



Office of Water (4601M)  
Office of Ground Water and Drinking Water  
Distribution System Issue Paper

## **The Potential for Health Risks from Intrusion of Contaminants into the Distribution System from Pressure Transients**

PREPARED FOR:

U.S. Environmental Protection Agency  
Office of Ground Water and Drinking Water  
Standards and Risk Management Division  
1200 Pennsylvania Ave., NW  
Washington DC 20004

Prepared by:

Mark W. LeChevallier, Richard W. Gullick, Mohammad Karim  
American Water Works Service Company, Inc., Voorhees, NJ

**Background and Disclaimer**

The USEPA is revising the Total Coliform Rule (TCR) and is considering new possible distribution system requirements as part of these revisions. As part of this process, the USEPA is publishing a series of issue papers to present available information on topics relevant to possible TCR revisions. This paper was developed as part of that effort.

The objectives of the issue papers are to review the available data, information and research regarding the potential public health risks associated with the distribution system issues, and where relevant identify areas in which additional research may be warranted. The issue papers will serve as background material for EPA, expert and stakeholder discussions. The papers only present available information and do not represent Agency policy. Some of the papers were prepared by parties outside of EPA; EPA does not endorse those papers, but is providing them for information and review.

**Additional Information**

The paper is available at the TCR web site at:

[http://www.epa.gov/safewater/disinfection/tcr/regulation\\_revisions.html](http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html)

Questions or comments regarding this paper may be directed to **TCR@epa.gov**.

## **The Potential for Health Risks from Intrusion of Contaminants into the Distribution System from Pressure Transients**

Mark W. LeChevallier, Richard W. Gullick, Mohammad Karim  
American Water Works Service Company, Inc., Voorhees, NJ

### **Issue Statement**

This paper examines the potential for public health risks associated with intrusion of contamination into water supply distribution systems resulting from transient low or negative pressures, as well as methods for preventing intrusion of contaminants that may lead to increased health risks, and mitigation of existing contaminant intrusion problems. This problem is defined as a specialized backflow situation that occurs in an otherwise pressurized system, and therefore the reader is referred to the cross connection white paper for a broader consideration of cross connection issues, health risks, and mitigation techniques.

### **Definition of the Problem**

A pressure transient in a drinking water pipeline is caused by an abrupt change in the velocity of water. This event is sometimes termed “surge” or “water hammer.” The energy at any point in the pipeline is composed of kinetic and potential energy. Water will move through a pipe from points of higher energy to points of lower energy regardless of its position. Any change in flow in a pipe (due to valve closure, pipe fracture, or pump stoppage) will result in an exchange of energy between flow and pressure. The change in pressure can be defined by the Joukowsky equation (Thorley 1991):

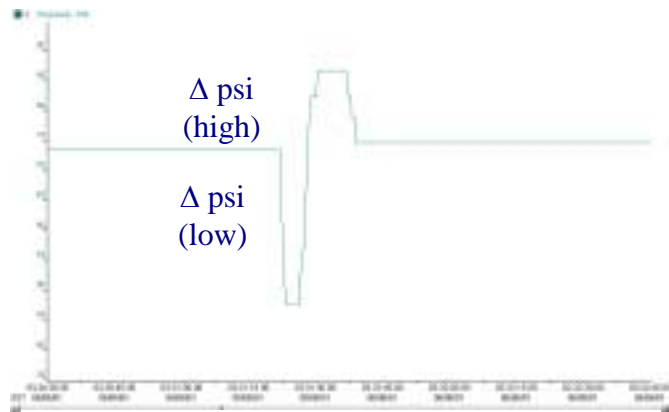
$$H = \frac{4660}{\left(1 + \frac{M_w * ID}{M_p * th}\right)^{0.5 * g}} * (V_i - V_f) \quad \text{where:}$$

- H = pressure increase (ft)
- M<sub>w</sub> = bulk modulus of water (psi)
- M<sub>p</sub> = bulk modulus of pipe materials (psi)
- ID = inside diameter of the pipe (in)
- th = wall thickness of the pipe (in)
- g = acceleration due to gravity (ft/sec<sup>2</sup>)
- V<sub>i</sub> = initial water velocity (ft/sec)
- V<sub>f</sub> = final water velocity (ft/sec)

The magnitude of the pressure change is influenced by the materials of construction, pipe characteristics, and the water velocity. Operational characteristics can further affect the significance of pressure transients, including: non-networked and dead-end pipelines, a lack of elevated distribution system storage tanks, undulating topography, entrained air, valve characteristics, and frequent power failures of pumping stations (AWWSC 2002).

For example, consider a pipeline on which an open valve is located at a distance downstream from a reservoir. If the valve is closed instantaneously, water will decelerate to zero velocity and the kinetic energy will be converted into pressure. The transient wave will travel upstream and downstream from the valve and ultimately reach the ends of the pipe. If the pressure wave in the pipe is not relieved (as in a surge tank), it will travel in the reverse direction back to the valve. Because the valve is closed and there is no relief for this flow, a negative pressure wave (suction) will be created at the valve (Simon and Korom, 1997). This wave will travel back and forth until the kinetic energy is dissipated by friction. The process will occur both upstream and downstream from the valve. However, the initial pressure will be positive on the upstream side and negative on the downstream side (Simon and Korom, 1997).

The analysis of transient flow in large distribution systems or other incompressible fluids requires the solution of the wave equations coupled to the boundary



**Figure 1.** A Pressure Transient

conditions of the flow. A widely used technique is the so-called method of characteristics (Streeter and Wylie 1967) or the wave plan method (Wood et al. 1966). Pressure transients can be described as waves (Figure 1), having both a positive and negative amplitude (Simon and Korom 1997, Funk et al. 1999). Because these waves travel through the distribution system, the resulting low or negative pressures may occur in many different locations. The circumstances that produce these pressure waves may commonly occur in every water system. Pressure transients can be caused by main breaks, sudden changes in demand, uncontrolled pump starting or stopping, opening and closing of fire hydrants, power failures, air valve slam, flushing operations, fire flow, feed tank draining and other conditions including venturi effects (Funk et al. 1992). As a general rule of thumb, for every 1 ft/sec of velocity forced to a sudden stop, water pressures increase 50 to 60 psi (depending on the pipe materials, topography, etc.). The opposite is true for a sudden velocity increase, resulting in an instantaneous low or negative pressure (Kirmeyer et al. 2001).

The production of negative pressure transients creates the opportunity for backsiphonage or backpressure of non-potable water from domestic, industrial or institutional piping into the distribution system (USC FCCCHR 1993). These conditions of backflow are more thoroughly addressed in the cross connection white paper. Intrusion refers to the flow of non-potable water into mains through leakage points, submerged air valves, faulty seals, or other openings.

### **Magnitude of the Risk**

The public health significance of intrusion from a pressure transient depends on the number and effective size of orifices (leaks), the type and amount of contaminant external to the distribution system, the frequency, duration, and magnitude of the pressure transient event, and the population exposed.

*Pipe Leakage, Orifices, and Location*

In the American Water Works Association Research Foundation (AwwaRF) report *Pathogen Intrusion into the Distribution System* (Kirmeyer et al. 2001), 77% of 26 utilities surveyed had a leak detection program that used a variety of different leak detection techniques (e.g., leakage correlator, comparison of metered sales, electronic noise detection). The percent of leakage (unaccounted for water) for these utilities ranged from less than 10 percent to as high as 32 percent. It is not uncommon for water systems to lose more than 10 percent of the total water production through leaks in the pipelines (AWWA and AwwaRF 1992). In reality it is very difficult to precisely know how much of the unaccounted water is due to leakage unless a significant effort is exerted to track all losses.

Hydraulic modeling can be used to estimate the impact of orifice diameter on the volume of water that could intrude during a negative pressure event (Funk et al. 1992, Funk et al. 1999, Kirmeyer et al. 2001). Depending on the effective size of the orifice, the external pressure, and the nature of the transient event, the volume of intrusion can range from milliliters to hundreds of gallons (Table 1).

**Table 1.** Determination of the Intrusion Volume (in gallons)  
During a 30 Second Negative Pressure Event

Orifice Diameter (in.)	Power Loss		Main Break		Fire Flow	
	1 ft	10 ft	1 ft	10 ft	1 ft	10 ft
1/32	0.01	0.08	0.04	0.12	0.04	0.12
1/8	0.2	1.2	0.6	1.8	0.6	1.8
1/2	3	18	8	27	8	26
1	8	58	23	96	24	87
2	13	185	55	335	46	244

From Kirmeyer et al. 2001.  
1ft and 10 ft refers to the height of the external water table above the pipe.

Pipes located below the water table are subject to pressure from the exterior water (depending on the height of the water table above the pipe) and thus an opportunity exists where water exterior to pipe could intrude into the pipe under low or negative pressure conditions within the pipe. Utilities were surveyed as to the percentage of mains that are submerged, and the results showed that at least 20% of the systems had pipes below the water table (42% had no information) (Kirmeyer et al. 2001). It is assumed that all systems have some pipe below the water table for at least some time of the year.

Water may also intrude into a distribution system by means other than pipelines. It has been speculated that faulty joints seals may leak under certain circumstances when exposed to negative pressures (Grigory, 2002). A survey of the percentage of flooded vaults or meter boxes showed that although the rate changed seasonally, approximately 20% of the systems reported between twenty-five and seventy five percent of meter boxes flooded, with about half of the systems



**Figure 2.** Submerged air release valve

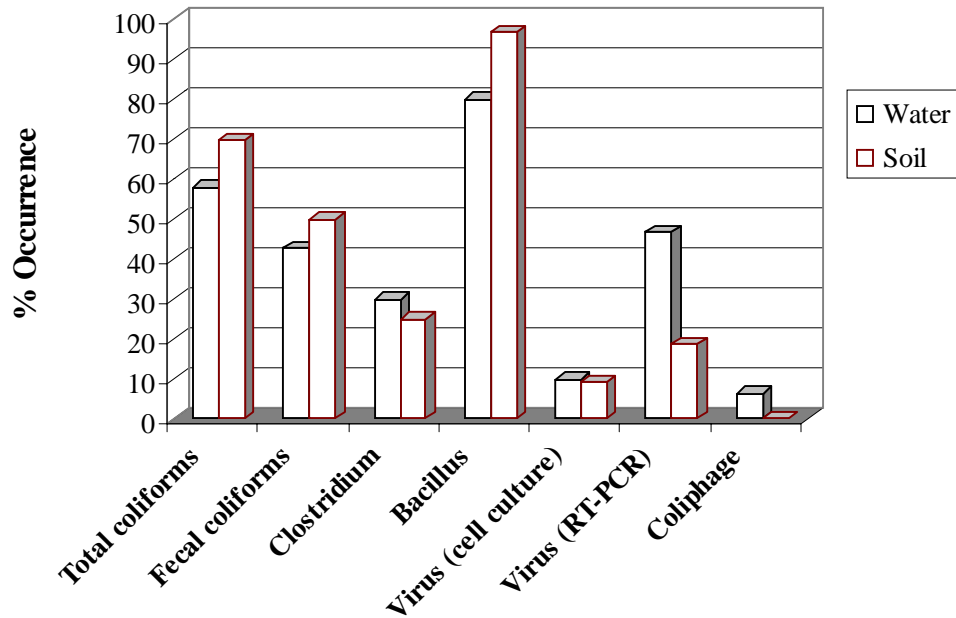
not knowing how much flooding had occurred (Kirmeyer et al. 2001). One utility provided pictures of an air valve vault that was flooded with an oily film and a second picture from a short while later when the vault was drained (Figure 2). It is presumed that a pressure transient caused the air valve to open and allowed the water to enter into the distribution system. Engineering standards (Recommended Standards for Water Works 1997) specify that all air release valves (and similar appurtenances) be designed with above-grade-venting (this venting should be tamper-proof to prevent deliberate contamination of the system), or be modified in a way to prevent the flooding of the vault (e.g., via drainage or a pump).

### *Presence of Contaminants External to the Distribution System*

Any contaminant exterior to the distribution system may enter potable water supplies during a negative pressure event. Chemical contaminants could include pesticides, petroleum products, fertilizers, solvents, detergents, pharmaceuticals, and other compounds. Predominant pesticides in urban areas include atrazine, simazine, prometon, and diazinon (Patterson and Focazio 2001). Other studies have detected insect repellants, fire retardants, and other industrial chemicals (Koplin et al. 2002). If chemical compounds intrude in sufficient concentration or volume, they might result in acute toxicity. Microbial contaminants are a concern because even with dilution, some microbes (e.g., viruses) could cause an infection with a single organism.

Karim et al. (2001) reported on a study that examined 66 soil and water samples collected from 8 utilities in 6 states. The samples were collected immediately adjacent to the drinking water pipelines. The purpose of the study was to determine the presence of microbial contaminants in the soil immediately external to the distribution system. Whenever a main was excavated, samples were collected of either the water or the undisturbed soil next to the pipe. Total coliform and fecal coliform bacteria were detected in water and soil in about half of the samples, indicating the presence of fecal contamination (Figure 3). *Bacillus* was found in almost all the samples, which is not a surprise since it is a normal soil organism. Viruses were detected using culturable methods in 12 percent of the soil and water samples, and by molecular methods in 19 percent of the soil samples and 47 percent of the water samples. When these data are combined, 56 percent of the samples were positive for viruses either in the water or the soil. Sequence analysis showed that these viruses were predominantly enteroviruses (the vaccine strain of Poliovirus), but Norwalk and Hepatitis A viruses were also detected, providing clear evidence of human fecal contamination immediately exterior to the pipe.

In the same study an analysis of the levels of organisms detected showed that they could be quite high; for example, total fecal coliform levels were as high as  $10^4$  bacteria per 100 grams of soil (Table 2). This may not be surprising considering that sewer lines are often located only a few feet away (Figure 4). Engineering standards call for a minimum separation of 10 ft between drinking water and sewer pipelines, although separations can be as little as 18 inches if the drinking water pipe is located at a higher elevation than the sewer pipe (Recommended Standards for Water Works 1997). In saturated soil conditions, microbes can move several meters in short periods of time (Abu-Ashour et al, 1994). This transport could be aided by water flowing out of the sewer (exfiltration).



**Figure 3.** Summary of Microbial Occurrence in Water and Soil Samples

The soil and water samples in the study (Karim et al. 2001) were randomly collected from urban environments and the location of adjacent sewer lines is not known. More detailed studies could develop better guidelines for the separation of water and sewer mains. The concentration of *Bacillus* spores in soil was as high as  $10^8$  colony-forming units (CFU) per 100 grams of soil, with some of the highest levels associated with samples containing human enteric viruses. It is possible that seepage of sewage stimulated the growth of the soil flora in these locations.

**Table 2.** Microbe Concentration in Water and Soil

Organism	Water CFU or PFU/100 ml	Soil CFU or PFU/100 gm
Total Coliforms	< 2 - $1.6 \times 10^3$	< 2 - $1.6 \times 10^4$
Fecal Coliforms	< 2 - $1.6 \times 10^3$	< 2 - $1.6 \times 10^4$
<i>Clostridium</i>	0 - $2.5 \times 10^3$	0 - $1 \times 10^5$
<i>Bacillus</i>	0 - $4.6 \times 10^6$	0 - $1.2 \times 10^8$
Phage	0 - $1 \times 10^4$	0

CFU, colony-forming units; PFU, plaque-forming units

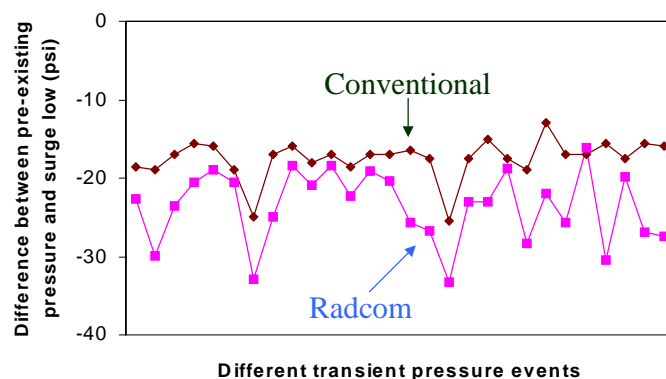


**Figure 4.** Leaky water pipe laid next to a sewer pipe  
(Source: Opflow 1999)

### *Frequency and Magnitude of Pressure Transient Events*

Problems with low or negative pressure transients have been reported in the literature (Walski and Lutes 1994, Qaqish et al. 1995). Recent research efforts have focused on documenting the frequency and magnitude of pressure transient events to determine whether negative pressure events occur during normal distribution system operations. A high-speed pressure logger (RDL 1071L/3 Pressure Transient Logger, Radcom Technologies, Inc.; Woburn, MA), with a monitoring rate of 1-20 measurements per second and a range from 0 to 300a psi, was used to detect negative pressure events. Other manufacturers offer similar equipment.

A comparison of a high-speed electronic data logger to a conventional strip chart recorder showed a good correspondence between the measurements of sudden high pressures, but the Radcom monitor was much more sensitive for capturing the low pressure events, on average showing values 10 psi lower than those recorded by the conventional recorder (Figure 5).



**Figure 5.** Comparison of the Radcom and Conventional Pressure Recorders for Measurement of Low Pressure Events

Application of high-speed pressure loggers to routine operations in approximately 10 systems has shown substantial variability in pressure values, however, negative values have only rarely been observed. Various attempts to examine hydrant flushing with different rates of valve opening demonstrated the production of pressure transients, but none



of the events produced negative distribution system pressures (Kirmeyer et al. 2001). Additional investigation of hydrant operation is warranted because hydraulic modeling has suggested that negative distribution system pressures could be produced under certain hydrant flushing circumstances.

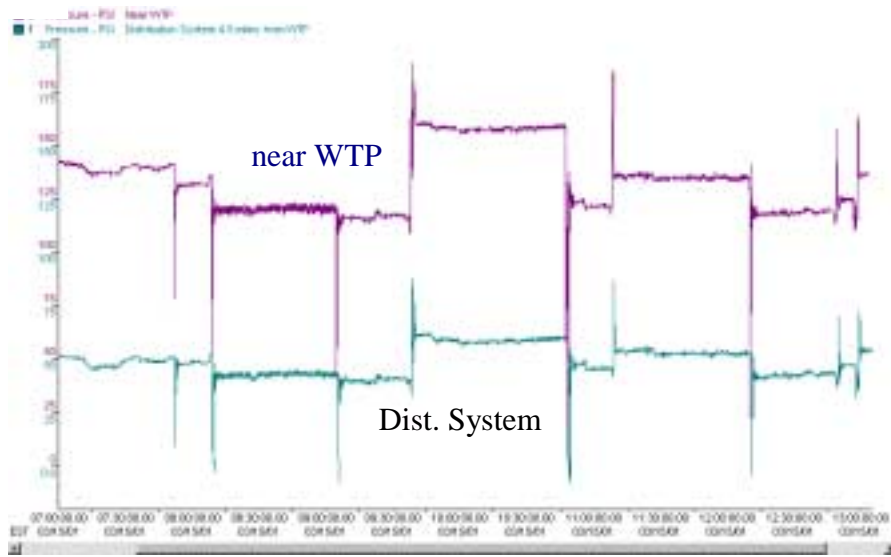
Examination of a household tap showed large fluctuations with pressures as low as 4.3 psi (data not shown). These fluctuations may be due to domestic water use patterns. If there was an external water table of 10 ft over the pipe (as in a stream crossing or low land area), there could be enough external water pressure to cause intrusion. The point is that it is not necessary to have a negative pressure – a low pressure can cause intrusion under certain circumstances.

Pressures were analyzed in one system while conducting a routine draw down test in Spring 2001 (an annual test to verify accuracy of the venturi meters at the water treatment plant). During this test, the main service pumps were shut down at the treatment plant clearwell and restarted with all flow going through one venturi meter. Two Radcom monitors were installed at high elevation points on a 30-inch main (one was ~2.5 miles from the plant, and the other was ~4.5 miles from the plant), and a third monitor was located about 80 feet from the treatment plant's high-service pumps. Pressure readings both near the treatment plant and within the distribution system showed large pressure fluctuations. While the static pressures near the plant ranged between 125 and 150 psi, the pressure transients caused by the pump shutdowns resulted in pressures as low as 18 psi in the plant effluent. However, several miles away in the distribution system these fluctuations resulted in a pressure of minus 10 psi lasting for 16 seconds (Figure 6). The valve closure speed for the main service pumps was 20 seconds, which may have been too fast, and thus contributing to the pressure transient. A second test was conducted with the valve closure speed slowed to 30 seconds, but negative pressures resulted from this second test as well.

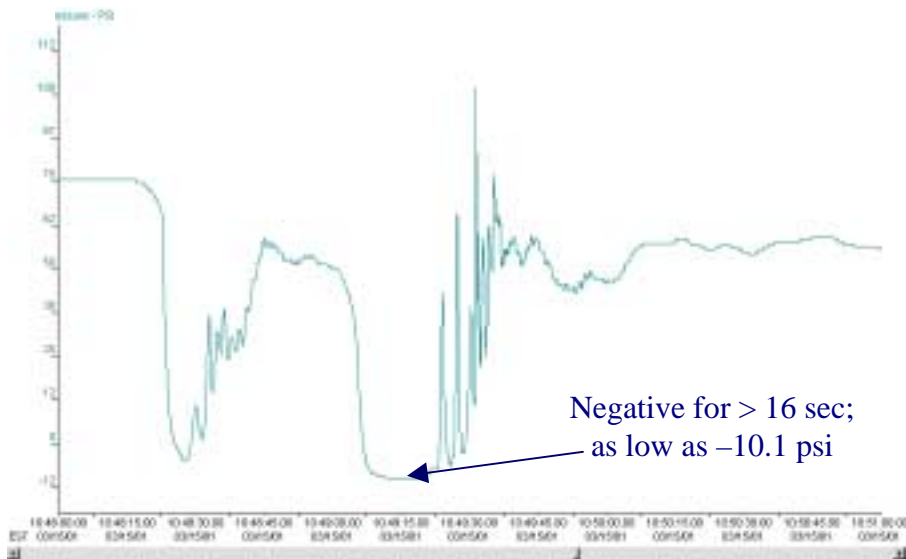
Routine pressure monitoring of another distribution system in December 2000 showed a negative pressure event during a power outage at a pumping station that lasted for 24 seconds and produced a negative 4.4-psi (Figure 7). Similarly, a power outage at the treatment plant of another system in July 2001 produced zero pressure for 51 seconds in a section of the distribution system (Figure 8).

Based on the above information, it is concluded that transient pressure events occur in distribution systems; that these events can result in negative pressures; that negative pressures provide a potential portal for entry of non-potable water into potable water distribution pipelines; and that fecal indicators and culturable human viruses are present in the soil and groundwater exterior to the distribution system. However, the characteristics of distribution systems that contribute to producing negative pressure transients have not been examined. These characteristics may include the presence of storage tanks, valve closure speed, placement of air relief and other surge control devices, pump operation, and shut down procedures. To date, all observed negative pressure events have been related to power outages or other pump shutdowns. More research is needed to better characterize the types of systems (e.g., those without distribution storage, without air or vacuum relief valves, etc.) most prone to negative pressure transient events.

A

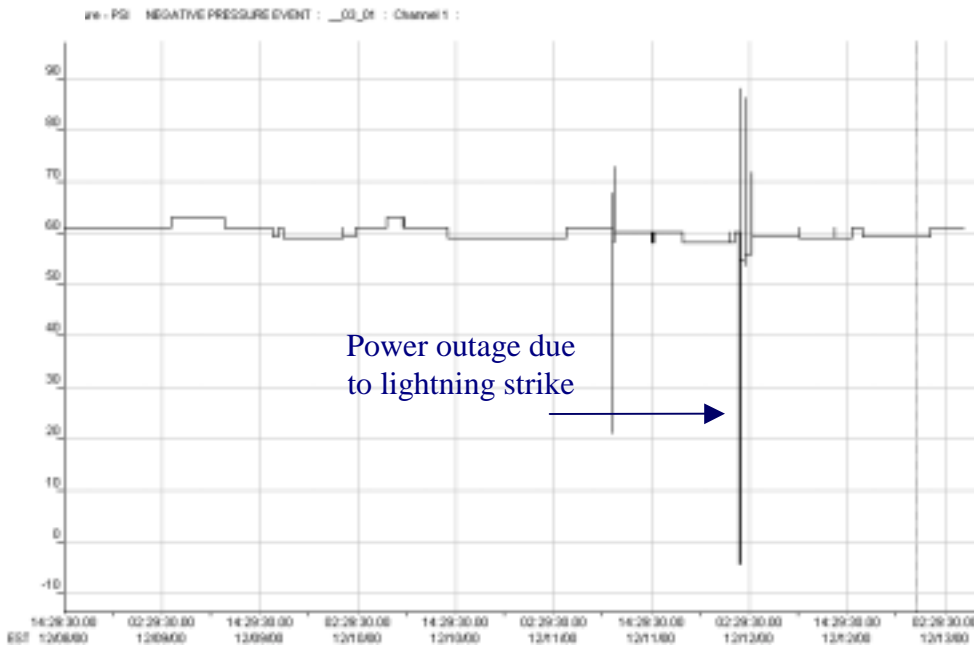


B

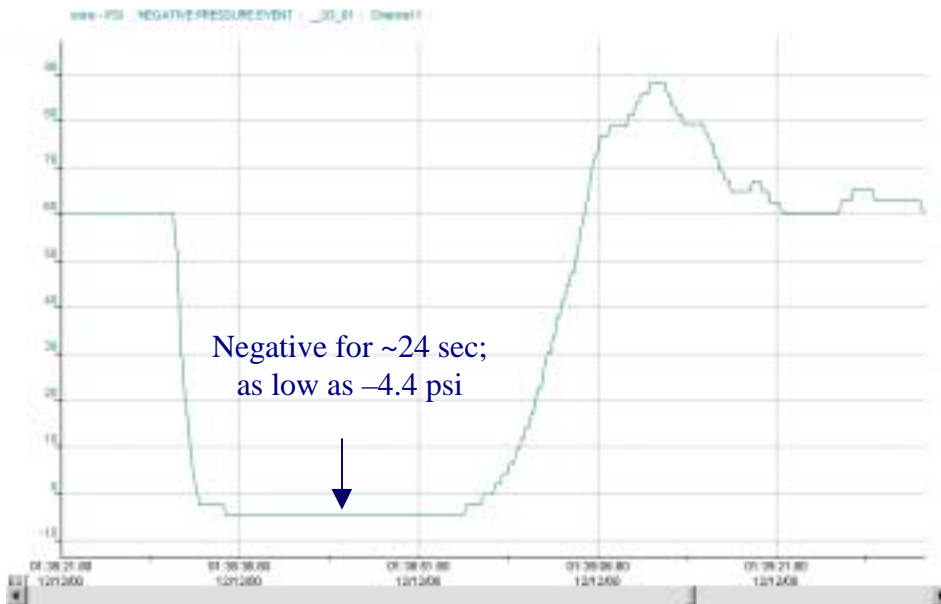


**Figure 6.** Pressure Recording During a Pump Draw Down Test. A) Pressures near the water treatment plant (WTP) and in the distribution system. B) Enlargement of one of the distribution system negative pressure events shown in A, illustrating duration of the negative pressure event. A second recorder in the distribution system showed similar results.

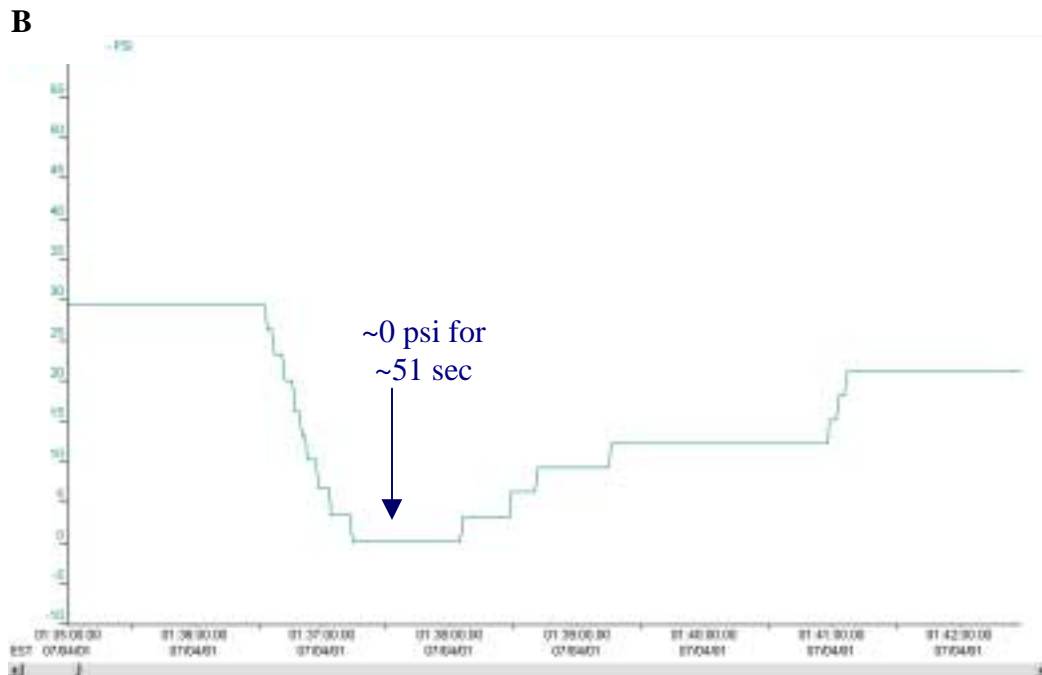
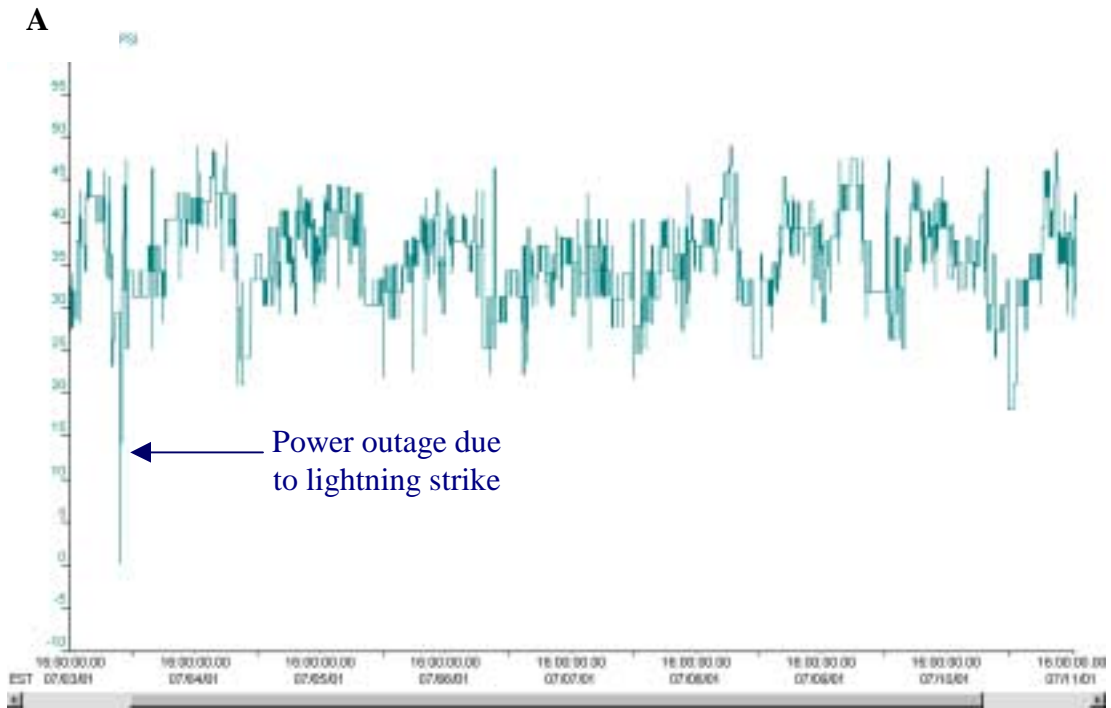
A



B



**Figure 7.** Distribution System Pressure Monitoring Following a Pump Station Power Outage. A) Daily monitoring data, B) Enlargement of the negative pressure event.



**Figure 8.** Distribution System Pressure Monitoring Following a Pump Station Power Outage due to a Lightning Strike. A) Daily monitoring data, B) Enlargement of the negative pressure event.

## *Public Health Impact*

Payment et al. conducted two epidemiology studies (Payment et al, 1991; Payment et al, 1997), each suggesting that the distribution system was at least partially responsible for increased levels of gastrointestinal illnesses. The studies examined the health of people who drank tap water and compared the group to people receiving water treated by reverse osmosis to determine which group had higher levels of gastrointestinal illness. Both studies pointed to the fact that people who drank tap water had increased cases of gastroenteritis. Analysis of Payment's data shows that people who lived in zones far away from the treatment plant had the highest risk of gastroenteritis. Transient pressure modeling (Kirmeyer et al. 2001) found that the distribution system studied by Payment was extremely prone to negative pressures, with more than 90 percent of the nodes within the system drawing negative pressures under certain modeling scenarios (e.g., power outages). The system is located in the Montreal area, and reported many pipe breaks, particularly during the Fall and Winter when temperature changes place added stresses on the distribution system. Although the system employed state-of-the-art treatment, the distribution network maintained low disinfectant residuals, particularly at the ends of the system. Low disinfectant residuals and a vulnerability of the distribution system to pressure transients could account for the viral-like etiology of the illnesses observed.

A double-blinded, randomized, trial was recently completed in Melbourne, Australia, to determine the contribution of drinking water to gastroenteritis (Hellard et al. 2001). Melbourne draws its drinking water from a protected forest watershed and has an unfiltered surface water supply using only free chlorine treatment. Free chlorine levels in the distribution system ranged from 0 to 0.94 mg/L, with a median of 0.05 mg/L, and 90% of samples had < 0.20 mg/L. Total coliform bacteria were detected in 18.9% of 1,167 routine 100-mL water samples, but fecal coliform bacteria were not detected. Distribution system samples were positive for *Aeromonas* spp. (50% of 68 weekly samples), *Campylobacter* (1 occasion) and *Giardia* (2 viable samples by reverse transcriptase-polymerase chain reaction). Six hundred families were randomly assigned to receive either a real or placebo water treatment unit installed on the kitchen faucet. Real units were designed to remove viruses, bacteria, and protozoa using microfiltration and ultraviolet light treatment. Study participants completed a weekly health diary reporting gastrointestinal symptoms during the 68-week observation period. The study found that the water was not a source of measurable gastrointestinal disease (the ratio of illness between the group drinking treated water compared to the normal tap water was 0.99, with a 95% confidence interval of 0.85–1.15;  $p = 0.85$ ). Analysis of 795 fecal specimens from participants with gastroenteritis did not reveal any difference in pathogen detection between the two groups. Pressure transient modeling of the Melbourne system has not been done and specialized pressure monitoring was not performed during the study.

The 1996 amendments to the Safe Drinking Water Act required the U.S. Centers for Disease Control and Prevention (CDC) and the U.S. Environmental Protection Agency (EPA) to conduct epidemiology studies to determine the occurrence of waterborne disease in the U.S. Dr. Jack Colford of the University of California at Berkeley School of Public Health is conducting one of these epidemiology studies in collaboration with the Iowa-American Water Company in Davenport, Iowa. The study began in November 2000, and will be completed in June 2002. The study is a randomized, triple-blinded, placebo-controlled, crossover intervention study. The

intervention to be tested is household-level treatment of drinking water. The water is treated using a kitchen countertop device that treats tap water with ultraviolet light and microfiltration. Participating households have been randomly assigned to two different groups. One group received the active device and the other received an identical-looking placebo device. Half way through the study, “cross-over” will take place: active devices will be replaced with inactive devices, and inactive devices will be replaced with active devices. The participants, the study staff, and the data analysis team will be blinded to (unaware of) which group each household has been assigned throughout the study. A total of 456 households residing in Davenport, Bettendorf, Panorama Park, and Riverdale have been enrolled.

The American Water Works Association Research Foundation has funded the American Water Works Service Company to conduct a water quality study in the Davenport area in parallel to the epidemiology study. The study is conducting extensive analysis of the raw water, treatment plant performance, distribution system and household water quality. Seven pressure data loggers (one in each pressure zone) are being used to monitor distribution system pressures to determine if pressure transients are associated with any health impacts that may be observed during the epidemiology study. To date, although fluctuations in pressures have been noted, no negative pressure events have been recorded in the distribution system. Modeling of the distribution system is underway to extrapolate the pressure data to the whole pipe network.

In summary, although there are data to demonstrate that negative pressure events do occur, there are insufficient data to indicate whether these events result in substantial risk to water quality in the distribution system. Direct monitoring of drinking water would be impractical due to the transient nature of the pressure effect, the relatively small volume of intrusion water (compared to the total volume within the pipe network), and the plug flow nature (e.g., limited dispersion) of water within distribution systems. In addition, a source of microbial contamination (e.g., leaky sewer lines) must be relatively near the pipe system, and the soil must be saturated to allow for microbial transport. These factors may be important variables explaining the disparate epidemiology results and should be factored into any future epidemiological studies.

## **Risk Mitigation**

The first step in risk mitigation for the issue of transient negative pressures in the distribution system is simply the recognition that the phenomenon does exist. Some have dismissed the issue as being not significant, too brief, or too small of a volume to be an important source of contamination. On-going studies are beginning to document the occurrence of negative transient pressure events within distribution systems, but additional research is necessary. The frequency of negative pressure transients need to be determined, as well as the characteristics of the distribution system that contribute to these events. Studies need to be conducted for ground water systems, particularly in non-disinfected systems.

Engineering standards require consideration of pressure transients for pipeline and pump design, distribution system network analysis, and valve selection and installation (Table 3). Information on transient analysis and control can be found in standard engineering texts on pump design, pipeline flow, and fluid dynamics (Karassik et al. 1976, Larock et al. 2000, Thorley 1991, Simon and Korom, 1997). Surge control, particularly control of high-pressure events, has typically

**Table 3.** Available Standards and Guidelines for Surge and Intrusion Mitigation

---

Existing Standards and Guidelines
<ul style="list-style-type: none"><li>• ANSI/AWWA C510 (Double Check Valve Backflow-Prevention Assembly)</li><li>• ANSI/AWWA C511 (Reduced-Pressure Principle Backflow-Prevention Assembly)</li><li>• ANSI/AWWA C512 (Standard for Air Release, Air/Vacuum, And Combination Air Valves for Waterworks Services)</li><li>• Recommended Standards for Water Works (10 State Standards)</li><li>• AWWA Manual M14 <i>Recommended Practice for Backflow Prevention and Cross-Connection Control</i></li><li>• AWWA Manual M32 <i>Distribution Network Analysis for Water Utilities</i></li><li>• AWWA Manual M36 <i>Water Audits and Leak Detection</i></li><li>• AWWA Manual M44 <i>Distribution Valves: Selection, Installation, Field Testing, and Maintenance</i></li><li>• AWWA Manual M51 <i>Air-Release, Air/Vacuum, and Combination Air Valves</i></li></ul>

---

been thought of in terms of preventing pipe bursts and efforts have been directed at reducing the maximum pressures. Concerns regarding negative pressure transients and their public health implications have not received similar attention. However, mitigation measures are well described and include slow valve closure times, avoiding check valve slam, minimized resonance, air vessels, surge tanks, pressure relief valves, surge anticipation valves, air release valves, combination two-way air valves, vacuum break valves, check valves, surge suppressors, and by-pass lines with check valves. A surge tank or standpipe provides water when system pressure decreases and can also absorb pressure increases. Four common types of surge tanks include: pneumatic or closed tank, open standpipe, a feed tank with a check valve, and a bladder tank. If water is stored in the tank for long periods of time the water quality may degrade and proper operation and maintenance is required to avoid poor quality water from entering the distribution system.

Air relief valves and similar appurtenances should be designed to have above-grade venting (at least 1-ft [0.3 m] and be designed to be tamper-proof to avoid deliberate contamination of the system). All below-grade vacuum or air relief valves should be retrofitted to above-grade venting, or modified in a way to prevent the flooding of the vault (e.g., drainage or pump).

The results of these studies emphasize the need to maintain an effective disinfectant residual in all parts of the distribution system. Although the effectiveness of a residual disinfectant has been debated (Trussell 1999), critics typically question the effectiveness of a disinfectant residual to inactivate volumes of sewage mixed with drinking water (Snead et al. 1980, Payment 1999). For distribution system negative pressure events, the volume of intruded water is a fraction (much less than 1%) of the water within the pipe network, so the opportunity for effective disinfection exists. Unknown is the effect of turbidity, compounds causing a chlorine demand, and limited mixing (in a relatively plug flow condition) on the disinfection efficacy of the residual disinfectant. Chloramine residuals will be particularly ineffective for viruses that intrude into the distribution system, as the CT (disinfectant concentration multiplied by the contact time) for preformed chloramines would not be effective for enteric viruses. Studies examining the microbial risk-risk tradeoffs (e.g., disinfection effectiveness for intrusion contaminants compared to biofilms) are needed as many U.S. water suppliers continue to convert from free chlorine to chloramines due to disinfectant by-product regulations.

Efforts to reduce distribution system pipeline leakage are beneficial not only from a water conservation standpoint, but also to minimize the potential for microbial intrusion into potable water supplies. Leaks are not simply a loss of revenue for a water utility, but the leak is a potential pathway for contamination. The public health benefits of leak control should be recognized and encouraged. Repair of leaking sewer lines should similarly be a top priority, not only to minimize the occurrence of pathogens near drinking water pipelines, but to reduce these sources of contamination being transported to groundwater supplies and receiving streams, particularly under wet weather conditions.

High-speed pressure data loggers would probably benefit distribution system monitoring, as they appear to be more sensitive, particularly for low-pressure events. Additional studies are needed to examine the accuracy of the pressure transducers and determine the appropriate placement of the recorders within the distribution system. Installation of the monitors at high elevation points within the distribution system would seem reasonable, but additional work is needed to identify other useful monitoring locations. The generation of high-quality pressure data would help determine the effect of routine operational practices on distribution system pressures. This monitoring data could evaluate the impact of hydrant operations, pump start-up and shut down procedures, and valve closing speed, among others. This information should be compiled to develop standard operating procedures to minimize low-pressure surges.

Surge modeling can be used to determine the potential vulnerability of a system to negative pressures under a number of worst-case scenarios (e.g., power failure, main break, flushing, etc.). This modeling would be useful especially after addition of new pipelines, interconnections, or changes in distribution system storage or consumption patterns that may have changed original design parameters. Modeling may be able to identify zones of the distribution system most prone to negative pressure events. These areas would then be prioritized for maintenance of a disinfectant residual, leak detection and control, main replacement, and rehabilitation of nearby sewer systems. This engineering analysis can apply surge control techniques, like installation of air relief valves (above grade), surge tanks, and other activities to mitigate negative pressure events.

Personnel training with respect to hydrant and valve operations, and prevention of unauthorized or inappropriate use of hydrants or blow-offs, would be useful so that maintenance and repair crews understand the concerns regarding the potential for intrusion.

## **Indicators**

Many States have requirements to maintain minimum distribution system pressures based on conventional pressure recorder data. It would be inappropriate, and possibly impractical to apply the same guidelines to data collected by electronic pressure loggers. Additional research is needed to evaluate new guidelines based on the frequency and duration of the event, the concentration and type of residual disinfectant, the proximity of the drinking water main to sewer lines, soil conditions and the level of the water table, and other data that still need to be collected to assess the public health significance of such events.



Additional research is needed to develop guidelines for proper placement of pressure monitors. Distribution system modeling of a power outage suggested that negative pressures may have occurred in locations other than those selected for pressure monitoring. Monitoring locations are often selected based on the availability of land, access, and electrical power or communications; not necessarily because the location is most prone to negative pressures.

Increased microbiological monitoring, particularly using existing methodologies, is not recommended because of the low probabilities of actually detecting an intrusion event. Use of continuous chlorine residual monitors may have some application, but the effectiveness of such an approach needs to be evaluated. Development of new on-line microbial monitoring techniques may have some future application, particularly those related to fiber optic or real-time analysis.

### **Current or Planned Research**

AwwaRF has completed one project related to distribution system intrusion (Kirmeyer et al. 2001) and has another project in progress (Field-Testing of Surge Modeling Predictions to Verify Occurrence of Distribution System Intrusion, #2686). The project is anticipated to 1) verify by field and pilot measurements surge model results and illustrate how operating conditions affect the production of low or negative pressures, 2) conduct pilot test studies comparing intrusion volume estimates for various operating conditions, and 3) develop guidelines for surge modeling, pressure monitoring, and other design and operation and maintenance practices to prevent intrusion. Drafts of this report should be available in 2003.

The Microbial/Disinfection By-Product Research Council organized a workshop in 2001 to identify the research gaps that were highlighted during development of the Stage 2 M/DBP Rules (M/DBP Research Council 2002). One workgroup dealt with distribution system issues, and the committee developed several projects that addressed intrusion. The project, "Characterizing the Importance of Distribution System Intrusion Events," would define the importance of distribution system intrusion events with respect to the frequency and level of contamination. Another project, "Distribution System Operations Assessment and Guidance Manual," would assess distribution system operational practices and goals (including intrusion) to develop a guidance manual outlining best operational practices. These recommendations will be forwarded to the USEPA and AwwaRF for consideration, but funds for these have not yet been allocated.

A report developed for the National Drinking Water Advisory Committee on recommendations for the USEPA drinking water research strategy identified a number of distribution system issues, including research on intrusion, as areas requiring future research (Working Group on Drinking Water Research 2002). The report concluded that research on the frequency, causes, mitigation, and health effects of intrusion events was one of the top research needs.

### **Summary**

In summary, it is concluded that transient pressure events occur in distribution systems; that during these negative pressure events pipeline leaks provide a potential portal for entry of groundwater into treated drinking water; and that fecal indicators and culturable human viruses

are present in the soil and water exterior to the distribution system. To date, all observed negative pressure events have been related to power outages or other pump shutdowns, although more research is needed to better characterize the types of systems most prone to these events. There is insufficient data to indicate whether pressure transients are a substantial source of risk to water quality in the distribution system. Nevertheless, mitigation techniques can be implemented, principally the maintenance of an effective disinfectant residual throughout the distribution system, leak control, redesign of air relief venting, and more rigorous application of existing engineering standards. Use of high-speed pressure data loggers and surge modeling may have some merit, but understanding the effectiveness of these tools requires additional research. More research is needed and this topic should become a priority for both the USEPA and industry-funded programs.

### **Acknowledgement**

This report was funded by the American Water Works Service Company, Inc. Much of the data provided is from American Water Works Association Research Foundation project #2686, and is used with their permission. Project members include Melinda Friedman, EES, Inc; James Funk and Don Wood, University of Kentucky; Glen Boyd, Tulane University; and AWWSC, Inc. The AwwaRF project manager is Stephanie Morales, and the Project Advisory Committee is Kevin Laptos, Tom Walski, Peter Gaewski, and Don Reasoner. The comments and suggestions of Richard Moser, John Young, Richard Hubel, Stephen Schmidt, Dave Reeves, James Funk, Don Wood, and Daniel Kelleher are appreciated.

### **REFERENCES**

Abu-Ashour, J. et al, 1994. Transport of microorganisms through soil. *Water, Air and Soil Pollution*. 75:141-158.

American Water Works Association and American Water Works Association Research Foundation. 1992. *Water Industry Database: Utility Profiles*. AWWA, Denver, CO.

American Water Works Service Company, Inc. 2002. American Water Works Service Company Buried Infrastructure Management Plan. White paper prepared for the US Environmental Protection Agency workshop on Distribution System Issues, March 7-8, Voorhees, NJ.

Funk, J.E., S.J. VanVuuren, D.J. Wood, M. LeChevallier, and M. Friedman. 1999. Pathogen Intrusion into Water Distribution Systems Due to Transients. Proceedings of the 3<sup>rd</sup> ASME/JSME Joint Fluids Engineering Conference, July 18-22, San Francisco, CA.

Funk, J.E., DJ. Wood, L.S. Reddy, and D.C. Denger. 1992. Pressure surges due to rapid expulsion of air. *In: Bettess & Watts (eds.), Unsteady Flow and Fluid Transients*, A.A. Balkema, Rotterdam, Holland.

Geldreich, E.E., 1996. *Microbial Quality of Water Supply in Distribution Systems*. Lewis Publishers, Boca Raton, Florida .

Grigory, S. 2002. Time for Leak Free Water Systems. [www.grigory.com/WaterpipeSeal.htm](http://www.grigory.com/WaterpipeSeal.htm).

Hellard, M.E., M. I. Sinclair, A. B. Forbes, and C. K. Fairley. 2001. A Randomized, Blinded, Controlled Trial Investigating the Gastrointestinal Health Effects of Drinking Water Quality. *Environ Health Perspect* 109:773–778.

Karassik, I. J., W. C. Krutzsch, W. H. Fraser, and J. P. Messina (eds.). 1976. *Pump Handbook*. McGraw-Hill Book Co., New York.

Karim, M, M. Abbaszadegan, and M.W. LeChevallier. 2001. Potential for pathogen intrusion during pressure transients. *JAWWA* submitted.

Kirmeyer, G.J., M. Friedman, K. Martel, D. Howie, M. LeChevallier, M. Abbaszadegan, M. Karim, J. Funk, J. Harbour. 2001. Pathogen Intrusion into the Distribution System. AWWA Research Foundation and the American Water Works Association, Denver, CO.

Kolpin, D. W., E. T. Furlong, M. T. Meyer, E. M. Thurman, S. D. Zuagg, L. B. Barber, and H. T. Buxton. 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in US streams, 1999-2000: a national reconnaissance. *Environ. Sci. Technol.* 36: 1202-2111.

Larock, B. E., R. W. Jeppson, and G. Z. Watters. 2000. *Hydraulics of Pipeline Systems*. CRC Press, New York.

LeChevallier, M.W., 1999. The Case for Maintaining a Disinfectant Residual. *JAWWA*. 91: 86-94.

M/DBP (Microbial Disinfection By-Product) Research Council. 2002. *Assessment of Microbial and Disinfection Byproduct Research Needs: Final Report*. AWWA Research Foundation, Denver, CO.

Working Group on Drinking Water Research. 2002. Cross-Cutting Issue Background Document, Final Draft. Water Distribution System Research Status and Needs. A report to the USEPA National Drinking Water Advisory Committee, Washington, DC.

Patterson, G.G. and M. J. Focazio. 2001. Contaminants and drinking water sources in 2001: recent findings of the U.S. Geological Survey. Open File Report 00-510. USGS, Denver, CO.

Payment, P., L. Richardson, J. Siemiatycki, R. Dewar, M. Edwardes, and E. Franco. 1991. Randomized trial to evaluate the risk of gastrointestinal disease due to consumption of drinking water meeting microbiological standards. *Am. J. Pub. Health* 81(6): 703-708.

Payment, P., J. Siemiatycki, L. Richardson, G. Renaud, E. Franco, and M. Prevost. 1997. A prospective epidemiological study of gastrointestinal health effects due to the consumption of drinking water. *Intern. J. Environ. Health Res.* 7:5-31.

Payment, P. 1999. Poor efficacy of residual chlorine disinfectant in drinking water to inactivate waterborne pathogens in distribution systems. *Can. J. Microbiol.* 45(8): 709-715.

Qaqish, A., D.E. Guastella, J.H. Dillingham, and D.V. Chase. 1995. Control of Hydraulic Transients in Large Water Transmission Mains, p 507-526, AWWA Annual Conference Proceedings - Engineering and Operations, Anaheim, CA, June 18-22, 1995 American Water Works Association, Denver, CO.

Recommended Standards for Water Works, 1997. *Great Lakes Upper Mississippi River Board of State Public Health & Environmental Managers*. Health Education Services, Albany, New York.

Simon, A. L. and Korom, S. C., 1997. *Hydraulics*. 4th edition. Upper Saddle River, NJ, Prentice Hall.

Snead, M. C., V. P. Olivieri, K. Kawata, and C. W. Kruse. 1980. The effectiveness of chlorine residuals in inactivation of bacteria and viruses introduced by post-treatment contamination. *Wat. Res.* 14:403-408.

Streeter, V.L. and E.B. Wylie. 1967. *Hydraulic Transients*. McGraw Hill Inc., new York.

Thorley, A.R.D. 1991. *Fluid Transients in Pipeline Systems*. D. & L. George, Ltd., Herts, England.

Trussell, R.R. 1999. Safeguarding distribution system integrity. *JAWWA* 91(1): 46-54.

USC FCCCHR. 1993. *Manual of Cross Connection Control, 9<sup>th</sup> ed.* University of Southern California Foundation for Cross Connection Control and Hydraulic Research. Los Angeles, CA.

Walski, T.M. and T.L. Lutes. 1994. Hydraulic Transients Cause Low-Pressure Problems. *JAWWA* 86(12): 24-32.

Wood, D. J., R.G. Dorsch, and C. Lightner. 1966. Wave Plan Analysis of Unsteady Flow in Closed Conducts. *Journal of the Hydraulic Division, Proc. Paper 4716, ASCE, 92( HY2): 83-110.*