Hydraulic transients cause low-pressure problems

Mysterious short-term pressure drops at the top of Cat Mountain prompted an investigation that revealed hydraulic transients as the culprit.

Thomas M. Walski and Teresa L. Lutes

Most engineers are familiar with hydraulic transients that cause problems with excessive pressure in water distribution systems. However, transients can also cause short-lived low-pressure problems. This article describes the analysis conducted by the Austin (Texas) Water and Wastewater Utility that identified transients as the source of low pressures in a portion of the city. Pressures recorded during controlled conditions provided the key in identifying pump and valve operation as the source of the problem.

Most water utilities get complaints from time to time about low pressure. Most often, the problem occurs either because the service location is at too high an elevation or because system carrying capacity is inadequate to meet demand. Carrying capacity may be inadequate if valves are mistakenly closed, if demand has outstripped existing capacity of the system, or if pipes are undersized, corroded, or scaled. The solution can be as simple as opening a mistakenly closed valve or as complex as undertaking a major capital improvement project.

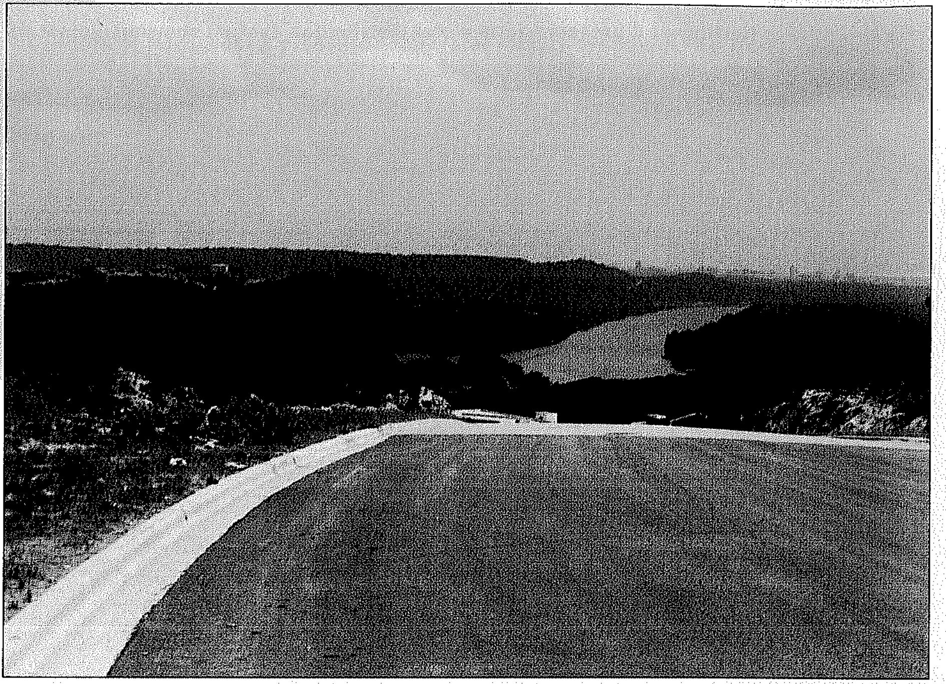
The duration of the drop in pressure is an important clue in identifying the cause and solution. If the problem is continuous, it is usually related to elevation. If it occurs during peak flow periods, it indicates an inadequate carrying capacity. Pressure drops that appear to be random are the most difficult to solve.

This article describes a difficult low-pressure problem that occurred occasionally in the Cat Mountain area of the Austin, Texas, water distribution system. Although the area is at a higher elevation, that alone did not seem to explain the low pressure. Extensive research and testing were needed to resolve the situation.

Pressure fluctuated in Northwest A zone

Austin's Water and Wastewater Utility serves about half a million people in a hilly area along the Colorado River in Texas. Because of the hilly terrain, the utility operates seven separate major pressure zones and numerous small reduced or boosted zones.

The low-pressure problems occurred in the Northwest A pressure zone, which has an average daily demand of 12.5 mgd. Another 5.8 mgd passes through this zone on its way to the next higher pressure zone, Northwest B. Figure 1 is a schematic map of the Northwest A pressure zone. The zone is served almost entirely from the Spicewood Springs Pump Station, although there is some inflow through the much smaller Highland Park West Pump Station. The Spicewood Springs Pump Station has nine pumps; their nominal capacities are given in Table 1.



Because of the hilly terrain in the Austin service area, the utility operates seven major pressure zones and numerous small reduced or boosted zones to help keep pressure within the system as constant as possible.

The most noteworthy thing about the Northwest A pressure zone is the dramatic change in elevations served; this zone includes Austin's steepest hills. The overflow elevation for the tanks (reservoirs) in the zone is set at 1,015 ft mean sea level. Customers in the unreduced part of the pressure zone are at elevations ranging from about 750 to 927 ft at Cat Mountain Cove (the site of the lowest pressures). Figure 2 is a schematic profile map of the pressure zone.

Three major tanks are located in the Northwest A pressure zone—Martin Hill (34 mil gal), Jollyville (11 mil gal), and Forest Ridge (3 mil gal). In addition, there is one smaller tank—Guildford Cove (0.28 mil gal). Pump stations that deliver water to the Northwest B pressure zone are located at the Jollyville and Forest Ridge tanks.

Some utility staff members viewed the Jollyville and Forest Ridge tanks as suction tanks for the Northwest B pressure zone. Often these tanks would be pumped full and the inlet butterfly valve would be closed, thus isolating the Northwest A zone from the tank until the Northwest B Pump Station drew the water level down sufficiently. During these times, peak flows in this zone were met from the Martin Hill tank and the Spicewood Springs Pump Station.

TABLE 1 **Capacity of pumps at Spicewood Springs Pump Station**

Pump	Capacity—*gpm*
S1	8,000
S2	8,000
S3	8,000
S4	7,000
S5	10,000
S6	5,000
S7	3,000
S8	10,000
S9	10,000

A check valve prevented the water in the Guildford Cove tank from flowing back into the main part of the Northwest A zone. The outflow from the Martin Hill tank was also controlled by a mechanically operated valve and a check valve (Figure 3). The 36-in. butterfly valve was often closed when the tank was nearly full.

Eight pressure-transmitting devices in the pressure zone transmit pressure data back to the main control room at the Davis Water Treatment Plant, where the information is logged on strip charts. The locations of the pressure transmitters (PTs) in the Northwest A pressure zone are shown in Figure 1 and listed here.

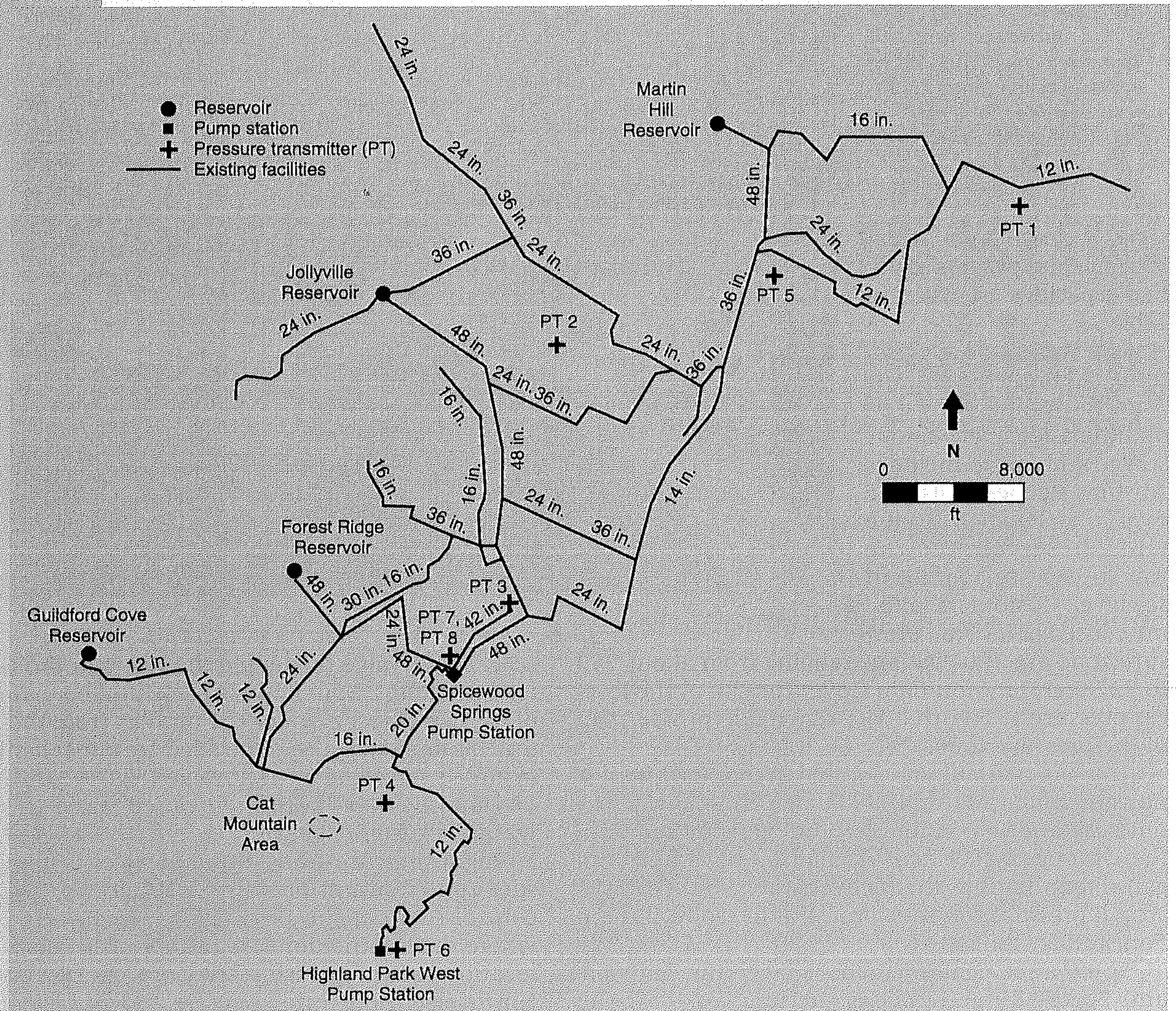
PT1—Hornborne Lane
PT2—Mustang Chase and Hereford Lane
PT3—US 183 and Mesa
PT4—Sierra and Mesa
PT5—Howard Lane
PT6—Highland Park West Discharge
PT7—Old Spicewood Springs Discharge
PT8—New Spicewood Springs Discharge

Troubleshooters seek answers

With service from the Northwest A pressure zone, pressure at Cat Mountain would never be very high. The elevation of the highest customer was at 927 ft and overflow of the tanks is 1,015 ft, so pressures generally ranged between 25 and 40 psi under normal conditions. Occasionally when the Forest Ridge and Jollyville tanks were full, the operators could pump over the 1,015-ft nominal hydraulic grade line as they filled the distant Martin Hill tank.

Utility personnel were accustomed to low-pressure problems in this area. However, they could not

FIGURE 1 Northwest A pressure zone water distribution system showing diameters of larger pipes



explain why customers on Cat Mountain were occasionally out of water. Other customers reported sputtering water or air-horn sounds when they turned their water on. These things should not happen at 35 psi. Utility employees found pressures of 25 to 40 psi when they investigated these complaints. Employees explored a number of possible explanations for the situation, but they could not come up with a reason for the low-pressure problems.

Air-release valves possible culprit. Because Cat Mountain is at a high elevation, the air-release valves on the line to Cat Mountain were examined as the possible culprit. Existing air-release valves were switched out, and some were added, but the complaints continued.

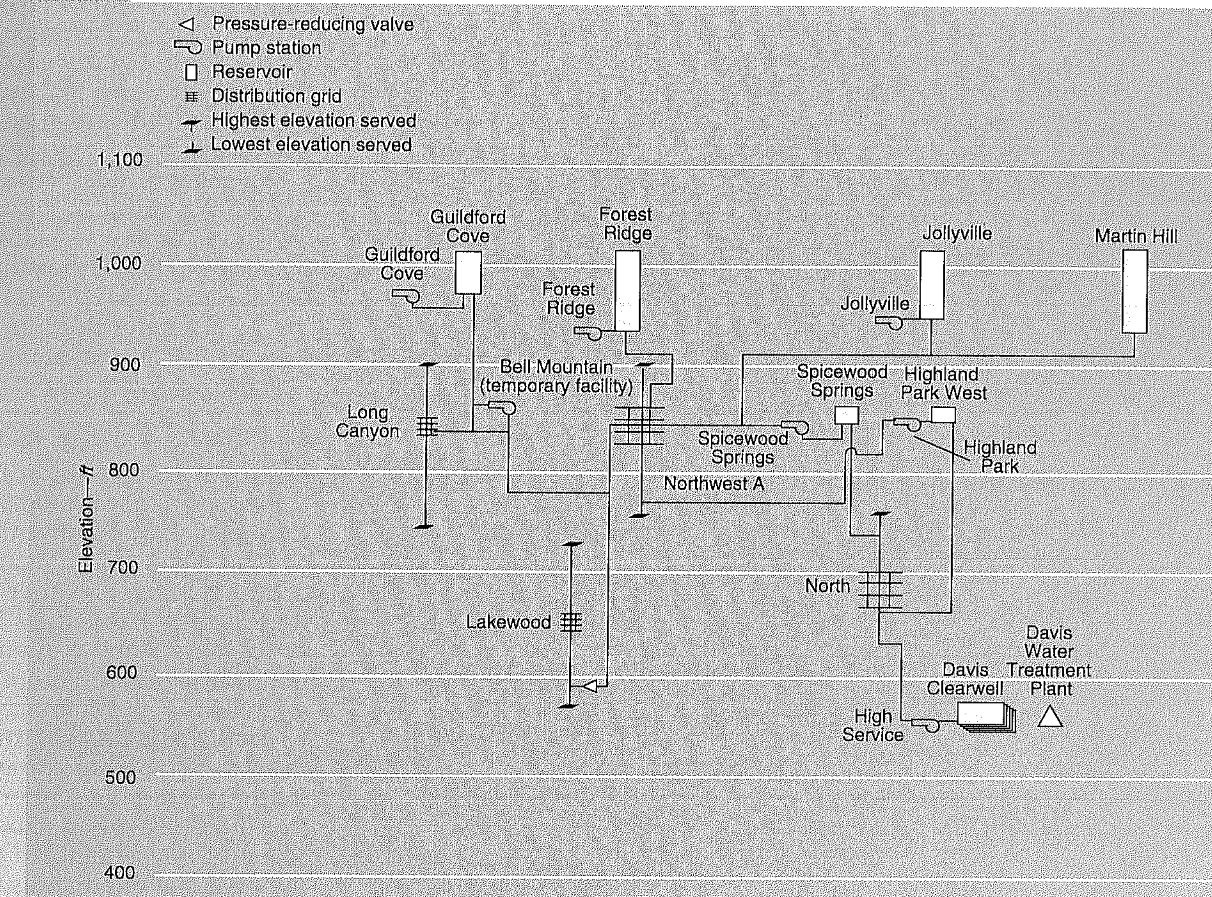
Water theft could lower pressure. The possibility existed that theft of water from area hydrants was lowering the pressure at Cat Mountain for short periods of time. No such thefts were confirmed, and a pipe network model run revealed that the flow would have had to have been on the order of 20,000 gpm to cause pressures to go to zero at Cat Mountain.

Carrying capacity could be poor. Fire hydrant flow tests in the area revealed adequate hydraulic carrying capacity, which indicated that normal fluctuations in water consumption would not seriously reduce pressure. This was further confirmed by pipe network model runs.

Valve may be malfunctioning. The behavior of pressure-reducing valves serving low areas off the Northwest A pressure zone was investigated on the premise that a valve might be malfunctioning and allowing water to rush down to a lower pressure zone. However, no malfunctioning valves could be found.

The only likely location where this might occur would be in the filling of a small hydropneumatic system off Beauford Drive. However, the fill line for the Beauford Drive booster pump had a properly

FIGURE 2 Schematic hydraulic profile of Northwest A pressure zone water facility system (no horizontal scale)



functioning flow regulator to prevent excessive high flows. All other normally closed valves that isolated Northwest A from lower pressure zones were checked and found to be set properly.

Complaints and telemetry data correlated. Utility personnel then correlated customers' complaints with pressure telemetry data. The pressure transmitter nearest Cat Mountain Cove was located about half a mile away at the intersection of Sierra Drive and Mesa Drive. The charted pressure drops were correlated with changes in pump operation at the Spicewood Springs Pump Station.

When pumps were turned off at Spicewood Springs, pressures sometimes dropped at the Spicewood Springs Pump Station and at the pressure measuring device at Sierra and Mesa. As one moved away from these locations and toward the Martin Hill tank, the pressure drops were much smaller (Figure 4).

Transient nature of problem raises suspicions. The significant word in the previous paragraph is that "sometimes" pressures dropped. Another ingredient in the mix could turn routine pump changes into serious pressure drops: the status of the inlet butterfly valves at the Jollyville and Forest Ridge tanks. When the inlet valves were closed and pumps were turned off, pressures fell for short periods of time ranging between 4 and 22 min.

The duration of the drop in pressure is an important clue in identifying the cause and solution.

Another clue to the source of the problem was the fact that the magnitude of the pressure drop correlated with the magnitude of the change in flow (Figure 4). The short-term nature of the pressure drops and their correlation with the magnitude of the velocity change in pipes pointed to hydraulic transients as the likely cause of the problem.

Hydraulic transients a possible explanation

Change in velocity causes change in pressure. Whenever the velocity of flow in a pipe

FIGURE 3 **Martin Hill Reservoir, schematic of inflow–outflow piping (not to scale)**

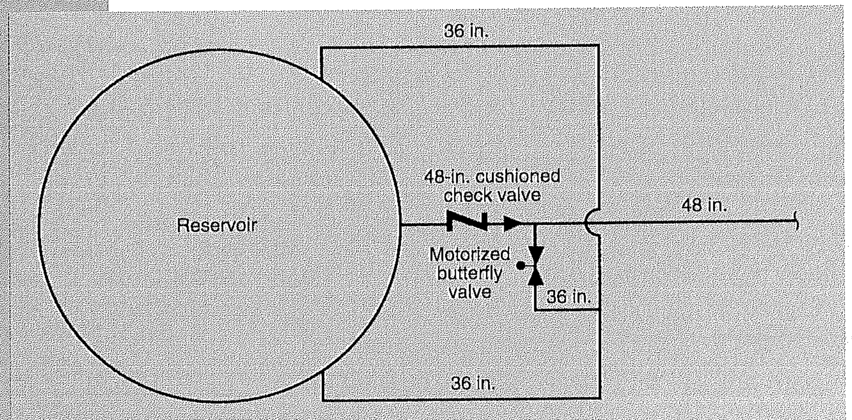
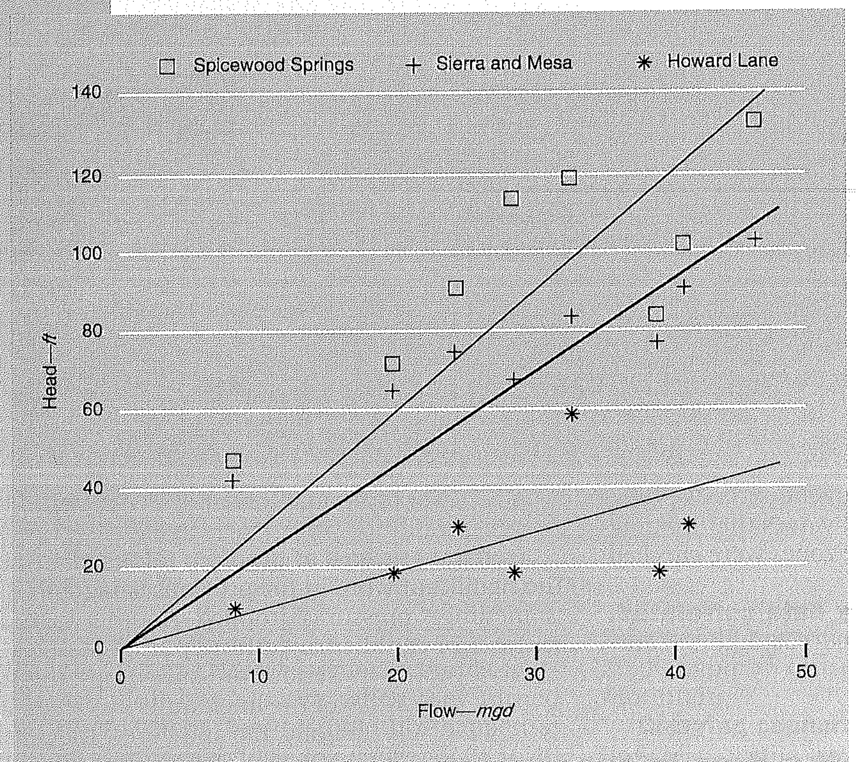


FIGURE 4 **Magnitude of transients**



changes, there is a corresponding change in pressure. This pressure change travels through the piping system as a wave and is eventually dampened out. Usually the change is so gradual it is barely noticed. This change can be referred to as a surge or (especially when it results in a large positive pressure in closed conduits) a waterhammer. A more general term for this phenomenon is "hydraulic transient" because it results from the transition from one condition to another.[1,2]

The magnitude of transients in water mains can be as high as a 100-ft change in head for every 1-fps change in velocity. In complicated pipe networks, the loops and intersections in the system reduce the magnitude of the transient event because some negative and positive waves tend to cancel each other out.

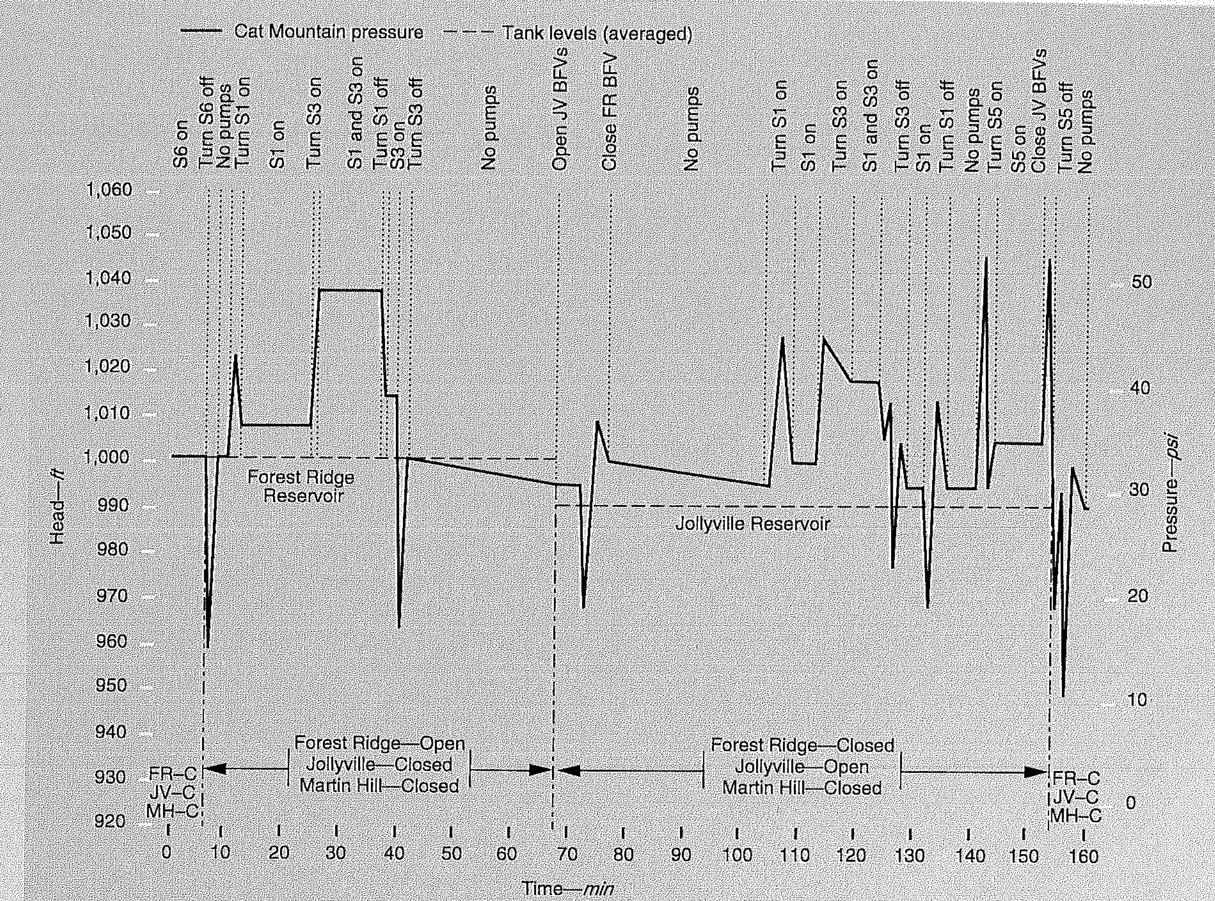
The magnitude of transients in a pumping system can be minimized by slowly opening or closing the pump discharge valve while starting or stopping the pump. This results in a smaller change in velocity than if the pump was started or stopped without the valve being throttled. The pumps at the Spicewood Springs Pump Station had slow closing discharge valves that operated properly. The presence of these valves had earlier led utility personnel to assume that transients would not be a problem in the system.

Tanks help dampen transients. The pressure waves from transients travel through the pipe network at about 3,000 fps, depending on the material pipes and joints are made of. When a pump shuts down, the negative pressure wave moves out from the pump station until it reaches a tank where the low pressure causes extra flow to leave the tank and dampen out the transient.

If tanks help dampen the transient, the practice of shutting the Forest Ridge and Jollyville tanks from the Northwest A system prevented those tanks from dampening out the transients. Because the Forest Ridge tank is only about 2 mi from the Spicewood Springs Pump Station, the negative transient could have reached the tank and returned to Spicewood Springs in 5 to 10 s. Instead, the surge had to travel to the Martin Hill tank to be reflected, a trip of some 20 to 30 s.

The problem was further exacerbated by the fact that when the fill valve was closed, the check valve from the Martin Hill tank did not appear to be opening fully, impairing that tank's ability to dampen out the surges. (Cat Mountain is on the opposite side of the pressure zone from the Martin Hill tank.)

FIGURE 5 **Cat Mountain pressure trace showing tank levels, reservoir valve switches, and pump changes (February 6 test)**



FR—Forest Ridge, JV—Jollyville, MH—Martin Hill, C—closed, O—open, BFV—butterfly valve

Therefore, the hypothesis could be made that the low pressures in the Northwest A pressure zone were caused by pump operation at Spicewood Springs combined with the fact that the tanks in the pressure zone could not completely dampen out the transients because their valves were fully or partly closed.

Field test undertaken

Although it was possible to hypothesize about the cause of the transients or even their existence, it would be necessary to prove that they existed under controlled conditions to convince operations personnel that changes in operation were necessary. This could be done by changing flows in pipes while painstakingly monitoring system pressures.

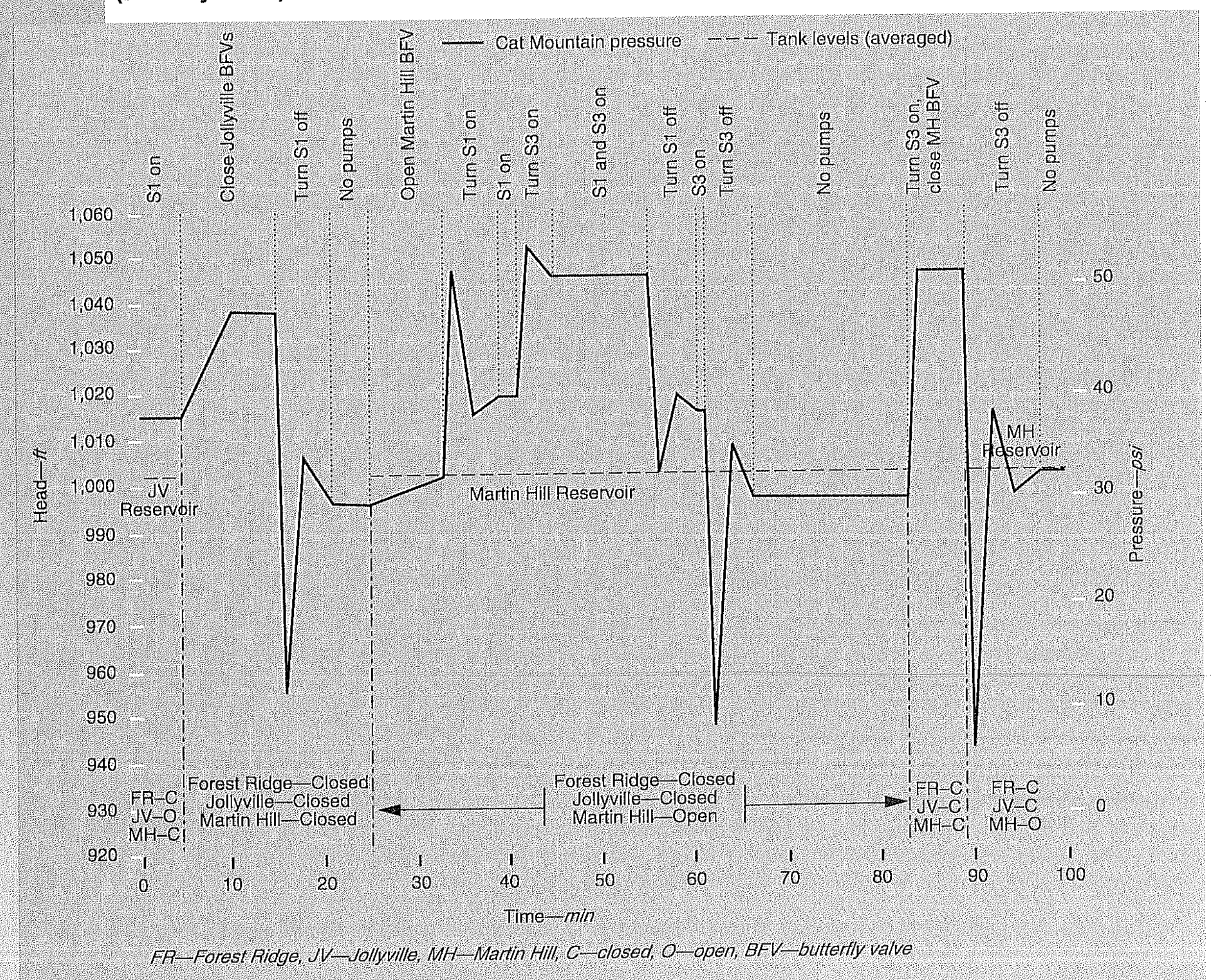
Three sets of tests were conducted, one set per day, to confirm the existence of transients and their effect on pressures. In addition to the permanent pressure transmitters, several portable pressure-recording gauges were placed throughout the system and two manned pressure gauges were used to monitor pressure during the tests. The tests consisted of turning pumps on and off while different tanks were open and closed.

TABLE 2 **Effect of reservoir fill-valve position on surge magnitude**

Forest Ridge	Jollyville	Martin Hill	Average Surge—*psi*
Closed	Closed	Closed	36
Closed	Closed	Open	31
Closed	Open	Closed	9
Open	Closed	Closed	9 (20)

Pump operation checked. The results of these tests are shown in Figures 5–7, which give the pressure and corresponding head at Cat Mountain during the tests. These figures show that significant transients occurred when pumps at Spicewood Springs were turned off while tanks were isolated from the pressure zone. The head at Cat Mountain should hover

FIGURE 6 **Cat Mountain pressure trace showing tank levels, reservoir valve switches, and pump changes (February 8 test)**



around 1,005 ft when the pumps are off and around 1,020 ft when the pumps are on. Instead, the heads drop to near 930 ft during a pump shutdown and rise to more than 1,050 ft when pumps are turned on. The only logical explanation for this is hydraulic transients.

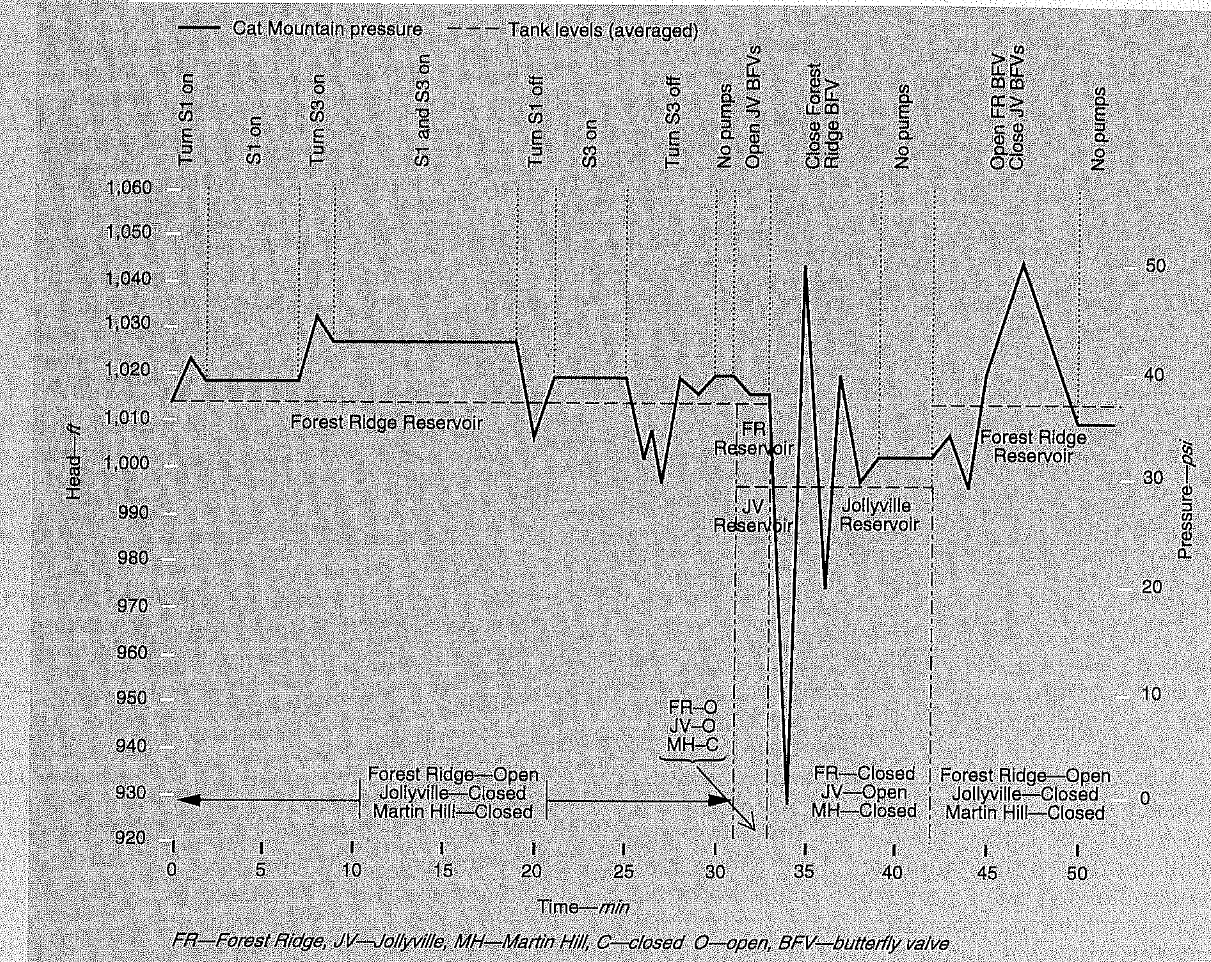
The magnitude of the negative surge when pumps were turned off indicates the importance of each tank in dampening surges. This is summarized in Table 2, which gives the average pressure drop for the shutdown of an 8,000-gpm pump (S1 or S3, depending on which tank was open). In Table 2, two values are given for the case in which the Forest Ridge tank is open, because during the first set of test a valve on an important transmission line to that tank was closed. The value in parentheses refers to that condition; the other value is for a date after that valve was opened. It shows that the more directly the Forest Ridge tank is connected to the system, the better it is able to dampen surges.

Table 2 also shows that the surges were especially large when all tanks were closed or only Martin Hill (the tank farthest from Cat Mountain) was open.

TABLE 3 **Pressures at Spicewood Springs Pump Station discharge**

Time *min:s*	Event	Pressure *psi*	Head *ft*
0:00	Switch pump S1 off (discharge valve begins to close)	76	1,026
3:40	Pressure begins to drop	76	1,026
5:00	Pump discharge valve closes completely		
5:20	Minimum pressure reached	42	947
6:30	Maximum pressure reached	61	991
7:10	Pressure begins to drop again		
9:00	Pressure levels off	57	982

FIGURE 7 **Cat Mountain pressure trace showing tank levels, reservoir valve switches, and pump changes (March 1 test)**



Finally, it shows that opening either the Forest Ridge or Jollyville tank can significantly inhibit the drop in pressure.

Valve operation supplies clue. Although pump shutdown caused negative pressure transients, strictly speaking the cause of the transients is not the shutdown of the pump but the change in velocity in the transmission mains. Such changes in velocity also occurred several times during the testing when valves were shut without any corresponding change in pump operation status.

This occurred most dramatically during the March 1 test, when the Forest Ridge tank valve was open and Jollyville was closed. At this time, the water level in the Jollyville tank was pumped down to 19 ft below the level of the Forest Ridge tank. When the Jollyville tank was reopened, water began flowing from Forest Ridge to Jollyville (and away from Cat Mountain). At this time, the head at Cat Mountain dropped from 1,014 to 927 ft (i.e., there was no pressure at Cat Mountain). Therefore, significant transients were caused not only by pump operation but by valve operation.

Duration of event. Hydraulic transients caused by a pump shutdown not only result in a drop in pressure, but they also actually begin a wave effect in which the pressure drops, then rises as the negative wave is reflected in the system, and then may drop again. This continues until the wave dampens out.

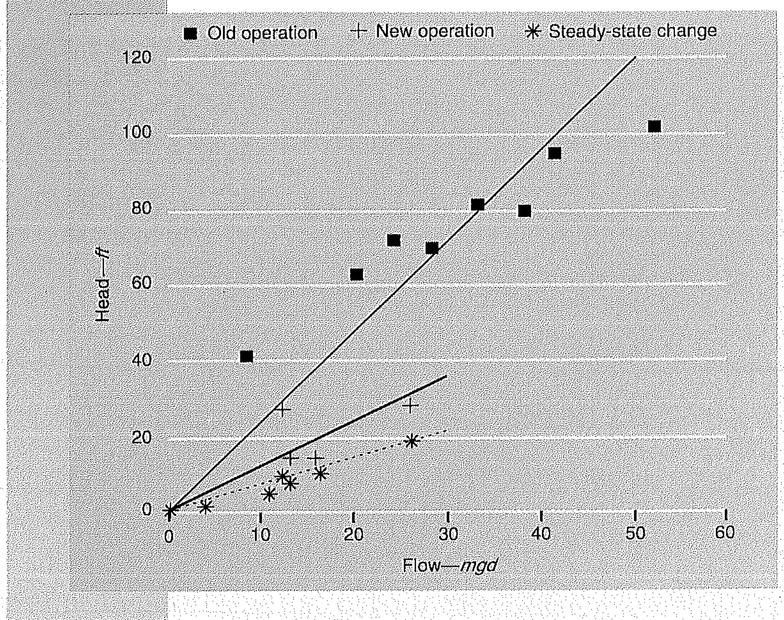
The sequence of events during a typical pump shutdown is shown in Table 3 for the case during the February 8 test with all tank fill valves closed. The pressures were recorded at a gauge at the Spicewood Springs Pump Station. A report detailing all of the tests conducted in the Northwest A pressure zone is available from the Austin Water and Wastewater Utility.[3]

Utility modifies operations

The field tests confirmed that hydraulic transients were the cause of the short-term low pressures in the Northwest A pressure zone. The problems were caused by isolating tanks from the rest of the pressure zone.

The Austin utility has modified its operations in the Northwest A pressure zone so tanks are no longer

FIGURE 8 Effect of operating changes, Sierra and Mesa



filled and taken off line to be used strictly as suction tanks for pumps to the next higher pressure zone. This has greatly reduced low-pressure problems in Cat Mountain and other high-elevation areas in the pressure zone. One customer even called to say he had noticed an improvement in water service.

Overall, the utility is now operating the Spicewood Springs Pump Station at a more constant discharge, allowing water stored in the tanks to dampen out demand fluctuations during the day. In addition, since this study was conducted, the Austin utility has added several new transmission mains between the Spicewood Springs Pump Station and the Martin Hill tank. These new mains have increased the capacity of the system so the Martin Hill tank can better dampen out pressure surges in the pressure zone.

A review of the pressure charts in the Northwest A pressure zone showing that the maximum pressure drops when one of the Spicewood Springs pumps is turned off is shown in Figure 8 for the Sierra and Mesa pressure transmitter. Some of the pressure change is caused by transients, and some of the change in head is caused by moving from one steady-state head to another. The data also show that the changes in flow at Spicewood Springs are now considerably smaller.

Although the hydraulic transient problem has greatly diminished and customers are generally satisfied with service, the fact remains that the normal operating pressure at the top of Cat Mountain is sometimes below the minimum pressure of 35 psi required by the Texas Health Department. To solve this problem, an engineering consultant is currently designing a small in-line booster pump station to significantly increase pressure during normal operation at the high points.

Summary

Most water system engineers and operators are familiar with hydraulic transients in terms of waterhammer events that can result in large positive pressures. Negative surges also can occur when pumps are shut off or valves are operated. As shown in this article, the magnitude of these surges can be significant and can result in low-pressure problems in a water distribution system.

Two keys to minimizing surges are (1) to close valves slowly and throttle pump discharge valves slowly when shutting off pumps and (2) to keep distribution storage tanks on line so they can help dampen out surges. Although Austin had good pump shutdown procedures, isolating tanks from the rest of the system allowed significant reductions in pressure to occur and persist. Changes in system operation have virtually eliminated these transient low-pressure problems. Other utilities that have short-term pressure problems may also want to consider the possibility that the problems are caused by hydraulic transients.

Acknowledgment

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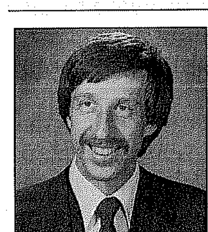

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Cost estimates for membrane filtration and conventional treatment

Membrane processes may offer small facilities a less expensive alternative for the removal of particles and organic materials.

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Costs of several ultrafiltration and nanofiltration processes are compared with the cost of conventional liquid–solid separation with and without GAC adsorption for small facilities. Data on raw-water quality, permeate flux, recovery, frequency of backflushing, and chemical dosage obtained from a pilot study were used with a previously developed model for membrane costs to calculate anticipated capital and operating costs for each instance. Data from the US Environmental Protection Agency were used to estimate conventional treatment costs. All of the membrane process calculations showed comparable or lower total costs per unit volume treated compared with conventional treatment for small facilities (<200,000 m³/d or about 5 mgd).

Membrane technologies have been proposed as a means of complying with current and anticipated regulations for particle removal and disinfection by-products (DBPs) in potable water. There is considerable interest in comparing the costs of emerging membrane technologies—microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF)—with costs for alternative potable water treatment processes.

The conditions of raw-water quality and treatment objectives that combine to make a given membrane process a cost-effective treatment option are poorly understood. The cost of membrane filtration is largely a function of the permeate flux.[1] Therefore, estimates of the cost of membrane technologies require accurate estimates of the permeation rate. A smaller membrane area, corresponding to fewer membrane modules, is required to produce a given design flow when