Drinking Water Distribution: Emerging Issues in Minor Water Systems

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Abstract This chapter addresses general characteristics of water distribution systems with focus on minor systems. Major systems are water mains that bring drinking water from water treatment plant to the building premises. Minor systems include service lines that connect major systems to minor system and in-building plumbing system. This chapter provides a detailed review of minor systems and mechanisms of minor systems' failures and describes experimental studies designed to replicate the range of pressures encountered in actual minor water distribution systems and how a pressure transient triggered within major and minor systems can impact service lines with possible contamination intrusion in minor systems. It is demonstrated that hydraulic transients triggered from water mains result in low-pressure events in service lines which can allow possible intrusion of microbial and chemical contaminants in service lines. It is concluded that the structural integrity of service lines and the hydraulic integrity of water distribution systems should be maintained in order to minimize public health risks from contaminant intrusion in minor systems and tap water.

Keywords Contaminant intrusion • Copper pitting • Water distribution systems • Hydraulic transients • Plumbing systems

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1 Introduction

President Clinton's Commission on Critical Infrastructure Protection 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 [1]. The National Research Council (NRC) categorized the drinking water distribution system's integrity in terms of the following components: (1) *physical integrity,* indicating the physical barrier between pipe externalities and inside the piping; (2) *hydraulic integrity,* consistently delivering the correct pressure, flow, water age, and capacity for providing fire flow; and (3) *water quality integrity,* maintaining a high standard of water quality without any degradation [2]. If any of the components fail to achieve the desired level of integrity, this can result in a serious *public health risk*. This indicates that the drinking water infrastructure bears significant operational and managerial responsibilities toward public health.

The growth in bottled water consumption and various kinds of point of use devices (filters) indicate citizens' concern regarding the quality of drinking water at the tap. However, the municipal public drinking water remains the top-ranked water supplier for established drinking water standards because of its cost advantage, the cost of maintaining point of use devices, and the relatively marginal water quality improvement which these devices provide.

The drinking water distribution system consists of "major system" and "minor system." A *major system* is generally defined as the water mains that bring drinking water from water treatment plant to the consumer's premises (homes and buildings) while a *minor system* is the plumbing system (including service lines) that transports water within the property boundaries [3]. Figure 1 shows a schematic diagram of the major and the minor systems. In the United States, major systems represent nearly 1.5 million km of piping [3]. America's water distribution infrastructure system is old and deteriorating. For major systems alone, 21,239 km of new pipes are installed every year to serve the nation's ever increasing population [4]. Minor systems are passive recipients of supplied water from the municipal system via major system network. It is noted that minor systems are known to be at least 5 or 10 times longer in total [3].

Over the past few decades, copper has been a preferred minor system (plumbing) material for a number of reasons including its proven record as a relatively corrosion resistant metal, as well as its durability, availability, affordability, better fire resistance, recyclability, and lower maintenance cost. A survey of materials used in plumbing found that 90 % of new homes had copper pipes, followed by PEX (cross-linked polyethylene) at 7 %, and CPVC (chlorinated polyvinyl chloride) at 2 % [5].

Table 1 shows the key characteristics of major and the minor systems. Municipalities manage major water distribution systems and management costs are distributed among consumers including schools, commercial buildings, residential housing, etc. However, when there is a leak in a house or building the property

Fig. 1 Schematic of major and minor systems (figure developed by author)

owner must cover the repair/replacement costs in their plumbing systems (minor systems). These typically include water damage and repair costs, service disruptions, a possible reduction in property value, and potential health consequences resulting from the growth of brown mold growth on the surface of walls, floors, and ceilings, which can cause allergic reactions including irritation of the eyes, skin, and throat. Copper corrosion can also result in copper concentrations in drinking water above those allowed by the EPA (1.3 mg/l); the consumption of excessive amounts of copper can cause health problems such as nausea, vomiting, diarrhea, and stomach cramps [3].

Repairs associated with plumbing failure can take up to several weeks, as the repairs extend beyond replacing the leaking sections to making good all the related damage to the building. Extensive repairs may cost property owners thousands of dollars and in many cases property insurance may not cover damage resulting from leaks. In addition to the financial and time costs, property owners may experience emotional stress due to dealing with these problems [3]. In this chapter, we address emerging issues in minor drinking water systems along with general characteristics of drinking water distribution systems as a whole.

Table 1 Characteristics of major and minor drinking water distribution systems [3]

Characteristic	Major system	Minor system
Pipe diameter	10 –36 cm[a]	1.2–2.54 cm
Pipe material	Ductile iron, plastic, cast iron	Copper, plastic, galvanized iron
Pipe length	10 to several 100 km per utility; about 1.4 million km of drinking water piping in the USA	Several 100 m per building.
Pipe wall thickness	Ductile iron 6.6 mm and above	Copper: K 1.25–1.7 mm; L 1.02–1.3 mm; M 0.71–0.89 mm
Corrosion	Both internal and external	Internal
Water flow velocity	0.9–1.8 m/s	~1.2 m/s
Demand	Specified	Pressure driven
Layout	Looped	Branched
Boundary condition	Energy head at the source or pump station	Energy head at the street level lateral
Life expectancy	Ductile iron ~80 years	Copper ~80 years; Galvanized iron 40–50 years
Ownership	Utility	End user (homeowner, business, organization)
Regulation	Government	Some plumbing codes
Cost	Distributed by water rates	Individual/insurance; replace piping $3,500–$6,000
Property damage	Distributed—few 100 s to several 1,000 s of dollars	Few 100 s to a few 1,000 s of dollars
Service response	Immediate	Delayed
Customer Dissatisfaction	Marginal to serious	Serious
Availability of data	Records kept—computerized	May not have records

[a]This pipe size is only for main line distribution pipes (not including larger transmission pipes)

2 Hydraulics of Major and Minor Systems

Drinking water is transported through major systems (water mains) to reach the minor systems, passing through curb stop (dividing line between major and minor systems), water meter, backflow preventer, bends, valves, junctions, and faucets, all of which can cause significant head losses (Fig. 1). To counter this, major systems are pressurized to deliver adequate flow rates and pressures to consumers. Hence, the pressure and velocity distribution in a minor system is dictated by the pressure maintained by the major systems or water mains. Below is a discussion of water pressure in major systems and its impact on water pressure in minor systems.

2.1 Major Systems

As mentioned, the water pressure and velocity within a minor system highly depend on the street level pressure. Pressure at street level is measured at the water mains, making it a boundary condition for the minor system (Fig. 1). Equation (1) shows the relationship between street level pressure and pressure in the minor system following energy equation (under steady state condition):

$$\frac{p_i}{\gamma_{\text{water}}} + \frac{v_i^2}{2g} + h_i + H_{\text{Losses}} = \frac{p_{\text{street}}}{\gamma_{\text{water}}}, \tag{1}$$

where P_{street} *is* street level pressure, p_i is the pressure in any pipe (i) in the minor system, v_i is the velocity of the water flowing through the pipe (i), h_i is the difference in elevation between the street level and the minor system point of measurement, g is the acceleration due to gravity, γ_{water} is the specific weight of water (assumed to be of a constant density), and H_{Losses} is the sum of the minor and friction losses from the street level to the point of measurement. It is noted that street level's velocity head values are negligible compared to those of minor systems. From equation (1), it is clear that both the velocity and pressure in a minor system is greatly affected by any changes in the street level pressure [6].

In drinking water distribution systems, the pressure level in main pipes changes with the high- and low-pressure zones according to the location of the pumping station or the elevation of the served region, so depending on the location of the building, the boundary condition can change markedly. In situations where the street main pressure is low or more energy is needed to raise the water to the top floor of a tall building, a booster pump is often used to supply additional head to the system. In addition, the street level pressure may drop significantly during peak hours due to simultaneous water use causing much lower pressures and velocities than normal conditions. Fire flow situations, when a fire truck is withdrawing large amounts of water from a fire hydrant, can also cause significant pressure drop in a building. In a case study of Arizona water system where several pressure drop reports had been received from customers, investigation found no problem in the minor systems, but an analysis of the nearby major water systems indicated that abrupt valve closures in the main system were causing problems at the household level [7]. This real situation confirms that street level pressure is a critical boundary condition for pressure distribution within a residential house and buildings.

2.2 Minor Systems

A minor system in a typical building/residential unit is composed of a number of fixtures that may include faucets, connections for bathrooms and water closets, dishwasher, hot water heater, and washing machine. Inside a typical house, there are three major locations for plumbing features: the kitchen, bathrooms, and the laundry room. The other elements in a domestic system include the service line that provides water to the building and the water meter, as well as various other internal valves, T-junctions, and bends.

The maximum pressure that the International Plumbing Code allows is 552 kPa and the typical steady state pressure for street level is 414–552 kPa [9]. In practice, water is normally distributed at pressures ranging between about 345 and 483 kPa through the street mains, which after factoring in the losses associated with the curb stop, water meter, backflow preventer, hot water heater, fittings, and friction, it drops to around 207 kPa at the end fixtures [9], Fig. 1. Novak [10] provides head loss calculations for a steady state system inside a house, given that the minimum pressure should be 241 kPa at the farthest point in the system and at least 138 kPa even in a fire flow situation [10]. This minimum pressure depends on the type of fixtures installed within the building. For example, if the hydraulically farthest plumbing fixture in the system requires 103 kPa, this will be the required minimum pressure. Significant amounts of energy (energy head) will dissipate through the various bends and T-junctions in a home plumbing system, and to maintain an adequate supply at the fixture, the minimum pressure must be satisfied.

In this vein, there are two boundary conditions for minor water distribution systems, the first of which is the pressure available at the street main and the second is that at the demand node or fixture, where minimum pressures are specified for each type of plumbing fixture. A conservative design process will utilize the minimum available street main pressure as this is the main source of energy for water flowing through a minor 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.

Minor system demand is defined by the loads imposed by plumbing fixtures (i.e., toilets, showers, sinks, dishwasher, etc.), which are designed to operate at certain pressures. Because all fixtures operate under pressure, they are usually referred to as "pressure driven" and the basic requirement is to maintain a certain minimum pressure, p_{min}, to deliver the necessary flow demand. This relationship takes the form, $\mathrm{Q} = \mathrm{Kp}^{\mathrm{a}}$ (for $\mathrm{p} \leq \mathrm{p}_{\mathrm{min}}$), and $\mathrm{Q} = \mathrm{Q}_{\mathrm{control}}$ (for $\mathrm{p} > \mathrm{p}_{\mathrm{min}}$), where K = emitter coefficient, Q = flow, p = pressure, a = exponent, and $Q_{control}$ = user controlled flow. Whenever p exceeds p_{min}, the pressure is capable of delivering more flow than actually needed [6].

3 Pipe Failure in Minor Systems

The predominant type of failures in minor systems is pitting or pinhole leaks. Pitting is defined as localized corrosion which develops as a result of nonuniform pitting corrosion [11–13]. Pipe corrosion is the major cause of pipe failure in minor systems. The cost of corrosion to public infrastructure was estimated to be about

$276 billion in 2002 (3.1 % of the nation's Gross Domestic Product), with water and sewer systems accounting for $36 billion, the largest share [14].

Lee and Loganathan [11] examined the nationwide distribution of pinhole pipe leaks for the period 2000–2004 and found that although pinhole leaks are a nationwide problem in the United States, several areas in California, Florida, Maryland, and Ohio experienced higher frequencies of leak incidents. A proactive monitoring system that involves condition inspection requires access to certain critical locations known to be prone to corrosion, but this is not currently available in most cases. Usually pipe leak data records are not kept by property owners and rarely reported to utilities. In order to address leak data deficiency, the Copper Development Association (CDA) collects failed pipe samples voluntarily donated by property owners, conducts analysis, and generates pipe failure reports which is cataloged in a database. While this is the largest national database of known copper water pipe failures, it has several limitations. Most notably, only pipe samples that are voluntarily submitted to CDA are analyzed. Due to this limitation, the database represents only a fraction of the copper pipe failures occurring in the United States.

Farooqi [12] mapped locations of copper pipe failures documented in CDA database. Some interesting conclusions can be drawn from the mapping geographical distribution of the reported pipe failures. Although failures have been documented nationwide, some localities have experienced a particularly high degree of premature pipe failures. Farooqi [12] found that data for certain states and certain large metropolitan areas were absent in CDA database. However, a telephone survey of a small number of plumbers in targeted communities in these areas confirmed that plumbers were called to repair pinhole leaks. Since a large percentage of pinhole leaks remain unreported, it can be inferred that, the extent of the problem is probably much larger than reflected in the failure database [13]. In the following section, an overview of copper pipe corrosion mechanisms and an in-depth literature review of the latest research in this area are presented, with a particular focus on those factors believed to cause pipe pitting and premature pipe failure in minor systems.

A number of different types of failures can occur in copper plumbing. One type of failure that has become particularly problematic in some communities is the pinhole leaks that develop as a result of nonuniform or pitting corrosion. In contrast to uniform corrosion, in which all parts of the internal pipe surface are attacked at roughly the same rate, nonuniform or pitting corrosion is localized, leading to the rapid loss of pipe wall thickness at that particular location.

Although copper is a relatively inactive metal, leaks due to corrosion are still the most common cause of residential copper pipe failures [13]. The term *corrosion* is exclusively used for metals [15, 16]. The four essential elements of aqueous electrochemical corrosion are an anode, a cathode, physical contact between the anode and the cathode, and an electrolyte [17]. In a drinking water pipe, an anode with a positive charge and a cathode with a negative charge are separated by a potential difference. The anode–cathode physical contact is the pipe permitting the electrons to flow from the anode to the cathode and the electrolyte is the water that conducts the ionic flow.

A metallic element, M, is oxidized as $M \rightarrow M^{n+} + ne^-$, constituting corrosion. The cathodic reactions are metal deposition by $M^{n+} + ne^- \rightarrow M$, metal ion reduction $M^{n+} + e^- \rightarrow M^{(n-1)+}$, hydrogen liberation in the absence of air or oxygen in a deaerated solution by $2H^+ + 2e^- \rightarrow H_2$, and the reduction of oxygen in aerated solutions as $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ in a neutral or basic solution with $pH \geq 7$ and $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ in an acidic solution with $pH < 7$. In drinking water, dissolved oxygen and residual chlorine can cause copper to oxidize as $Cu \rightarrow Cu^+ + e^-$. The cuprous ion Cu^+ is further oxidized into cupric ion Cu^{2+}. The corrosion current for copper in aerated neutral water is so small that the corrosion rate is only 10^{-2} mm/year [18]. However, real-world data point to the possible occurrence of nonuniform corrosion [12].

As mentioned, pitting is localized corrosion that occurs at a surface scratch or at a location of mechanically induced break in the protective film (passivation layer) or at a location where there is a material compositional heterogeneity such as an inclusion, segregate, or precipitate [19]. Pit formation can be explained as follows. Cuprous ion C^+ combines with Cl^- to form cuprous chloride CuCl next to the copper metal. This cuprous chloride is usually removed from the surface by hydrolysis [forming cuprite (cuprous oxide) Cu_2O by $2CuCl + H_2O \rightarrow 2HCl + Cu_2O$], oxidation, formation of cupric salts, and dissolution into the bulk solution. These reactions result in the formation of a passivating scale over the copper that protects it. However, when cuprous chloride is produced at a rate greater than its loss from the aforementioned processes, it remains under the cuprous oxide, leading to pitting. A comprehensive assessment of copper corrosion in drinking water systems is available in cited references [20, 21].

4 Copper Pipe Pitting

Several factors have been thought to influence pinhole leaks. However, scientific certainty regarding causal mechanisms of pinhole leaks is often limited due to inherent difficulty of reproducing pinhole leaks in controlled laboratory studies. As described below, copper corrosion and pitting reported in scientific literature can be broadly classified as either physical or chemical in nature. Most corrosion problems are due to the complex synergy between physical and chemical parameters [12, 13] and are affected by the source water, treatment plant processes, water quality changes within the major distribution system, and physical and chemical conditions within minor system. The formation of passive scales or dosing with corrosion inhibitors may also affect corrosion and pitting. The three most common conventional corrosion inhibitor additives are silicates, orthophosphates, and polyphosphates.

4.1 Chemical Parameters

Below water-related parameters are believed to influence corrosion in copper pipes, namely: (1) the concentration of dissolved oxygen (DO); (2) the pH; (3) the temperature; (4) the water flow velocity; (5) the concentration and type of chlorine residuals; (6) the chloride [Cl^-] and sulfate [SO_4^{2-}] ion concentrations; and (7) the concentration of dissolved inorganic carbon (DIC), defined in terms of the total alkalinity and pH [22].

One type of pitting that has been successfully reproduced in the laboratory included conditions of high pH (>7.8), high residuals of free chlorine, aluminum solids, and continuous water flow [14, 23, 24]. The experimental conditions led to multiple pinhole leaks in new copper piping after 9 months: In many instances chloride is associated with pitting [25] and Nguyen [26] provides a detailed review of chloride-induced pitting.

Some gases such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S) are considered to be particularly damaging to copper tubing. Research has shown that the copper corrosion rate increases with increasing concentrations of free carbon dioxide [27], but it is often difficult to differentiate between other influential corrosion factors that also affect carbon dioxide concentrations such as pH and alkalinity. Hydrogen sulfide, which is known for its characteristic "rotten egg" odor, can form from either the reduction of sulfur in mineral deposits or as a by-product of biological activity from sulfate reducing bacteria (SRB) [28, 29]. As little as 0.02 mg/l of H_2S can lead to perforations in copper, and sulfide attack can originate from sulfides present in the bulk water or from SRB growing on the pipe wall [30].

By-products from microbial activity are often thought to produce a chemical reaction causing microbial induced corrosion (MIC), such as in the case of SRB described earlier. Another suspected cause of failure is the presence of nitrifying bacteria, which could produce pH levels that are much lower than that in the average bulk water as the bacteria grow on the pipe surface. Corrosion or pitting can potentially increase due to the removal of natural organic matter (NOM) and poor practices after pipe installation [31]. For example, improper flushing of pipes followed by a long stagnation period between installation and building occupancy has been shown to cause pitting corrosion in new copper plumbing [32, 33].

4.2 Scale Layers

Pitting tendencies could potentially decrease if a protective layer of scale, known as a passivation layer, is allowed to form on the surface of the copper. A film of cuprous chloride (Cu_2Cl_2) is formed when the copper is immersed in a solution containing the chloride ion. This cuprous chloride is removed from the surface by a number of pathways, including hydrolysis, to form cuprite (cuprous oxide Cu_2O), followed by the oxidation and formation of cupric salts, and dissolution into the bulk solution. These reactions typically result in a passivating scale [20]. However, if the rate of formation of cuprous chloride exceeds the rate of its loss by the aforementioned reactions, pitting can take place. All pits are thought to include a layer of basic copper salts overlying a cuprite Cu_2O layer, with the basic salts being predominantly malachite $Cu_2(OH)_2CO_3$ in cold water and brochantite $Cu_4(OH)_6(SO_4)$ in hot and soft waters [20].

Since the solubility is relatively lower for malachite ($Cu_2(OH)_2CO_3$) and tenorite (CuO), other copper solids such as copper hydroxide, copper chloride, and cupric nitrate are not typically present within domestic plumbing systems [20]. Brochantite ($Cu_4(OH)_6(SO_4)$) is commonly present at high temperature (greater than 60 °C/140 °F) and is often found over pits in hot water pipes or hot water recirculation systems. The formation of the brochantite is subject to the concentration of bicarbonates (HCO_3^-) and $pH < 7$ conditions, and for waters with high sulfate to bicarbonate ratios pitting is therefore likely in hot water. In cold water pipes the formation of brochantite is favored at not only high sulfate to bicarbonate ratios but also high sulfate to chloride ratios. Brochantite formation is therefore likely to increase pitting in water that has undergone softening [20]. Sulfate ions are more aggressive than chloride ions in inducing pit germination and nitrate ions appear to be more aggressive than sulfate ions [34].

4.3 Inhibitors

Inhibitors may either form a protective film over the pipe surface or change the nature of the corrosion [22]. As noted earlier, the three most common conventional corrosion inhibitor additives are silicates, orthophosphates, and polyphosphates. The selection of an inhibitor may depend on factors such as water quality parameters (e.g., pH and alkalinity), the type of corrosion, and the material to be protected. Silicates ($H_3SiO_4^-$) form a protective film by reacting with corrosion by-products on the pipe surface, thus forming a physical barrier between the pipe wall and its environment. Silicates have been shown to be more effective as inhibitors at a higher pH [22].

Orthophosphates (HPO_4^{2-}) are thought to slow the rate of oxidation of copper at near neutral pH and even become counterproductive at pH values above 8.0 [22]. The early formation of a protective scale containing tenorite or cuprite [CuO or Cu_2O] has been reported to depend on the pH in water containing chlorine and orthophosphate. Dosing with orthophosphates has successfully reduced the extent of pinhole leaks after 1 year of their application in some Maryland communities that were previously observing a high rate of failure [35].

Polyphosphates have also been found to be effective for treating localized or pitting corrosion by changing it to more uniform corrosion [22]. However, polyphosphates could interfere with the deposition of protective calcium containing layers and also enhance the solubility of the copper. The latter may not be as serious problem as it first appears. Although it causes an increase in total metal loss, the overall life cycle of the pipe is increased since the corrosion becomes more uniform. Polyphosphates are sometimes used with orthophosphates to yield optimal benefits. While orthophosphate is believed to form Copper (II) Phosphate [$Cu_3(PO_4)_2$] or a similar scale on the copper pipe surface, at a pH of 7.2 and alkalinity of 300 mg/l with calcium carbonate ($CaCO_3$), the phosphate dosing led to increased copper release by hindering the formation of the malachite scale [14]. The same study also suggested that polyphosphates are not as beneficial as orthophosphate in controlling copper leaching to water.

4.4 Physical and Hydraulic Parameters

Physical damage from erosion can also be responsible for the formation of pinhole leaks. The calculated, safe design flow velocity in copper tube has been cited to be anywhere from 0.4 to 4.2 m per second (m/s), but 1.5 to 2.4 m/s is the most commonly used upper bound for design [8]. Factors that can make a pipe more susceptible to failure at lower velocity include (1) the presence of particulate matter in water that can impinge on surfaces and exacerbate erosion and (2) bubbles that form due to either vaporous or gaseous cavitation that can cause wear by implosion or impingement [10]. In a typical situation a maximum velocity of 0.9 m/s is recommended for water temperature above 60 °C [36], but if particulates or bubbles are present, failures can occur at even lower velocities.

Vapor pressure of water at ambient temperature (10–40 °C) typically varies between 1.2 kPa and 7.4 kPa and the total dissolved gas pressure of natural water is normally in the range 81.1 kPa to 121.6 kPa [37]. When the pressure of the medium drops below the saturation pressure of the dissolved gases it contains, bubbles of gas are formed and this phenomenon is known as *gaseous cavitation*. When the pressure in the liquid medium drops below the liquid's vapor pressure, vapor cavities are created in the liquid by phase transformation, or *vaporous cavitation*.

The primary dissolved gases in drinking water in the tap water are the same as those in the air we breathe, namely, nitrogen, oxygen, and carbon dioxide, though the precise composition of these gases changes according to the temperature, season, and even whether it is day or night [37]. The gas release rate is known to be proportional to the degree of under-pressurization. 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 [10]. These bubbles can grow or shrink depending on a number of factors, including surface tension, ambient liquid pressure, vapor pressure of the liquid, and gas pressure inside the bubble. Also, large bubbles may be formed by two or more smaller bubbles coalescing, and from free gas molecules entering existing bubbles [38]. The cavity inside the bubble increases in size until the internal pressure is sufficient to offset the decreasing external pressure and surface tension [39]. When this critical size is reached, the cavity becomes unstable and expands explosively, which can cause erosion corrosion [10].

Just as the major system is susceptible to hydraulic transients, water hammer within a domestic plumbing system can also induce transient pressure propagation. Water hammer is the term used to describe the destructive forces that manifest as pounding noises and vibration which develop in a piping system. When water hammer occurs, a high intensity pressure wave travels back through the pipe system until all the energies are dissipated [40]. The most common water hammer cause is the quick closing of valves in the plumbing system and it is known that the speed of the last 15 % of the valve closure is directly related to the intensity of the surge (hydraulic transients or water hammer) pressure. The average flow velocity in a plumbing system is 1.22–2.44 m/s. This destructive force may result in a number of undesirable outcomes, including 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, and the premature failures of other equipment and devices [41].

A survey of plumbers revealed that in their experience, most of water hammer incidences arise due to dishwashers and washing machines operated by mechanical solenoid valves [42]. They recommended the use of water hammer arrestors or mitigating the problem by designing flow velocities to not exceed 1.22 m/s (whereas the rest of the system is generally designed to provide flow velocity of around 1.83 to 2.44 m/s).

Attempts have been made to predict the likelihood that household plumbing will fail under a given set of conditions [43]. While there are reports in the literature identifying pipe failures due to the mechanisms and causal factors described above, there is no explanation as to why other pipes did not fail when subjected to similar water quality and hydraulic conditions. This anomaly can be resolved by assuming that these mechanisms have a certain likelihood of occurrence. In other words, the presence of a set of causal factors that have previously caused failures does not guarantee reoccurrence of failure and the term "scientific certainty" can be utilized as an index to measure the likelihood of failure [43]. It should be advantageous to associate failure mechanisms with the likelihood of failure as far as possible.

5 Alternative Pipe Materials for Minor Systems

Public perceptions of risk and reaction to hazards, while hard to measure, play a fundamental role in consumers' drinking water-related decisions. Objective risks are based on the relative frequencies of historical occurrences or experimental studies. Perceived or subjective risk involves personal or subjective judgment and is a function of confidence [44]. Minor system decisions that may affect drinking water risks include the choice of when to repair or replace a minor system, as well as the type of material to use in replacement.

Information should be provided on the implications of risk to consumers. In the decision-making process, consumers are influenced by various factors. The main alternative pipe material includes various types of plastic or stainless steel. There is concern regarding the behavior of plastic pipes with respect to strength, fire hazard, final disposal, reaction to chlorine, and health effects. The regulations and standards of the federal, state, and local governments all have a major impact on ultimate decision making [11]. These regulations also influence plumbers, material producers (e.g., pipe manufacturers, interior coating providers), insurance companies, and water utility companies. Consequently, consumers are influenced by all of the above service providers.

When informed about the attributes of each plumbing material alternative, consumers can decide on the alternative most preferable to them based on the preference trade-offs among plumbing materials' attributes. The choice of 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 longevity in the event of a fire. In addition, the perception of risk for plumbing materials can be quantified by assessing the willingness-to-pay (WTP) for a (hypothetical) 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 [45]. Different materials pipe should be examined for cost, consumer preferences, corrosion, susceptibility, water quality including microbial growth, strength, and fire hazard. Table 2 shows the general characteristics of various plumbing materials and their unique attributes.

6 Economic Aspects of Pipe Pitting

This section summarizes the major findings of two surveys that focused on economic impacts related to minor systems [46, 47]. One study included a mail survey that was designed to identify the frequency of pinhole leaks [46]. This study, which was sent to residents of the Maryland in July 2004, also evaluated the financial impact, time, and emotional costs of these inconveniences [46]. The mail survey in Maryland included a variety of interesting findings. 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 and about 10 respondents had spent more than $10,000. 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,

Table 2 Attributes of plumbing water pipe materials [11]

	Copper	PEX	CPVC
Corrosion resistance	May corrode under select conditions	Not susceptible to corrosion	Resists corrosion and oxidation
Fire retardance	Can withstand temperatures up to 1,093 ºC without melting and emitting toxic fumes	May melt and emit toxic fumes at temperatures above 80 ~95 ºC	Can withstand temperatures up to 1,093 ºC without melting and emitting toxic fumes
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 has a 50-year manufacturer's warranty	Some types of plumbing made of this material have a 10-year manufacturer's warranty	Plumbing made of this material has a long life span
Price/m	½″ diameter pipe: $6.48 ¾″ diameter pipe: $10.04 (1 in. = 2.54 cm)	½″ diameter pipe: $2.84 ¾″ diameter pipe: $4.67 (1 in. = 2.54 cm)	½″ diameter pipe: $19.46 ¾″ diameter pipe: $30.11 (1 in. = 2.54 cm)

clothes, and inherited furniture. In addition, 70 % of the respondents who had pinhole leaks spent at least 10 h dealing with the leaks and the resulting damage. More than half of the respondents felt much stressed regarding this problem and "aggravated or worried" about the possibility of leaks in the future. The researchers concluded that overall anxiety increased due to (1) a lack of adequate knowledge and information on the causality of pinhole leaks, (2) a lack of sufficient advice or assistance from local water utility and insurance companies, (3) the full financial responsibility borne by the homeowner, and (4) the lack of a local government response to these problems [46].

A nationwide telephone survey was conducted to gain a better understanding of the cost of leaks to the owners of homes, apartment dwellings, and commercial buildings and homeowner's WTP for materials guaranteed to remain leak free for 50 years (give reference). 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 the United States) is nearly $930 million per year. More than 50 % is due to single-family homes while multifamily 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 WTP for leak-free materials was $1,130, and for those who had not experienced leaks, the WTP for leak-free materials was $1,007. 6 % of respondents were willing to pay a premium of at least $4,000 [47].

7 Service Lines

Service lines connect major systems to minor systems and are known to be the weakest spot within the drinking water infrastructure. To make matters worse, the documentation of failures is rare because they occur on private property. Due to this documentation limitation predicting future failures using statistical analysis is difficult. This section examines the general characteristics of the service lines that connect the inner plumbing of homes (minor systems) to the municipal water mains (major systems).

Water utilities and regulators are responsible for the maintenance of the system, including its physical condition, water quality, etc., up to the curb stop but after that point a major portion of the service line and all of the dwelling's plumbing systems and water quality are the homeowner's responsibilities [2], Fig. 1. Water quality tests of lead and copper levels are measured at the consumer's tap, within the property line, while disinfectant residuals and disinfection by-products (DBPs) are measured within the main distribution systems [2]. It has been noted that the incidences of waterborne disease outbreaks due to distribution systems are increasing [2]. The major culprits are (1) cross-connections and backsiphonage outbreaks associated with distribution systems and (2) pipe breaks and contamination of storage facilities. Outbreaks at premise plumbing level may not be easily recognized and reported compared to water main outbreaks. Water has a long contact time with service lines due to the intrinsic nature of minor plumbing systems, which leads to low disinfectant residuals and consequently microbial regrowth and DBP formation [2].

As mentioned, service lines are structurally weakest components in drinking water infrastructure systems. Excessive water loss or a puddle in the front lawn may be the first signs of a service line failure. Leaks in the service line rarely flow upwards so it is possible for leaks to go unnoticed for relatively long periods of time. Some utilities have detected leak incidents lasting more than a month. In order to detect water leaks in a service line, sonic and ultrasonic leak detectors can be used for metallic service lines while for plastic service lines, tracer gas or ground penetrating radar must be used. Service lines are susceptible to both internal and external corrosion. For external corrosion, soil corrosivity, stray electrical current, soil stability, bedding conditions, and temperature extremes could all be important factors. Major causes of failure for service lines include (1) contractors exposing piping with a backhoe or other mechanical equipment, (2) improper installation of fittings and pipes, and (3) the original installation supervision was inadequate [50].

As mentioned in pipe pitting section, hydraulic surges or transients are another cause of failures. Piping material, material age, size, location, service pressure, flows, and other hydraulic parameters will also dictate the general characteristic of failure mechanisms. Due to structural stability and economic issues, replacing all components of the service line is generally a better option than trying to repair the service line alone, so proper installation practice and workmanship (from licensed workers with good training) under strict supervision with inspection are essential in order to maintain the physical integrity of service lines [50]. This prolongs the life of the service line and reduces the need to engage in unnecessary and expensive repair/rehabilitation/replacement.

According to the American Water Works Association (AWWA), 60.5 % of service line materials are copper followed by polyethylene (12.4 %), galvanized steel (8.6 %), and PVC (6.3 %). Remaining service lines consist of other materials such as lead. Surveys of 12 utilities across the United States revealed that Portland Water Utility (ME), Louisville Water Company (KY), and Brown Deer Water utility (WI) all used copper for more than 90 % of the service lines, although new materials including PEX and tri-layer pipes are beginning to emerge in service line applications [48]. Copper pipe has a particularly high rated internal working pressure (for more details, please refer to [49]). Copper pipes have the added advantage that they do not become brittle or subject to fatigue failures, although they can be noisy at high water velocities.

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

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

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 = constant. For copper pipe, due to its superior corrosion resistance, the B31 code permits the factor C to be zero and the equation reduces to $P = \frac{2St_{\min}}{D_{\max} - 0.8t_{\min}}$. For the nominal or standard size of K, L, and M copper pipes, the outside diameter is the same for all three, but the inside diameters are different; K pipes are thicker than L pipes and L pipes thicker than M pipes. These values for the outside diameter, thickness, and maximum allowable pressure in tension enable the allowable pressure to be determined using the above formula. The technical data for rated pressure, burst pressure, and thickness can be found in the Copper Tube Handbook [49].

The pressures at which a copper tube will actually burst are many times higher than its rated working pressure, which ensures that tubes can withstand the unpredictable pressure surges likely to occur during the long service life of the system. For domestic use, when designing a copper tube water supply system the minimum tube size for each branch is determined by considering the following criteria: 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 [6].

Several testing methods are utilized for pressure piping materials: (1) a sustained pressure test, where test specimens are selected randomly and individual specimen tested with water at the three controlled temperatures and pressures given in The American Society for Testing and Measurement (ASTM) (ASTM F 876; (2) a burst pressure test, where the minimum burst pressure is determined for at least five specimens in accordance with ASTM Test Method D1599; (3) an environmental stress cracking test, where a notch is made on the inside walls of six randomly selected tubes in the axial direction in accordance with the standard burst pressure testing procedure; and (4) oxidative stability in potable chlorinated water is tested in accordance with ASTM Test Method F 2023 to determine the extrapolated time to failure.

The ASTM has developed a set of minimum performance standards to determine the suitability of PEX tubing for high temperature and pressure fluid distribution applications (ASTM F876). The following values have been defined for performance standards at three different temperature and pressure ranges: 1103 kPa (160 psi) @23 °C (73.4 °F), 689 kPa (100 psi) @ 82.2 °C (180 °F), and 552 kPa (80 psi) @ 93.3 ° C (200 °F); Minimum Quick Burst Capability: 3,275 kPa (475 psi) @ 23 ° C (73.4 °F), 1,448 kPa (210 psi) @ 82.2 °C (180 °F), and 1,241 kPa (180 psi) @ 93.3 °C (200 °F); and Sustained Pressure Tests: 1,000 h at 1,310 kPa (190 psi) @ 82.2 °C (180 °F). The water hammer pressure rise in PEX is 25 % of that in copper pipes, so water hammer arrestors are not necessary for PEX systems [51]. Table 3 shows the maximum pressure rise when water at a given velocity stops abruptly.

8 Contaminant Intrusion in Water Distribution Systems

It is widely believed that because a drinking water distribution system is pressurized, the water can only leak out of the system. However, there is considerable evidence to show that pump trips, the opening and closing of fire hydrants, valve closures or malfunctions, pipe breaks, sudden changes in demand, and resonance can all induce significant transients leading to low-pressure events within a drinking water distribution system. During such events, a greater external pressure can easily lead to contamination intrusion through available openings. Tests of the surrounding soil and pipe specimens from repair locations clearly demonstrate the presence of pathogens. In the year 2000 alone, 6,988 water systems affecting about 10.5 million people violated microbial drinking water standards in the United States [52].

Table 3 Hydraulic shock for different pipe types

Velocity (m/s)	PEX (kPa)	Copper (kPa)
1	400	1,379
2	600	2,068
2	800	2,758
3	1,000	3,482

Intrusion is defined as the backflow situation in which contaminated water from the environment outside of the distribution piping enter into the pipe through leaking sections [52]. Comprehensive reviews and detailed discussions on the pathogen intrusion problems into the municipal drinking water systems are available in the literature [4, 53]. Water treatment plants are the primary barrier against pathogens before the water enters the distribution systems [4]. These barrier mechanisms include the removal (inactivation) of pathogens, turbidity and organic matter to prevent biological regrowth in the distribution system, as well as disinfection, treatment to maintain optimal contact time for bacterial inactivation, and filter blockage of particle–contaminant carryover into the distribution system. Any breakthrough in water treatment plant barrier is considered a high risk and the probability of contamination occurrence is also considered high. The physical mechanisms involved are separated into "transitory contamination" due to low-pressure propagation in the system drawing in contaminants from the exterior surroundings with a higher pressure; "cross-connection" between a potable water system and a source that can potentially introduce contaminants into the potable water; and "pipe break, repair, and installation" activities that expose the distribution system to externalities as routes of entries. Storage facilities both covered and uncovered, intentional contamination for terror purposes, growth, and resuspension serve as additional sources for pathogen intrusion.

Two epidemiology studies related to a drinking water distribution system in Montreal, Canada, found that people who consumed tap water had increased levels of gastrointestinal illnesses and that people who lived farther away from the treatment plant had the highest risk of gastroenteritis [54, 55]. Another study revealed that the 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 [4]. Although this system had a state-of-the-art treatment plant, its highly vulnerable water distribution system made it vulnerable to potential contamination.

8.1 Hydraulic Transients

Transient high and low pressures can be triggered by many different events, as explained above. LeChevallier et al. [52] provided pictures of an inundated air valve vault that initially had an oily film on the surface of the water. After a transient passes through, the vault is completely drained allowing the contents, including the oil contaminant, to enter the distribution system. In another dramatic incident, a cracked sewer pipe lay on top of a leaky water pipe [4]. Soil and water quality tests at water main repair sites have been found to contain fecal coliform bacteria in 43 % of the water samples and 50 % of the soil samples, suggesting that waterborne pathogens are very common in the environment external to water distribution mains [4]. Another study found bacteria and viruses in 66 soil and water samples collected next to drinking water pipelines in eight water utilities with total coliform and fecal coliform bacteria in about 50 % of the samples; 56 % of the samples were positive for viruses, providing evidence of human fecal contamination immediately surrounding the exterior of the pipes [56].

A study of transitory low-pressure propagation in a municipal potable water system that typically uses 10.2 cm to 25.4 cm pipes documented intrusions of contaminants and low pressures of the order of negative 68.95 kPa [53]. Distribution mains downstream of pumps, high elevation areas, low static pressure zones, areas far away from elevated water storage tanks, and segments of pipes upstream and downstream of active valves in high flow areas are the most susceptible to 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 contamination intrusion. Most hydraulic transients occur as the result of pump operations and outages [57]. Novak [10] provided experimental evidence that in a pipe bent at a 90° angle with a pressure range of less than 68.95 kPa and a flow velocity of about 1.83 m/s, contamination can indeed be sucked into downstream of the bend.

Leakage rates (water lost in transit between the treatment plant and minor systems) in drinking water systems has been found to reach 32 % in some utilities, which indicates a high potential of contamination intrusion [4] and some six billion gallons of treated water is disappearing during distribution every day [58]. According to AWWA [58], the majority of water leaks occur at service lines, service fittings, and connections. As mentioned, 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 [2].

While it is known hydraulic transients are common inside a home, the range of pressures experienced within the plumbing system requires further investigation. As a minor system is a passive recipient from the water mains, if there is contamination in the service line this is bound to enter into tap water and thus poses a serious health risk. An experimental plumbing system that replicates the range of pressures typically encountered in service lines and minor plumbing systems when connected to the water mains was therefore designed and constructed. This experimental water system was then used to (1) examine how a low-pressure wave such as those produced by street level transients and transients triggered within a house moves through the service line in order to predict the potential intrusion of contaminants from the surrounding soil or water; (2) measure pressure variations at various locations within the minor systems, for example, in vertical sections within a house, as a function of valve positions and sudden valve closing/opening; and (3) evaluate any cavitation produced by the hydraulic transients.

8.2 Hydraulic Transient Scenarios

Here, minor system was simulated by directly connecting the experimental system to the water mains. Three scenarios, referred to as Transient Scenarios I, II, and III, that can trigger a hydraulic transient in a service line were considered. For Transient Scenario I, transients were triggered by actions initiated from inside the house, such as shutting off a valve, shower heads, or the automatic on/off of the solenoid valve on the washing machine. For Transient Scenarios II and III, transient-causing actions were initiated from the major municipal water system upstream and downstream from the house, respectively. These examples would include, but are not limited to, pump on/off events, the opening and closing of fire hydrants, valve slams or malfunctions, pipe breaks, and sudden changes in demand and resonance (Table 4).

Hydraulic transients were induced by a valve suddenly closing the ball valve or solenoid valve in the pipe system, causing a sudden change in both velocity and pressure. As the pressure wave passed through the pipe, maximum and minimum pressure measurements of 100 readings per second were employed to visualize the pressure variation, with the baseline pressure being the water line's steady state pressure. The piezoelectric pressure sensor therefore provided a relative pressure measurement based on the water line's steady state pressure. For example, if the baseline water line pressure was 206.8 kPa (measured by the static pressure gage), then a 206.8 kPa static water line pressure would give a zero reading on a piezoelectric pressure sensor, but a regular static sensor would read 206.8 kPa.

The average static pressure in the water mains was 551 ± 27 kPa when all the valves were closed. The fluctuations observed were probably due to the existing weak transients within the municipal system. However, when the faucets were fully opened (with a flow rate of 37 ± 3 l/min), the residual pressure fell to 275.8–310.3 kPa within the experimental system. The level of residual pressure was controlled by adjusting the valve at the water mains. When the main valve was partially opened, the residual pressure was 103.4–137.9 kPa (a flow rate of 20 ± 3 l/min). Initially, the system was set at a steady state of 275.8 kPa (residual pressure). The solenoid/ball valves were then abruptly closed/opened as required to produce the three transient scenarios (Table 4). The solenoid valve closing/opening time was < 0.3 s according to the manufacturer, while the ball valve closing/opening time was less than 0.1 s after operator training.

Table 4 Experimental conditions for each transient scenario [59]

	Transient scenario I	Transient scenario II	Transient scenario III
Valve 1	*Open/close*	Open	Open
Valve 2	Open	*Open/close*	Open
Valve 3	Closed (to maintain residual pressures)	Closed (to maintain residual pressures)	*Open/Close*
Test Description	Transient initiated from inside the minor system or household plumbing	Transient initiated from the major system or water main upstream from the house	Transient initiated from the major system or water main downstream from the house

8.3 Pressure Variations in Service Line

The pressure variations in the service line are shown in Figs. 2, 3, and 4. Transient Scenario I was triggered by the opening or closing of valve 1, Transient Scenario II by opening or closing valve 2, and Transient Scenario III by opening closing valve 3 (Table 4). During Scenarios I and II, no water was flowing through the branched sections in order to maintain a higher residual pressure inside the system.

Figure 2 show that when valve 1 was suddenly closed to trigger Scenario I, the pressure went up sharply to 482.6 kPa above the steady state. So, within a fraction of a second the service line experienced an instant pressure increase of the order of 482.6 kPa or a gage pressure of (275.8 + 482.6) = 758.4 kPa, which could result in *repetitive fatigue impact on service lines* due to constant on/off events inside the house. However, when valve 1 was reopened, this caused an instant reduction in pressure of the order of –206.8 kPa, with a gage pressure of 344.7 kPa (i.e., 551.6 kPa [system static pressure when valves 1 and 3 are closed] –206.8 kPa [pressure variation]), which did not create a low enough pressure to cause suction. When the residual pressure was around 137.9 kPa, the trend was the same, but the magnitude was smaller than for the fully open case.

Scenario II was triggered by closing valve 2 in the major system upstream from the minor system and the resulting pressure variations (Fig. 3). After a sudden closure, the pressure dropped to −68.9 kPa for a fraction of a second as Transient Scenario II caused an instant pressure drop of 344.7 kPa, leading to a negative pressure [275.8 kPa (steady state) – 344.7 kPa (pressure variation) = −68.9 kPa] in the service line. When the residual pressure was 103.4 kPa, the pressure variation was smaller than in the fully open case but still caused a negative pressure.

Scenario III was triggered by closing a valve in the major system downstream from the minor system and the resulting pressure variations are shown in Fig. 4. After a sudden closure, the pressure variation rose to 170 kPa for a fraction of a second and Transient Scenario III caused an instant pressure drop of 200 kPa. Here, the residual pressure (steady state pressure) was around 130 kPa, which is lower than either of the other cases as the two branch pipes were open for both. Scenario III created pressure peaks but did not cause a negative pressure surge sufficient to cause suction when the valve was reopened.

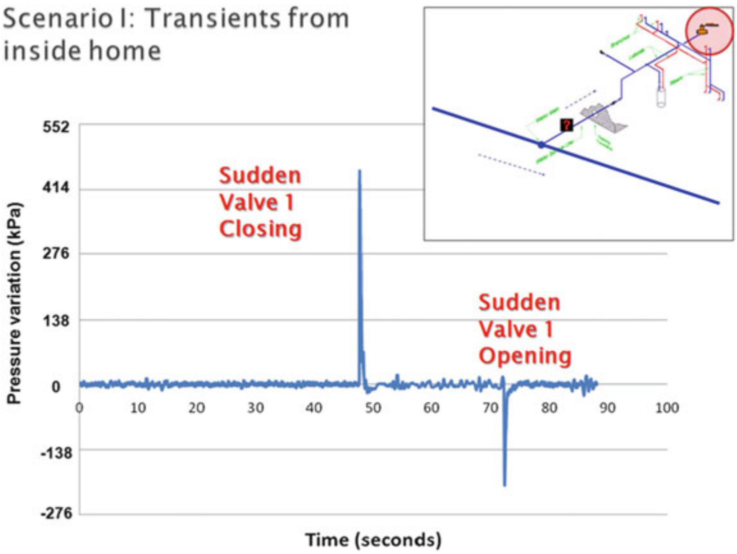

Fig. 2 Pressure variation at P3 due to valve 1 maneuver, Transient Scenario I [59]

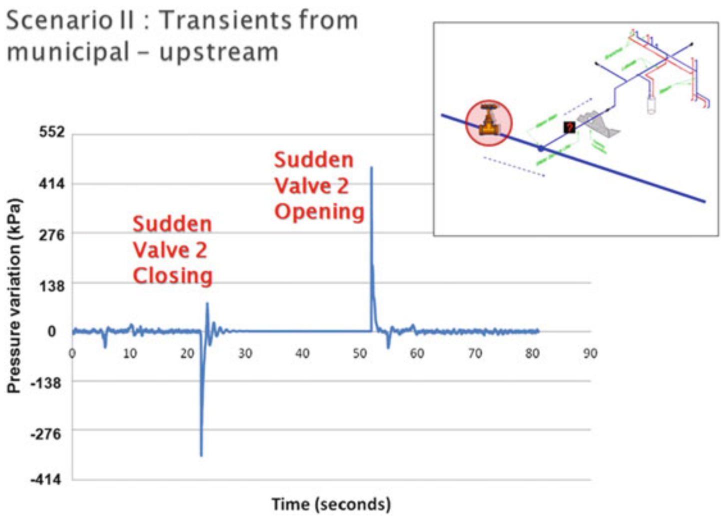

Fig. 3 Pressure variation at P3 due to valve 2 manuever, Transient Scenario II [59]

8.4 *Pressure Variations within Minor Systems*

The pressure variations in a vertical riser section with a dead end were then measured when the transients were triggered. Figure 5 shows the pressure variations in this vertical section produced by Scenario I, which produced a very high-

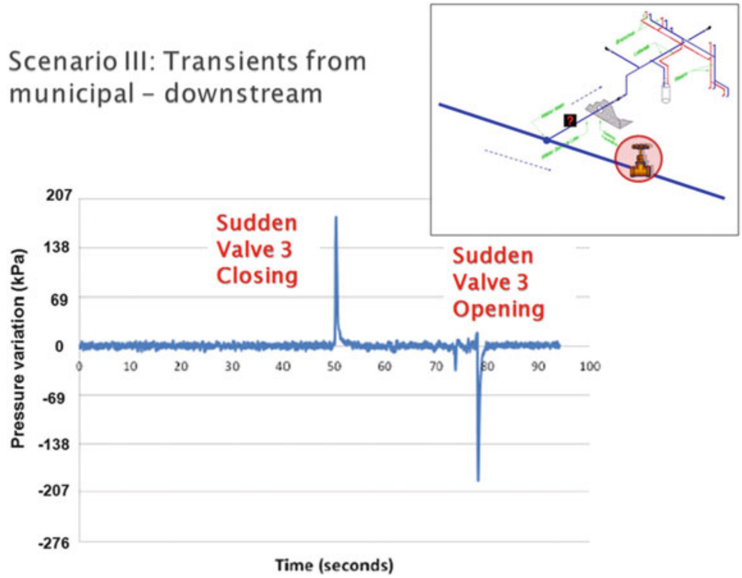

Fig. 4 Pressure variation at at P3 due to Valve 3 maneuver, Transient Scenario III [59]

pressure variation of more than 689.5 kPa when valve 1 was closed suddenly. Reopening the valve caused a much smaller negative pressure event, but this was again insufficient to create the type of serious suction likely to lead to contamination.

Pressure variations at the vertical riser with a dead end caused by the sudden closing of valve 1 showed pressure spikes of 827.4 kPa. Dead ends are thought to amplify pressures by factors of up to two, depending on the topology of the systems. Network simplifications that eliminate dead ends from transient analysis are invalid and modelers should therefore check key transient runs with a complete model that includes dead ends [60]. The results shown in Fig. 5 support Jung et al's [60] findings regarding the high-pressure variations experienced in vertical dead-end sections.

8.5 *Gaseous Cavitation*

Using a High Definition video camera, an effort was made to capture the cavitation occurring within the horizontal pipework in the minor system by taking pictures of the clear section every 0.033 s (30 frames per second, Fig. 6). The number of bubbles created and their shapes appeared to be almost random, with gas evolution and dissolution timing remaining almost constant as long as the hydraulic transient triggering mechanism was controlled (i.e., the valve closing time remained

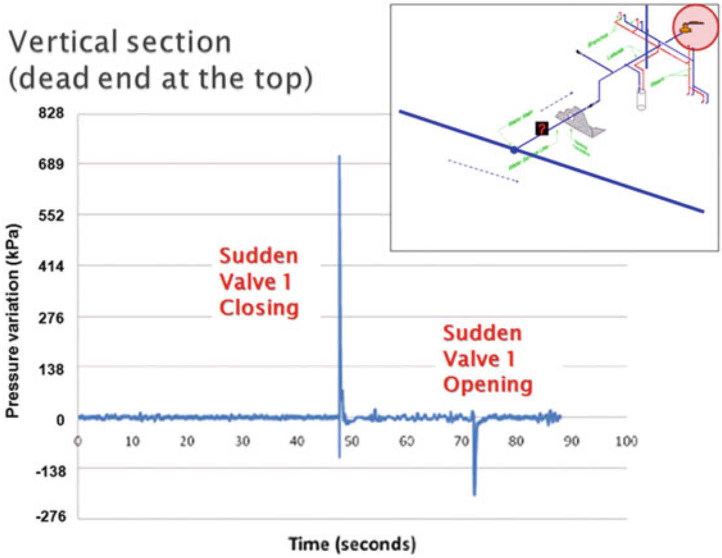

Fig. 5 Pressure variation at P2 (vertical riser with dead end), Transient Scenario I [59]

constant). As the diameter of the clear plastic pipe was known to be 1.9 cm, the size of the created bubbles could be estimated to a fair degree of accuracy.

In this experiment, whenever the pressure dropped to −68.9 kPa (gage pressure) or below, the formation of gaseous bubbles in the clear plastic pipe section was observed. These bubbles disappeared within less than 1 s once the pressure recovered to above the gas saturation pressure. Interestingly, the bubble formation time was quicker (less than 1 s) than is provided for by the traditional theory of gaseous cavitation formation timing (from 1 to several seconds). However, the presence of preexisting gas nuclei attached to particles in the bulk solution may have provided nucleation centers, accelerating the growth of the observed bubbles.

9 Conclusions

In this chapter, we covered general characteristics of the drinking water distribution systems which consist of “major” and “minor” systems. A *major system* is generally defined as the water mains that bring drinking water from water treatment plant to the consumer’s premises (homes and buildings), while a *minor system* is the plumbing system (including service lines) that transports water within the property boundaries. America’s water distribution infrastructure system is old and deteriorating. It is noted that minor systems are known to be at least five or ten times longer in total than major systems. We focused on several emerging issues in minor

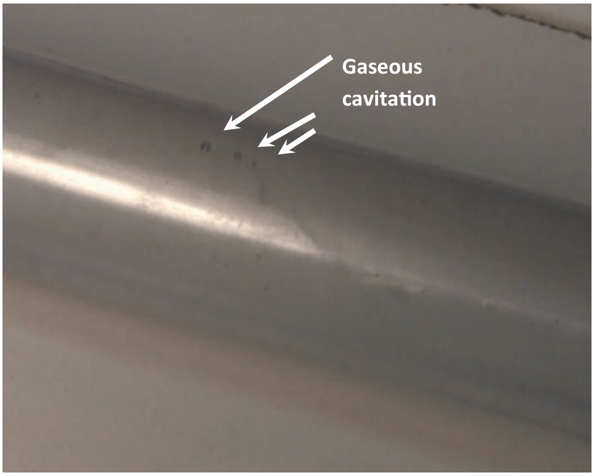

Fig. 6 Hydraulic transients induced gaseous cavitation [59]

systems: pipe failure mechanisms, alternative pipe materials, economic aspect of pipe failures, and contamination intrusion into service lines.

The literature associates copper pinhole failures with a number of different causal factors (water quality, hydraulic, and anthropogenic conditions) that seemingly combine to act in a complex synergy. Given the inherent complexity of any plumbing system and the synergistic effects of causal mechanisms, at present, it is difficult to conclusively predict the extent of pitting with absolute certainty. For instance, controlling one mode of failure may not necessarily completely mitigate pitting and may even initiate other mechanisms of failure. This underlines the necessity for a global assessment that simultaneously encompasses all possible failure mechanisms.

To assess the impacts due to pipe failures and water quality deterioration, pressure variations at the service line corresponding to typical street level pressures encountered in a real water supply system were introduced and examined in detail [59]. This study was specifically developed for a typical one- or two-story house for a plumbing system consisting of 46–76 m of pipes. The major findings of this research were as follows:

1. Street level transients can propagate a low-pressure wave (up to −68.9 kPa for a fraction of a second) along the experimental service line. This pressure drop would be sufficient to induce potential contamination intrusion in the service line.
2. A transient triggered within the house (due to sudden valve closure) may structurally tax the experimental service line but did not exhibit a possible suction effect. If an actual service line is not sufficiently robust, this may cause constant fatigue effects and may result in bursting.
3. Vertical sections with dead ends experience higher pressure variations (up to 758 kPa variations) when transients are triggered from inside the house. This may be related to noise effects in the home and could bear further examination.

4. Gaseous cavitation was observed due to water hammer-induced low pressure (as a result of street level transients), with bubble formation times due to gaseous cavitation of less than 1 s. This contradicts previous theories that predict times of 2–3 s. This phenomenon has practical implications for implosion or gaseous impingement of the kind that is known to erode protective scales on the wall.

Hydraulic transients in water mains clearly exhibit a high potential to create sufficiently low pressures in service lines to allow the possible intrusion of microbial and chemical contaminants. It is therefore recommended that this new knowledge should be broadly disseminated to homeowners, water utility personnel, homebuilders, and public health officials. Specifically, the *physical integrity of service lines* and the *hydraulic integrity of water mains* should be rigorously maintained, with the utmost effort being devoted to protecting against any possible human health risk involved with service lines. Appropriate outreach programs targeted at educating the public regarding these issues should be developed.

1. *Physical integrity of the service lines*: All service line construction and installation activities should be performed under strict supervision to ensure good workmanship (i.e., a professional license, including high-quality training). All the appurtenances associated with the service line (including piping materials, fittings, joints, and valves) should meet strict pressure ratings and corrosion susceptibility requirements for their specific environment. Leaks should be checked for after installation and leak detection performed on a regular basis. Service line condition should become part of the routine inspection carried out when purchasing a house. For water utilities, it is recommended to maintain a comprehensive database (e.g., GIS) for service lines that includes failure data, soil condition, pipe materials, installation date, and any repair/replacement history so future leaks can be predicted. The integrity of a service line can only be maintained with careful planning, management, and knowledge of the environmental conditions where the line is buried.
2. *Hydraulic integrity in the major systems*: As shown above, hydraulic transients from major systems largely dictate pressure variations in the service lines. At the utility level, it is recommended that surge protection devices be installed to protect against both negative pressures and high pressures (pipe bursts due to high-pressure spikes), which will include training or hiring transient flow analysts to identify weak spots. State or federal regulation may be needed to create tax incentives to encourage such industry initiatives.
3. *Public perception:* Water professionals and policy makers need to 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 encourage homeowners' increased awareness of little known but potentially serious problems such as the unique characteristics of service lines and their associated public health risks. Education can be done through *education outreach from research universities* to K-12 including high school and middle school teachers. Official websites maintained by government agencies or utilities should make this information available to

homeowners. Regular public newsletters or a small handbook issued to all homeowners could also be helpful.

Service lines should deliver water with no deterioration in quality, which may necessitate the development of new water sampling methods to detect possible intrusion events at distribution systems. Paradigm shift of ownership issues could also be considered. For example, the city government in Seoul, South Korea, is planning to include minor systems as part of their public assets and some utilities in the UK have opted to become responsible for the entire service line except for the plumbing system inside the house in order to facilitate the resolution of water leakage issues. These will lead to safer designs not only within dwellings but also better maintenance practices for municipal systems.

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