VCHAR TYPE 2 GATE 100. 0. 0.
DISCOEF 1.0 0. 0. FINI

schedule
vsched 2 T 0.0 G 100. T 5.0 G 100. T 10.0 G 100.0
FINISH

HISTORY
NODE 2 PSI

DECIMAL 3
FINI

PLOT
NODE 2 Q HEAD PSI
NODE 3 Q HEAD PSI
NODE 200 Q HEAD PSI
FINI

DISPLAY ALL FINI

CONTROL
DTCOMP 0.001 DTOUT 0.001 TMAX 10.
FINI

GO
GOODBYE
```

APPENDIX I -C

SCENARIO I

```
%THIS PROGRAM IS FOR SOLVING SCENARIO I PROBLEM USING MATLAB (EXAMPLE 3 IN
THEME I)


clear all;

g =32.2; %FT/sec2 gravitational acceleration

t_final = input('Enter end of time in seconds:       ');


%%********************EVERY M IS WRITTEN IN M1************
%*******CAUTTION!!!****************************************
%=================PIPE CHARACTERISTICS====================

delT1=0.001;
delT2=0.001;
delT3=0.001;     %time step

time_step_N1 = t_final/delT1;
time_step_N2 = t_final/delT2;
time_step_N3 = t_final/delT3;

h1=5;
h2=5;
h3=5; % in feet; distance step

M1=20/h1; %number of sections M's
M2=5/h2;
M3=10/h3;

a1 =1000; %FT/s celerity
a2 =1000;
a3 =1000;

A1 = 0.0031; %FT2 area of pipe
A2 = 0.0031;
A3 = 0.0031;

f1=0.1; %darcy-weisbach friction coeff.
f2=0.1;
f3=0.1;

D1=0.063;% in feet; Diameter of the conduit
D2=0.063;
D3=0.063;

AA1=delT1*((a1)^2)/(h1*g*A1);%constant AA
AA2=delT2*((a2)^2)/(h2*g*A2);
AA3=delT3*((a3)^2)/(h3*g*A3);

BB1=delT1*g*A1/h1;% constant BB
```

```
BB2=delT2*g*A2/h2;
BB3=delT3*g*A3/h3;

CNumber1=a1*delT1/h1; % Courant Number should be less than 1
CNumber2=a2*delT2/h2;
CNumber3=a3*delT3/h3;

R1= f1/(2*D1*A1);
R2= f2/(2*D2*A2);
R3= f3/(2*D3*A3);

Hold1=zeros(1,M1+1);% preallocation for Hold
Qold1=zeros(1,M1+1);

Hold2=zeros(1,M2+1);
Qold2=zeros(1,M2+1);

Hold3=zeros(1,M3+1);
Qold3=zeros(1,M3+1);

%---CAUTION!!-----%TIME IS CONSTANT FOR EVERY PIPE!!!=========
for m=1:M1+1 %set initial data

    Qold1(m)=0.023;
    Hold1(m)=100-6.25*(m-1);
end

for m=1:M2+1
    Qold2(m)=0;
    Hold2(m)=75+6.25*(m-1);
end

for m=1:M3+1
    Qold3(m)=0.023;
    Hold3(m)=75-6.25*(m-1);
end
%---------------------

Hstar1=zeros(1,M1+1); % preallocation for Hstar
Qstar1=zeros(1,M1+1);

Hstar2=zeros(1,M2+1);
Qstar2=zeros(1,M2+1);

Hstar3=zeros(1,M3+1);
Qstar3=zeros(1,M3+1);

%---------------------

Hnew1=zeros(1,M1+1); %preallocation for Hnew
Qnew1=zeros(1,M1+1);

Hnew2=zeros(1,M2+1);
Qnew2=zeros(1,M2+1);
```

```
Hnew3=zeros(1,M3+1);
Qnew3=zeros(1,M3+1);

%------------------Preallocation for Hs: Head values according to time at a
certain location-----------

    H1=zeros(1,time_step_N1);
    H5=zeros(1,time_step_N1);
    H11=zeros(1,time_step_N1);
    H15=zeros(1,time_step_N1);
    H21=zeros(1,time_step_N1);

    HH1=zeros(1,time_step_N2);
    HH5=zeros(1,time_step_N2);
    HH10=zeros(1,time_step_N2);
    HH15=zeros(1,time_step_N2);
    HH21=zeros(1,time_step_N2);

    HHH1=zeros(1,time_step_N3);
    HHH5=zeros(1,time_step_N3);
    HHH10=zeros(1,time_step_N3);
    HHH15=zeros(1,time_step_N3);
    HHH21=zeros(1,time_step_N3);

%-------TIMESTEP IS THE SAME!!!--------- McCommas Scheme--------------------
-----

for j=1:time_step_N1 %time step


        CP1 = Qold1(M1)+g*A1/a1*Hold1(M1)-R1*delT1*Qold1(M1)*abs(Qold1(M1));
        CN1= Qold1(2)-g*A1/a1*Hold1(2)-R1*delT1*Qold1(2)*abs(Qold1(2));
        CA1= g*A1/a1;

        CP2= Qold2(M2)+g*A2/a2*Hold2(M2)-R2*delT2*Qold2(M2)*abs(Qold2(M2));
        CN2= Qold2(2)-g*A2/a2*Hold2(2)-R2*delT2*Qold2(2)*abs(Qold2(2));
        CA2= g*A2/a2;

        CP3= Qold3(M3)+g*A3/a3*Hold3(M3)-R3*delT3*Qold3(M3)*abs(Qold3(M3));
        CN3= Qold3(2)-g*A3/a3*Hold3(2)-R3*delT3*Qold3(2)*abs(Qold3(2));
        CA3= g*A3/a3;


    alterna=mod(j,2);

    if alterna==1

         for i=1:M1

             Hstar1(i)=Hold1(i)-AA1*(Qold1(i+1)-Qold1(i));
             Qstar1(i)=Qold1(i)-BB1*(Hold1(i+1)-Hold1(i))-
R1*abs(Qold1(i))*Qold1(i)*delT1;
         end
```

```
        for i=1:M2
            Hstar2(i)=Hold2(i)-AA2*(Qold2(i+1)-Qold2(i));
            Qstar2(i)=Qold2(i)-BB2*(Hold2(i+1)-Hold2(i))-
R2*abs(Qold2(i))*Qold2(i)*delT2;
        end

        for i=1:M3
            Hstar3(i)=Hold3(i)-AA3*(Qold3(i+1)-Qold3(i));
            Qstar3(i)=Qold3(i)-BB3*(Hold3(i+1)-Hold3(i))-
R3*abs(Qold3(i))*Qold3(i)*delT3;
        end


        for i=2:M1

            Hnew1(i)=0.5*(Hold1(i)+Hstar1(i)-AA1*(Qstar1(i)-Qstar1(i-1)));
            Qnew1(i)=0.5*(Qold1(i)+Qstar1(i)-BB1*(Hstar1(i)-Hstar1(i-1))-
R1*abs(Qstar1(i))*Qstar1(i)*delT1);
        end

        for i=2:M2
            Hnew2(i)=0.5*(Hold2(i)+Hstar2(i)-AA2*(Qstar2(i)-Qstar2(i-1)));
            Qnew2(i)=0.5*(Qold2(i)+Qstar2(i)-BB2*(Hstar2(i)-Hstar2(i-1))-
R2*abs(Qstar2(i))*Qstar2(i)*delT2);
        end

        for i=2:M3
            Hnew3(i)=0.5*(Hold3(i)+Hstar3(i)-AA3*(Qstar3(i)-Qstar3(i-1)));
            Qnew3(i)=0.5*(Qold3(i)+Qstar3(i)-BB3*(Hstar3(i)-Hstar3(i-1))-
R3*abs(Qstar3(i))*Qstar3(i)*delT3);

        end

       %%%%%BOUNDARY CONDITION

        % PIPE 1 B.C.
           Hnew1(1)= 184.62; %set the left B.C.
           Qnew1(1)= CN1 + CA1* Hnew1(1);

           Hnew1(M1+1)= (CP1-CN2-CN3)/(CA1+CA2+CA3);
           Qnew1(M1+1)= CP1-CA1*Hnew1(M1+1);

         % PIPE 2 B.C.: VERTICAL SECTION!!
           Qnew2(M2+1)=0; %set the right B.C.
           Hnew2(M2+1)=CP2/CA2 ;

           Hnew2(1)=(CP1-CN2-CN3)/(CA1+CA2+CA3);
           Qnew2(1)= CN2+CA2*Hnew2(1);



         % PIPE 3 B.C.
           Qnew3(M3+1)= 0; %set the right B.C.
           Hnew3(M3+1)= CP3/CA3;
```

```
            Hnew3(1)=(CP1-CN2-CN3)/(CA1+CA2+CA3);
            Qnew3(1)= CN3+CA3*Hnew3(1);



    else

        for i=2:M1+1

             Hstar1(i)=Hold1(i)-AA1*(Qold1(i)-Qold1(i-1));
             Qstar1(i)=Qold1(i)-BB1*(Hold1(i)-Hold1(i-1))-
R1*abs(Qold1(i))*Qold1(i)*delT1;
        end

        for i=2:M2+1
             Hstar2(i)=Hold2(i)-AA2*(Qold2(i)-Qold2(i-1));
             Qstar2(i)=Qold2(i)-BB2*(Hold2(i)-Hold2(i-1))-
R2*abs(Qold2(i))*Qold2(i)*delT2;
        end

        for i=2:M3+1
             Hstar3(i)=Hold3(i)-AA3*(Qold3(i)-Qold3(i-1));
             Qstar3(i)=Qold3(i)-BB3*(Hold3(i)-Hold3(i-1))-
R3*abs(Qold3(i))*Qold3(i)*delT3;

        end



        for i=2:M1

             Hnew1(i)=0.5*(Hold1(i)+Hstar1(i)-AA1*(Qstar1(i+1)-Qstar1(i)));
             Qnew1(i)=0.5*(Qold1(i)+Qstar1(i)-BB1*(Hstar1(i+1)-Hstar1(i))-
R1*abs(Qstar1(i))*Qstar1(i)*delT1);
        end

        for i=2:M2
             Hnew2(i)=0.5*(Hold2(i)+Hstar2(i)-AA2*(Qstar2(i+1)-Qstar2(i)));
             Qnew2(i)=0.5*(Qold2(i)+Qstar2(i)-BB2*(Hstar2(i+1)-Hstar2(i))-
R2*abs(Qstar2(i))*Qstar2(i)*delT2);
        end

        for i=2:M3
             Hnew3(i)=0.5*(Hold3(i)+Hstar3(i)-AA3*(Qstar3(i+1)-Qstar3(i)));
             Qnew3(i)=0.5*(Qold3(i)+Qstar3(i)-BB3*(Hstar3(i+1)-Hstar3(i))-
R3*abs(Qstar3(i))*Qstar3(i)*delT3);

        end



       %%%%%BOUNDARY CONDITION
```

```
        % PIPE 1 B.C.
           Hnew1(1)= 184.62; %set the left B.C.
           Qnew1(1)= CN1 + CA1* Hnew1(1);

           Hnew1(M1+1)= (CP1-CN2-CN3)/(CA1+CA2+CA3);
           Qnew1(M1+1)= CP1-CA1*Hnew1(M1+1);

         % PIPE 2 B.C.: VERTICAL SECTION!!
           Qnew2(M2+1)=0; %set the right B.C.
           Hnew2(M2+1)=CP2/CA2 ;

           Hnew2(1)=(CP1-CN2-CN3)/(CA1+CA2+CA3);
           Qnew2(1)= CN2+CA2*Hnew2(1);


         % PIPE 3 B.C.
           Qnew3(M3+1)= 0; %set the right B.C.
           Hnew3(M3+1)= CP3/CA3;

           Hnew3(1)=(CP1-CN2-CN3)/(CA1+CA2+CA3);
           Qnew3(1)= CN3+CA3*Hnew3(1);


    end

%     for mm=1:(time_step_N)+1
%     time(mm)=mm*delT;
%     end
%
%     figure (1)
%     plot(time,Hnew(1),'-g',time,Hnew(10),'-r', time, Hnew(21),'-r')

           H1(j)=Hnew1(1);
           H5(j)=Hnew1(2);
           H11(j)=Hnew1(4);
%            H15(j)=Hnew1(15);
%            H21(j)=Hnew1(21);

           HH1(j)=Hnew2(1);
           HH5(j)=Hnew2(1);
           HH10(j)=Hnew2(2);
%            HH15(j)=Hnew2(15);
%            HH21(j)=Hnew2(21);

           HHH1(j)=Hnew3(1);
           HHH5(j)=Hnew3(2);
           HHH10(j)=Hnew3(3);
%            HHH15(j)=Hnew3(15);
%            HHH21(j)=Hnew3(21);

           AAA1=[H1;H5;H11];
           AAA2=[HH1;HH5;HH10];
           AAA3=[HHH1;HHH5;HHH10];
```

```
    for kk=1:M1+1

        Hold1(kk)=Hnew1(kk);
        Qold1(kk)=Qnew1(kk);
    end

    for kk=1:M2+1
        Hold2(kk)=Hnew2(kk);
        Qold2(kk)=Qnew2(kk);
    end

    for kk=1:M3+1
        Hold3(kk)=Hnew3(kk);
        Qold3(kk)=Qnew3(kk);
    end

end
```

Appendix I-D

Figure App. I-D 1 (t=0.033)

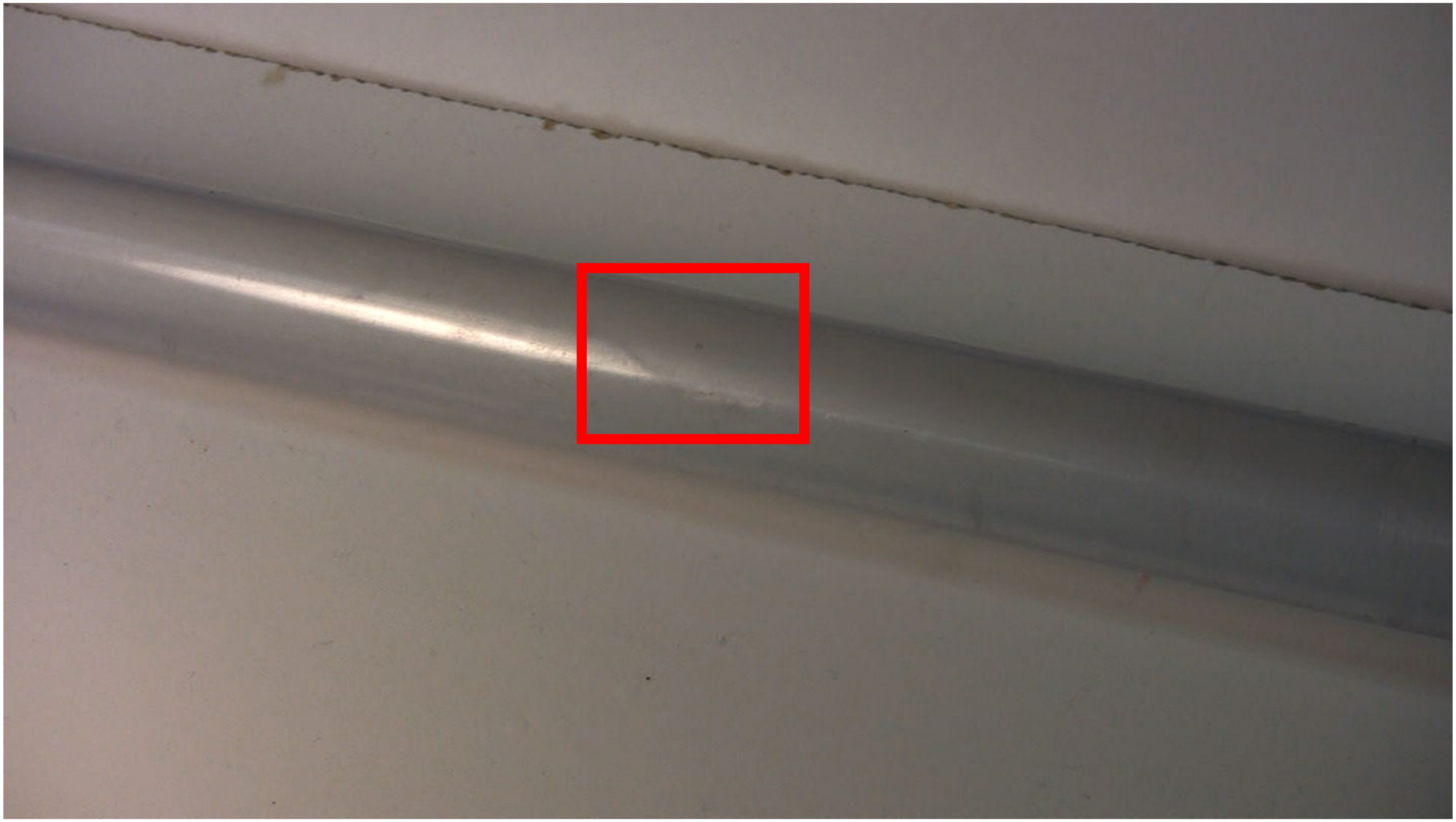

Figure App. I-D 2 (t=0.066)

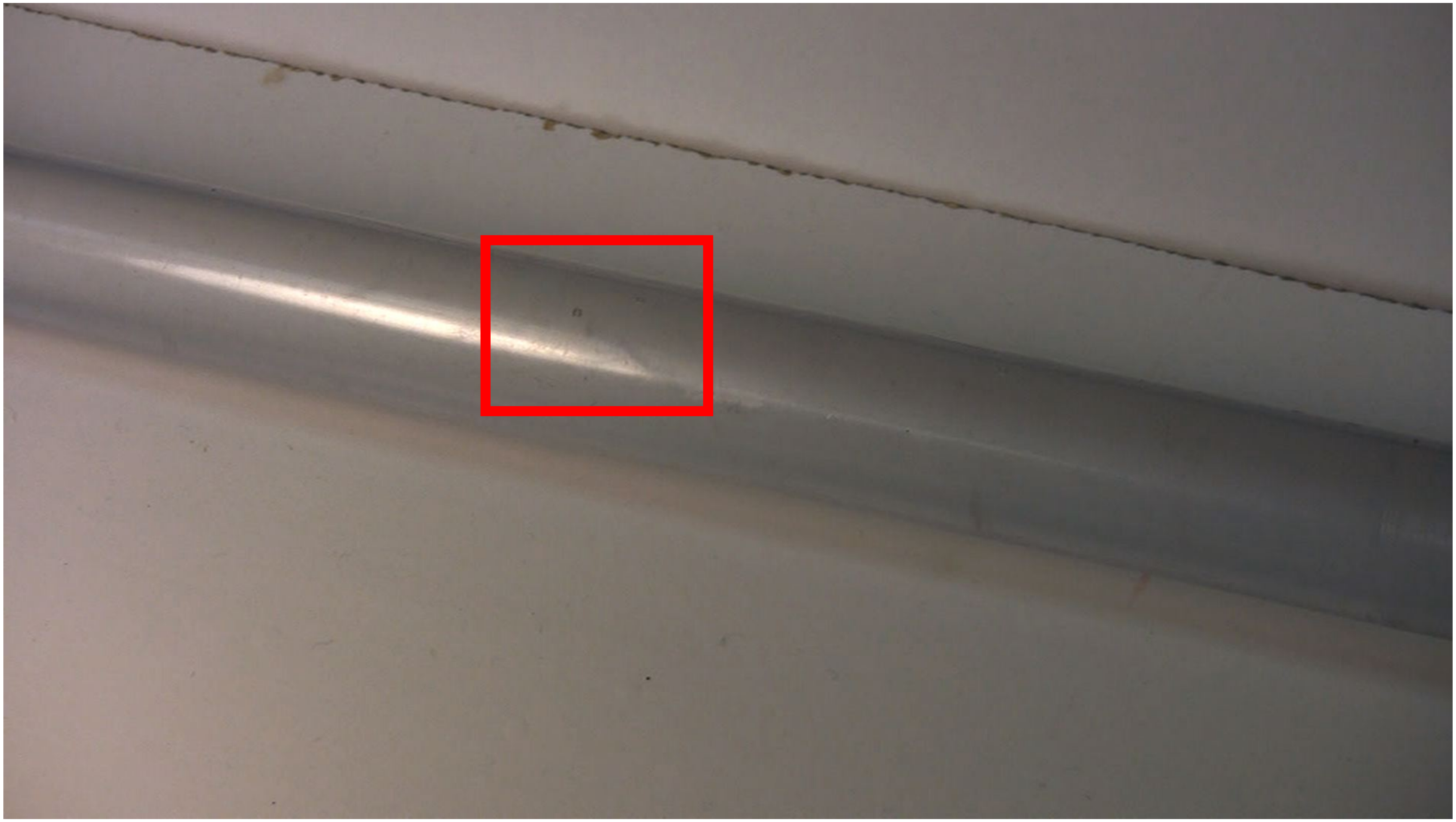

Figure App. I-D 3 (t=0.198)

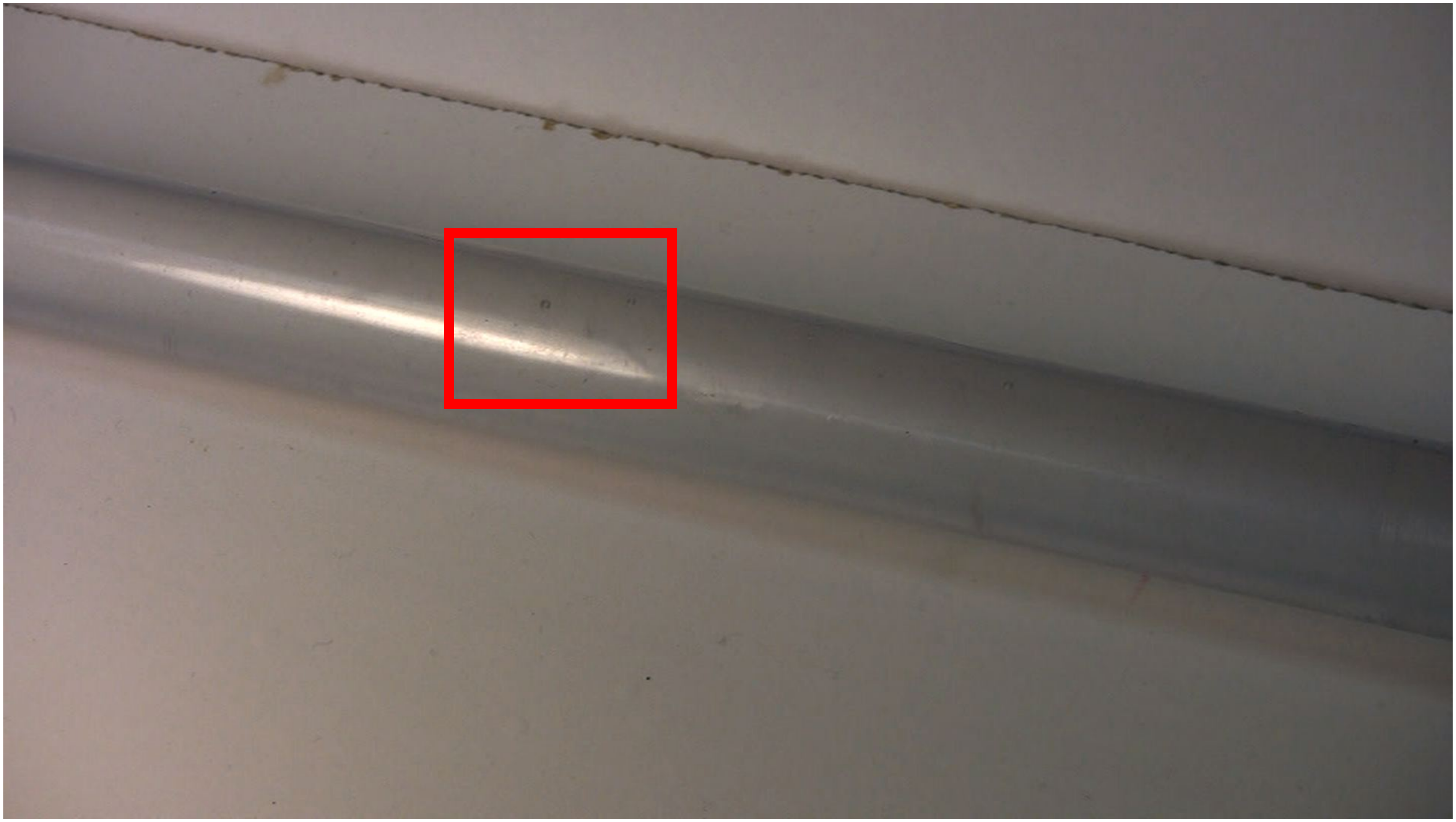

Figure App. I-D 4 (t=0.297)

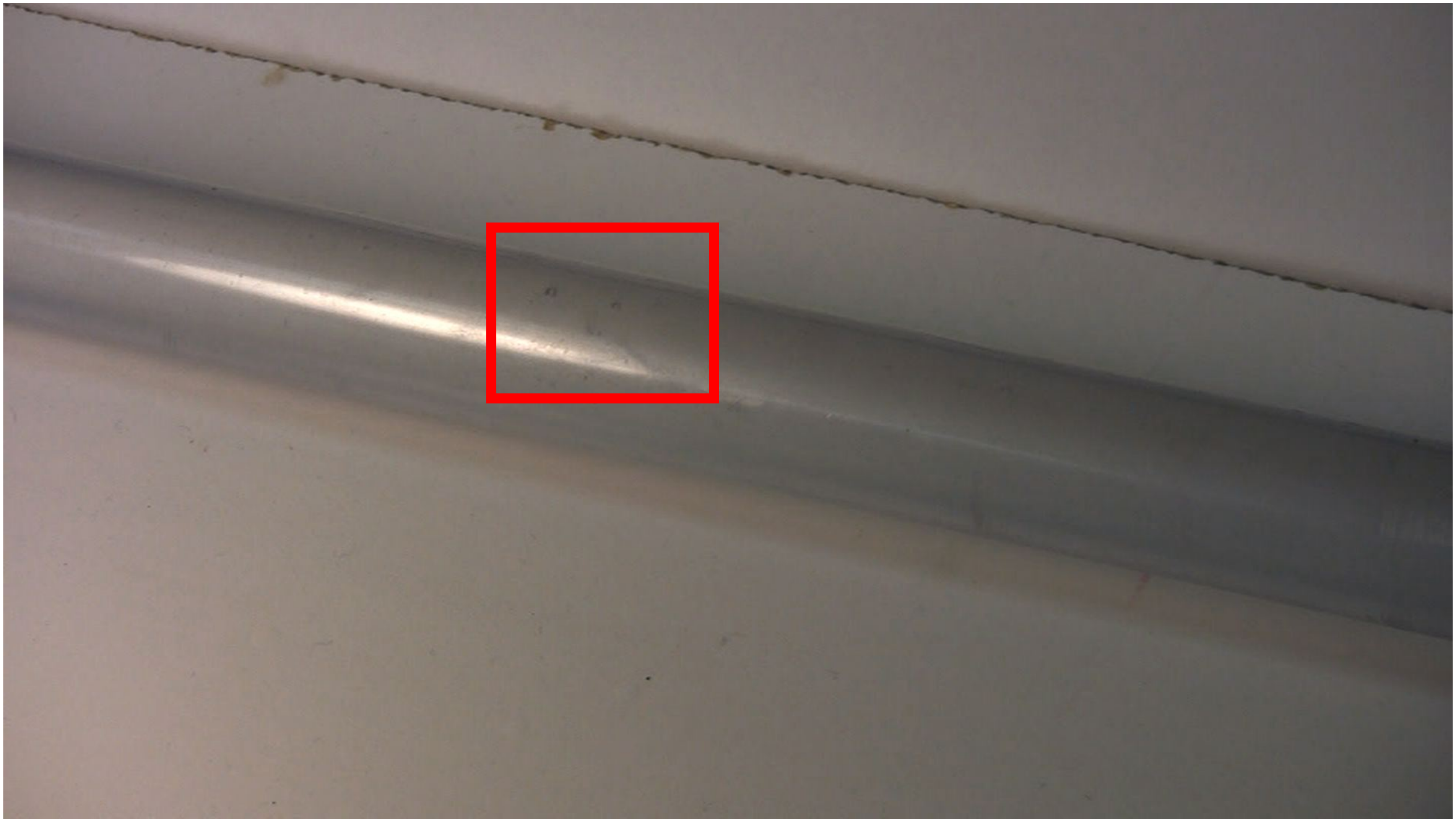

Figure App. I-D 5 (t=0.429)

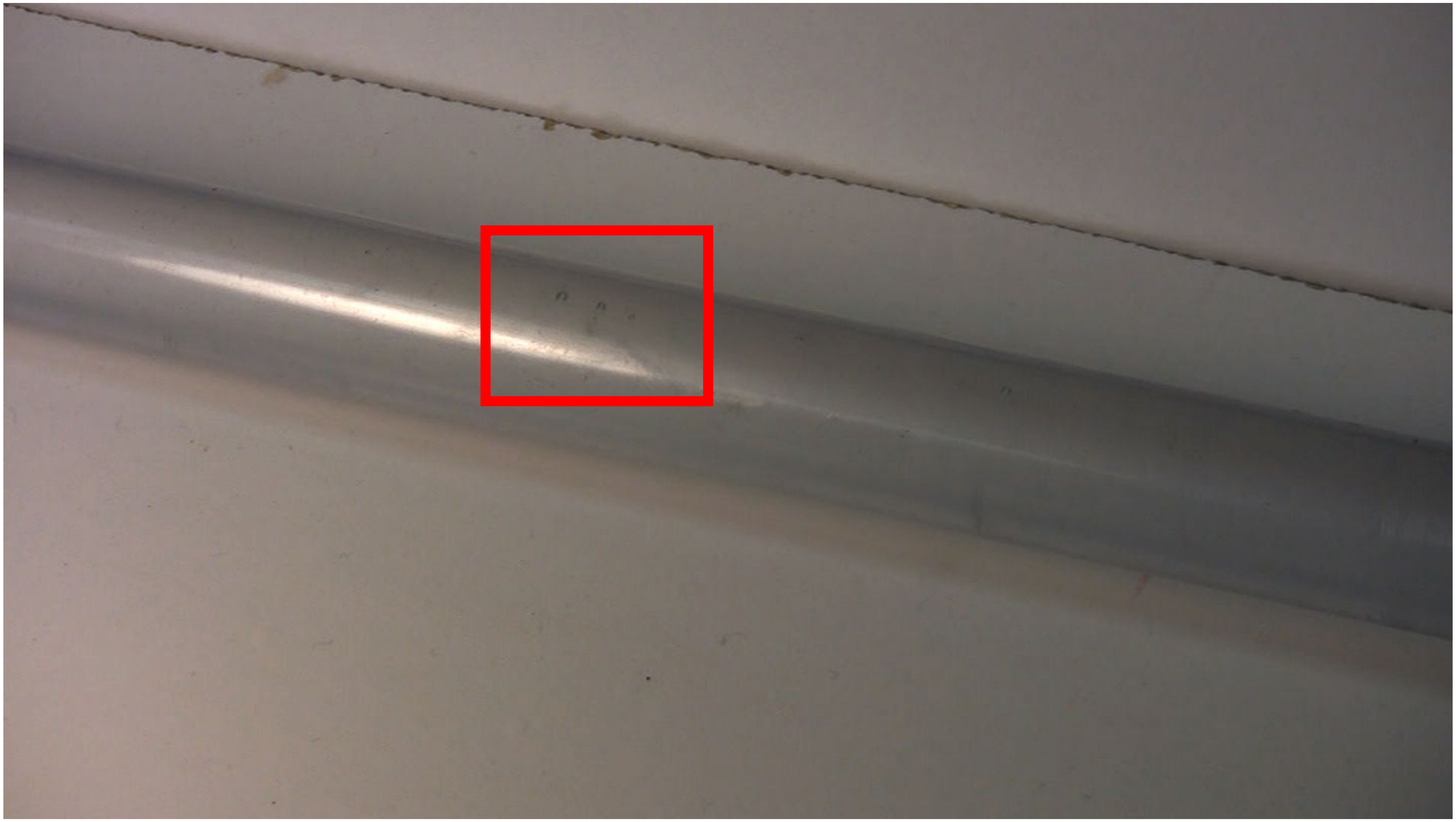

Figure App. I-D 6 (t=0.594)

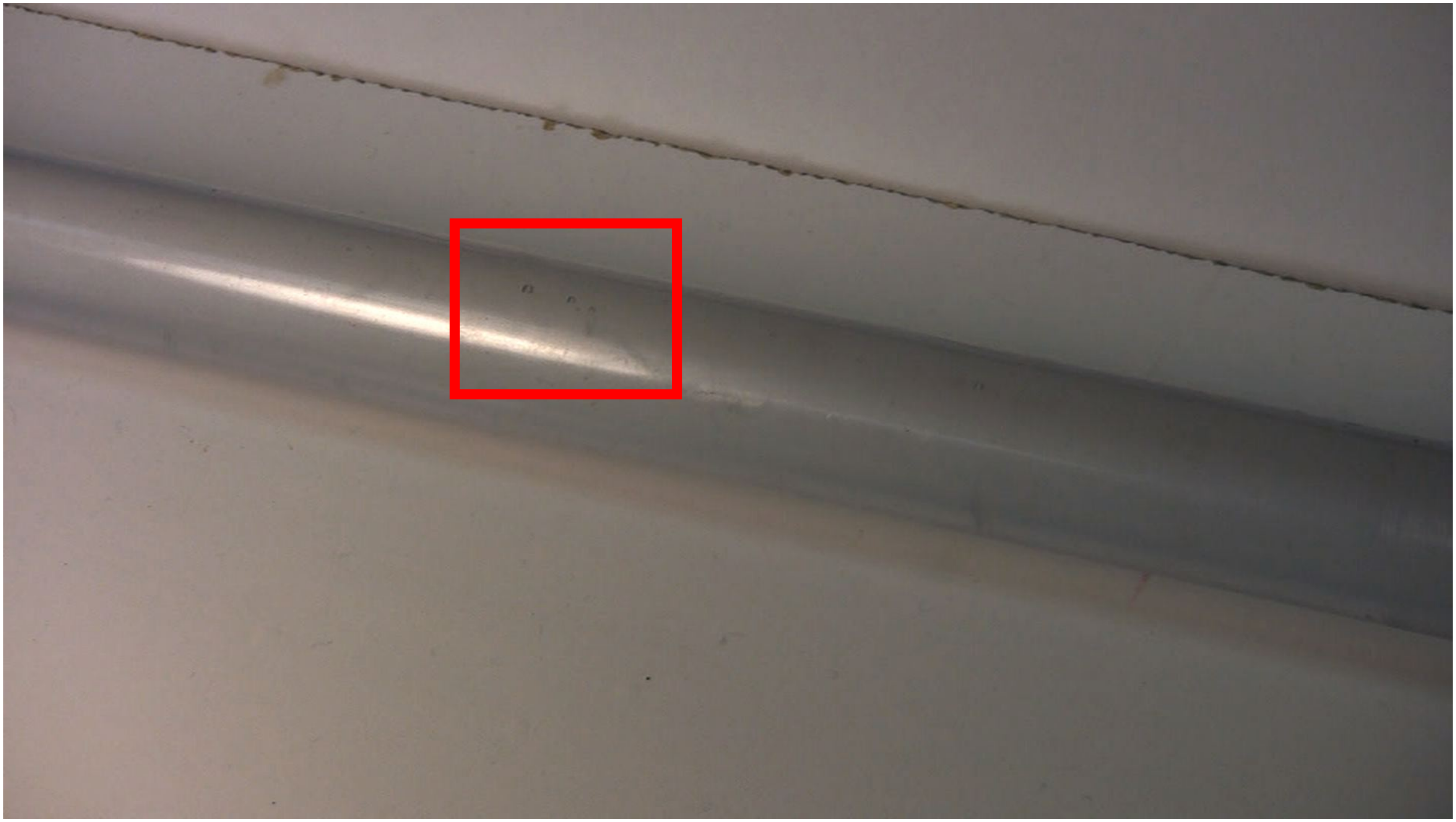

Figure App. I-D 7 (t=0.726)

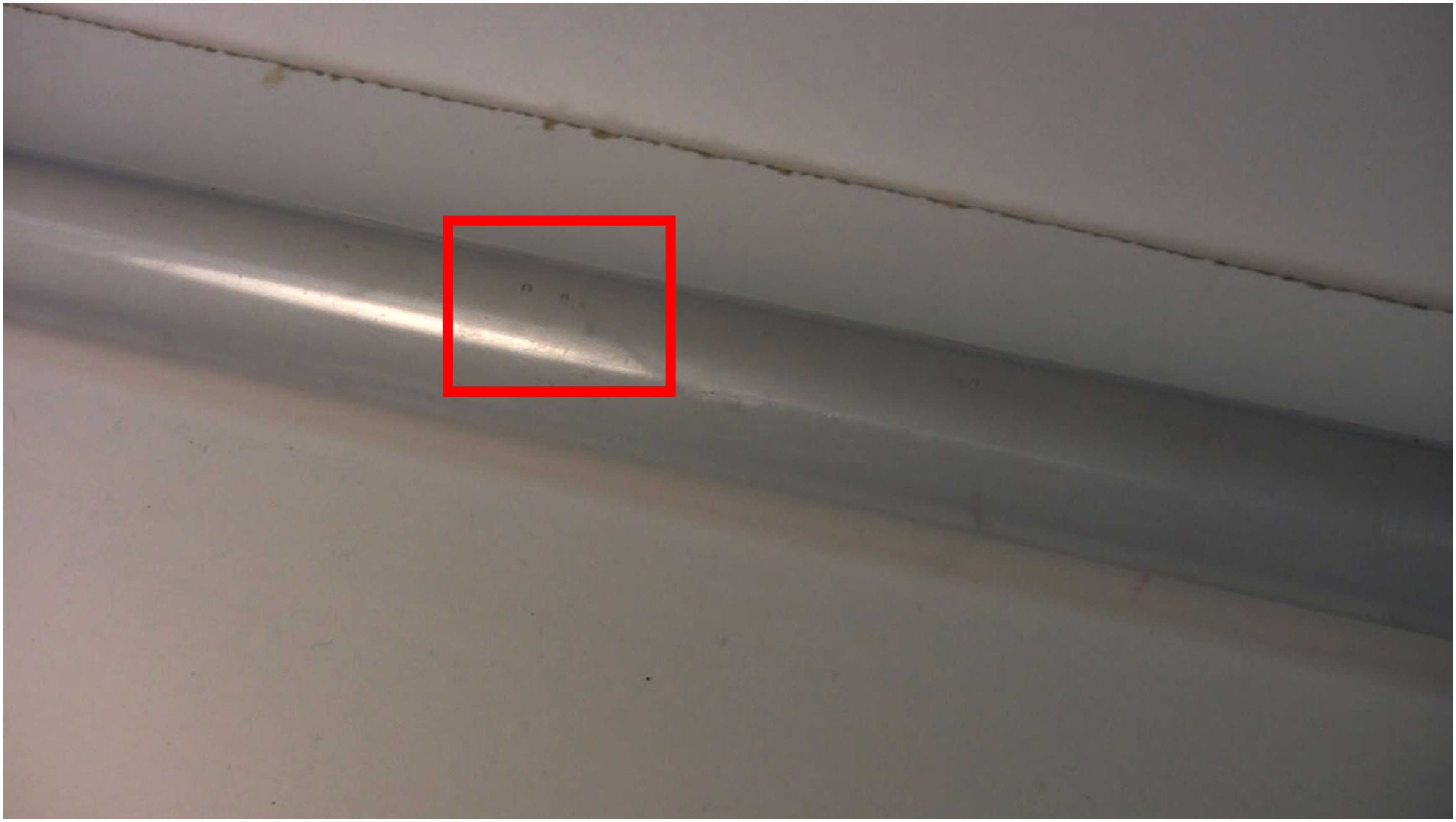

Figure App. I-D 8 (t=0.825)

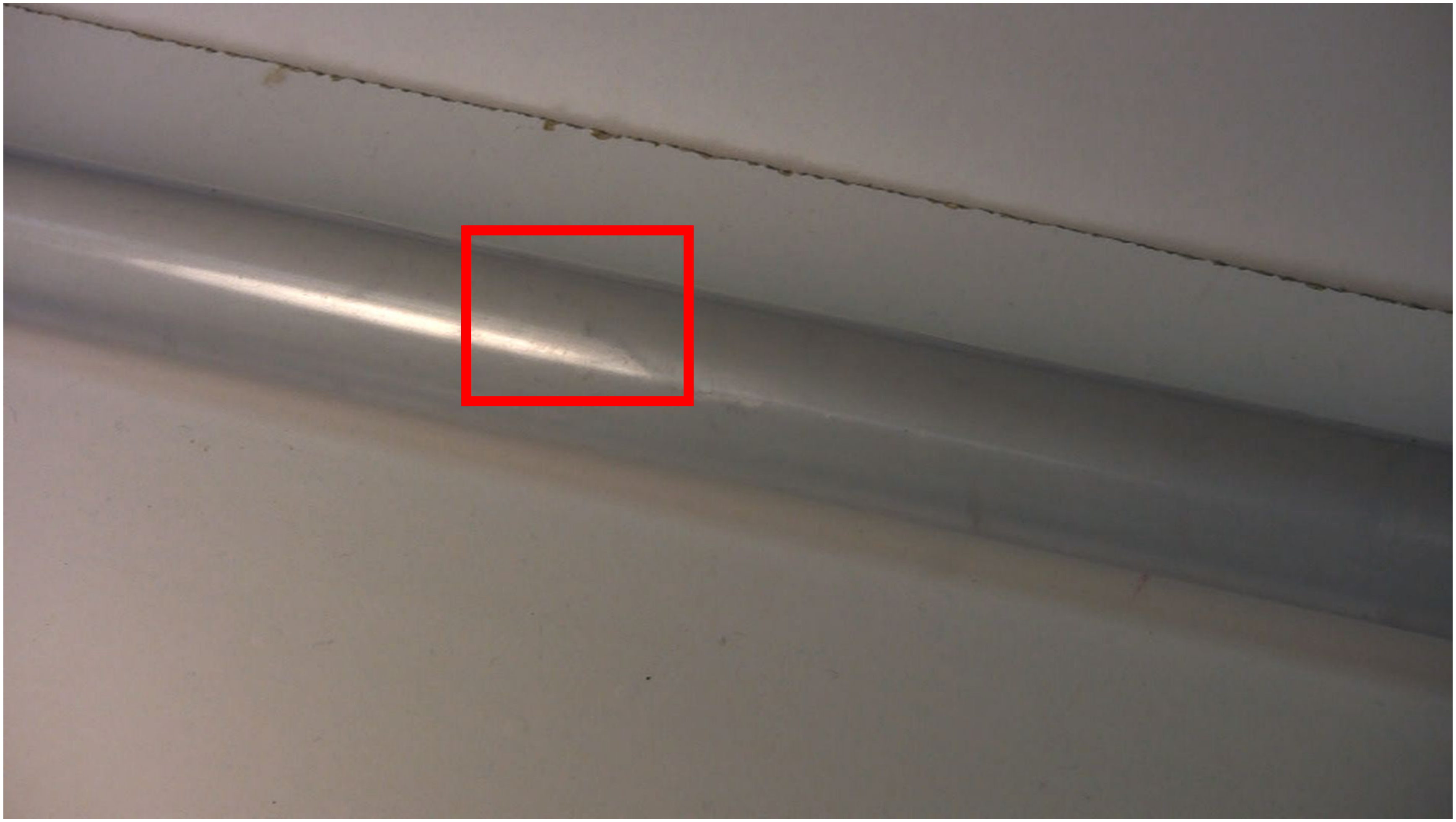

Figure App. I-D 9 (t=0.924)

Figure App. I-D 10 (t=0.957)

Appendix I-E

Figure App. I-E 1 (t=0.033)

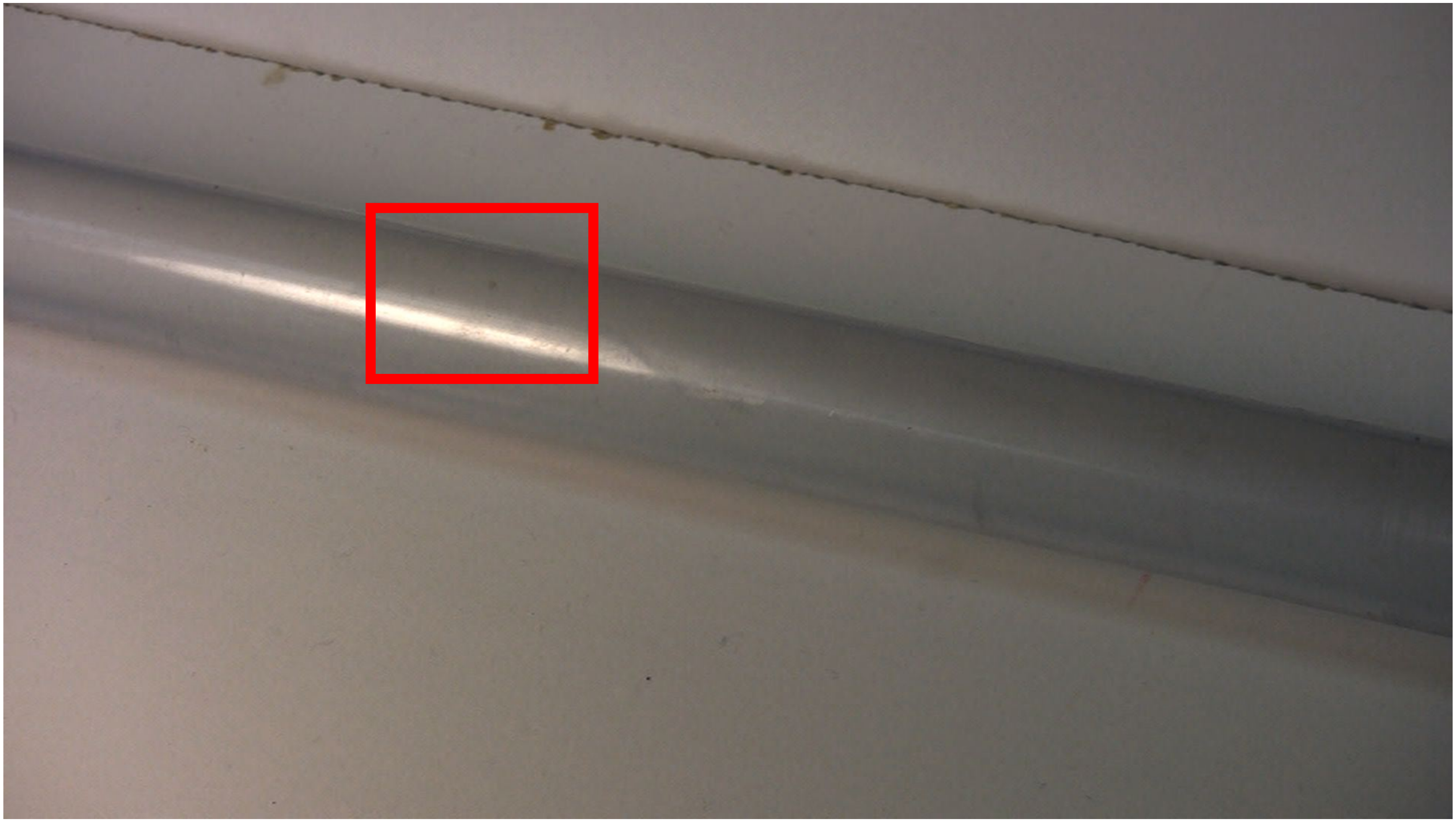

Figure App. I-E 2 (t=0.066)

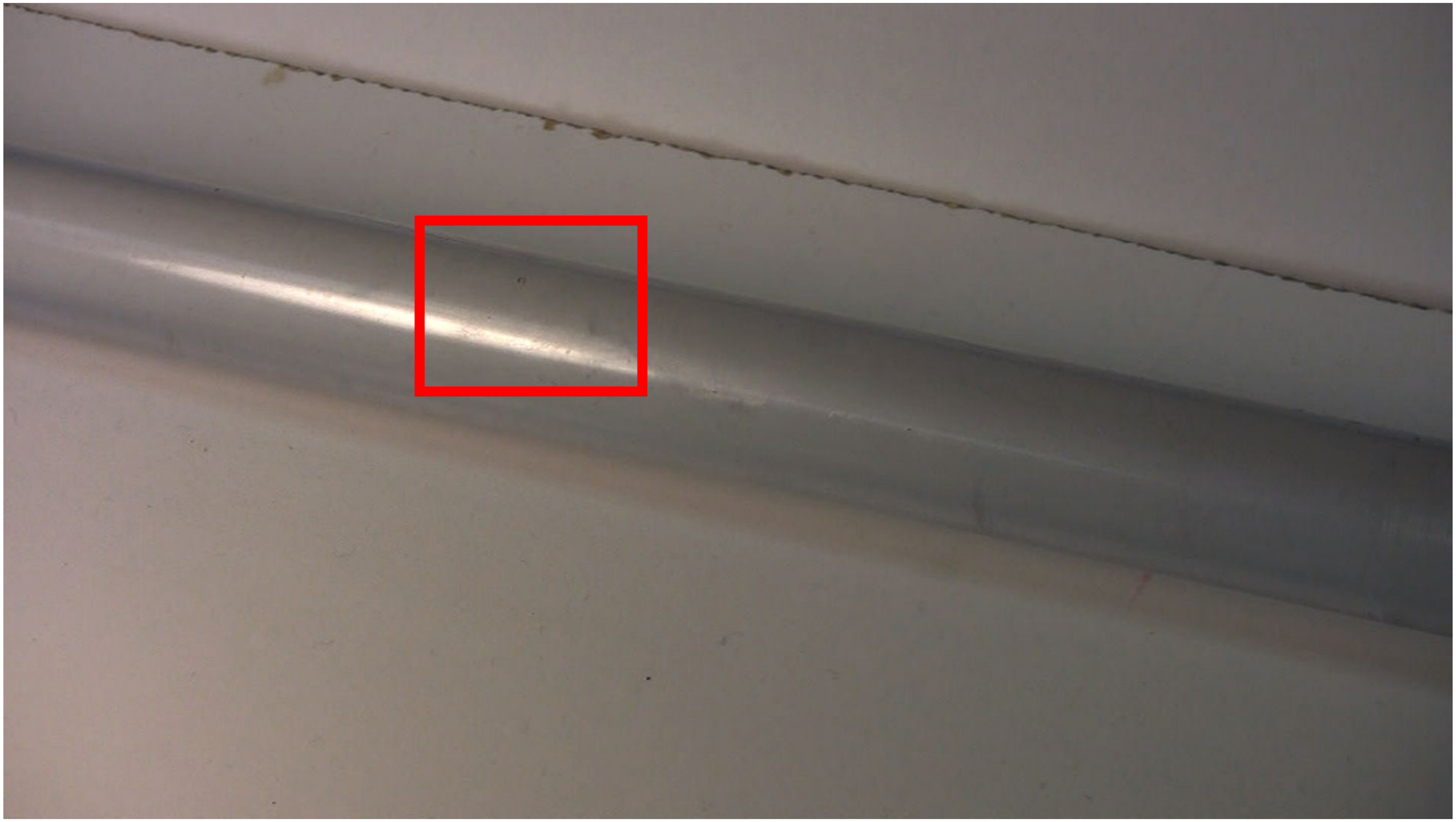

Figure App. I-E 3 (t=0.099)

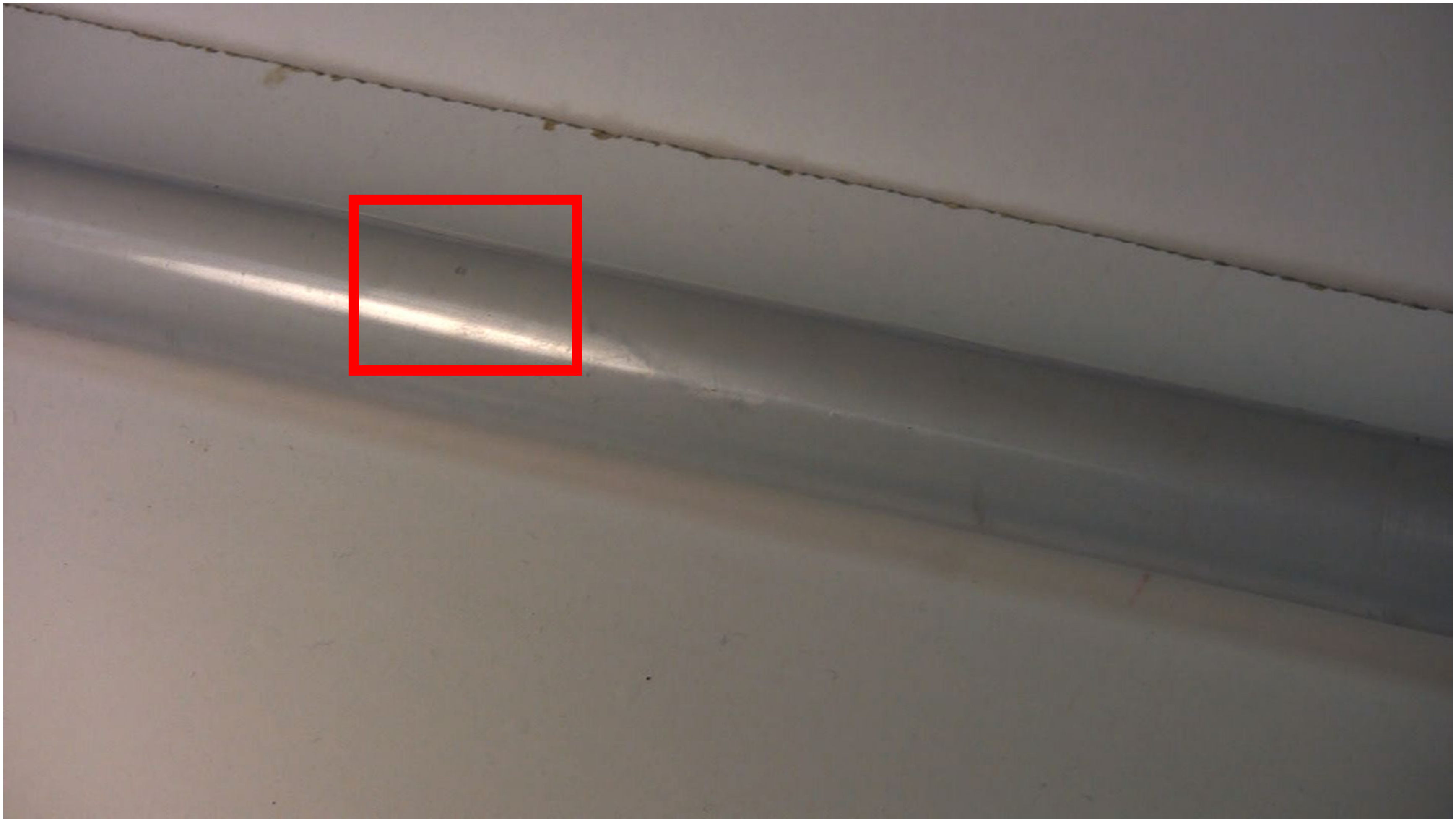

Figure App. I-E 4 (t=0.297)

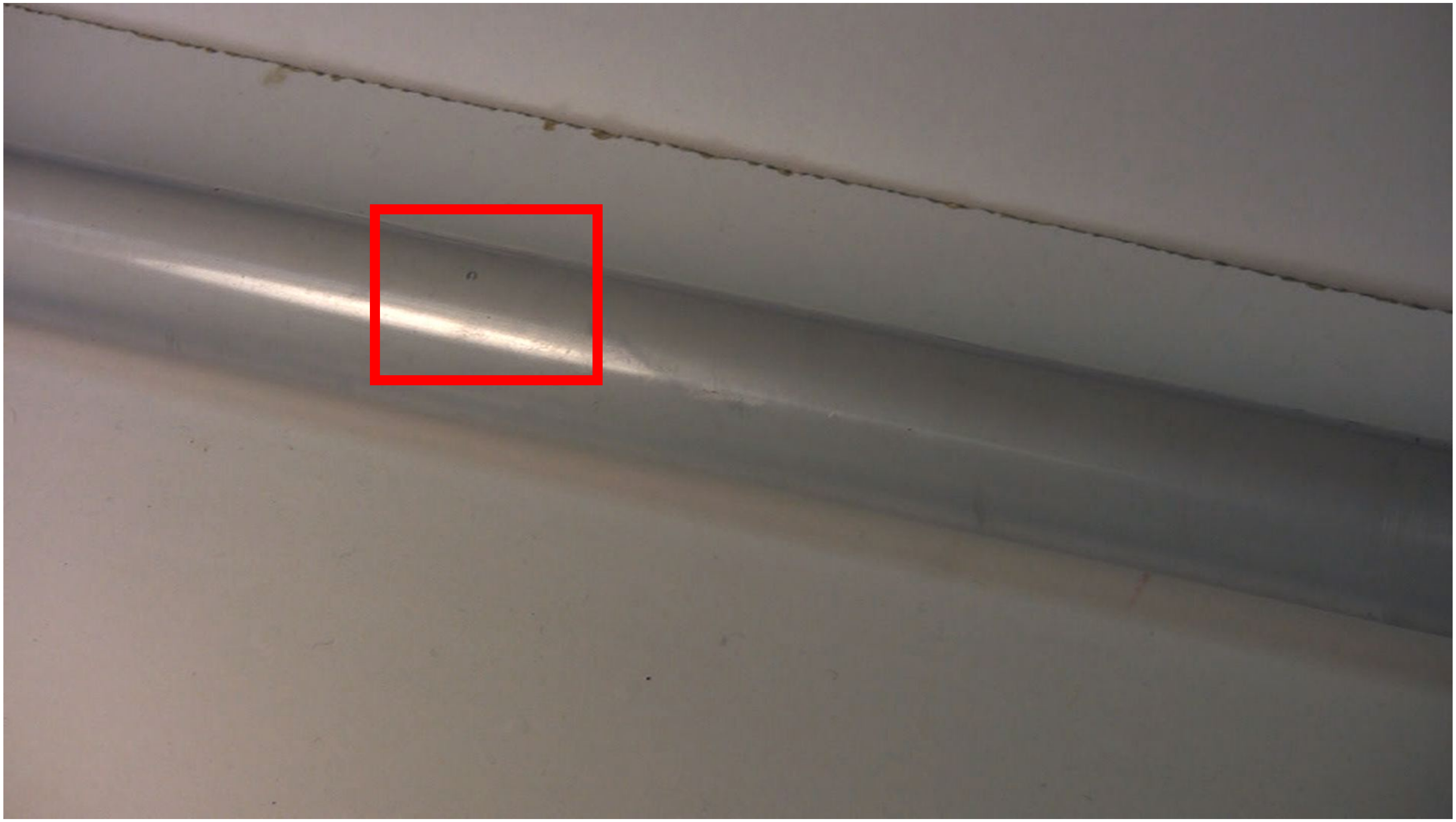

Figure App. I-E 5 (t=0.33)

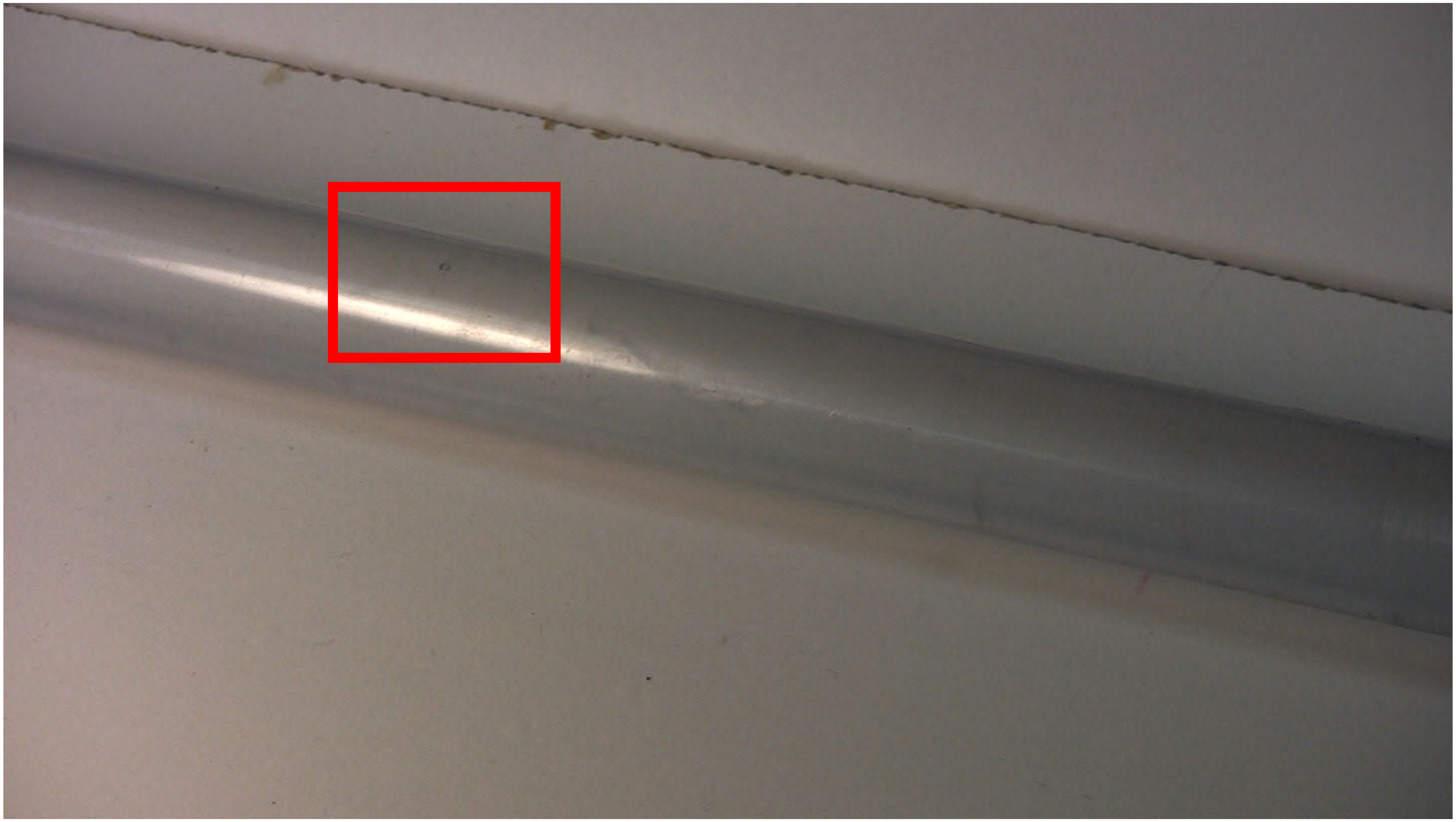

Figure App. I-E 6 (t=0.561)

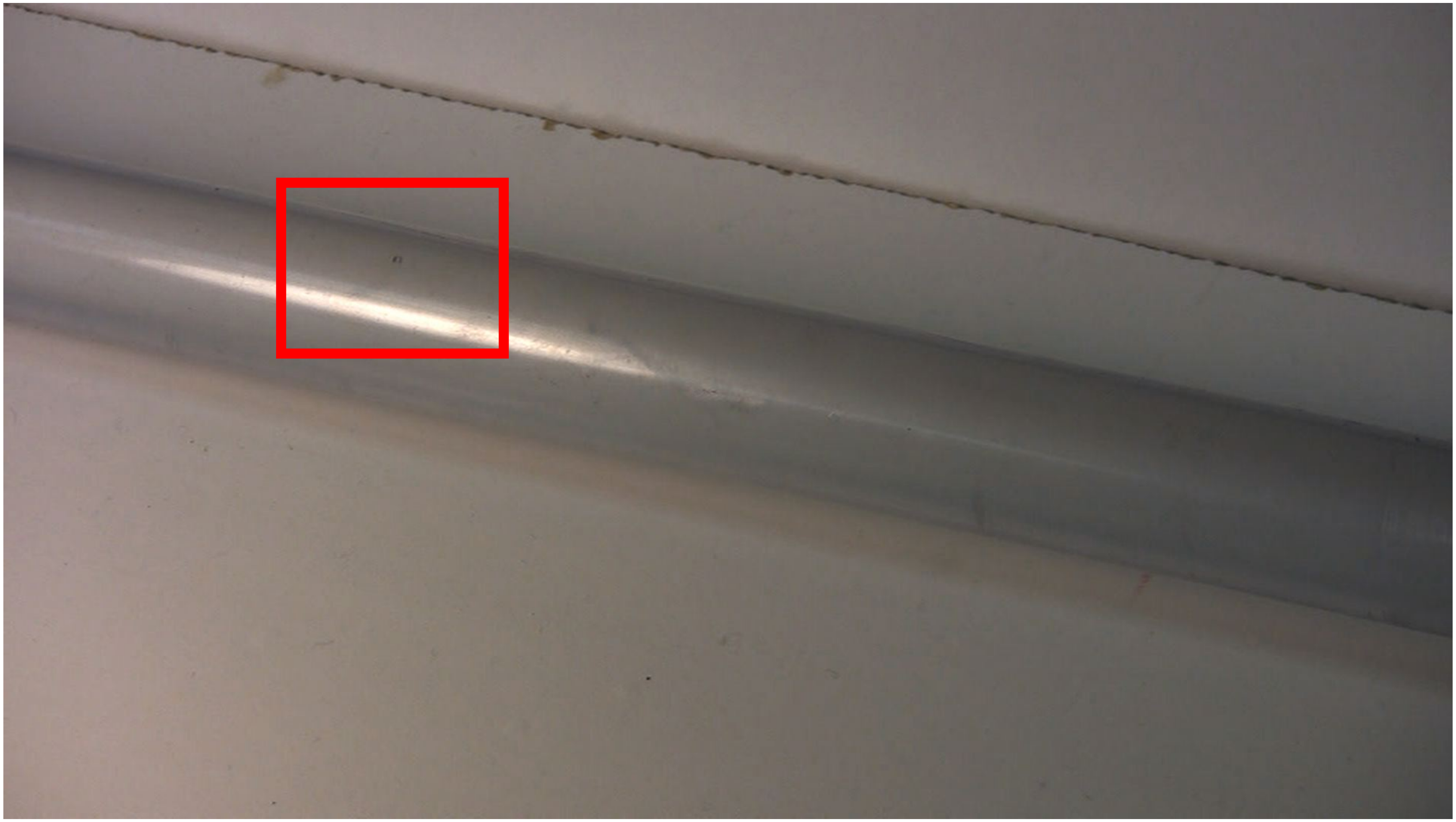

Figure App. I-E 7 (t=0.825)

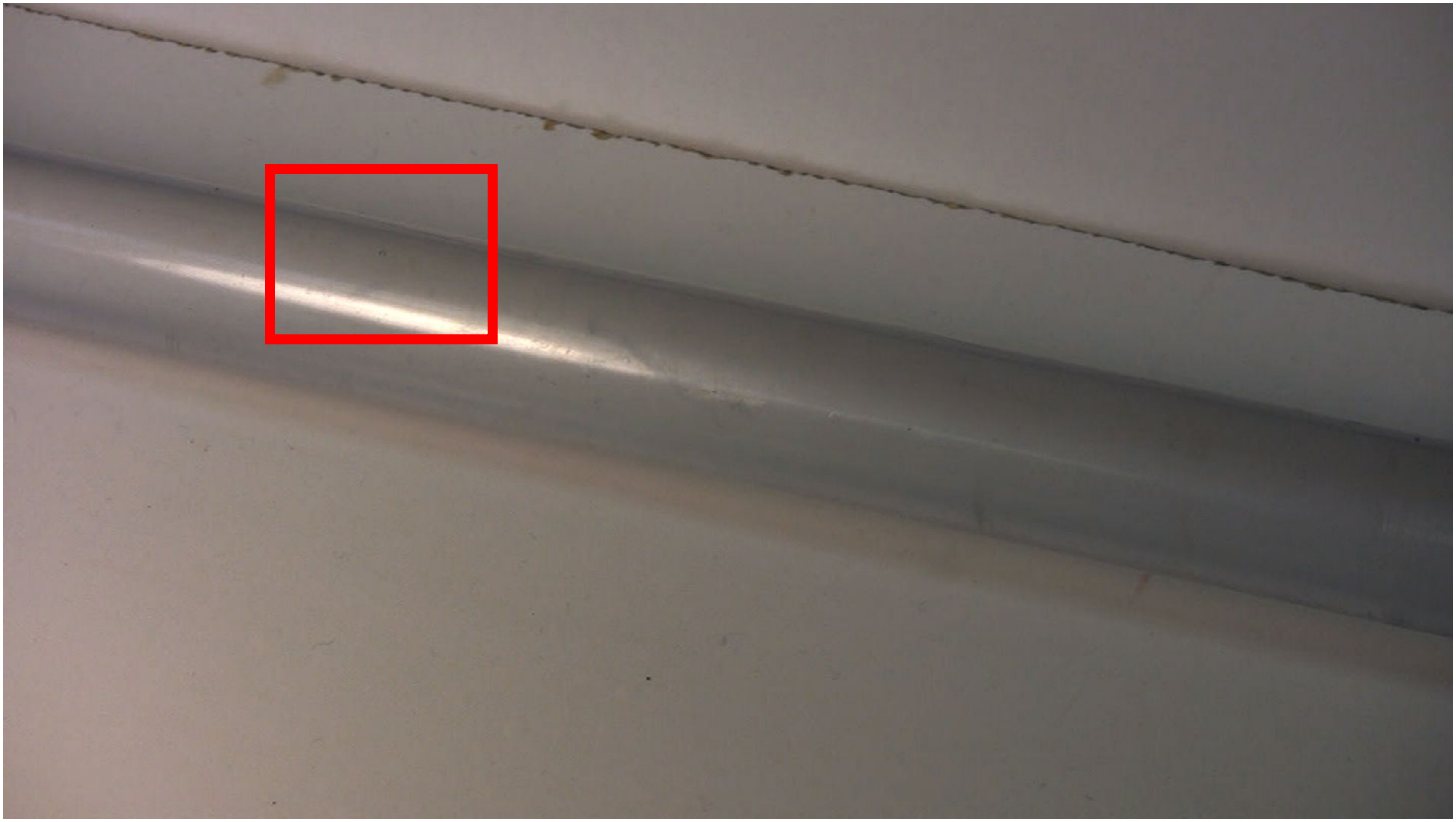

Figure App. I-E 8 (t=1.287)

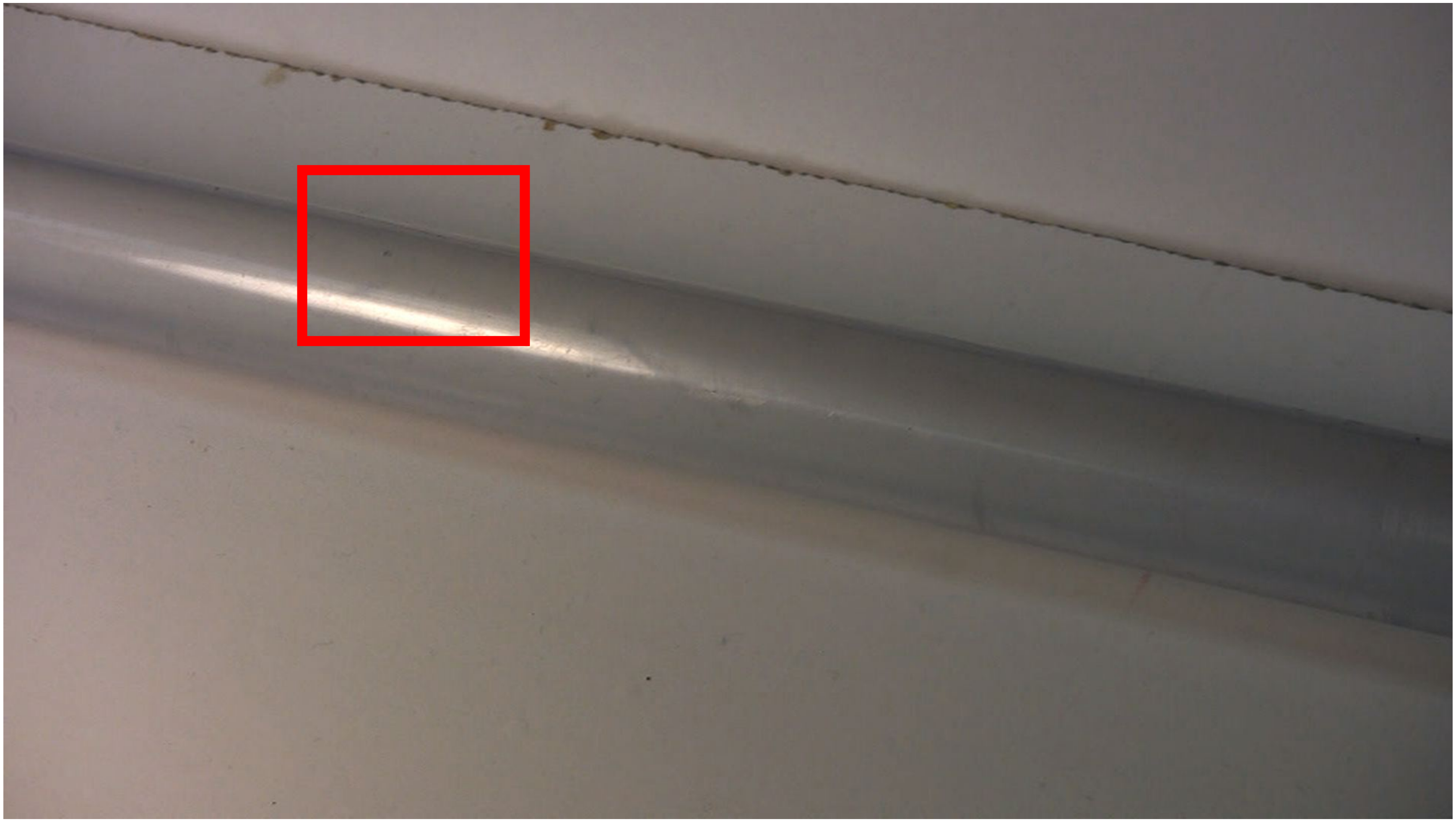

Figure App. I-E 9 (t=1.32)

Figure App. I-E 10 (t=1.518)

Appendix II-A
Engineering student survey

Assessment of Plumbing Materials

Survey Three

Consumer choices of home drinking water plumbing systems and materials have important implications for costs, reliability, aesthetics, and health of drinking water. The purpose of the survey is to elicit your preferences for home drinking water plumbing attributes and materials. The information you provide will be useful to policymakers, water utility managers, educators, researchers, and other professionals concerned with the quality of drinking water quality.

There are no right or wrong answers to the survey questions. Please give the answers, which reflect your preferences. Thank you for taking the time to complete this survey. ***Please note that the participation in this survey is completely voluntary.***

Typical two-story house (2000 square foot) has installed plumbing fixtures including two hose bibs, a dishwasher, a hot water heater, and a washing machine. Plumbing features mainly connect to the kitchen, bathrooms, and laundry room. The other elements include main street connection, which provides water supply to the house, water meter valve, various other internal valves, tee junctions, and bends. These plumbing systems require around 200 or 250 feet of pipes.

When leak occurs in the plumbing system, the homeowner is typically faced with the following issues: water damage cost, repair cost, service disruption, possible decrease of home value, home insurance premium increase/ non-renewal, and health problem, resulting among others from mold growth and emotional stress. Affected homeowners seek advice on repair and/or replacement of their home plumbing system. If they decide to replace their plumbing system, they have to decide on the appropriate pipe material for their house. A replacement of the entire plumbing system in a typical two-story house usually costs around $3,000 to $4,000, depending on the plumbing material selection.

Imagine you were deciding on plumbing materials for the house you grew up in or lived in most recently with your parents. After reviewing the given information on plumbing materials, please fill in the matrix.

Table A-II. 1 Attributes for drinking water pipe materials

	Pipe Material A	Pipe Material B	Pipe Material C
Corrosion Resistance	May corrode under select conditions	Not susceptible to corrosion	Resists corrosion and oxidation
Fire Retardance	Can withstand temperatures up to 2,000 degrees Fahrenheit without melting and emitting toxic fumes	May melt and emit toxic fumes at temperatures above 180~200 degrees Fahrenheit	Can withstand temperatures up to 2,000 degrees Fahrenheit without melting and emitting toxic fumes
Effects on Resale Value of Home	May increase resale value of a home	May have a negative effect on the resale value of a home compared to other plumbing materials	May increase the resale value of a home
Taste / Odor	Compounds released from this material in drinking water plumbing may give a bitter or metallic taste or odor to the water	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water	No effects on taste and odor of drinking water have been found
Health Effects	Compounds from plumbing made of this material that are released into drinking water, and exceed EPA standards, may cause vomiting, diarrhea, stomach cramps, and nausea	Compounds from plumbing made of this material that are released into drinking water may lead to microbial growth in water	No adverse effects on health have been found
Longevity	Plumbing made of this material have a 50-year manufacturer’s warranty	Some types of plumbing made of this material have 10-year manufacturer’s warranty	Plumbing made of this material has a long life span
Price	Price for ½’’ diameter pipe: $6.48 Price for ¾’’ diameter pipe: $10.04	Price for ½’’ diameter pipe: $2.84 Price for ¾’’ diameter pipe: $4.67	Price for ½’’ diameter pipe: $19.46 Price for ¾’’ diameter pipe: $30.11

Using the scale in Table 1, please indicate which attribute is more important to you by filling in the Table 2. For example, if ***heath** is extremely preferred to **fire retardance***; put 9 in the [H row, F column]. You will automatically fill the [F row, H column] cell as 1/9.

Table A-II. 2 Standard numerical scores

Preference Level	Score
Equally preferred	1
Equally to moderately preferred	2
Moderately preferred	3
Moderately to strongly preferred	4
Strongly preferred	5
Strongly to very strongly preferred	6
Very strongly preferred	7
Very strongly to extremely preferred	8
Extremely preferred	9

Table A-II. 3 Pair-wise preference weight matrix

	PRICE	CORROSI-ON RESISTANCE	FIRE RETARDANCE	HEALTH EFFECTS	LONGE-VITY	RESALE VALUE OF HOME	TASTE AND ODOR
PRICE	**1**						
CORROSION RESISTANCE		**1**					
FIRE RETARDANCE			**1**				
HEALTH EFFECTS				**1**			
LONGEVITY					**1**		
RESALE VALUE OF HOME						**1**	
TASTE AND ODOR							**1**

Please compare the three materials with respect to the attributes given in Table 3 through 9. Like the previous exercise, use the numerical scale given in Table 1. For example, in Table 3 (for price) *Material A is moderately preferred to Material B*; then put 3 in [Mat. A row, Mat. B column]. You will automatically fill 1/3 in [Mat. B row, Mat. A column].

Table A-II. 4 Price

Material	Mat. A	Mat. B	Mat. C
Mat. A	1		
Mat. B		1	
Mat. C			1

Table A-II. 5 Corrosion resistance

Material	Mat. A	Mat. B	Mat. C
Mat. A	1		
Mat. B		1	
Mat. C			1

Table A-II. 6 Fire retardance

Material	Mat. A	Mat. B	Mat. C
Mat. A	1		
Mat. B		1	
Mat. C			1

Table A-II. 7 Health effects

Material	Mat. A	Mat. B	Mat. C
Mat. A	1		
Mat. B		1	
Mat. C			1

Table A-II. 8 Longevity

Material	Mat. A	Mat. B	Mat. C
Mat. A	1		
Mat. B		1	
Mat. C			1

Table A-II. 9 Resale value of home

Material	Mat. A	Mat. B	Mat. C
Mat. A	1		
Mat. B		1	
Mat. C			1

Table A-II. 10 Taste and odor

Material	Mat. A	Mat. B	Mat. C
Mat. A	1		
Mat. B		1	
Mat. C			1

Lastly, please *rank the plumbing materials* if you are purchasing one of them.

Material A: __________

Material B: __________

Material C: __________

Thank you for completing the survey! Please go to next page for additional questions.

Question I

How much time did it take you to do the survey?

Answer:

____

Question II

Were there parts of the survey that you found misleading and/or confusing?

Answer:

Yes ☐
No ☐

If yes, what was misleading/confusing?

Answer:

Question III

What did you like about the survey?

Answer:

Question IV

What did you dislike about the survey?

Answer:

Appendix II-B
Southeastern community 1st phase survey

National Home Drinking Water Assessment
Attn: Darrell Bosch
Department of Agricultural and Applied Economics (0401)
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

June 2007

Dear Southeastern community Village Resident:

Researchers from Virginia Tech, funded by a grant from the National Science Foundation, are investigating pinhole leak damages in home drinking water plumbing in select U.S. locations. With cooperation of Southeastern community Village Public Works staff along with Loudon and Monroe Counties water utilities and the Southeastern community Village Copper Pipe Pinhole Leak Committee, we are gaining a better understanding of pinhole leak problems. The Southeastern community Village Pinhole Leak Committee has encouraged us to survey their residents along with other residential locations concerning their attitudes and experiences regarding their drinking water and home plumbing.

With this survey, we seek to understand the costs in terms of money, time, and stress related to pinhole leaks that have accrued throughout the United States. Also, we wish to understand the decision-making processes residents use to cope with their particular circumstances. We encourage you to complete the survey even if you have never had problems with your plumbing. Your responses will assist in providing a more accurate picture of drinking water and home plumbing in Southeastern community Village. Survey results will help water utilities and policy experts plan strategies to deal with home plumbing corrosion. Be assured that your responses will be treated confidentially. Individual responses will not be reported. All responses from residents will be compiled, analyzed, and reported together. Questions that refer to repair choices or spending decisions are provided as examples only and are not connected to any group or business now or in the future.

The survey will take about fifteen minutes to complete. ***After completing the survey, please return it in the enclosed, postage-paid envelope or send it to the address above.*** If you would like to receive a summary of results, please include your contact information on the enclosed card and return it with the survey or mail it separately. If you have questions, contact me at 540-231-5265 or by email at bosch@vt.edu.

Thank you very much for your help with this important survey.

Sincerely,

Darrell Bosch
Professor

1. Which Southeastern community Village neighborhood do you live in? (CIRCLE ONE NUMBER)

   1. Chatuga
   2. Chota
   3. Coyatee
   4. Kahite
   5. Mialaquo
   6. Tanasi
   7. Tommotley
   8. Toqua
   9. Don't know

2. Have you had any problems with the following attributes of your tap water? (CIRCLE ALL THAT APPLY)

   1. Taste
   2. Odor
   3. Color
   4. Other (Specify) ________________________________
   5. No problems

3. How satisfied are you with the quality of tap water in your house (CIRCLE ONE NUMBER)?

   1. Very satisfied
   2. Somewhat satisfied
   3. Somewhat dissatisfied (Specify why________________________________)
   4. Not at all satisfied (Specify why___________________________________)

4. How aware are you of pinhole leak problems (small holes in home drinking water pipes) in the area where you live? (CIRCLE ONE NUMBER)

   1. Very aware of this problem and have had experience with pinhole leaks
   2. Very aware of this problem but have not had any pinhole leaks
   3. Have heard about the problem and know some details
   4. Have heard about this problem but do not know any details
   5. Not at all aware of this problem

5. How did you hear about the pinhole leak problem? (CIRCLE ALL THAT APPLY)

   1. Own experience
   2. Neighbor / friend
   3. Media (Channel 3, The Village Connection)
   4. Copper Pipe Pinhole Leak Committee of Property Owner's Association
   5. Other (Specify) ______________________________________

6. What type of drinking water pipes do you have in your home? (CIRCLE ALL THAT APPLY)

1. Copper
2. CPVC
3. PEX
4. Other (Specify)____
5. Don't know

7. Have you ever had to replace or repair any of the drinking water pipes in your house? (CIRCLE ONE NUMBER)

1. Yes (please specify why repair/replacement was made)_______________
2. No
3. Don't know

8. If yes, when were the pipes replaced or new ones added? (CIRCLE ALL THAT APPLY)

1. Since 2004
2. 2000-2003
3. 1995 to 1999
4. 1990 to 1994
5. Before 1990
6. Don't know

9. Have you ever had a pinhole leak (small hole in pipe) in the hot or cold drinking water pipes in your current home? (CIRCLE ONE NUMBER)

1. Yes
2. No
3. Don't know

10. Have you had other kinds of failure in your drinking water pipes? (FILL IN THE BLANK)

____

If you have never had pinhole leaks, please go to question 25. If you have had pinhole leaks in your current home, please continue to the next question.

11. What material was the pipe with the leaks made of? Was it copper, iron, plastic or PVC, stainless steel, brass or another material? (CIRCLE ALL THAT APPLY)

1. Copper
2. CPVC
3. PEX
4. Brass (specify: leak around valve stem, brass cracked or pinhole leak on the brass)____

5. Other (Specify)_______________________________________
6. Don't know

12. In approximately what year did you **first** have a pinhole leak or small hole in your drinking water pipes? (CIRCLE ONE NUMBER)

1. Since 2004
2. 2000-2003
3. 1995 to 1999
4. 1990 to 1994
5. Before 1990
6. Don't know

13. How many pinhole leak incidents have you had in your home? (CIRCLE ONE NUMBER)

1. 1 – 2
2. 3 – 4
3. 5 – 6
4. 7 – 10
5. More than 10 (Specify) _____________
6. Don't know

14. Over what period of time did these leaks occur? (CIRCLE ONE NUMBER)

1. Less than one year
2. 1-3 years
3. 3-6 years
4. More than 6 years
5. Don't know

15. Were the leaks in a horizontal, vertical pipe or pipe bend? (CIRCLE ALL THAT APPLY)

1. Horizontal pipes
2. Vertical pipes
3. Pipe bend
4. Don't know

16. Did the pinhole leaks occur underground, in your basement, on the first floor or higher? (CIRCLE ALL THAT APPLY)

1. Under slab or underground
2. Crawl space
3. Unfinished basement
4. Finished basement/walkout
5. First floor
6. Second floor or higher
7. Don't know

17. Did the leaks occur in cold or hot water pipes? (CIRCLE ONE NUMBER)

1. Cold water pipes
2. Hot water pipes
3. Both cold and hot water pipes
4. Don't know

18. Who fixed your leak problems? (CIRCLE ALL THAT APPLY)

1. Fixed them myself
2. Household member (other than myself)
3. Relative/friend/neighbor
4. Professional plumber/contractor
5. Other (Specify) ______________________
6. Don't know

19. How did you fix the leaks? (CIRCLE ALL THAT APPLY)

1. Clamp over leak
2. Replaced only leaking section of pipe (please specify material used) ____
3. Applied coating/epoxy to all plumbing
4. Entirely replaced/replumbed (please specify material used for replumbing) ____
5. Other (Specify) ____________________________________
6. Don't know

20. What was the approximate cost to you, your landlord, and/or your insurance company to repair the leaks (plumbing repair expenses only)? (CIRCLE ONE NUMBER)

1. Less than $100
2. $100 - $500
3. $501 - $1,000
4. $1,001 - $3,000
5. $3,001 - $5,000
6. $5,001 - $10,000
7. $10,001 - $20,000
8. More than $20,000 (Please specify) ______________________
9. Don't know

21. About how much money was spent by you, your landlord, and/or your insurance company to make repairs <u>for property damage to your home</u> resulting from leaks? (CIRCLE ONE NUMBER)

1. Less than $100
2. $100 - $500
3. $501 - $1,000
4. $1,001 - $3,000
5. $3,001 - $5,000
6. $5,001 - $10,000
7. More than $10,000 (Please specify) ______________________
8. Don't know

22. Did the leaks cause the need for you to replace or repair anything else in your home or the loss of valuable family heirlooms? (CIRCLE ONE NUMBER)

1. Yes (please describe repairs/replacements/losses)____________________
2. Had damage but has not yet been replaced or repaired
3. No
4. Don't know

23. About how many hours in total would you estimate you have spent dealing with pinhole leak problems in your home? (CIRCLE ONE NUMBER)

1. Less than 10
2. 11 – 20
3. 21 – 40
4. 41 – 80
5. More than 80 (Please specify) ______________
6. Don't know

24. Would you say that your overall experience with pinhole leaks was very stressful, somewhat stressful, not very stressful, or not at all stressful? (CIRCLE ONE NUMBER)

1. Very stressful
2. Somewhat stressful
3. Not very stressful
4. Not at all stressful
5. Don't know

ALL RESPONDENTS (WITH OR WITHOUT PINHOLE LEAKS) PLEASE CONTINUE ANSWERING HERE.

25. Do you use any of the following applications to **prevent** plumbing corrosion or pinhole leaks in your home? (CIRCLE ALL THAT APPLY)

1. Preventive replumbing (replumbed without experiencing any leaks) (Specify material used) ___________________________________
2. Applied coating/epoxy to all plumbing without experiencing any leaks
3. In-line injection of phosphate (corrosion inhibitors) into home water system
4. Water softener/water conditioning system
5. Copper Knight
6. Other (Specify) ___________________________________
7. I have not used any preventive device (Go to question 27)

26. If you used preventive replumbing or other corrosion prevention devices, what is the approximate cost of purchasing and installing the devices since you have moved in your home? (CIRCLE ONE NUMBER)

1. $1 - $99
2. $100 - $499
3. $500 - $999
4. $1,000 - $2,499
5. $2,500 - $4,999
6. $5,000 - $7,499
7. $7,500 – $9,999
8. $10,000 -14,999
9. $15,000 - $19,999
10. 20,000 or more (Specify) ____________________
11. Do not know

27. What is your approximate total monthly maintenance expenditure on corrosion prevention (including service contracts for corrosion treatment devices, water softeners, other chemicals, etc.)? (CIRCLE ONE NUMBER)

1. $0
2. $1 -$24
3. $25 - $49
4. $50 - $74
5. $75 - $99
6. $100 or more
7. Do not know

28. Consider the current condition of the drinking water plumbing system in your house. Your options include staying with your current plumbing system and fixing any problems which may arise or changing the entire plumbing system. Or, suppose, as another alternative, there is a government backed insurance program to cover all future costs of corrosion damage and repairs including collateral damage to home and personal property. With the second option, would you be willing to make a one-time payment of $6,500 for such an insurance program? (CIRCLE ONE NUMBER)

1. Yes, I would pay this amount
2. No, I would not pay this amount

29. Consider the current condition of the drinking water plumbing system in your house. You have the opportunity to replace your current plumbing with one of the alternatives listed. Please read carefully the descriptions of the alternatives and choose the alternative that you would most likely undertake.

Attribute	**Alternative**		
	A	**B**	**C**
Risk of corrosion after replumbing	5% risk	No risk	Stay with my current plumbing. Corrosion risk may range from 0% - 10%
Additional cost (materials, labor and general contractor)	$6,500	$9,000	$0

Which alternative would you choose? (CIRCLE ONE NUMBER)

1. Alternative A
2. Alternative B
3. Alternative C

30. How concerned are you that your home plumbing will develop pinhole leaks in the future? (CIRCLE ONE NUMBER)

1. Very concerned
2. Somewhat concerned
3. Not very concerned
4. Not at all concerned
5. Don't know

31. Do you use any of the following for purposes other than corrosion prevention? (CIRCLE ALL THAT APPLY)

1. Filter for the entire home water system
2. Filter as part of the refrigerator
3. Water softener/water conditioning system
4. Pitcher or bottle that filters drinking water
5. Store purchased drinking water / bottled water
6. Filter on faucet or under kitchen sink
7. Ultra violet (UV) system
8. Other (Specify) ___________________________
9. I do not use anything to improve home drinking water

32. If you use any of these items, please check the reason why you do so. (CIRCLE ALL THAT APPLY)

1. Improve safety of my drinking water
2. Improve the clearness of my drinking water
3. Improve taste or smell of my drinking water
4. Sales information or presentation
5. Other (Specify) _______________________________________

The following questions will help us better characterize the Southeastern community Village Community for statistical reference in our survey analysis. All responses will remain confidential. Overall results will be reported in summary form only.

33. Which of the following describes your home? (CIRCLE ONE NUMBER)

1. Single family home which I own
2. Single family home which I rent

34. Approximately what year was your house built? (CIRCLE ONE NUMBER)

1. Since 2000
2. 1995 to 1999
3. 1990 to 1994
4. Before 1990

35. What month and year did you move into your current home? (FILL IN THE BLANK)

___________ of _________
(month) (year)

36. What is the highest level of formal education you have completed? (CIRCLE ONE NUMBER)

1. Grade School
2. Some High School
3. High School grad (or GED)
4. Trade/Voc. School after High School
5. Some College
6. Completed Community College
7. Four-year College/University Graduate
8. Graduate School/Professional School
9. Do not know

37. Counting yourself, how many people live in your home now? (FILL IN THE BLANK)

____

38. What is your gender? (CIRCLE ONE NUMBER)

1. Male
2. Female

39. What is the approximate current market value of your home? (CIRCLE ONE NUMBER)

1. Less than $200,000
2. $200,001 - $250,000
3. $250,001 - $300,000
4. $300,001 - $350,000
5. $350,001 - $400,000
6. $400,001 - $500,000
7. $500,001 - $750,000
8. Over $750,001

40. Please choose the bracket that includes your best estimate of your household income before taxes last year: (CIRCLE ONE NUMBER)

1. Less than $35,000
2. $35,001 - $55,000
3. $55,001 - $75,000
4. $75,001 - $100,000
5. Over $100,000
6. Do not know

41. In what year were you born? OPTIONAL (FILL IN THE BLANK)

19_______

37. Do you consider yourself to be: OPTIONAL (CIRCLE ONE)

1. Caucasian
2. African American
3. Asian
4. Hispanic
5. Other (Please specify) _______________

Do you have additional comments regarding pinhole leak problems in home plumbing?

Are there other problems you would like to share about your home drinking water?

Thank you for completing this survey!

On separate postcard

If you would be interested in receiving a report summarizing the results of the survey, please include your contact information below.

Name ____

Address ____

City____

State and Zip Code____

Email: ____

Telephone Daytime:_______________   Evening:______________ _______________

☐ Check here if you are willing to be contacted for follow up interviews. Include your telephone number.

Appendix II-C
Southeastern community 2nd phase survey

National Home Drinking Water Assessment
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Dear Southeastern community Village Resident:

Thank you for agreeing to be contacted again for a follow-up survey on home drinking water plumbing. Virginia Tech researchers are conducting this follow-up survey with funding from the National Science Foundation.

In this survey, we seek to understand your decision making process in the choices of home drinking water plumbing systems and materials. Plumbing materials have important implications for costs, reliability, aesthetics, taste, odor, and health impacts of drinking water. The main purpose of the survey is to elicit your preferences for home drinking water plumbing attributes and materials. The information you provide will be very useful to policymakers, water utility managers, educators, researchers, and other professionals concerned with the quality of drinking water.

Please be assured that your responses will be treated confidentially. Individual responses will not be reported. All responses from residents will be compiled, analyzed, and reported together. ***After completing the survey, please return it in the enclosed, postage-paid envelope or send it to the address above.*** If you would like to receive a summary of results, please include your contact information on the enclosed card and return it with the survey or mail it separately. If you have questions, contact me at 540-231-5265 or by email at *bosch@vt.edu*. We greatly appreciate your help with this important survey.

Sincerely,

Darrell Bosch
Professor

Introduction

This survey asks you to compare plumbing materials, which may differ according to the following attributes:

Corrosion resistance—ability of the material to resist corrosion.

Taste/odor—effect of the material on the taste or odor of drinking water.

Health—possible health effects of the material on those who consume drinking water.

Convenience of installation—ease of installing the plumbing material in the home.

Proven performance in market—time the plumbing material has been successfully used in the market.

Cost (material and labor)—material and labor cost to install the plumbing material in the home.

Warranty—length of time the plumbing material is guaranteed against failure.

Section 1. Comparing plumbing material options

In this section of the survey, you will see 3 questions consisting of two groups of messages describing plumbing material options. Imagine you were choosing plumbing materials for your house. After reading the messages in each question, please indicate your preference for each plumbing material option.

Question 1: Here is the first group of plumbing material options.
How would you rate each of the two plumbing material options described below?

Table A-II. 11 Numerical scores and Q1

Preference Level	Score
Not preferred	1
Moderately preferred	3
Strongly preferred	5
Very strongly preferred	7
Extremely preferred	9

Circle one number showing your preference level for each option.

Option A

1 3 5 7 9

Option B

1 3 5 7 9

Table A-II. 12 Information on options A and B

	Option A	**Option B**
Corrosion Resistance	Corrosion proof	Same as material A
Taste / Odor	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water.	Same as material A
Health Effects	Material meets EPA Standards. There is a very small chance that compounds from plumbing made of this material that are released into drinking water may lead to microbial growth in water. Microbial growth may cause severe illness.	Same as material A
Convenience of Installation	No need to tear into the wall and/or floor. Installation takes around 4 days.	Need to tear into some sections of wall for installation. Installation takes 5-6 days.
Proven Performance in Market	Less than 10 years in the market.	Less than 20 years in the market.
Cost (labor + material)	$9,000 ~ 14,000 depending on the size of house.	$6,500 ~ 13,000 depending on the size of house.
Warranty	Warranty is 15 years for the material.	Warranty is 10 years for the material.

Question 2: Here are two different plumbing options.
How would you rate each of the two plumbing material options described below?

Table A-II. 13 Numerical scores and Q2

Preference Level	Score
Not preferred	1
Moderately preferred	3
Strongly preferred	5
Very strongly preferred	7
Extremely preferred	9

Circle one number showing your preference level for each option.

Option A

1	3	5	7	9

Option B

1	3	5	7	9

Table A-II. 14 Information on options A and B

	Option A	**Option B**
Corrosion Resistance	Corrosion proof	Some risk of corrosion
Taste / Odor	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water.	Compounds released from this material in drinking water plumbing may give a bitter or metallic taste or odor to the water.
Health Effects	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may lead to microbial growth in water. Microbial growth may cause severe illness.	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may cause vomiting, diarrhea, stomach cramps, and nausea.
Convenience of Installation	No need to tear into the wall and/or floor. Installation takes around 4 days.	Need to tear into the wall and/or floor to replace the existing system. 7-9 days required for installation.
Proven Performance in Market	Less than 10 years in the market.	More than 50 years in the market.
Cost (labor + material)	$9,000 ~ 14,000 depending on the size of house.	$9,000 ~ 16,000 depending on the size of house.
Warranty	Warranty is 15 years for the material.	50 years manufacturer’s warranty. Some exceptions apply, e.g. warranty reduces to one year if compounds in water corrode pipes.

Question 3: Here are two different plumbing options.
How would you rate each of the two plumbing material options (circle one number with your preference level for each option below)?

Table A-II. 15 Numerical scores and Q3

Preference Level	Score
Not preferred	1
Moderately preferred	3
Strongly preferred	5
Very strongly preferred	7
Extremely preferred	9

Circle one number showing your preference level for each option.

Option A

1 3 5 7 9

Option B

1 3 5 7 9

Table A-II. 16 Information on options A and B

	Option A	**Option B**
Corrosion Resistance	Corrosion proof	Some risk of corrosion
Taste / Odor	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water.	Compounds released from this material in drinking water plumbing may give a bitter or metallic taste or odor to the water
Health Effects	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may lead to microbial growth in water. Microbial growth may cause severe illness.	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may cause vomiting, diarrhea, stomach cramps, and nausea.
Convenience of Installation	Need to tear into some sections of wall for installation. Installation takes 5-6 days.	Need to tear into the wall and/or floor to replace the existing system. 7-9 days required for installation
Proven Performance in Market	Less than 20 years in the market.	More than 50 years in the market.
Cost (labor + material)	$6,500 ~ 13,000 depending on the size of house.	$9,000 ~ 16,000 depending on the size of house.
Warranty	Warranty is 10 years for the material.	50 years manufacturer's warranty. Some exceptions apply, e.g. warranty reduces to one year if compounds in water corrode pipes.

Section 2. Comparing Plumbing Attributes

In this section, you will compare the attributes of the plumbing materials. Using the scale in the table below, please indicate which attribute is more important to you by circling the number. For example, if ***cost (material and labor)*** *is equally preferred to* ***health***; circle 1. Similarly, if ***convenience of installation*** is *moderately preferred* to ***taste and odor***, circle 3 in convenience of installation side.

Table A-II. 17 Standard numerical scores

Preference Level	Score
Equally preferred	1
Moderately preferred	3
Strongly preferred	5
Very strongly preferred	7
Extremely preferred	9

Example

Cost (material + labor)						Health		
9	7	5	3	(1)	3	5	7	9

Convenience of installation						Taste/Odor		
9	7	5	(3)	1	3	5	7	9

Please circle the number to show your preference on each line below.

Comparison									
Comparison (a)	Corrosion resistance					Cost (material + labor)			
	9	7	5	3	1	3	5	7	9
Comparison (b)	Health					Proven performance in market			
	9	7	5	3	1	3	5	7	9
Comparison (c)	Convenience of installation					Warranty			
	9	7	5	3	1	3	5	7	9
Comparison (d)	Warranty					Proven performance in market			
	9	7	5	3	1	3	5	7	9
Comparison (e)	Cost (material + labor)					Taste/Odor			
	9	7	5	3	1	3	5	7	9
Comparison (f)	Health					Cost (material + labor)			
	9	7	5	3	1	3	5	7	9
Comparison (g)	Taste/Odor					Warranty			
	9	7	5	3	1	3	5	7	9
Comparison (h)	Warranty					Health			
	9	7	5	3	1	3	5	7	9
Comparison (i)	Proven performance in market					Corrosion resistance			
	9	7	5	3	1	3	5	7	9
Comparison (j)	Health					Taste/Odor			
	9	7	5	3	1	3	5	7	9
Comparison (k)	Taste/Odor					Corrosion resistance			
	9	7	5	3	1	3	5	7	9
Comparison (l)	Proven performance in market					Cost (material + labor)			
	9	7	5	3	1	3	5	7	9

Comparison (m)	Cost (material + labor)					Convenience of installation			
	9	7	5	3	1	3	5	7	9
Comparison (n)	Convenience of installation					Taste/Odor			
	9	7	5	3	1	3	5	7	9
Comparison (o)	Health					Corrosion resistance			
	9	7	5	3	1	3	5	7	9
Comparison (p)	Warranty					Corrosion resistance			
	9	7	5	3	1	3	5	7	9
Comparison (q)	Convenience of installation					Health			
	9	7	5	3	1	3	5	7	9
Comparison (r)	Corrosion resistance					Convenience of installation			
	9	7	5	3	1	3	5	7	9
Comparison (s)	Proven performance in market					Taste/Odor			
	9	7	5	3	1	3	5	7	9
Comparison (t)	Convenience of installation					Proven performance in market			
	9	7	5	3	1	3	5	7	9
Comparison (u)	Cost (material + labor)					Warranty			
	9	7	5	3	1	3	5	7	9

Section 3. Comparing Plumbing Materials

In this section you are asked to compare plumbing materials with respect to specific attributes: Cost, Taste and odor, Health, Corrosion resistance, Convenience of installation, Warranty, and Proven performance in the market. Using the scale in the table below, please indicate which option is preferred to you by circling the number. For example, if ***Option A*** *is equally preferred to* ***Option B,*** circle 1.

Table A-II. 18 Standard numerical scores

Preference Level	Score
Equally preferred	1
Moderately preferred	3
Strongly preferred	5
Very strongly preferred	7
Extremely preferred	9

Example: **Option A** and **Option B** are *equally preferred* when we consider taste and odor effects only. So, number 1 is circled in this example.

Taste and odor

Option A	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water.
Option B	Compounds released from this material in drinking water plumbing may give a bitter or metallic taste or odor to the water.

Please circle the number to show your preference for option A or B.

Option A					Option B			
9	7	5	3	(1)	3	5	7	9

I. Corrosion resistance

The following question asks you to compare two options for corrosion resistance.

Option A	Some risk of corrosion
Option B	Corrosion proof

Please circle the number to show your preference for option A or B.

Option A					Option B			
9	7	5	3	1	3	5	7	9

II. Taste and odor

The following question asks you to compare two options for taste and odor.

Option A	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water.
Option B	Compounds released from this material in drinking water plumbing may give a bitter or metallic taste or odor to the water.

Please circle the number to show your preference for option A or B.

Option A					Option B			
9	7	5	3	1	3	5	7	9

III. Health

The following question asks you to compare two options for health effects.

Option A	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may lead to microbial growth in water. Microbial growth may cause severe illness.
Option B	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may cause vomiting, diarrhea, stomach cramps, and nausea.

Please circle the number to show your preference for option A or B.

Option A					Option B			
9	7	5	3	1	3	5	7	9

IV. Cost (material + labor)

The following question asks you to compare three options for cost of installation.

Option A	$9,000 ~ 14,000 depending on the size of house.
Option B	$6,500 ~ 13,000 depending on the size of house.
Option C	$9,000 ~ 16,000 depending on the size of house.

Comparison (a) Please circle the number to show your preference for option A or B

Option A						Option B		
9	7	5	3	1	3	5	7	9

Comparison (b) Please circle the number to show your preference for option B or C

Option B						Option C		
9	7	5	3	1	3	5	7	9

Comparison (c) Please circle the number to show your preference for option C or A

Option C						Option A		
9	7	5	3	1	3	5	7	9

V. Convenience of installation

The following question asks you to compare three options for convenience of installation.

Option A	No need to tear into the wall and/or floor. Installation takes around 4 days.
Option B	Need to tear into some sections of wall for installation. Installation takes 5-6 days.
Option C	Need to tear into the wall and/or floor to replace the existing system. 7-9 days required for installation

Comparison (a) Please circle the number to show your preference for option A or B.

Option A						Option B		
9	7	5	3	1	3	5	7	9

Comparison (b) Please circle the number to show your preference for option B or C

Option B						Option C		
9	7	5	3	1	3	5	7	9

Comparison (c) Please circle the number to show your preference for option C or A

Option C						Option A		
9	7	5	3	1	3	5	7	9

VI. Proven performance in the market

The following question asks you to compare three options for proven performance in the market.

Option A	Less than 10 years in the market.
Option B	Less than 20 years in the market.
Option C	More than 50 years in the market.

Comparison (a) Please circle the number to show your preference for option A or B.

Option A					Option B			
9	7	5	3	1	3	5	7	9

Comparison (b) Please circle the number to show your preference for option B or C

Option B					Option C			
9	7	5	3	1	3	5	7	9

Comparison (c) Please circle the number to show your preference for option C or A

Option C					Option A			
9	7	5	3	1	3	5	7	9

VII. Warranty

The following question asks you to compare three options for warranty of material..

Option A	Warranty is 15 years for the material
Option B	Warranty is 10 years for the material.
Option C	50 years manufacturer's warranty. Some exceptions apply, e.g. warranty reduces to one year if compounds in water corrode pipes.

Comparison (a) Please circle the number to show your preference for option A or B.

Option A					Option B			
9	7	5	3	1	3	5	7	9

Comparison (b) Please circle the number to show your preference for option B or C

Option B					Option C			
9	7	5	3	1	3	5	7	9

Comparison (c) Please circle the number to show your preference for option C or A

Option C					Option A			
9	7	5	3	1	3	5	7	9

Section 4. Choosing a plumbing material

Lastly, using the information in below table, please choose the material you would choose if you have to replace your current home plumbing system.
Circle the number by the material you would choose.

1) Material A **2) Material B** **3) Material C**

Table A-II. 19 Material information matrix

	Material A	Material B	Material C
Corrosion Resistance	Corrosion proof	Same as material A	Some risk of corrosion
Taste / Odor	Compounds released from this material in drinking water plumbing may give a chemical or solvent taste or odor to the water.	Same as material A	Compounds released from this material in drinking water plumbing may give a bitter or metallic taste or odor to the water.
Health Effects	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may lead to microbial growth in water. Microbial growth may cause severe illness.	Same as material A	Material meets EPA Standards. There is a very small chance that compounds from this plumbing material that are released into drinking water may cause vomiting, diarrhea, stomach cramps, and nausea.
Convenience of Installation	No need to tear into the wall and/or floor. Installation takes around 4 days.	Need to tear into some sections of wall for installation. Installation takes 5-6 days.	Need to tear into the wall and/or floor to replace the existing system. 7-9 days required for installation.
Proven performance in market	Less than 10 years in the market.	Less than 20 years in the market.	More than 50 years in the market.
Cost (labor + material)	\$9,000 ~ 14,000 depending on the size of house.	\$6,500 ~ 13,000 depending on the size of house.	\$9,000 ~ 16,000 depending on the size of house.
Warranty	Warranty is 15 years for the material.	Warranty is 10 years for the material.	50 years manufacturer's warranty. Some exceptions apply, e.g. warranty reduces to one year if compounds in water corrode pipes.

Thank you for completing this survey!