Control of Transient Induced Contaminant Leakage and Infiltration by Implementation of Air Valves

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ABSTRACT

Pressure transients wreak very extensive damages to water and wastewater transmission systems. Until recent years, most of the concern related to pressure transient damages was focused on the obvious extreme events of pipe burst or collapse that result in major spills or flooding. But, there are many damages, far more widespread and often more dangerous, that are less obvious and attract less attention. Pressure transients cause cracks and unseen small breaks in buried pipelines, pipe fittings, and accessories. They cause joints to fracture or to come apart, they cause damage to seals and gaskets or cause them to shift out of their sealing positions. These damages result in leakage and in contaminant intrusion and their consequent economic, environmental, and public health repercussions.

Municipal and industrial wastewater leaking from transmission pipeline and force main systems damaged by pressure transients infiltrate, pollute, and contaminate ground and surface water, soil and the environment in which they pass, becoming dangerous health and environmental hazards and nuisances, spreading odor and providing havens for mosquitoes, flies, and other disease spreading insects. Water and soil polluted and contaminated by leaking wastewater can bring to pathogen and toxin intrusion into drinking water systems.

All these repercussions of pressure transients have come, more and more, into the limelight in the past few years, and great efforts are being made to control them.

The advantages of air valves as efficient and cost effective tools for the control of both, pressure transients, and their dangerous consequences, are often overlooked or unfamiliar. Modern, well designed, often innovative air valves, with the help of modern design tools, such as air valve sizing, location, and specification software and advanced transient analysis software, can control and dampen transients and eliminate or limit their damages.

KEYWORDS

Air valve, air release valve, air vacuum valve, wastewater, pressure transients, surge, upsurge, down-surge, vaporous cavitation, cavitational hammer, leakage, leak, gap, contaminant infiltration, pathogen intrusion, contamination, pollution.

The Problem

Pipeline systems are usually designed assuming homogeneous construction and structural integrity of the pipes and accessories, assuring leak free, efficient operation. In real life, though, this is not always the situation. Sometimes, even a brand new pipeline may not be homogeneous, and some segments of pipe wall may not be uniformly thick and/or uniformly strong all around the pipe's circumference. This is especially true for aging pipes and pipes operated under severe and/or corrosive environments. Actually, many pipelines suffer from cracks and faulty joints, seals, and gaskets. Most of these gaps go unnoticed until they result in severe pipe ruptures and pipe bursts. In the Professional and Technical Resources section of the American Water Works Association's website, in a chapter titled "*Apparent and Real Losses*", it is stated that: " Many drinking water utilities around the world respond to leaks only after they receive a report of water erupting from a street or a complaint from a customer about a damp basement". [25] The same can be said for wastewater systems.

The transition from a small gap to a noticeable pipe rupture or burst may take many years, while the pipeline leaks. These leaking gaps are two-way breaches in the pipeline consistency, allowing conveyed liquids to leak out, and external fluids (both liquid and gas) and particles to intrude into the pipeline – for instance, at pressure drop.
Leakage of conveyed liquids out of the pipeline can bring on financial losses and other damages. When the conveyed liquid is a potential pollutant, such as wastewater or fuel, discharge leakage could result in very serious pollution of ground water, surface water, soil, and the local environment.

Potable water transmission pipelines often pass through polluted environs. If these polluted environs contain contaminated ground water, polluted runoff, wastewater, or some other form of contamination, pathogen and contaminant intrusion into the pipeline through gaps, at low or negative pressure, is inevitable.

Assessment of the problems

Expanding population and the general rise in the standard of living have a great impact on the environment. This raises widespread public concern for both, the environment and for public health, on a global basis. National and international organizations are reacting to these concerns, devoting resources to study problems of pollution and contamination by leaking pollutants, and to search for solutions. Studies were conducted to determine the extent of the phenomena of deteriorating pipelines, of pollution from leaking and broken wastewater force mains, of pathogen and contaminant intrusion, etc. Much has been done in the field of leak detection and on the subject of pressure management for reducing the intensity of leakage. Much has been done in the development of equipment and procedures for pipe repair, and for making repairs quicker, thus decreasing inconvenience and nuisance, as well as lessening environmental and financial damages.

But, all these measures assume leaks as being an inevitable part of life.

Damaged pipelines

Concerned with deteriorating conditions of pipeline systems, the United States Environmental Protection Agency (EPA) published a special Distribution System Issue Paper in May 2002, which deals with the deteriorating conditions of infrastructures. In this paper, the authors list some of the characteristics of deteriorating water distribution systems, including leaks, main breaks, taste, odor and red water, reduced hydraulic capacity due to internal pipe corrosion, and increased disinfectant demands due to the presence of corrosion products, biofilms, and regrowth. The paper reviews and assesses the problems, their technical, economic, and health aspects, and discusses subjects such as rehabilitation decision-making (is it preferable to fix or replace?), about choosing pipe material, and even about some preventive technology, such as cathodic protection. In the conclusion, among other observations and suggestions, the paper points out the merit of considering more preventive technologies and the importance of including the subjects of hydraulic transients and pipe failure mechanism in the technical content of the training and education of personnel. [12] Though this paper deals with potable water systems, the problems and solutions can be related to wastewater systems as well.

Pollution and contamination from leaks

When potable water leaks out of transmission mains and distribution networks, the consequences are mostly economic and sometimes affect local shortage. But, when the leaking liquid contains pollutants or contaminants such as raw wastewater, for instance, the consequences could be much more severe. Wastewater, leaking out of force mains, can infiltrate into ground water and aquifers and contaminate drinking water, soil, rivers, etc. Contaminants from leaking wastewater can intrude into drinking water supply pipelines and facilities, endangering the health of thousands of people.

In an article in the May 2003 issue of Journal AWWA, *Potential Pathogen Intrusion during Pressure Transients*, Mohammad R. Karim refers to the AWWA Research Foundation study, *Pathogen Intrusion Into the Distribution System*, where soil and water samples adjacent to drinking water pipelines were tested for pathogen contaminants. 65 samples, 33 of soil and 32 of water, were collected from eight utilities in six states in the United States, and tested for pathogens. Most of the samples contained pathogens, some in substantial concentrations, almost all contained Bacillus. [13] See Figure 1.

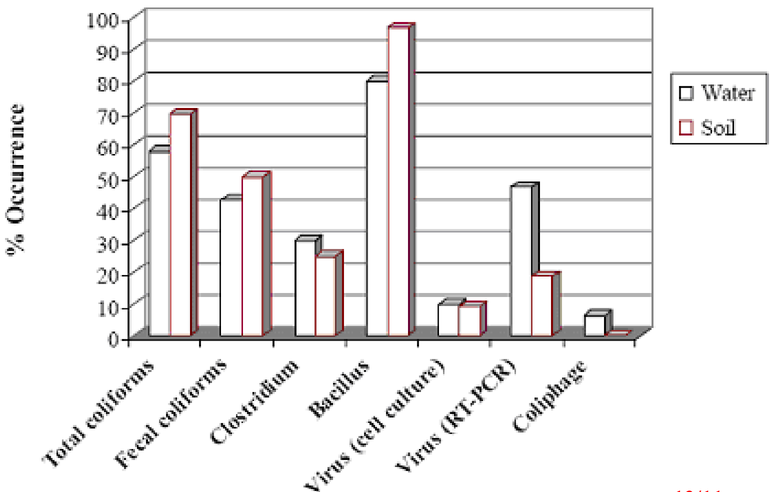


Figure 1: Microbial Occurrence in Soil and Water [13/11]

The samples were collected randomly, and it is not known how many were located adjacent to wastewater sewers or force mains. Engineering standards (in the United States) call for a minimum spacing of 10 ft (3 m) between drinking water pipelines and wastewater pipelines, but, if the water pipeline is above the wastewater pipeline, separation as small as 18 inches (46 cm) is possible. High concentrations of total fecal coliform, reaching levels of 10^4 bacteria per 100 grams of soil, could be a credible sign for the presence of human sewage in the vicinity. In saturated soils, microbes can move several yards in a short time, and this movement can be enhanced by wastewater flowing out of sewers or force mains. High concentrations of Bacillus spores in soil samples, as high as 10^8 colony-forming units (CFU) per 100 grams (3.53 oz) of soil, some of the highest level samples containing human enteric viruses, affirm the possibility "that seepage of sewage stimulated the growth of the soil flora in these locations" [11]

Pathogen and contaminant intrusion

As stressed in the EPA distribution system issue paper: *The Potential for Health Risks from Intrusion of Contaminants into Distribution System from Pressure Transients,* reduction of distribution pipeline leakage is not only important for water conservation, for energy conservation, or for reducing loss of revenue for water utilities, but much more. A leak (a gap) is a potential pathway for contamination. [11] Any drinking water pipeline passing through an area of contaminated water and/or soil is a potential pathogen carrier. As stated in the issue paper: "The public health benefits of leak control should be recognized and encouraged". [11] A leak (a gap) in a wastewater force main is also a potential pathway for contamination, only here the pathway is from the pipe outward to the environment. Leaking sewage and wastewater contaminate water and/or soil that can intrude into drinking water pipelines.

The EPA issue paper above mentions two epidemiological studies that were made in 1991 and 1997, and both indicated that people drinking tap water had increased cases of gastrointestinal illnesses compared to those who did not. Data from the studies showed that people living farther away from the water treatment plant and the supply source had a higher risk of gastroenteritis.[11] This could be an indication that the illness causing pathogens entered the pipelines after the treatment plant, and not at the supply source. The EPA issue paper further reveals that in a report published in 2001 on transient pressure modeling of the distribution system studied above, it was found that the system 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)". [11] This strengthens the assumption that the illness-causing pathogens entered the system through the distribution piping and not at the source.

In addition to pathogen contamination through intrusion, water distribution systems are also prone to intrusion of biological and chemical contaminants originating in wastewater force mains, that could cause extensive health and property damages and could be very dangerous. Harmful biological and chemical contaminants in the pipeline external environs can easily intrude the pipeline, endangering the consumers and presenting serious health hazards.

Causes for pipeline damages

There are many causes for pipeline damages resulting in leakage and intrusion. There are natural causes such as soil movement, soil erosion, extreme temperature changes resulting in damaging expansion and contraction of pipelines, freezing of water inside the pipeline exerting internal pressure due to the expansion of ice, etc'. Granular materials and aggressive hydraulic regimes (high velocity flow, etc') can cause physical erosion of pipeline walls. Vehicles, digging equipment (backhoe, etc'), and other implements of everyday activities can cause external physical damage. Aggressive biological, chemical, and electrical environments cause corrosion and erosion, weakening, pitting, fissuring, and/or breaching in pipe walls. Wastewater often contains dissolved oxidants, such as oxygen and chlorine, originating in the potable water supply (dissolved oxygen is always required in drinking water and a minimum residual chlorine concentration is also usually required). When in contact with metallic iron, these oxidants present a driving force for active corrosion. It is claimed that the corrosion rate is probably limited by the rate at which oxygen (that comes out of solution) is provided to the surface. [12]

Another corrosion process, this time in systems carrying liquids with very low or zero dissolved oxygen concentrations, is hydrogen sulfide corrosion. Hydrogen sulfide corrosion is a major cause of wastewater transmission pipe damage and deterioration. This biochemical process is often thought to affect only gravity sewers and pipelines that are not surcharged (full-pipe flow). But, force mains, inverted siphons, and other surcharged wastewater pipes, and sometimes even very long pressurized water pipelines carrying water with low oxygen concentration and high sulfur concentration are susceptible to hydrogen sulfide corrosion in places where air pockets accumulate. Air pockets accumulate at the crown of the pipe, creating conditions similar to partial pipe flow.

The United States EPA, concerned with the problems of hydrogen sulfide corrosion, sponsored a number of research studies on the subject. In a report of one of these studies, entitled "*Detection, Control, and Correction of Hydrogen Sulfide Corrosion in Existing Wastewater Systems*", it is written that: "Since the pipes are generally full of wastewater, corrosion will not occur within surcharged pipes unless they contain air pockets. If an air pocket exists, corrosion may occur very quickly". [19] Pipes of almost all materials, other than plastic materials, are susceptible to hydrogen sulfide corrosion. These include steel pipes, cast and ductile iron pipes, concrete pipes, cement or mortar lined steel and iron pipes, asbestos cement pipes, and more.

Hydraulic pressure transients (surges) present one of the most prevalent causes for pipe damage, including pipe bursts, pipe collapse, pipe cracking and pitting, leakage and intrusion. Damages brought about by hydraulic transients are even more prevalent and more severe when the pipeline or pipeline sections are already weakened by events or processes mentioned above.

Hydraulic pressure transients (Surge)

When referring to surge, people usually think of an upsurge, an extreme, sudden, pressure rise. But, most surge events are transient episodes involving both, upsurges and down-surges. Pressure transients can be described as waves possessing both, positive and negative amplitudes. These transients are caused by sudden extreme changes in flow velocity brought about by events such as pipe bursts, sudden changes in demand, sudden pump start-ups and shut-offs, opening and closing of fire hydrants, quick closing and opening of in-line isolating valves, flushing and draining operations, fire flow, feed tank draining, and other similar events. "As a general rule of thumb, for every 1 ft/sec (0.3 m/sec) of velocity forced to a sudden stop, water pressures increase 50 to 60 psi (3.45 to 4.14 bar) (depending on the pipe materials, topography, etc'). The opposite is true for a sudden velocity increase, resulting in instantaneous low or negative pressure." [11]

The transients that generally attract most concern are the extreme upsurges that cause severe damages to pump stations or to pipelines.

Customarily, transient analysis focused almost entirely on preventing disastrous failure at pump stations and their connecting distribution pipelines. Less attention was given to transients occurring in distribution systems and minor pipelines. Surge control was very often focused on extreme upsurges and on preventing pipe bursts by reducing maximum pressures. Not enough emphasis was given to negative pressure transients and their public health implications. Pipe collapse was attributed to “vacuum”, which was not always recognized as a hydraulic transient event or a down-surge.

Great emphasis is given to pressure surges at pump stations because of economic consequences of these extreme transient events. Pumps and other equipment in the pump station are expensive, as are consequent damages they may incur under severe transients. But, there is another reason why some water and wastewater system operators focus their attention to the pump station - the misconception that a surge event is restricted to its source. If a surge event was initiated by a pump trip, for instance, some operators believe surge will affect only the pump station. This, of course, is a fallacy. Pressure transient waves, with their positive and negative amplitudes, propagate from their source (pump, closed valve, etc.) to the water/wastewater transmission system. Some of these waves can reflect off different obstacles along the pipeline, such as fittings, joints and accessories, and propagate back to the source. When two or more waves of similar amplitude (positive or negative) meet, the intensity of the resulting pressure (positive or negative) at the point of encounter is equal to the sum of the pressures of the individual waves. So it is possible for the intensity of transients at locations along the pipeline to be greater than at their source.

Tests made in 2001 at a water treatment plant pump station and its distribution system revealed large pressure fluctuations. Static pressure near the plant ranged between 125 and 150 psi (8.62 and 10.34 bar), but pressure transients caused by pump shutdowns resulted in pressures as low as 18 psi (1.24 bar) at the pump discharge. Several miles away, in the distribution system, these fluctuations resulted in a pressure of minus 10 psi (0.69 bar) lasting for 16 seconds.[11]

Water column separation, down-surge, and vapor cavity

Many pressure transient events are accompanied by water column separation. When a pump shuts off, or when an isolating valve is closed rapidly, water (wastewater) supply down stream stops, but the water continues to flow away from the pump or valve, driven by inertia. The water flowing away from the pump or valve is referred to as a “water column” and this phenomenon is called “water column separation”. Water column separation also occurs when there is a sudden flow velocity increase, such as at pipe burst or pipe drainage. Already in 1900, Joukowsky, who proposed the law for instantaneous water hammer in a simple pipe system, expressed in the Joukowsky Equation ($\Delta H = \frac{aV_0}{g}$), was the first to observe and understand column separation.[3]

Joukowsky refers to the space left by the parting water column, not calling it “vacuum”, as some do, and not referring to it as a complete void, but calling it a “rarefied void”. He also indicates that separation can occur in other locations in the pipeline other than the closed valve that initiated the separation. Explaining one of his experiments, he wrote: “The water column will be separated from the gate, ahead of which a small rarefied void develops. Similar separations can also form in other parts of a liquid column, the parts towards which the reduced pressure propagated.”[3]

At water column separation, if nothing replaces the parting water column, leaving a void behind, pressure drops and a down-surge occurs at the point of separation. When pressure drops below vapor pressure of the liquid, some of the liquid vaporizes, filling the void with vapor. The void is now called a “vapor cavity”.

A complete water column separation is not a prerequisite for vapor cavity formation. When negative amplitudes of pressure waves meet, and their total intensity is greater than the local head, resulting in a local pressure drop below the vapor pressure of the liquid, a gap and vapor cavity will form in the liquid body. This phenomenon is called “cavitation”. The gap does not have to occupy the full diameter of the pipe, and it can be located anywhere along the pipeline. [3]

As mentioned before, a transient event includes upsurges and down-surges. Whichever occurs first depends on what initiated the transient event, liquid acceleration or deceleration. If the transient event is initiated by a pump shut-off or by a quick closing valve (looking down-stream from the valve), the transient event will commence with a down-surge. If we look upstream from a quick closing valve, the transient event will commence with an upsurge, as the water column movement is suddenly blocked by the closing valve. After the formation of a vapor cavity, when the water column and/or an upsurge transient wave return, raising pressure back to above vapor pressure, the vapor changes phase back to liquid. This is called “vapor cavity collapse”. A hydraulic pressure transient event that includes the formation and collapse of a vapor cavity is called “vaporous cavitation”, “cavitation transient”, “cavitation surge”, “cavitation hammer” or, simply “cavitation”.

Hydraulic transients in pipeline systems can be divided into two distinct flow regimes, the *water hammer regime*, where cavitation does not occur, and the *cavitation regime*, where cavitation does occur. The classical water hammer equations are not valid in regions of cavitation.[3]

Usually, in a cavitation regime, the consequent upsurge is much higher than in a regular upsurge following column separation, resulting in a water hammer regime.

Joukowsky did not use the term “vapor cavity”, but he realized that in a transient event commencing with the impact of a water column against a closed valve (gate), the second upsurge is often greater than the initial upsurge. In Joukowsky’s words: “The condition, that water column is separated from the gate, prolongs the duration of the reduced pressure and makes the second impact stronger than the first, because it takes place with the velocity, at which the liquid column speeds into the rarefied void.” [3] In the quote above, Joukowsky implies that the duration of the down-surge (reduced pressure) has an intensifying effect on the resulting upsurge. Figure 2, below, shows Joukowsky’s graph, describing the transient event above. The x-axis is the time axis, where each dot indicates half a second, and the y-axis is the pressure axis. The top horizontal line is the static pressure, and the bottom line is the atmospheric pressure (absolute pressure). [3]

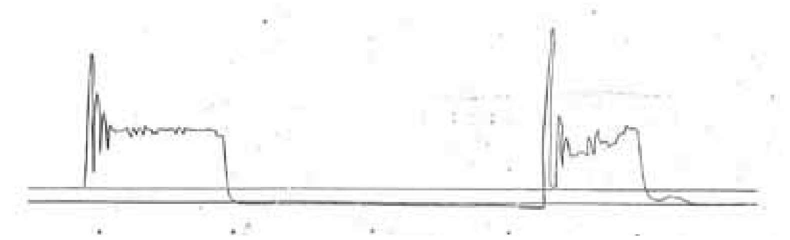


Figure 3: Joukowsky's pressure record exhibiting the initial upsurge at left, a down-surge, at water column separation, lasting about 1.15 seconds, and a second, higher upsurge [3]

Vapor cavities develop not only adjacent to closed valves or pumps. Surge researchers, such as Simpson, Wylie and Bergant, have shown clear experimental evidence of formation of intermediate vapor cavities.[3] Sometimes, upsurges following intermediate vapor cavity formation and collapse can be greater than those close to, say, a closed valve. A German surge researcher, A. Kottmann showed, by using the rigid-column theory, that the collapse of a midpoint cavity-caused upsurge pressure could reach three times Joukowsky.[3]

Pipe damage from pressure transients

If a pipe is new and its walls are of uniform thickness and strength, at a very extreme down-surge, the pipe could collapse to look like an open channel (see Figure 3).

In many cases, a pipe's walls are not uniformly thick and strong around its circumference. Because of manufacturing faults or because of corrosion, erosion, wear, etc., quite often, certain areas on the pipe wall's circumference are thinner and weaker than the rest of the circumference.

When hydrogen sulfide corrosion attacks a wastewater pipeline, for instance, this internal

Figure 3:
A steel pipeline, newly laid above ground (in India), collapsed when a drainage valve was opened for flushing, too fast.

corrosion develops at the crown of the pipe. If groundwater level rises above the bottom of a pipeline, external corrosion may attack at the bottom of the pipe. In both cases, a section of the pipe wall circumference is weaker than the rest. At water column separation and/or down-surge, the weaker area of the pipe wall will buckle inwards. At column return and/or upsurge, the same weak area will buckle outwards. Pressure transients will usually recur again and again at the same points in the system. With recurring down-surges and upsurges, resulting in inward and outward buckling, the weaker areas on the pipeline will crack longitudinally along the weak section of the pipe. With recurrent pressure transients, cracks and gaps

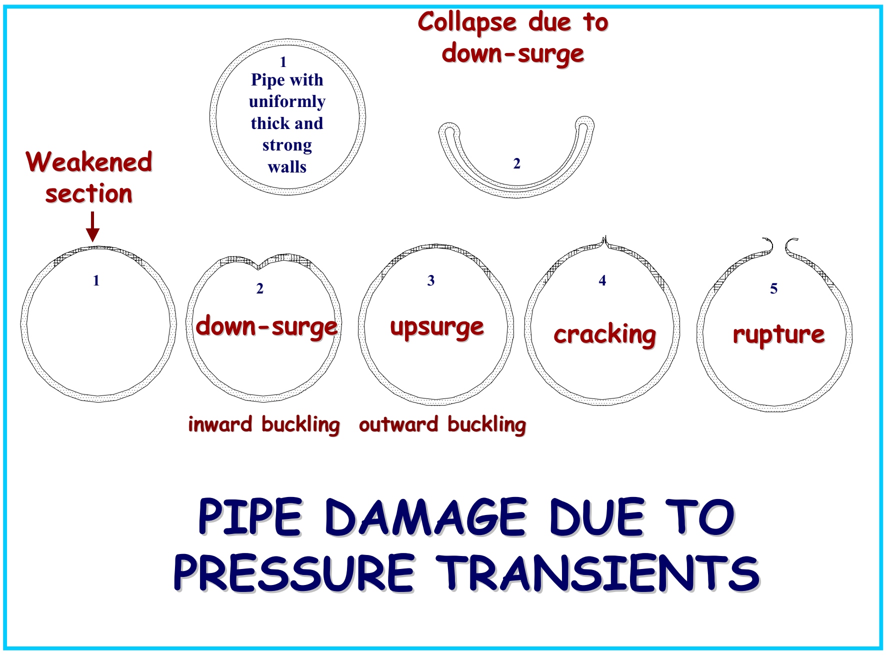


Figure 4: Pipe reaction to Pressure transients

become larger and larger. After continuously recurring transient events the pipe will eventually rupture. But this could take days, months, or years. These transients do not have to be extreme. Very slight transients can, in some cases over long periods and in other cases in shorter periods of time, induce this pipe deterioration process.

Air/gas pockets and pressure transients

Surge experts have come to realize that air/gas pockets of certain sizes and in certain locations can intensify pressure and pressure surges. A.R.D. Thorley, in his book, *Fluid Transients in Pipeline Systems*, states that: "extremely high shock loads can be generated when moving slugs of liquid following pockets of gas suddenly encounter valves, pipe bends and similar obstructions to the flow".[15] In the publication, *Air problems in pipelines – A design manual*, it is pointed out that several investigators reported that peak transient pressures can be larger in pipes with air pockets (which are referred to as air-filled voids), than in pipes without air pockets. It is also stated that: "In the absence of air valves on the summits of undulating pipeline profiles, the presence of air pockets, even if migratory, is inevitable, with potential impact on resulting surge." The publication indicates that pressure magnifications in factors as high as 2.6 and even 9, have been observed by researchers.[2]

R. Burrows and D.Q. Qiu, in their article, *Effects of air pockets on pipeline surge pressure*, show that small air pockets (V=0.025 m^3 = 0.883 ft^3) can cause a very substantial increase in peak pressures. Figure 5 shows an example of the variations of surge pressures at a pump exit of a particular pipeline, with and without an air pocket located at a point on the pipeline, at a distance equal to 0.41 the pipe's length, from the pump. [4]

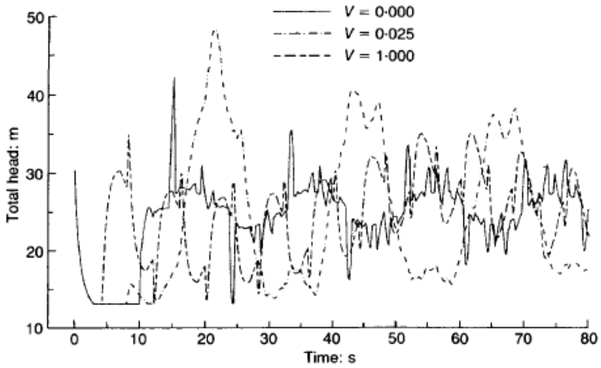


Figure 5:
Variations of surge pressure at pump exit with and without an air pocket at a point 0.41 of the pipe's length down-stream from the pump [4]

O. Pozos-Estrada, in his paper, *Investigation on the Effects of Entrained Air in Pipelines*, also shows that small air pockets cause a considerable increase in the intensity of transients, both, positive and negative. Figure 6 below, shows an example of results of surge analyses of transients caused by power failure at a three-pump pump station, pumping at a flow rate of 1.875 m^3/s (66.2 ft^3). There are 4 air pockets, positioned as marked on the pipeline profile in points 1,2,3, and 4. Four analyses were run – one with no air pockets, and three with small, large, and intermediate size air pockets. For the small volume air pocket analysis the air pockets were sized: V_1=0.145 m^3 (5.12 ft^3), V_2=0.448 m^3 (15.82 ft^3), V_3=1.038 m^3 (64.91 ft^3), and V_4=0.412 m^3 (14.55 ft^3). For the intermediate volume air pocket analysis the air pockets were sized: V_1=0.761 m^3 (26.87 ft^3), V_2=1.235 m^3 (43.61 ft^3), V_3=1.747 m^3 (61.69 ft^3), and V_4=0.856 m^3 (30.23 ft^3). For the large volume air pocket analysis the air pockets were sized: V_1=4.099 m^3 (144.75 ft^3), V_2=5.244 m^3 (185.19 ft^3), V_3=5.456 m^3 (192.68 ft^3), and V_4=3.449 m^3 (121.80 ft^3). As can be clearly seen, the small air pockets resulted in both, the highest upsurges, and highest down-surges. [5]

In a comprehensive report on studies of air in pipelines, *Experimental and numerical studies on movement of air in water pipelines*, M. Escarameia and his colleagues list a number of observations and conclusions regarding amplification affects of air pockets on pressure transients, among them; a) that small air pockets have the potential to enhance the frequency and amplitudes of pressure waves; b) that air pockets at the upstream section of a pipe and close to the pump have a greater potential for destructive enhancement of pressures; c) that smaller air pockets produce higher pressures at upstream junctions on the pipeline, and larger air pockets produce higher pressures at downstream junctions on the pipeline, depending on the pipeline configuration; d) that there is a limit to the size of a small air pocket that enhance pressure peaks – a 'critical' size; e) that in certain pipe small air pockets produce peak pressures along the majority of the pipeline and also result in cavitation along part of the pipeline profile; f) that in certain pipe profiles larger air pockets enhance peak pressures along sections of the pipeline; and g) that the 'critical' size of an air pocket depends on the pipeline configuration and air pocket location on the pipeline – in the examples presented = 0.05 m^3 – 0.10 m^3 (1.77 ft^3-3.53 ft^3). One very important conclusion of this study determines that: "The presence of air pockets have been shown, in certain circumstances to cause both high and low pressure fluctuations which are sufficiently large to potentially cause pipe fracture and pipeline failure. This, therefore, highlights a need for consideration of the transient wave interaction with entrapped air pockets during design stage”. [16]

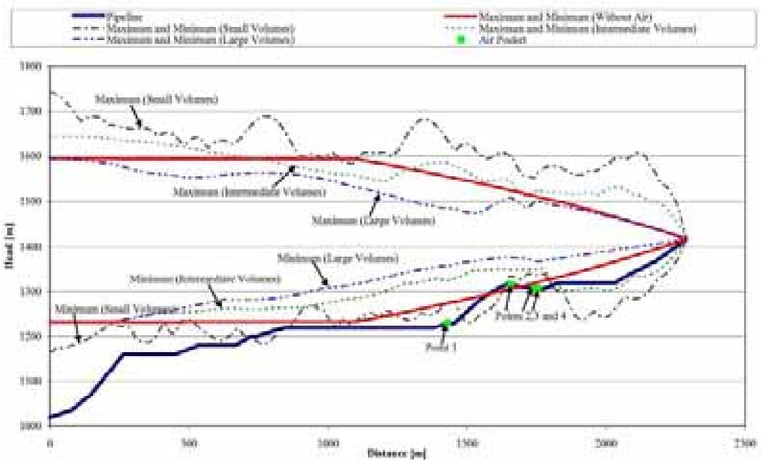


Figure 6: Maximum and minimum head envelopes with different size air pockets located at points 1,2,3, and 4, and flow rate $Q=1.875\ m^3/s$ [5]

Leak intensification by pressure transients

Besides causing damages that promote leakage and pathogen and contaminant infiltration, pressure transients increase the rates and the amounts of leakage and contamination.

At higher pressure, the flow rate of leakage through gaps in the system is higher. The longer the period of high-pressure, the greater is the volume of leakage. During upsurges, the rate of leakage is greatly amplified, much higher than at steady state pressure, and the rate of leakage increases with the intensity of the upsurge. The volume of leakage increases as the duration of the upsurges in the transient event increases.

Devices for mitigating and controlling pressure transients

There are many types of transient restraining and/or control devices available today, from the classic elevated tanks and flywheels to the most advanced pressure control valves. Some of the more common devices used today are flywheels, surge control valves, surge anticipators, surge towers, surge tanks, air vessels, air chambers, surge shafts, air valves, and more.
It was found that floating storage tanks (elevated and non-elevated) are also very effective transient controllers when located strategically throughout the distribution system. [1]

But most of these tools have restrictions in their applications. Some, like the flywheel are restricted to use at the pump station. Some require external power (electricity, compressors, etc’). Some, like the hydraulically controlled surge control valves, require a clean water source. Some, like the pressure anticipating valve, require a drainage receptor. Some are very large and cannot be installed in all required locations in the distribution system. Most of them can be very expensive, and most are restricted to clean water only and are not applicable for wastewater. Some of the solutions above are overkill for minor transient control.
Air valves are the most cost effective tools for protection against damage induced by the majority of the common everyday pressure transient events, when designed and mounted correctly. When combined with other surge protection tools, air valves can greatly reduce the required size and/or cost of these tools (air vessels, surge tanks, etc.).

Air valves for reducing and controlling pressure transients

Most water supply and distribution engineers and wastewater system design engineers are familiar with the contribution of air valves to efficient liquid transmission, to pump efficiency, and to energy conservation, but many of these engineers are not fully aware of the contribution of air valves to pressure transient reduction and control. Engineers are aware more of the capabilities of air valves in what they generally refer to as “vacuum protection” than of their capabilities in restraining and controlling complete transient events. Some engineers call kinetic air/vacuum valves “vacuum breakers” and there are even engineers who do not recognize “vacuum events” as, in fact, being transient events.

There are, actually, three major types of air valves, but all are sometimes wrongly called “air release valves”. AWWA standard C512-07 distinguishes between the three types of air valves, calling them: *Air-release valve*, *Air/vacuum valve*, and *Combination air valve.* [21]

The air/vacuum valve, sometimes called “large orifice air valve” or “kinetic air valve”, has a large orifice that discharges air at pipe filling and at water column return (following water column separation). Through this large orifice, air enters the pipeline at pipe draining, at water column separation, and at sudden, extreme pressure drops. Because of the size of the orifice, this type of air valve will not open when the pipeline is full and pressurized. It will only open when internal pipe pressure is lower than the external pressure. Because of its high capacity for air intake, this type of air valve is essential for down-surge control, and is sometimes falsely called “vacuum breaker”. The air-release valve, sometimes called “small orifice air valve”, or “automatic air valve”, has a small orifice that is able to open even when the pipeline and the air valve are under pressure. The air-release valve continuously releases air that accumulates in its body, at smaller flow rates, thus preventing the accumulation of air pocket that form air bubbles in the pipeline. When properly located and assembled on a pipeline, air release valves can prevent any air from accumulating.

The combination air valve, sometimes called “double orifice air valve”, combines the functions of the air/vacuum valve and the air release valve in one body or in two bodies connected together, with a single pipe connection. This is the most commonly used type of air valve since, in most cases, both functions are required in the same location.

In addition to the vacuum breaking aspect of the air/vacuum valve and the air/vacuum component of the combination air valve, and their protection against pipe collapse and siphonage, there are other aspects to the air/vacuum operation that may be somewhat less familiar.

At water column separation the air/vacuum orifice performs two very important functions. Firstly, it allows a large amount of air into the pipeline very quickly, mitigating the down-surge. This air replaces the displaced water, preventing the formation of a void cavity. Secondly, the air/vacuum orifice exposes the relevant region to the atmosphere, discontinuing the pressure drop, and balancing pressure to atmospheric pressure.

In order for the air/vacuum orifice to open, there must be a pressure drop. However, both air/vacuum functions discussed above restrain the intensity and the duration of the pressure drop (down-surge), and prevent harmful cavitation.

In the AWWA Research Foundation's *Susceptibility of Distribution Systems to Negative Pressure Transients*, the authors are mostly concerned about negative pressure transients (down-surges). They state that: "The presence/absence of storage tanks, placement of air relief valves and other surge control devices and pump operation procedures are all factors that may affect the occurrence and severity of low or negative pressure transients in the distribution system and ultimately affect a distribution system's potential for intrusion and/or long term pipe fatigue." [1]

They survey different studies that were made on the subject and conclude that even when air valves are not necessarily located in all critical locations, their presence greatly reduce the number of negative nodes in the distribution system. In one system, installation of just five air valves reduced negative nodes in the system by 40%. [1]

The air/vacuum orifice also aids in reducing the positive amplitudes (upsurges) by restraining the negative amplitudes (down-surges), since a pressure transient is a wave propagating down and up a pipeline with negative and positive amplitudes. Furthermore, since cavitation amplifies upsurges to intensities much greater than normal Joukowsky surge, prevention of cavitation reduces or prevents consequent upsurges to a far greater degree.

In his paper, *Hydraulic/Forensic Transient Analyses of Two Pipeline Failures*, Marko V. Ivetic' reports about hydraulic transient problems experienced at a large desalination plant and how these problems could be alleviated using air valves (which he calls "double action vacuum breakers).

In the desalination plant, a large pipeline system collects water from four desalination production blocks, and conveys the water, using four pump stations with 10 pumps each, a total of 40 pumps operating at the same time, to seven production water tanks (PWT) (Figure

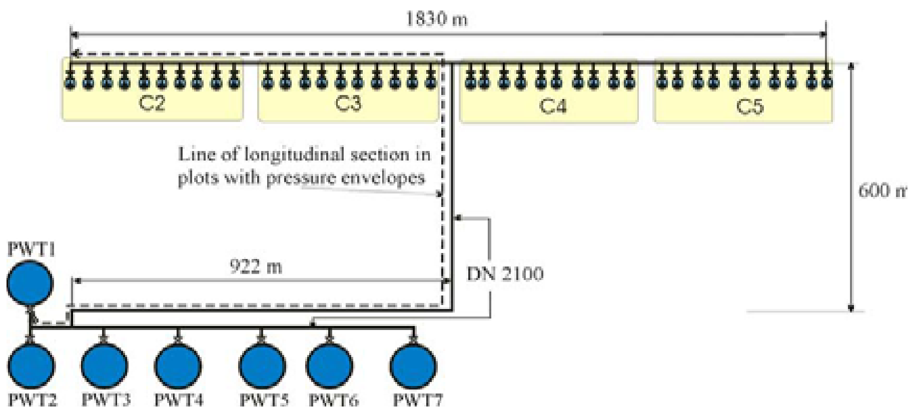


Figure 7: Layout of the system and presentation in the model [10]

9). Problems occurred during hydraulic transients caused by power cut to certain groups of pumps. [10]

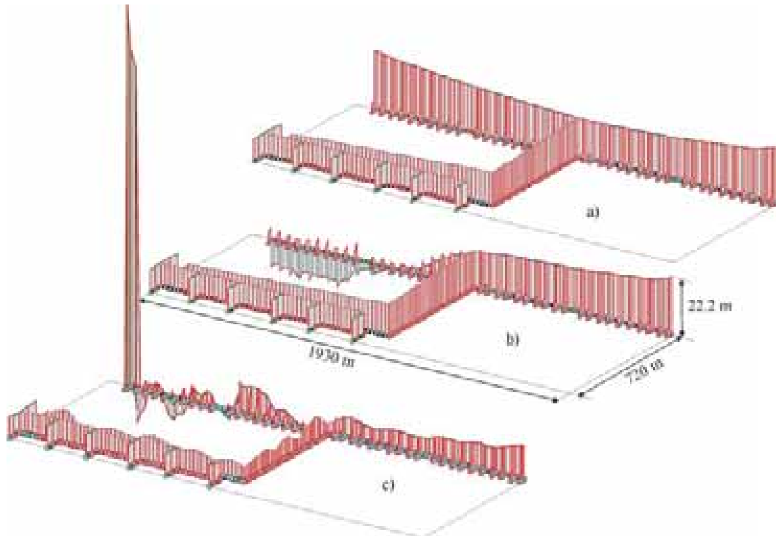


Figure 8: Snapshots from the simulation of power cut to pumps in the Production Block C2, a) steady state, b) minimum pressures with vaporous cavitation, and c) maximum pressures after cavity collapse [10]

Though velocity of flow was relatively high, over 3 m/s (about 10 ft/s), it was thought that since the designed operating pressures were very low, between 2 and 3 bar (29-43.5 psi), there was no danger of destructive hydraulic pressure transients to occur. When a power cut to pump station C2 was simulated, it turned out that serious transients developed. The transient simulation is presented as pressure history snapshots at critical instances throughout the system (Figure 8). Snapshot a) shows the system at steady state. Snapshot b) shows the system at the down-surge phase, when the vapor cavity is formed (referred to by Ivetic' as "vaporous cavitation"). Snapshot c) shows the extreme upsurge at cavity collapse. This is a simulation of the system without surge protection. [10].

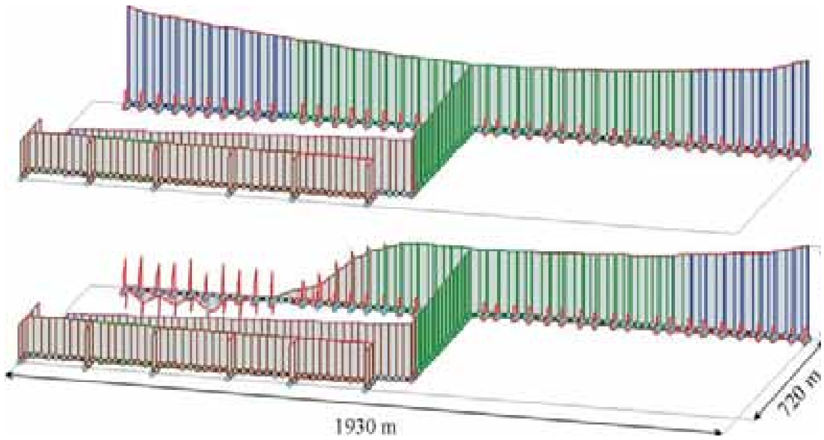


Figure 9: Snapshots of simulation of power cut to pumps in the Production Block C2 with vacuum breakers, steady state (upper) and minimum pressures (lower) [10]

"As a first measure to reduce risk of pressure surge, vacuum breakers were installed at every second pump connection (it was suggested on every pump, but not implemented)". [10] Though air valve protection was only partial, when simulating a power cut to pump station C2, this partial air valve protection was enough to greatly reduce the down-surge, and prevent cavitation[10] (Figure 9).

When simulating power cuts in pump stations C2, and C3 simultaneously, the resulting down-surge and resulting cavitation were far more severe, extending to cover the entire left portion of the pump manifold, almost half the right side of the manifold, and the full length of the transmission line to the seven reservoirs [10] (Figure 10).

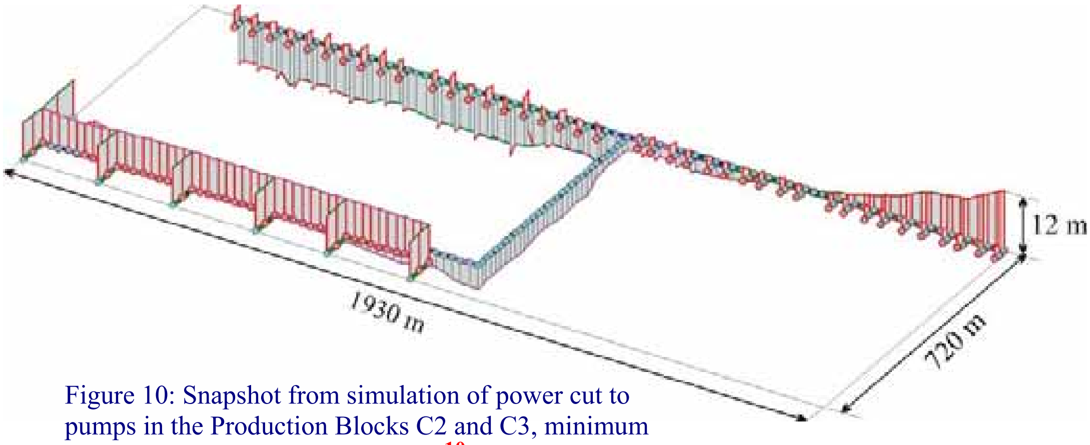


Figure 10: Snapshot from simulation of power cut to pumps in the Production Blocks C2 and C3, minimum pressures with vaporous cavitation [10]

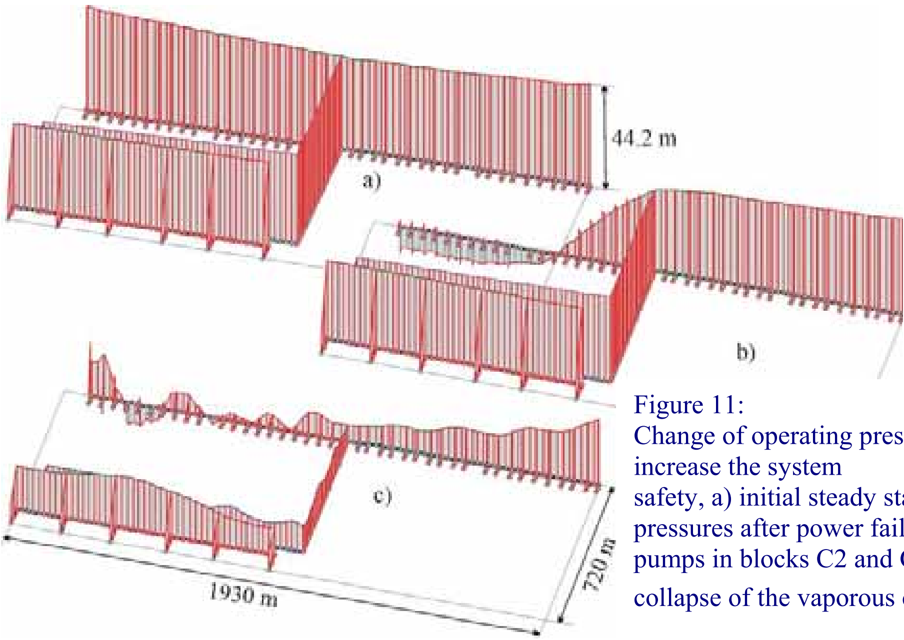


Figure 11:
Change of operating pressure as a measure to increase the system safety, a) initial steady state, b) minimum pressures after power failure for pumps in blocks C2 and C3, c) moment after collapse of the vaporous cavity. [10]

When air valves were placed at every second pump in stations C2 and C3 and power was cut to the two stations, the resulting transients were greatly reduced. Though the down-surges were not completely eliminated since protection was only partial (an air valve only at every second pump), they were reduced enough to prevent damage. Upsurges were completely eliminated as result of reducing the down-surges [10] (Figure 11).

Mistrust of air valves and modern solutions

Though most surge engineers and scientists are aware of the ability of air/vacuum and combination air valves to reduce down-surges and cavitation, some of them are of the opinion that automatic (non-manual) air valves are not reliable.

These fears may have been plausible years ago, when automatic air valves were less reliable, but today, more advanced and innovative automatic (non-manual) air valves that are fully dependable and efficient are readily available.

Mistrust and uncertainty relating to wastewater air valves are even more widespread than for water air valves, due to the very difficult operational environments and conditions under which wastewater air valves are required to function. Traditional automatic (non-manual) wastewater air valves, that were improved very little in past decades, have an extremely poor operational record.

George Tchobanoglous, in his Metcalf & Eddy textbook, *Wastewater Engineering: Collection and Pumping of Wastewater*, expresses his mistrust of wastewater air release valves and air/vacuum valves: "Automatic air-release valves should not be installed if their use can be avoided. From past experience it has been found that automatic air-release valves require frequent maintenance in order for them to function as intended... In most cases, manual air valves could be used instead of automatic air valves... Automatic air and vacuum valves have been used to allow the quick automatic admission of air that might be needed to prevent collapse of thin-walled pipeline during the fast drainage that would take place through a broken force main, or during water-column separation following a power failure. They also have been used for venting air during filling of the force main. However, these valves are subject to maintenance problems similar to those of air-release valves. Furthermore, their malfunction could create additional water hammer problems. In general, automatic air and vacuum valves should not be used on sewage force mains. Instead, the problem of possible collapse of force main pipes because of internal pressures less than atmospheric should be solved by the use of pipe having walls sufficiently strong to withstand the induced added crushing load." [14] Here, the author considers only pipe integrity, disregarding other probable damages and dangers of down-surges. His recommendation is to increase the wall thickness of the pipe, an approach less accepted today because of the added cost of thick walled pipes, and because of the greater concern today for pollution from leaking force mains, and for the danger of intrusion of leaking wastewater into drinking water pipelines.

There were some very advanced, far-reaching changes in the design of the conventional wastewater air valves that make these advanced, modern air valves completely dependable, efficient, and simply and effectively maintained. Unlike the malfunctioning traditional wastewater air valves that are still available and in use, the modern, cutting-edge wastewater air valves are available with body shapes and textures that resist buildup and clogging, in a variety of body materials, plastic and metal, and with a wide range of special coatings that enable dependable, corrosion and damage free use in almost any application. There is an assortment of wastewater air valve models available which was never available before. Today, innovative subsurface water air valves, complete with their integral under-ground valve box, can be fully serviced and disconnected from ground level, and are readily available.

Another reason for distrust of traditional air valves for water and wastewater is related to pressure transients. It is claimed that air valves cause slam and upsurge at closure that can affect the integrity of the system. Burrows and Qiu point out this potential problem, stating that "..in certain circumstances, air valves can exacerbate peak surge pressures.." [4] Escarameia et. Al., also note this problem: "It is to be noted that excessive air release capacity can result in very high 'impact loading' as the last of the air is evacuated." [2] The problem of air valve slam and resulting local surges is more prevalent in North America because of the provisions in the AWWA standards C512-07 restricting air valve design, such as the provision requiring air valves to be nominal, i.e. requiring the air discharge orifice and its inlet to be equal or larger in area than its nominal size. Article 4.3.2.1.2 of the standard states: "Inlet and outlet ports of the body for air/vacuum valves and combination air valves shall be sized to ensure that the minimum flow area of each port shall be equal to or greater than the flow area of a circle of diameter equal to the nominal valve size." [21]

The latest version of the AWWA standards for air valves, C512-07, does not cover air valves for wastewater applications, but actions are presently in process by committee members, to include wastewater air valves in C512. Air valves with nominal orifices are not required in most countries. Air valves whose discharge orifices are smaller than their inlet ports are usually less susceptible to slam and local surge than nominal air valves, due to the throttling effect of the smaller orifice.

Srinivasa Lingireddy, Don J. Wood, and Naftali Zloczower, in the article, *Pressure surges in pipeline systems resulting from air releases*, examined this issue. In this article they state: "Air valves are integral part of long pipelines passing through undulating terrains. Although large inflow orifices are warranted to alleviate cavitation conditions during transient events, same size outflow orifices could sometime result in detrimental pressure surge following final release of air."[9] But, Lingireddy et al. went on to show that reducing the size of the air discharge orifice can reduce or even eliminate (when sized correctly) the "air slam" or upsurge. Referring to two simulations performed, they report: "Both examples show that an outflow orifice smaller than the inflow orifice is desirable to alleviate undue secondary pressure surges due to final release of air."[9] Figure 12, below, shows the results of surge analyses performed for one air valve with a 4-inch discharge orifice and a second with a 0.5-inch discharge orifice.

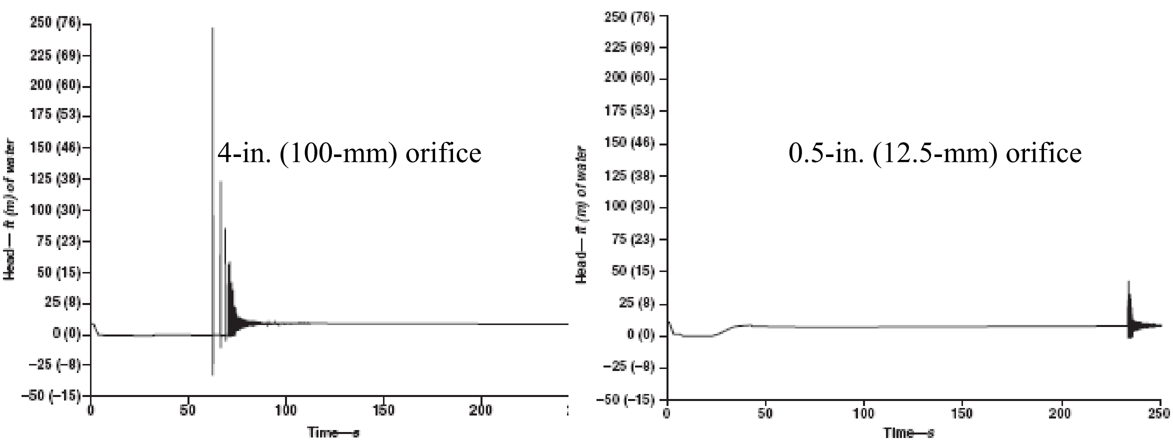


Figure 12: Surge analyses for secondary pressure surges due to final air release through 4 inch and 0.5 inch air discharge orifices [9]

Dr. Lingireddy's conclusions, based on lab tests, calculation and analyses, are, that the use of air valves with large air intake capacities and much smaller air discharge capacities is highly desirable for ensuring effective and efficient surge control. Modern air valves with non-slam and three-stage accessories that utilize the principles expressed in Dr. Lingireddy's article have been readily available for a number of years. These accessories enable the use of nominal air valves for efficient down-surge control, and still allow non-slam, surge-suppressing closure. One such air valve is a three-stage, non-slam combination air valve that has a nominal air intake orifice for down-surge protection, and a throttling disc with a much smaller orifice that throttles air discharge at a predetermined differential pressure across the valve. The throttling disc throttles air discharge, causing the remaining slowly depleting air pocket to slow down the returning water column and to dampen returning positive transient waves (upsurge pressure waves) by absorbing much of the energy, like a shock absorber. At final air valve closure, because the velocity of the returning water column is much lower, ΔV in the Joukowsky Equation is smaller, slam is prevented, and upsurge is suppressed. [22]

The latest version of AWWA standard C-512 for air valves, C-512-07, which was formally approved in January, 2008, resolved the problems presented by the requirement of nominal orifices by allowing non-slam and throttling accessories to restrain slam and upsurge at air valve closure. Article 4.3.3 allows the use of a *throttling device* and Article 4.3.4 allows the use of a *slow-closing device*. [21] These two articles still constrain the use of some available and future innovative devices by limiting device design and its approved materials of construction, but they are a significant improvement on the previous, C512-04 version, and they could be trail blazers for further improvements in the standards, and in future advances in air valve technology.

Air valve technology has improved greatly in the past few years. Air valves with aerodynamic cylindrical floats and independent rolling seal mechanism were developed. They have slanted, rectangular orifices, allowing the breaking of the air flow 90 degrees to the vertical (not directly opposite to the inlet). The combination air valve combines the air/vacuum and air release components in one unique orifice. These features were designed for resisting premature closure, yet providing a more gradual, softer, slam-preventing closure. The wastewater versions of these air valves were designed with buildup-resistant conical bodies, with large air pockets to prevent wastewater from reaching the sealing mechanism, and with non-corrosive body and internal parts.

Figure 13: Stainless steel and composite material combination air valve for wastewater

Actual air valve performance testing for transient protection

The Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT (Fraunhofer UMSICHT) is a non-profit scientific/technical institution in Oberhausen, Germany, that specializes, among other areas, in surge research. The Division of Pipeline Technology of the institute has a very elaborate surge test rig with hundreds of feet of pipe and a ten-meter (about 33 ft.) high tower. In November 2004, Dr. Andreas Dudlik, the head of the Division of Pipeline Technology, conducted an investigation to determine if air valves tested "are capable of protecting a pipeline system against cavitational hammers, induced downstream of a fast closing valve." [6]

Six different A.R.I. combination air valve models were tested: one regular nominal, ball-float type; one regular non-nominal, ball-float type; one regular non-nominal, cylindrical-float, independent rolling seal type; one nominal ball-float, non-slam, three stage type; one non-

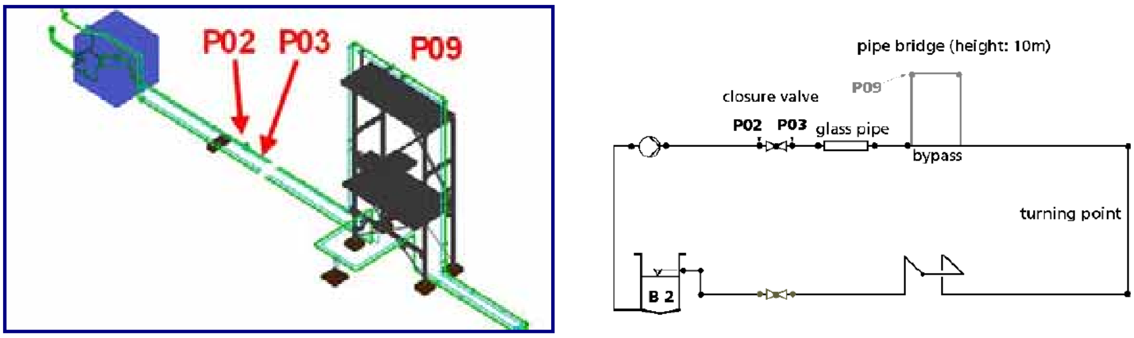


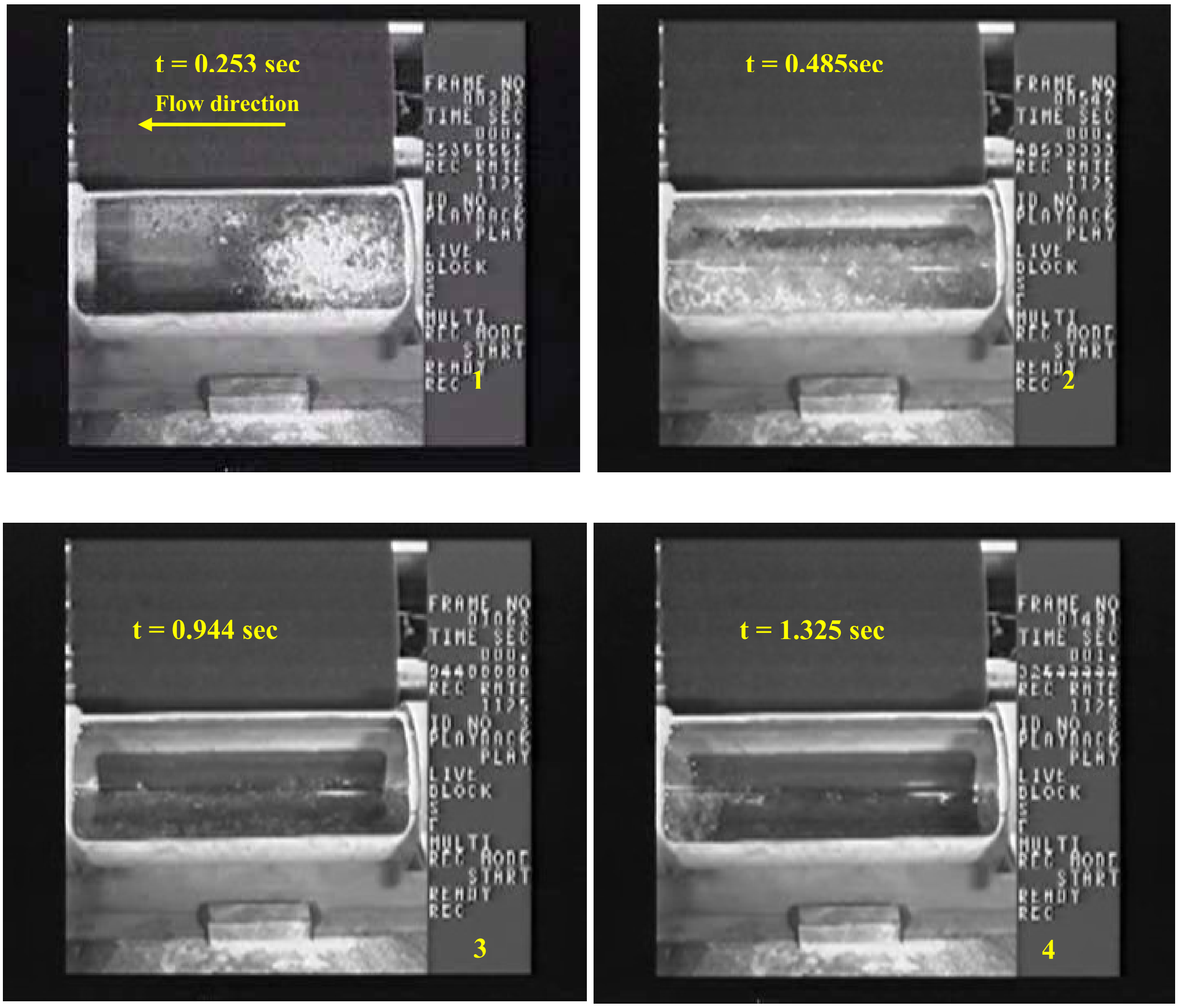
Figure 14: Faunhofer UMSICHT Division of Pipeline Technology surge test rig [6/22]

nominal, non-slam, cylindrical-float, independent rolling seal type; and one dynamic type. In addition to claims mentioned above against the use of air valves as surge control tools, some surge engineers and scientists claim that the reaction time of air valves is too long, and that serious down-surges can develop before the air valves open. In these experiments conducted by Dr. Dudlik's team at Fraunhofer UMSICHT, it was clearly shown that the air valves tested were very fast acting, and were extremely effective and efficient in protecting pipelines “against cavitational hammer”, stifling the down-surges, as well as the upsurges.

In these tests on the surge test rig, water was pumped from a reservoir in a 100mm (4 inch) pipeline, about 200 meters (about 650 feet) long, at a steady state velocity of 4 m/s (13 ft/s), when an automatic shut-off valve was closed very rapidly. Tests were conducted without any surge protection, and afterward, with protection provided by each of the six types of air valves. Air valves where located at position PO 3, down-stream from the isolating valve and at position PO 9, on top of the tower (see Figure 14).

For the first run, without air valves, the initial down-surge lasted about 2.16 seconds and surge reached nearly 45 bar (650 psi) (see red line in Figure 16).

Figure 15 shows selected frames from a video that was filmed during a very similar test, without any protection (without air valves), on the same Fraunhofer UMSICHT surge test rig, and with the same setup (see schematic in Figure 14). The video was filmed through a glass



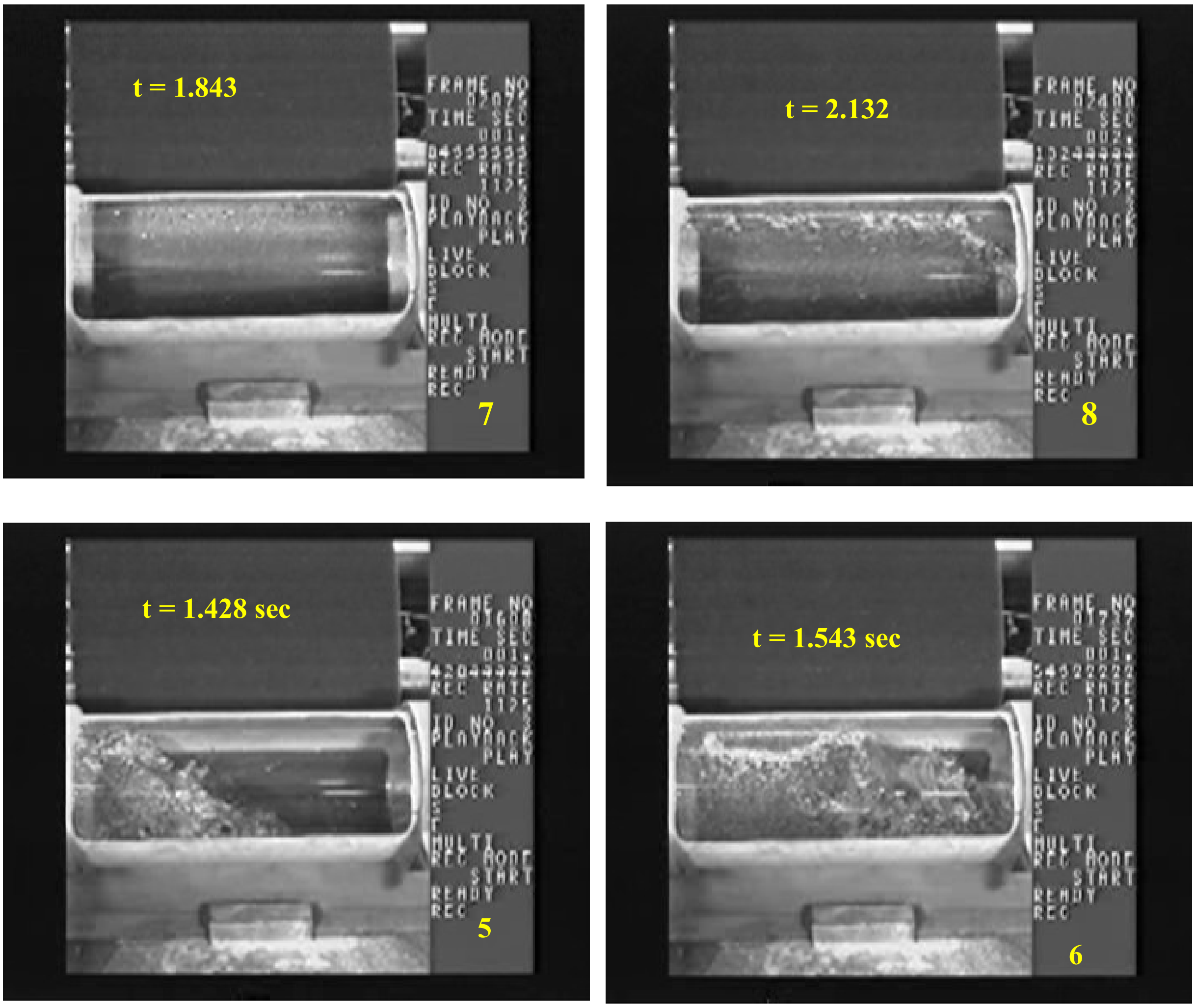


Figure 15: Views through a window, into the pipeline of the Fraunhofer UMSICHT surge test rig, showing water column separation and return and vapor cavity formation and collapse, down-stream from a fast closing shut-off valve. These views are frames from a video that was filmed at 1125 frames per second to capture the event and process.[24]

window on the pipeline, down-stream from the shut-off valve, at a fast motion of 1125 frames per second, so the process of column separation, the vaporization (boiling) of the water (vapor cavity formation), the vapor void, the column return, and the re-condensation of the vapor (change of phase, back, from vapor to liquid – vapor cavity collapse), could be viewed. The direction of flow is from right to left, and the shut-off valve is located to the right of the window.

Frame #1 shows the water column separation at time t = 0.253 seconds from the valve shut-off, and the "boiling" of the water at the tail end of the water column. Frames #2 and #3 show the continuous evaporation and the vapor void/cavity. In frame #4, the returning water column starts The video is much more impressive than the separated frames, and shows the process of column separation and return and vapor cavity formation and collapse in live movement.

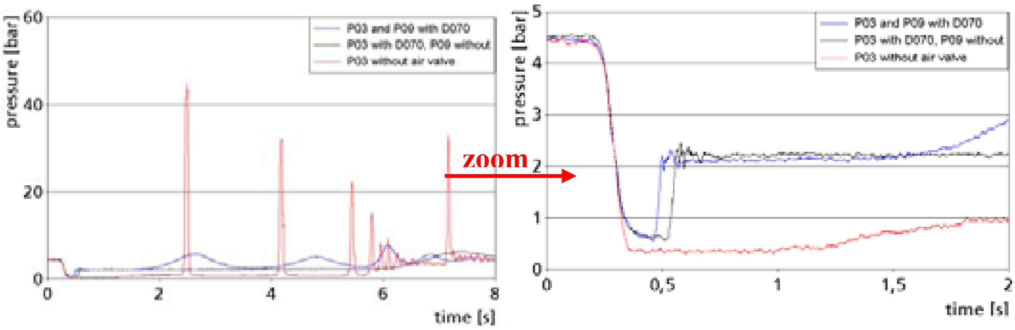


Figure 16: Graphs of pressure histories down-stream from the shut-off valve: red line, no air valve protection; black line, only the air valve at PO 3, down-stream from the shut-off valve, is active; blue line, both air valves, at PO 3 and at PO 9, at the top of the tower, are active. Dynamic D-070 air valves in both locations [6]

In the air valve experiment of November 2004, when only the air valves at PO 3 were activated (one air valve type each run), the air valves tested cut the duration of the down-surge to about 0.16-0.32 seconds and eliminated the upsurge completely. The graphs in Figure 16 compare the pressure histories of the transient event directly down-stream from the shut-off valve in three conditions: 1) without any air valves (red line), 2) with a dynamic combination air valve, D-070, activated only at PO 3 (black line), and 3) with the D-070 activated at both, PO 3 and PO 9 (blue line). It can be clearly seen that the intensity of the down-surge was reduced, the duration of the sub-atmospheric phase of the down-surge was greatly reduced, and the upsurge was completely eliminated (maximum pressure was just slightly above steady state pressure), in both cases where air valves were used.

When comparing the performance of the different air valve types when only the air valve at PO 3 is activated, as seen in Figure 17, it can be seen that for this particular transient event, the ball-float type air valves with the larger air intake orifices, the nominal D-060 and D-060 NS, functioned best, and the dynamic D-070 functioned the poorest. This is because the D-060 and the D-060 NS had the quickest reaction time due to the weight of the float compared to the orifice size, and due to the large size of their air intake orifices. It must be stressed that all air valves performed exceptionally well by preventing the formation of a significant vapor cavity and thus, eliminating any consequent upsurge. The slight rise in pressure at about t =7 seconds, to almost 6 bar (87 psi), is due to the reopening of the shut-off valve.

When the air valve located down-stream from the shut-off valve, at PO 3, and the air valve at the top of the tower, at PO 9, were both functional, the pressure histories directly down-stream of the shut-off valve were different than when only the air valve at PO 3 was functional. All the ball float air valves had a minor rise in pressure, up to about 12-13 bar (174-185 psi), and the dynamic air valve had only a very slight pressure rise, to about 5 bar (73 psi). The air valve with the cylindrical float, the rolling seal sealing mechanism, and the non-slam accessory, the D-040 NS, had no pressure rise at all.

The events that affected the difference in reaction to the shut-off valve closure when the air valve on the tower was functional and when it was not, are that at shut-off valve closure, when the air valve on the tower was functional, there was a water column separation at the top of the tower.

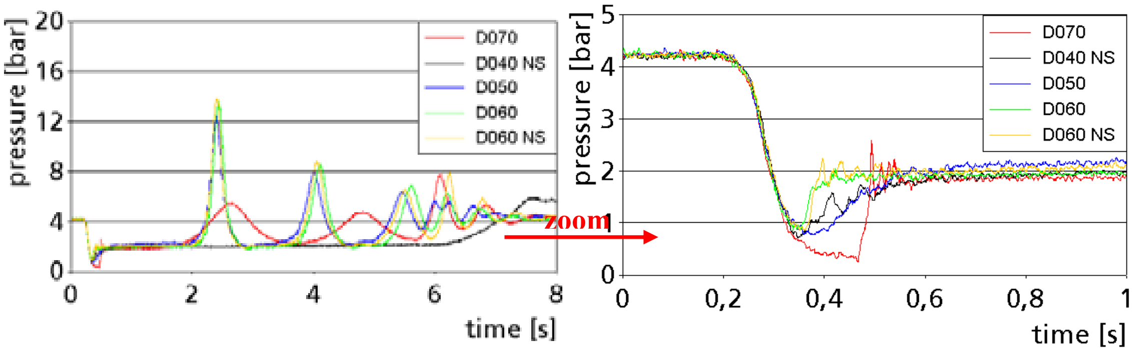
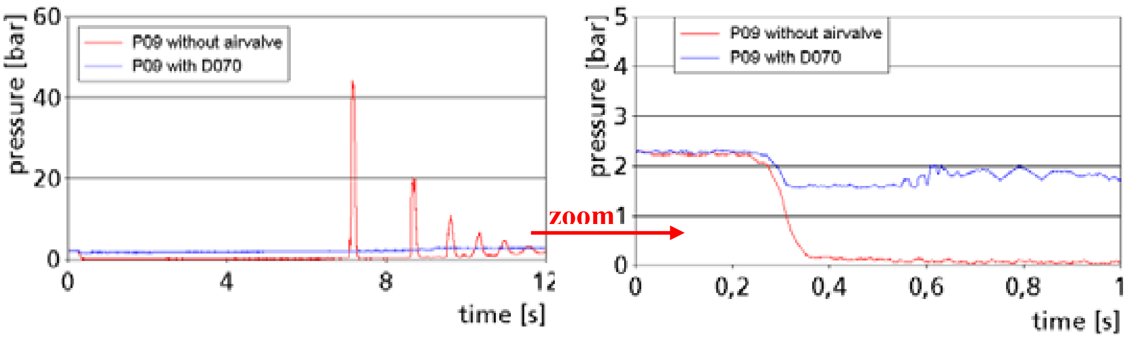


Figure 18: Comparison of pressure histories down-stream from the shut-off valve when different types of air valves are active at both PO 3 and PO 9 at the same time. The air valves at PO 3 and PO 4 are of the same type and size [6]

The down-stream water column did not return because of the great elevation difference. The upstream column oscillated back and forth between the shut-off valve and the tower's upstream leg, slamming against the closed shut-off valve every time it returned. The D-040 NS throttled the air discharge sufficiently to slow down the returning water column smoothly, thus eliminating the pressure rise. The dynamic air valve released a very small amount of water, thus relieving the pressure, and not allowing a substantial pressure rise. All the other air valves tested did not slow the returning water column enough to prevent the slight slam and pressure rise. But, again, the pressure rise did not constitute a significant upsurge, and was minute, compared to the nearly 45 bar (650 psi) upsurge, without air valve protection.

The air valve located at position PO 9 on top of the tower, seemed not to help the situation down-stream from the shut-off valve, at position PO 3. In order to appreciate the importance of this air valve, we have to look at the pressure histories at the top of the tower.

As can be seen in the graphs of Figure 19, the steady state pressure at position PO 9 on top of the tower was under 2.5 bar (about 36 psi). Without air valve protection, PO 9 was under a constant down-surge for the whole duration of the transient event. When the shut-off valve was reopened at about t = 7 seconds, starting a new transient event, a very high upsurge of about 45 bar (650 psi) occurred at PO 9, as a result of the collapse of the large vapor cavity that was formed at the long down-surge phase of the transient event. This extreme down-surge (vacuum) can explain why there were no pressure rises at PO 3, down-stream from the shut-off valve. The ongoing down-surge at the top of the tower "pulled" on the water column upstream of PO 9, and restricted its oscillation between the shut-off valve and tower. When the air valve at the top of the tower was active, it allowed air in and prevented the down-surge, so the water column was able to oscillate. Different types of air valves, mounted at the top of the tower near PO 9, provided different levels of surge protection at PO 9. All, greatly reduced the down-surge intensity and duration, preventing the formation of vapor cavities and the consequent cavitation surge (hammer). In this location, all the larger orifice air valves, both dynamic and ball-float types, extremely reduced the down-surge and the consequent up-surges. The non-slam D-040 NS, with the smallest intake capacity, performed the poorest at this location, due to inadequate air intake. But it, too, reduced the intensity of the down-surge. Though the D-040-NS was probably the most efficient at PO 3, its



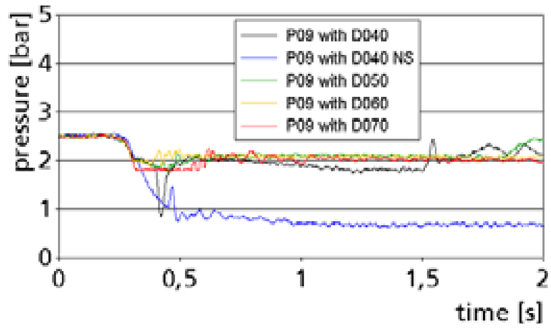


Figure 19: Pressure histories at position PO 9, at the top of the tower, without air valve protection in this area, and with the protection of a dynamic air valve, D-070 (top) and other air valve models (left) [6]

Application at this location was the least efficient. This shows that each location along the pipeline should be carefully assessed and the most efficient air valve should be chosen for that particular application. The D-040 without the non-slam accessory resulted in a down-surge of similar intensity, but, by far, a shorter duration. Though performing somewhat poorer than the other, larger orifice models at this location, the D-040, with its lower cost, may be more cost effective.

This experiment at Fraunhofer UMSICHT shows very clearly why it is very often not enough to provide surge protection only at the source of the transient event. In this experiment, the transient events were initiated at the shut-off valve. At its closure, a series of initially extreme down-surges and upsurges occurred down stream from the shut-off valve, at PO 3, and when it reopened, additional, lighter upsurges and down-surges occurred. But, the same valve closure initiated additional transient events in other locations along the pipeline. Air valves had to be applied at both locations to prevent the serious surges.

Only water air valves were used in the Fraunhofer UMSICHT experiment, but well designed wastewater air valves function similarly to water air valves. The D-020 and the D-025 wastewater air valves seen in Figure 13 are very similar to the D-040 and the D-020 NS and D-025 NS are very similar to the D-040 NS.

Studies, analyses and experiments conducted by Dr. Marko Ivetic', Dr. Srinivasa Lingireddy, and Dr. Andreas Dudlik and their colleagues, as well as the experience of this author, have shown that advanced, modern air valves, some employing innovative designs and cutting edge technology, at times applied to solve specific problems, such as air slam and clogging, are reliable and efficient tools for the alleviation and restraining of pressure transients. When appropriately and meticulously sized, located, and specified, these modern air valves are easily maintained, are very dependable and efficient, will not cause significant local transients (air slam), and, in most cases, are the most cost effective surge controllers. They are almost always the most cost effective, and, in many cases, the only solution for minor gap producing, leak and intrusion enhancing, transient pressure events and down-surges. Properly sized and located air valves prevent vacuum cavity formation and collapse (cavitation) that greatly amplify pressure transients. These air valves discharge existing air/gas pockets from pipelines (including those admitted in by the air valves), and prevent the formation of new air/gas pockets (which always form in absence of air valves). These air/gas pockets were shown to intensify pressure transients and to enhance internal pipeline corrosion, especially hydrogen sulfide corrosion. By the different functions listed here, air valves prevent or curtail the creation of new gaps and the enlargement of existing gaps, thus preventing or restraining leakage and intrusion. Air valves eliminate or constrain leakage-intensifying upsurges and intrusion-intensifying down-surges. Unlike most other surge control devices, air valve location is not restricted to pump stations or to locations accessible to external power sources, but can be located along the full length of the pipeline. In this way, air valves protect the whole pipeline.

SUMMARY

1. This paper deals with two major problems in wastewater systems:
    a. Pollution and contamination of ground water, surface water, soil, and environment by wastewater infiltration.
    b. Health hazards from these contaminants and pathogens related to intrusion into drinking water systems and to contact with people.
2. Pollution and contamination are caused by leakage of wastewater and other contaminated liquids.
3. The health problem is caused by intrusion of contaminants from the pipeline's environment (soil, water, etc'), polluted by wastewater leaking from wastewater pipelines, into the drinking water pipeline.
4. The portals for both, leakage and intrusions are pipeline breaks, cracks, dislocated or damaged seals, gaskets, joints, fittings, etc', referred to by this paper as gaps.
5. This paper relates to gaps caused by pressure transients and corrosion.
6. Pressure transients and corrosion cause gaps and also continue enlarging existing gaps.
7. Enlarged gaps intensify leakage and intrusion.
8. Pipeline pressure is usually enough to cause leakage, and upsurges of transient events enhance this leakage.
9. Very low pipeline pressures and down-surges (including what is commonly called vacuum) are driving forces for intrusion.
10. Intensified pressure transients accelerate the creation of new gaps and the enlargement of existing gaps.
11. Enhanced corrosion accelerates the creation of new gaps and the enlargement of existing gaps.
12. Air/gas pockets enhance internal corrosion in pipelines, especially hydrogen sulfide corrosion.
13. Powerful upsurges of intensified pressure transient events greatly intensify leakage.
14. Intense down-surges of intensified pressure transient events greatly intensify intrusion.
15. Air/gas pockets of certain sizes and in certain locations in the pipeline intensify pressure transients.
16. Cavitation (the formation and collapse of vapor cavities) greatly intensifies pressure transients.

17. The solution recommended in this paper is the use of modern air valves, appropriately and meticulously sized, located, and specified.
18. Advanced, modern air valves, properly sized, located, and specified:
    a. Restrain and alleviate pressure transients.
    b. Prevent cavitation.
    c. Discharge existing air/gas pockets from pipelines (including those admitted in by the air valves themselves), and prevent the formation of new air/gas pockets (which always form in absence of air valves).
    d. Are easily maintained, are very effective and efficient, will not cause significant transients themselves, and in most cases are the most cost effective surge controllers.
    e. Are the most cost effective, and in many cases, the only solution for minor, gap-producing and leak and intrusion enhancing, transient pressure events and down-surges.

Conclusion

Sighting studies and surveys, this paper highlights international concern for infiltration of pathogens and other pollutants and contaminants into ground water, soil and environment, and for the intrusion of these pathogens and contaminants into drinking water. The paper determines that the major paths of these subjects of concern are leakage of wastewater from pipelines, pollution and contamination of soil, ground and surface water, and intrusion into drinking water pipelines. The portals of leakage and intrusion are pipe breaks, cracks, dislocated and damaged seals, gaskets, joints, fittings, etc', generally refered to as "gaps", in this paper. It was established that pressure transients, both major and minor, are a major cause for the creation of new gaps and for the expansion of existing gaps. It was further established that internal corrosion, enhanced by the presence of air pockets, especially hydrogen sulfide corrosion, weaken pipelines, and is a major contributor to the creation of new gaps and for the expansion of existing gaps. In addition to steady state pressure in pipelines, the upsurges of transient events are a major driving force for leakage. The down-surges of transient events are the major driving force for intrusion into pipelines and for seal and gasket displacement resulting in leakage. Again, by sighting studies and surveys, it was shown that air pockets of certain sizes and in certain locations along the pipeline, significantly amplify pressure transients. Cavitation surges (the formation and collapse of vapor cavities) were shown to greatly intensify pressure transients. Intensified pressure transients quicken the creation of gaps, create larger gaps, and greatly enlarge existing gaps. Intensified upsurges greatly strengthen leakage. Intensified down-surges greatly boost intrusion.

Distrust of some air valves may have been justified in the past, as expressed in writings sighted in this paper, but it is shown that today, the wide range of modern, innovative air valves that are readily available, should diminish this distrust. This paper sights studies, analyses, and advanced experiments that prove that air valves are reliable and efficient tools for the alleviation and restraining of pressure transients. Air valves discharge existing air pockets and prevent the accumulation of new air pockets, thus preventing air enhanced corrosion and pressure transient intensification. It was shown that air valves prevent cavitation and the consequent intensification of pressure transients. Air valves prevent or curtail the creation of new gaps due to hydraulic transients and the enlargement of existing gaps, thus preventing or restraining leakage and intrusion.

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