Transient Analysis of Water Distribution Systems

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The pressures generated by transient (water hammer) conditions in pipe systems are frequently three or more times the value of normal operating pressures. Thus, transient pressures must be known if the size and strength of the required pipe is to be rationally selected, if surge-suppression equipment is to be logically sized, and if system operating rules are to be intelligently specified. In practice, however, analysts frequently neglect transient conditions, particularly in complex systems such as distribution networks. With modern computer techniques it is possible to analyze distribution systems under a wide range of flow conditions and with relatively few restrictions. Examples are presented of the dangers of oversimplifying either the physical system or the operating conditions.

Pressure pipe systems are subject to a wide range of physical loads and operational requirements. For example, underground piping systems must withstand internal and external corrosion, various forms of bedding stresses, differential settlement, construction damage, local stresses at connections, as well as other external and internal forces. As a result of this ongoing chemical and physical attack, both the hydraulic and structural capacities of the pipe are reduced over time until some kind of failure occurs. The failure may be physical in nature, such as a break that causes loss of water and pressure, or it may be economic, arising from increased fluid friction with its associated reduced flow capacity, increased power costs, or both. In Canada alone, the estimated cost of repairing water main breaks exceeds Can$100 million annually.

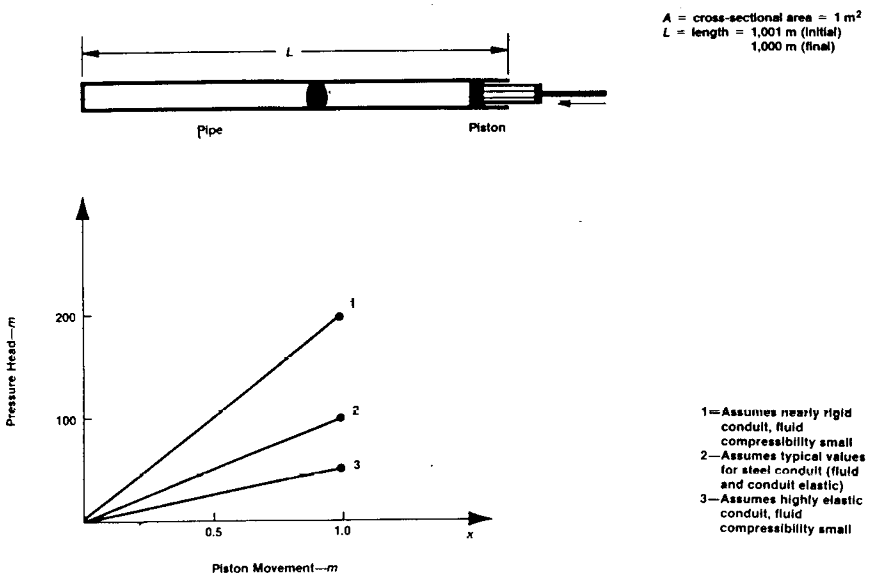

Figure 1. Relation between fluid compressibility and pressure head in a closed conduit

One source of loading that is commonly neglected in water distribution system analysis is due to water hammer or transient conditions. Although it is well known that the pressures generated during transient conditions should be an important consideration when simple pipeline systems are being designed, there is widespread belief that transient conditions are intrinsically less severe in network applications. In fact, several examples in this article demonstrate that the maximum transient pressure in some branched and looped systems may exceed the corresponding pressure rise in a simple system. Thus, if the size and strength of the required pipe are to be rationally selected, if the surge-suppression equipment is to be logically sized, and if system operating rules are to be intelligently specified, reliable transient analysis is essential.

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In the past few years, many refinements and improvements have been made in the accuracy and efficiency of transient analysis. More attention, however, has frequently been given to how the analysis is performed than to what is being modeled. Many articles have been written on the relative accuracy and computational merits of various numerical procedures; few have considered the sensitivity of transient conditions to the assumed initial state or what kind of interaction between automatic control devices can lead to the most severe transient problems. Yet such issues are central to system design and operation.

This article emphasizes that the details of how a hydraulic system is modeled or represented can have a critical impact on the predicted transient conditions. Examples illustrate the following three points: (1) in some pipeline systems, the maximum transient pressure is quite sensitive to the assumed initial steady-state velocity; (2) transient conditions may sometimes be more severe in branched or looped systems than in simple series pipelines; and (3) oversizing surge-suppression equipment such as relief valves may degrade a system's transient response. The key result is that transient phenomena in a pipeline system can be both surprising and dramatic. Because of the complexity of system response, the transient analyst must learn to think fundamentally and analyze comprehensively.

Transient analysis and design

Unfortunately, transient analysis is not easy. The governing equations describing the flow are of the nonlinear partial differential variety, the hydraulic devices are complex and data on their performance are difficult to obtain, and the pipeline systems themselves are subject to a host of operating conditions and requirements. To make matters worse, the physical character of the pulse wave propagation is frequently hard to visualize or interpret even for the analyst accustomed to transient phenomena.

The complexity of transient phenomena has, at times, induced many analysts to adopt simplified design procedures. The analysis of hydraulic systems is often facilitated in two primary ways: (1) complex components and other complications in the physical system itself may be ignored, or (2) the range of operating and loading conditions to which the system is subjected is greatly reduced. These simplifications are rationalized on the grounds of necessity (the actual physical system cannot be analyzed) and conservatism (the analyzed system performs worse than the real one). Unfortunately, the assumption that some rudimentary and conservative system can be found is questionable. It is difficult to simplify a pipeline system to ensure worst-case performance under all transient conditions, particularly if the simplifications are made before any analysis has been performed.

Traditional wisdom for identifying worst-case scenarios is based on elementary equations, rules of thumb, or common sense; in other words, simple relations that may have little or no bearing on the performance of more complex systems. Several of the most common of these ideas are presented in this article along with counterexamples

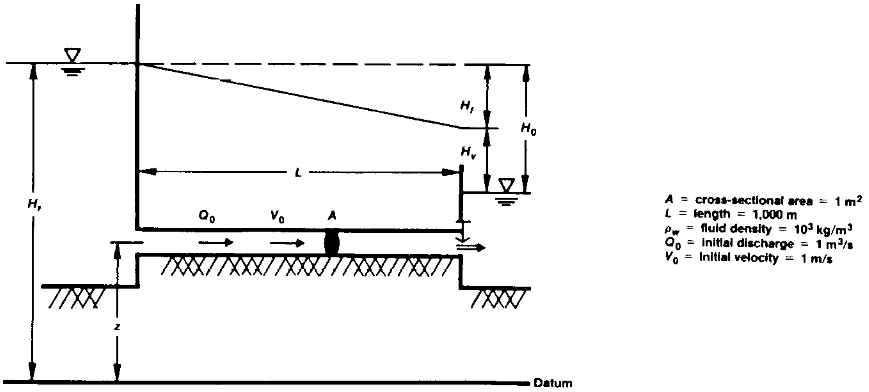

Figure 2. Fluid and pipeline properties of two constant head reservoirs joined by a series pipeline with a downstream valve

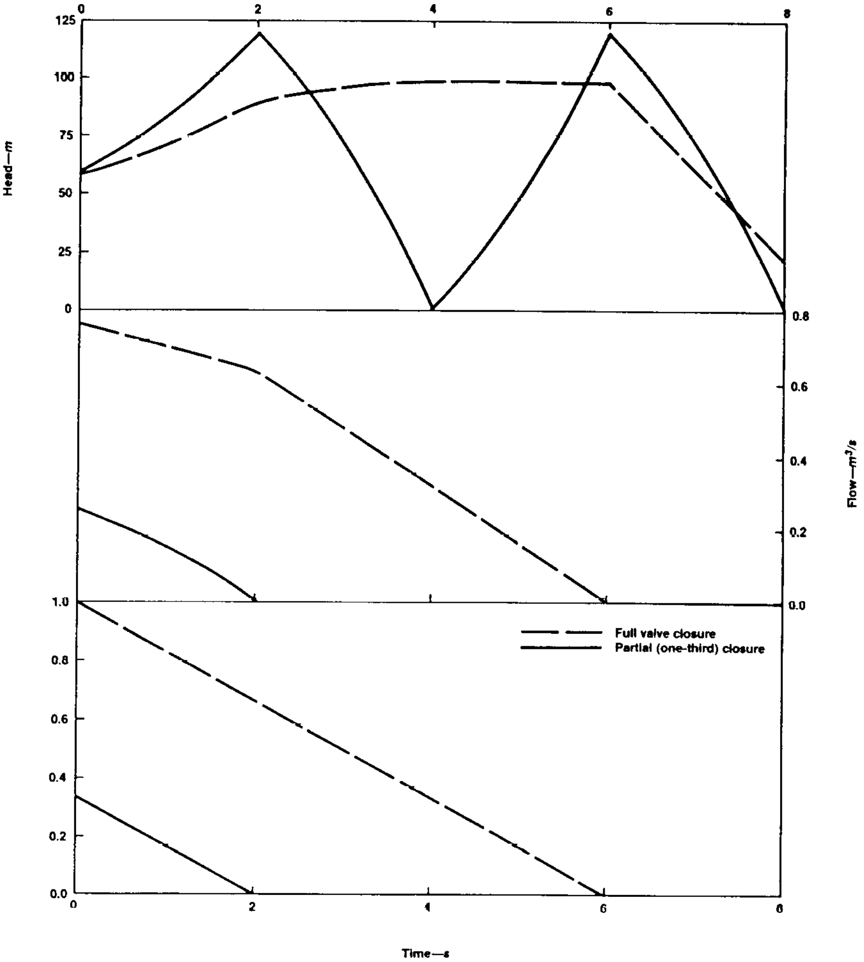

Figure 3. Valve action and transient response of a single-pipe system to valve closure from full and partial (one-third) opening (*head and discharge values are given at the valve end of the pipe;* $H_0 = 60$ *m,* $f = 0.010$)

to show how they can break down. The main point, however, is that: comprehensive transient analysis is both technically and economically possible. Only comprehensive analysis can ascertain the relevant and most critical range of loading conditions. Moreover, the analysis should be performed on a realistic representation of the physical system without making unwarranted, and possibly incorrect, assumptions about what components can safely be neglected.

Although it should be pointed out that all of the warnings and some of the examples presented in this article have been known for years, in practice there has been a tendency to rely on a priori assumptions of what constitutes good transient design. These before-the-fact assumptions may well be valid under some circumstances, but there is little reason to be presumptuous. Water supply systems are costly to build, operate, and maintain, whereas computer resources are cheap and plentiful. In many applications, comprehensive transient analysis is economically justified.

Several of the examples presented in this article are based on analysis of a water transmission and distribution system owned by the city of Calgary, Alta., Canada. The engineering department of the city of Calgary is pioneering a comprehensive investigation of transient conditions in its large and sophisticated pipe network. The purpose of this study is to rationally identify those conditions under which transient pressures are most severe and to investigate the influence of various remedial strategies. This information may have significant implications for the design, protection, and operation of water distribution systems.

Transient phenomena

Fluid properties. An air of mystery and confusion often surrounds the role and significance of transient phenomena in closed conduits. Because of the complexity of the governing differential equations and the dynamic nature of system response, transient analysis has frequently been relegated to a backwater of pipeline design. Like many other backwaters, this one is inhabited by a rare species—the transient specialist—who is believed to have a rather unnatural appetite for higher mathematics. At the most fundamental level, however, transient conditions arise as a direct consequence of basic fluid properties and simple conservation laws.

Two of water's properties will be obvious to almost anyone: liquid water is immensely heavy and is very difficult to compress. What is not obvious, however, is that these two properties go a long way to explain why transient pressures can be so large and under what conditions the largest pressures tend to occur.

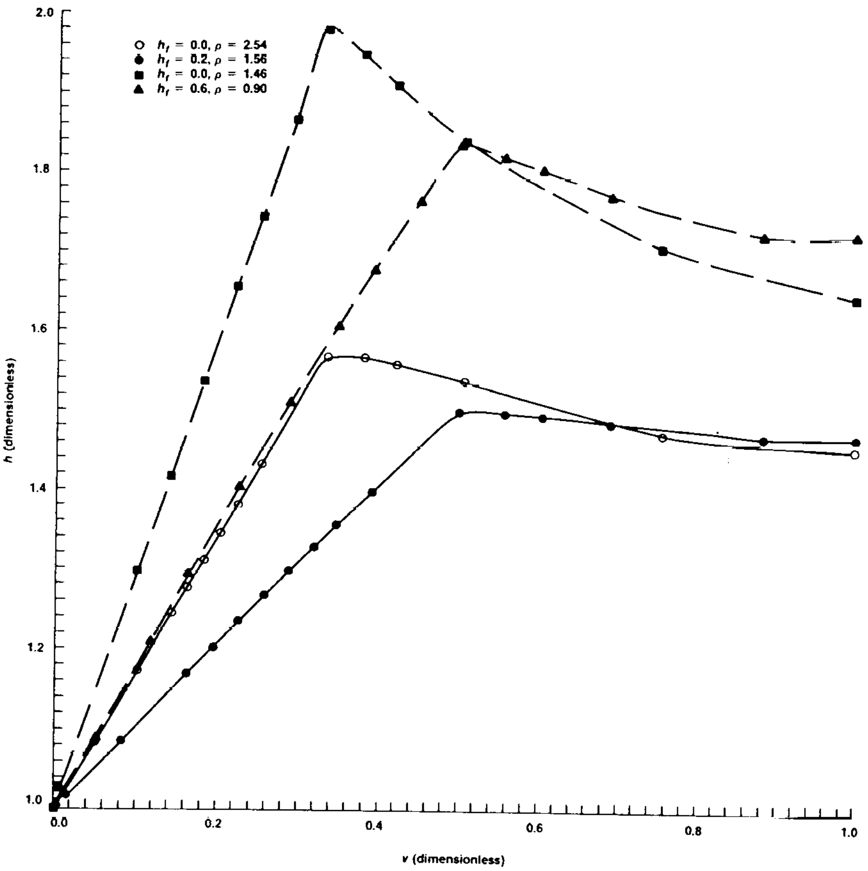

Figure 4. Effect of valve closure from partial opening on maximum head at valve end (*dimensionless friction loss* $h_f = H_f/H_r$; *pipeline constant* $\rho = aV_0 / 2gH_0$; $t_c = 3$)

Liquid water has a density of approximately 1,000 kg/m^3 under normal temperatures and pressures. As a result, water pipelines tend to contain vast amounts of mass, momentum, and kinetic energy. For example, a closed conduit 1,000 m long and 1 m^2 in cross section carrying water at 1 m/s contains 1,000 m^3 of water having a mass of 10^6 kg, a momentum of 10^6 kg m/s, and a kinetic energy of 500,000 J. Clearly, because such large amounts of momentum are involved, Newton's second law requires equally large forces to change the flow velocity for the entire pipe. This is particularly true if the changes in velocity take place rapidly.

But how can these large forces be generated? In open-channel flow it is possible to change the elevation of the fluid surface and produce a surge wave that will propagate in the channel. In essence, this wave uses the force of gravity to accelerate or decelerate the free-surface flow. When water flows or is contained in a closed conduit, however, no free surface is present; it is not possible to lift the fluid against gravity (unless the pipe breaks). The only location at which gravity might play a role is in devices such as reservoirs or surge tanks at the ends of the pipe. Even here, however, changes in elevation can take place only relatively slowly as a result of mass accumulation taking place over a period of time. To generate large forces rapidly, a different mechanism is required, and it is here that the compressibility of water plays such a vital role.

The role of fluid compressibility can be understood by study of Figure 1, which depicts a piston in a closed conduit and the resulting change in fluid pressure (head) as the piston is very slowly moved in the pipe. The resulting head change will be a function of the piston's travel and how elastic the pipeline is. Typical values of both parameters are shown for a pipeline with an initial length of 1,001 m and a final length of 1,000 m. Clearly,

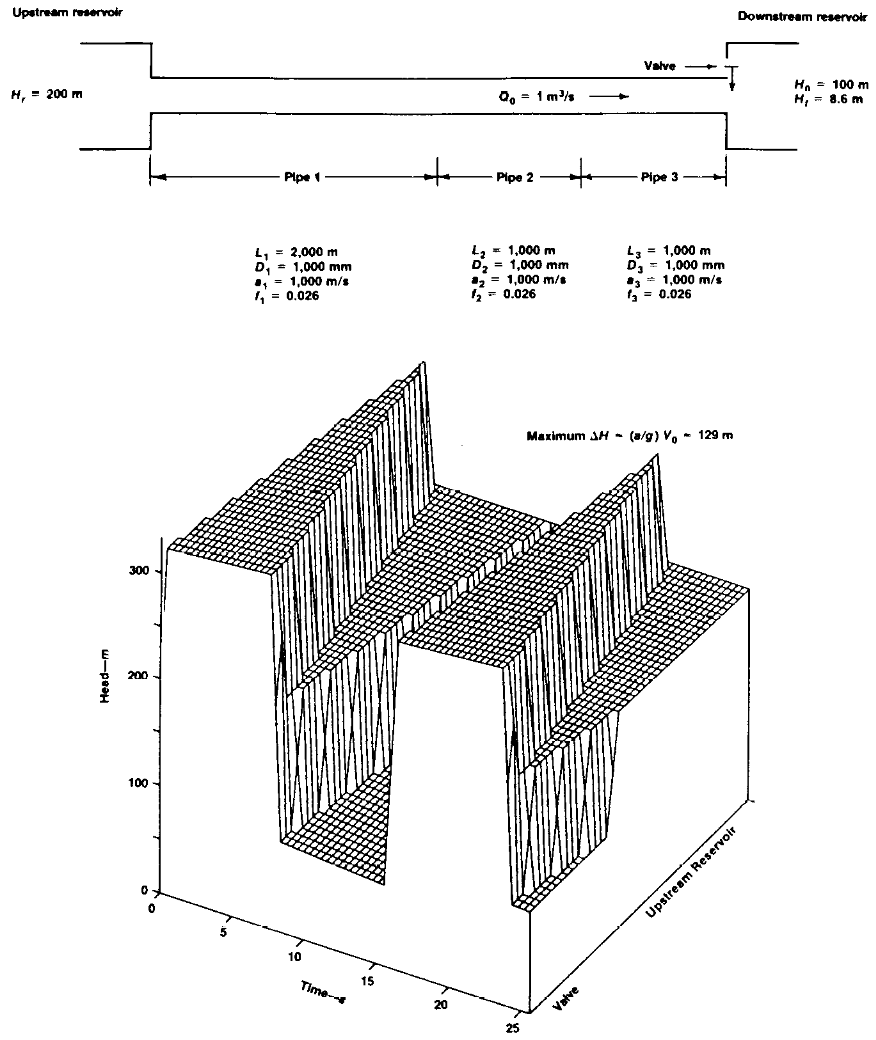

Figure 5. Plan sketch, parameter values, and three-dimensional response surface for instantaneous downstream valve closure in a simple series pipeline

any movement of the piston, no matter how slowly accomplished, will be accompanied by changes in fluid density, conduit dimension, and pressure. Even though the resulting changes in density and dimension are typically small, the changes in fluid pressure can be large and cannot be neglected.

The connections between this simple static compression test and a pipeline transporting fluid are easily made. If the actual conduit length in the static case is taken to be the final value of 1,000 m, what this pipe experiences during the compression can be thought of as a mass imbalance. That is, more fluid is forced to enter the conduit than was originally contained within it. Whenever such an imbalance occurs, compressibility effects must play a role. Thus, whenever flow conditions in a pipeline result in more fluid entering one end than is leaving the other, large pressure changes can be expected. In addition, the greater the mass imbalance, the more severe the resulting pressure changes tend to be. In anticipation of ideas to be broached subsequently, it could be suggested that mass imbalance constitutes a more natural and theoretically satisfying criterion for the severity of a system's transient response than does fluid velocity.

The origin of transient conditions. The connections between fluid properties (density and compressibility) on the one hand and the law of mass conservation on the other are fundamental to an understanding of fluid transients. Suppose, for example, an adjustment is made to a valve at the downstream end of a pipeline carrying fluid at some initial velocity (Figure 2). For simplicity, it is assumed that the valve is suddenly closed. The valve, of course, can only act locally—it specifies a relationship between flow through the valve and the head loss across the valve. In this case, the discharge and velocity of the fluid at the valve become zero the instant the valve is shut. However, in order for the fluid mass as a whole to be stopped, a decelerating force sufficient to eliminate the substantial 10^6 kg m/s of momentum must be applied. The only way to provide the required decelerating force is to compress the fluid, thereby generating an increase in pressure large enough to arrest the fluid flow. Because water is heavy, the required force is large; but because water is only slightly compressible, the wave or disturbance will travel quickly. In a system like the one shown, a pressure wave of approximately 100 m would propagate along the pipeline at roughly 1,000 m/s.

In many ways, this system is typical. Closed-conduit systems frequently carry huge amounts of momentum and kinetic energy, and, in addition, hydraulic conditions are in an almost continual state of change. For such systems, the only available mechanism for controlling or changing the flow conditions is shock wave propagation resulting from fluid and pipeline elasticity. Only if the changes in flow rate take place gradually, such that the mass imbalance in the line is always small, is it possible to go smoothly from one steady condition to another. Under these circumstances, no large fluctuations in pressure head or velocity occur, because the pipeline is always near a state of equilibrium.*

If rapid changes occur, whether caused by standard operating procedures or accidental events, a relatively large mass imbalance may arise. The associated pressure pulses are of great magnitude and are capable of bursting or damaging pipelines. In order to model or predict these rapid transient phenomena, complete equations of motion need to be written and solved, both for the pipeline and for all the devices used to control the flow. Standard texts such as those by Wylie and Streeter[1] and Chaudhry[2] provide the details. The more complete mathematical description should not, however, detract from fundamental insights. Transient conditions arise from local disturbances to the fluid flow that create a mass imbalance. This mass imbalance then acts through the combined effects of fluid and pipeline elasticity to accelerate the flow and, ultimately, create a new steady state.

Special devices that are designed to control or eliminate transient effects should be viewed with caution. It is the physical nature of the control problem that dictates that transient conditions must occur and that frequently deter-

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*Even in cases such as this, however, the actual mechanism for maintaining equilibrium in the pipe is still mass imbalance and compressibility effects. The only difference is that the pressure waves are much smaller in magnitude and travel quickly relative to the changes that occur at the ends of the conduit. In such applications, it is often justified to approximate transient behavior by assuming the fluid to be incompressible. Neglecting fluid compressibility leads to the so-called "rigid water column" model.

mines how dramatic transient conditions will be. Often, as in other areas of engineering, no design is superior from all points of view. Instead, there may be compromises that trade off a degree of control under some circumstances for less control under others.

Transient folklore

Much traditional "wisdom" has evolved over time on how to cope with the intricacies of transient phenomena. This wisdom often pertains to design assumptions that simplify the analyst's task by restricting the number and complexity of transient cases that need to be analyzed or specified. In light of modern computer power, however, the rationale for these assumptions needs to be questioned. Indeed, many of the a priori design assumptions are so misleading and so frequently false that they should not be regarded as rational design rules but more as outdated and discredited transient folklore.

In this article, several of these misconceptions are addressed, and, by means of counterexamples, their potential for erroneous application becomes clear.* To avoid misleading the reader, the title of each topic is stated as the converse of the often improperly understood and applied design axiom.

The three most widely revered axioms of transient folklore probably are:

- maximum steady-state velocities (flows) produce maximum transient head change,
- networks fare better (i.e., looped or branched configurations alleviate water hammer), and
- if one surge-protection device is good, then two (or more) are better.

The examples that follow were not difficult to find, nor have they been substantially altered to make the results contradict the aforementioned notions. They simply demonstrate that there are important cases for which these guidelines are either false or, at the very least, misleading.

Like much of what is called folklore in other areas, the previously stated transient rules have some basis in fact. For example, the origin of the first two rules can be traced to the famous fundamental equation of water hammer, which is also called the Joukowski relation. This relation equates changes in head (ΔH) in a pipe to the associated changes in fluid velocity (ΔV):

$$\Delta H = \pm (a/g)\, \Delta V \qquad (1)$$

in which a is the wave speed and g is the acceleration resulting from gravity. Clearly this equation implies that the

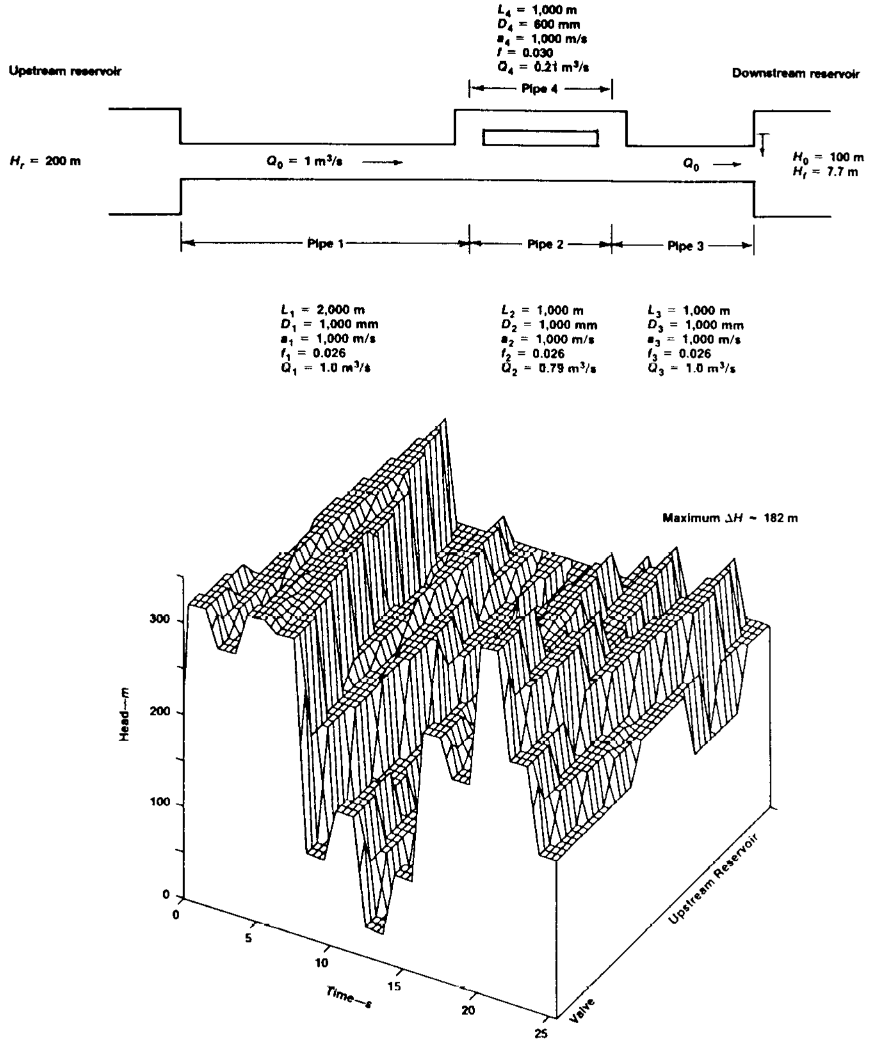

Figure 6. Plan sketch, parameter values, and three-dimensional response surface for instantaneous downstream valve closure in a looped-pipe network

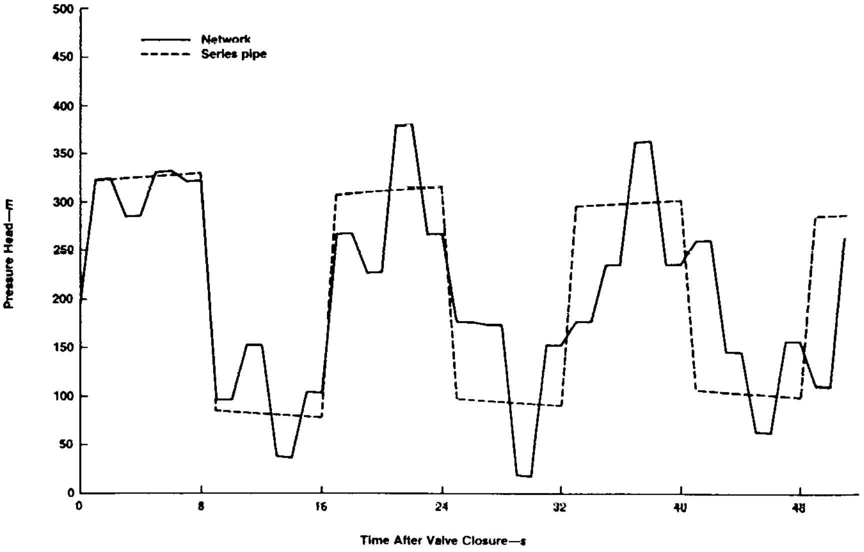

Figure 7. Variation in pressure head at the valve end for a simple series pipeline and a looped network

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*All of the transient simulations presented here were produced using $\mathrm{T_R A_N SAM}$ (acronym for Transient Analysis Model), which is a proprietary software product of HydraTek Associates, Toronto, Ont., Canada.

greater the value of ΔV, the greater the resulting change in pressure head.

Because the maximum possible change in velocity occurs when the initial velocity is greatest, it appears that the first rule must apply. In addition, networks carry flow in parallel lines, which must make it more difficult to change velocity quickly and must attenuate pressure surges by causing wave reflections at junctions. Therefore, the second rule also appears to be true. The logic leading to these two rules is faulty, however, and the conclusions are dangerous.

Most simple expressions, such as the Joukowski relation, are only applicable under restricted circumstances. When the required conditions are met, the simple relationships are often both powerful and accurate. In the case of the Joukowski relation, the two most important restrictions are that there should be no head loss resulting from friction and no wave reflections (i.e., there is no interaction between devices or boundary conditions in the system). If these conditions are not met, the Joukowski expression is no longer valid. In addition (and what is more frequently forgotten), the conclusions that are based on this rule may no longer be valid. To be specific, if the Joukowski relationship does not apply, it may be difficult to identify the set of conditions that produces worst-case response.

Maximum velocities do not necessarily mean maximum heads. A simple and convincing demonstration of the limitations of the Joukowski relation can be found in the two-reservoir, single-pipe and downstream-valve system of Figure 2. The closure behavior of the valve is given nondimensionally by its τ curve, which describes the relative valve opening as a function of time. The length of the pipe is 3,280 ft (1,000 m), its wave speed is 3,280 fps (1,000 m/s), and its diameter is 2.46 ft (0.75 m). The following four cases are simulated over a 16-second time period (H_0 is the difference between reservoir heads and f is the Darcy-Weisbach friction factor):

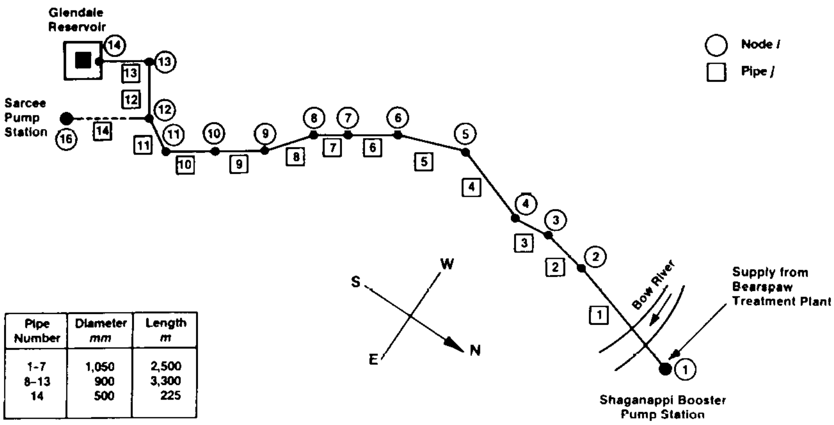
$$H_0 = 65.6 \text{ ft (20 m), and } f = 0.010$$

$$H_0 = 65.6 \text{ ft (20 m), and } f = 0.500$$

$$H_0 = 196.9 \text{ ft (60 m), and } f = 0.010$$

$$H_0 = 196.9 \text{ ft (60 m), and } f = 0.500$$

Under each of the four conditions, the rate of valve closure remains constant at 16.67 percent of the fully open value per second. In other words, it takes 6 seconds to close the valve completely from full opening ($\tau = 1$). Figure 3 shows the variation over time of the valve end pressure head, the valve end discharge, and the gate opening as given by τ for (1) closure from full opening, and (2) closure from one-third open for $H_0 = 197$ ft (60 m) and $f = 0.010$. The figure indicates that



Pipe Number	Diameter *mm*	Length *m*
1-7	1,050	2,500
8-13	900	3,300
14	500	225

Figure 8. Plan sketch of the Glendale feeder main (*not to scale*)

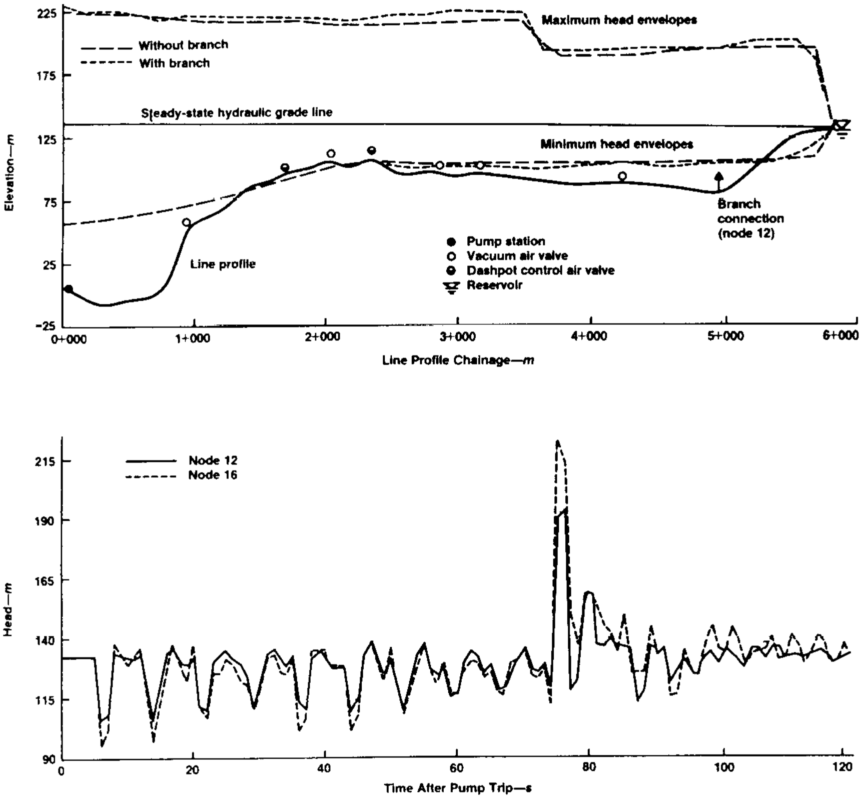


Figure 9. Profile of the Glendale feeder main (showing maximum and minimum transient head envelopes and steady-state hydraulic grade line) and pressure head traces at branch connection (node 12) and at end of branch pipe (node 16)

the rate of valve closure is identical in both cases but that the partial closure takes only 2 seconds to complete. Because of the throttling effect of the partially closed valve, the initial flow rate is much smaller than the initial discharge through the fully open valve. Despite the fact that the flow rate is significantly smaller in the case of the partial closure, the head increase at the valve is much greater (Figure 3). This apparent contradiction of Eq 1 arises because reflected waves have no opportunity to attenuate the peak pressure at the valve as they do for the case of the closure from full opening. The head rise for the closure from one-third opening could be approximately predicted by Eq 1 for the low-friction case. This is because the pipeline period of $2L/a$ is equal to the closure time of 2 seconds. In other words, the first low-pressure wave to be returned from the reservoir would not reach the valve until it had just closed, and no destructive wave interference would be possible before the maximum velocity change had occurred.

It is perhaps more instructive to perform this experiment for a number of gate closures from different partial openings. The rate of valve closure remains, as before, constant. The results of a number of such experiments are plotted in dimensionless form in Figure 4. The nondimensional velocity v is the initial fluid velocity (discharge) divided by the steady-state velocity (discharge) in the pipeline with the valve fully open. The dimensionless pressure head at the valve h is the maximum pressure head achieved (at the valve) divided by the upstream reservoir head. The dimensionless friction head h_f is the pipe friction head loss at full gate opening divided by the upstream reservoir head. Similarly, the pipeline constant ρ is given by

$$\rho = (aV_0)/(2gH_0) \qquad (2)$$

in which V_0 is the full gate opening initial velocity. The dimensionless closure time t_c is the actual time of closure divided by $2L/a$.

The key feature in Figure 4 is that the maximum head rise does not occur when the velocity (discharge) is at its maximum possible value of $v = 1$. The belief, fostered by the Joukowski equation, that maximum flow rates constitute a worst-case condition is not justifiable. It should be emphasized that these valve closure results are well known; it is the implication for more complex systems that is forgotten.

Fluid transients are not influenced only by the fundamental physical characteristics of the system; their intensity and behavior depend heavily on a host of factors, such as system configuration, timing of events, and initial conditions.

Networks may not improve system transient response. Using the two-reservoir and downstream-valve system of the previous section for any initial steady-state flow, a low value of pipe friction, and an (effectively) instantaneous valve closure, the maximum head rise can be accurately predicted by Eq 1. Figure 5 shows in three-dimensional form the result of such a simulation experiment for the system parameters indicated in the top portion of the figure. The bottom part of the figure shows the variation in pressure head over the entire length of the pipeline as a function of the time elapsed since the valve was closed.

The intensity and behavior of fluid transients depend heavily on a host of factors, such as system configuration.

The response surface is strikingly geometric, having a square wave form, and might loosely be termed a Joukowski response because the change in head can be readily approximated by Eq 1. The wave does not satisfy the frictionless pipe requirement, however, and thus the peak pressure increases slightly following the rapid initial head increase. Neither are wave reflections absent from this hypothetical case. It is simply that the wave reflections for the homogeneous pipe and upstream reservoir do not alter the magnitude of the initial pressure change. As noted on the figure, the maximum rise in pressure head is 423 ft (129 m), as predicted by the Joukowski relation.

If a branched pipe is now placed in parallel with this pipeline (shown in the top half of Figure 6), the system does not appear to be significantly different. The same initial velocity exists at the valve, and the most discernible change is that the flow has been split between pipes 2 and 4, causing a slight reduction in the total pipe friction loss. From the transient point of view, however, the simple network structure has introduced substantial complexity insofar as the transmission and reflection of waves at pipe junctions are concerned. It is immediately clear from the three-dimensional response surface shown in the bottom portion of Figure 6 that the transient behavior of the pipe system has been radically altered. Complex cycles of wave propagation interact constructively to produce far greater changes in the pressure head than those experienced in the series pipeline. The maximum head increase obtained at the valve for the looped-pipe configuration is about 597 ft (182 m), roughly 40 percent greater than would be expected if the fundamental law of water hammer was invoked. The details of the valve end pressure head trace appear in Figure 7.

The next scenario, although less dramatic, shows the same type of behavior in a completely realistic situation. Many transient analyses involve networks in which one line, a major feeder main with some minor branch connections for example, is considered to be of overriding importance in determining transient effects in the system. In such cases, it is often assumed that a conservative approximation results by modeling the major line in isolation, provided that (1) all of the flow (in the analysis) passes through the main line and (2) the actual branch flows are small compared with the discharge of the feeder main. Implicit in this supposition are two factors: (1) that maximum velocity produces maximum head changes and (2) that the existence of branch pipes in the actual system will to some extent absorb the water hammer. That is, it is assumed that the branch line capacitance will act in a manner somewhat similar to a surge tank. The problem with the latter assumption is that the wave transmission and reflection properties of the branch lines are being neglected entirely.

Figure 8 is a schematic view of the Glendale feeder main in the city of Calgary. Treated water from the Bearspaw water treatment facility at the northwest edge of the city is pumped along the Bow River valley to the Shaganappi booster pumping station. The Glendale line consists primarily of 42-in.- (1,050-mm-) and 36-in.- (900-mm-) diameter reinforced concrete pipe with some short steel sections in the vicinity of the river crossing. The line climbs approximately 135 m over its nearly 6-km length and terminates in the Glendale storage reservoir. Under most operating conditions, nearly all of its approximately 21.6-mgd (80-ML/day) capacity passes from the Shaganappi pump station into the Glendale reservoir. Only one of the three minor connections that occur along the line is indicated in Figure 8. This is a 20-in. (500-mm) reinforced concrete line that has a fictitious length of 740 ft (225 m) (the actual connection, which runs to the Sarcee pump station, is roughly 3,280 ft [1,000 m] in length). When the Shaganappi pump station is operating, this branch line is effectively a dead-end pipe because the Sarcee pumps are only used to supply the Glendale line when the Shaganappi pumps are inoperative.

This system could be modeled under the conservative single-line assumptions listed previously. To illustrate the effect that adding the branch pipe (connecting nodes 12 and 16) has on the transient initiated by a loss of power to the Shaganappi pumps, the Glendale feeder main has been modeled with and without the branch connection. Because the branch line is a dead end, all of the discharge from the pumping station still passes into the downstream reservoir during steady-state pumping.

A useful way of summarizing the results of a transient analysis is to record the maximum and minimum pressures that occur throughout the system over the period of simulation. These values can be plotted along the length of the pipeline and produce an envelope delimiting the range of pressure variation at a particular location. The maximum and minimum pressure head envelopes developed in this way are plotted in the top graph of Figure 9. The results given correspond to the two cases of interest, namely, with and without the branch line at node 12. The plot also indicates the (initial) steady-state hydraulic grade line and the profile of the pipeline, as well as the location of the Shaganappi pump station, several air valves, and the Glendale reservoir.

The dashpot control air valve shown at station 2 + 280 m (elevation 107 m) is one of the primary determinants of the Glendale feeder main's transient behavior. As the pump speed begins to dwindle following the power trip, a low-pressure wave is transmitted from the pump station toward the reservoir. This falling hydraulic grade line reaches the elevation of the air valve at station 2 + 280 and causes it to admit a large quantity of air into the pipe in order to maintain the line pressure at near-atmospheric conditions. (Two other air valves are similarly activated [station 1 + 650 and station 2 + 040], but their associated air cavities are small and less influential in obtaining the peak pressures.) The large air cavity collapses after approximately 72 seconds have elapsed, and the impact of the rejoining water columns causes a sudden and severe pressure increase.

The traveling wave front caused by this event can be seen in the pressure head trace (bottom graph) of Figure 9 as the surge reaches the branch connection a few seconds later en route to the reservoir. A portion of the wave is transmitted into the branch pipe. Upon reaching the dead end of the branch pipe, the initial pressure change becomes doubled in magnitude and returns toward the feeder main. The pressure trace of Figure 9 shows that the head changes are more extreme at the end of the branch pipe (node 16) than at the branch connection (node 12). The high- and low-pressure fronts thus produced travel back into the main line and interact with other waves, causing constructive interference in some regions and destructive interference in others.

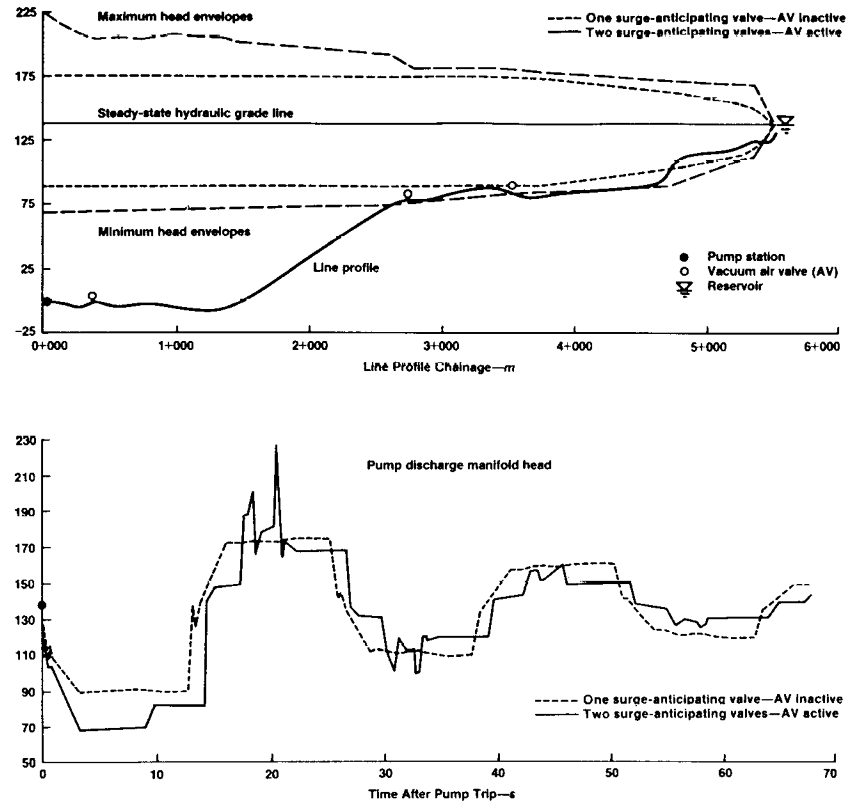


Figure 10. Profile of hypothetical feeder main (showing maximum and minimum transient head envelopes and steady-state hydraulic grade line) and pressure head traces at the pump discharge header for one and two surge-anticipating valves

The overall effect of the wave interactions can be seen from the differences in the extreme head envelopes for the branched and nonbranched cases. Although the increases in maximum pressures with the branch line present are modest (in this case), the point is clearly made that ignoring the existence of branched or looping pipes does not necessarily result in a more conservative analysis. Neither is the hydraulic grade line elevation at the nodes where these attachments occur a particularly reliable indicator of the pressure heads to be expected in the omitted pipes, as evidenced by the 45-psi (30-m) discrepancy in peak heads observed in the bottom plot of Figure 9.

More surge protection is not always safer. This final example extends the ideas introduced thus far beyond the purely physical aspects of the system. Operational and functional considerations can take precedence over other factors in establishing the appropriate type and degree of transient protection needed to ensure a reliable system.

In most civil engineering systems overdesign implies a higher degree of safety. It seems strange that the converse could be true but, in hydraulic transient design, such a situation is neither impossible nor uncommon.

The preoccupation with maximum velocity as a critical cause for water hammer obscures the fact that several factors working in concert at low values of discharge can also produce disastrous consequences. A case in point is the operation of surge-anticipating valves installed to protect against excessive pressures following pump failure. As mentioned in the previous example, loss of power to the pumps initiates a low-pressure wave as the momentum of the water column in the pipe continues to move the fluid in the absence of any motive force (apart from the pump impeller and rotor inertia). Surge-anticipating valves derive their name from the fact that they open in response to this low-pressure condition and so are able to provide maximum pressure relief when the returning high pressure reflection reaches the pumps.

Most often, surge-anticipating valves are installed in pairs, one serving as a backup to the other. If the valves are well maintained and properly installed, they both open at some preselected value of low pressure as the dynamic head of the pumps decreases following a power trip. What often is not realized, though, is that an opening valve produces its own downsurge, which causes an additional drop in the hydraulic grade line.

The effect is naturally greater for the opening of two valves. This increased downsurge may cause other devices that react to low pressure to be activated, and these, in turn, can alter the transient behavior of the system. Thus, without more complete analysis, it would be dangerous to assume that two surge-relief valves behave more favorably than one relief valve.

The upper plot in Figure 10 shows extreme pressure profiles for the scenario just described. This test system is identical to one of the city of Calgary's major feeder mains except that one of the high-point air valves has been changed from dashpot control (slow closing) to a standard vacuum air valve. For the simulation results presented, only one pump supplying approximately 30 percent of the total pumping capacity of 25 mgd (95 ML/day) is operating. The 3.4-mi (5.5-km) reinforced concrete pipeline has a nominal diameter of 54 in. (1,350 mm) and undergoes an elevation gain of more than 425 ft (130 m).

In the case of a single operating surge-anticipating valve, the minimum position of the hydraulic grade line is above the elevation of the air valves, which do not open. Thus, no water column separation occurs and the maximum and minimum pump discharge manifold pressure changes are 30 and 36 percent, respectively, of the total dynamic head.

If a second surge-anticipating valve is included in the pump station, the maximum downsurge at the pump increases to about 50 percent of the total dynamic head. The result is that the hydraulic grade line drops below the elevation of the air valve located on the rising portion of the pipeline (station 2 + 750) and water column separation takes place. The water columns rejoin as the air cavity collapses, and a potentially calamitous pressure spike ensues. The increase in maximum discharge manifold pressure head rises to nearly 70 percent of the total dynamic pumping head. Details of the varying pump discharge manifold pressure head can be seen in the bottom graph of Figure 10.

Without performing additional analyses, it is not clear whether performance of the system is worse when it is operating at full capacity with two surge-anticipating valves. In any event, the purpose of the illustration is not to decide the issue of which set of operating conditions constitutes the worst case. On the contrary, along with the preceding examples of fallacious reasoning, it should emphasize the question "Is there a worst case?" in the context of transient analysis. It should be abundantly clear that transients, even in relatively simple systems, are complex phenomena whose behavior is governed by fluid properties, the physical setting, the topology, and the location, service condition, and mode of operation of installed devices. If data and model uncertainty, the stochastic nature of the (initial) state of the system, and the sensitivity of system response to all of these factors are added to this list, gaining any meaningful qualitative or quantitative insight into transient phenomena might appear unlikely. But, the prospects are anything but dismal.

Whereas in the past the inherent immensity of realistic transient computations compelled analysts to adopt many of the simplifying assumptions just discussed, the current state of the art is much less restricted. As in other technical fields, the advent and spread of cheap and plentiful computer resources is having a profound impact on the modeling of fluid transients. Analysis of only a few potentially misleading worst-case scenarios based on some shaky rules of thumb is no longer an imposed necessity. The relatively complex lines of the latter two counterexamples required approximately 3 and 10 minutes, respectively, to run on a personal computer.* The time needed for a particular computer run depends on the selected time step, the complexity of system components, and the specified simulation duration. These figures strongly suggest that the benefits of comprehensive transient capabilities are at hand.

Conclusions

Transient conditions play an essential role in the operation of pipeline systems. The only mechanism whereby flow conditions within a closed conduit can change is through the generation of transient pulses. These pressure waves communicate or transmit information about changing conditions throughout the hydraulic system. If flow conditions change slowly, the resultant pressure changes are small and do not threaten the pipeline. If conditions change rapidly, however, large pressures can be generated, frequently of sufficient magnitude to burst pipes and damage equipment. Power failure of pumps, sudden valve actions, and the operation of automatic control systems are all capable of generating high-pressure waves in domestic water supply systems.

The current practice in many utilities is to ignore transient conditions in large networks or, occasionally, to contract out particularly obvious problems relating to transients to specialized consultants. If transient analysis is done at all, gross simplifications and assumptions are commonly made in order to make the analysis tractable. Until recently, there has been no alternative to this approach—the generalizations and programming required for comprehensive analysis of transient conditions have been either incomplete or prohibitively expensive. This is no longer the case. The sophistication of transient models has increased while computer costs have steadily been reduced.

Of course, transient analysis is not a sovereign remedy for all hydraulic problems and pipe-system failures. The exact reason for which a given pipe fails is often complex and can be related to corrosion, earth pressures, construction faults, and other causes. Transient pressures are sometimes great enough, however, to directly cause failure in new and strong pipes; weakening the pipe for any other reason simply makes the pipe more vulnerable to failure. Thus, in causing pipeline breaks, transient conditions play a dual role: They can rupture a pipe directly through excessive pressure, or they can exploit an existing weakness to damage the pipe indirectly.

An old adage contends that a little knowledge can be a dangerous thing. The originator of that homily might well have been a water hammer specialist as it points directly to one the most prevalent problems in the application of fluid transient analysis: the misuse of some basic concepts of unsteady fluid flow in the analysis and design of pipeline systems. If transient analysis is to be successful, it must be comprehensive in scope. This implies that a wide range of flow conditions, operating scenarios, and device combinations must be investigated. Only then can the designer have any confidence that transient conditions have been rationally and logically accounted for. The potential benefits of such an approach include an improved model of system behavior, more economical system operation, and, possibly, a lower capital cost.

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*IBM AT with an Intel 80287 chip