Transient and Surge Related Pipe Bursts, Water Loss and Damage Prevention

Brad Clarke, VP of Sales & Marketing for Singer Valve Inc

Abstract

Pipe bursts as a result of transients and surges within a piping network are very common problems throughout the world. Not only are the maintenance costs of these repairs extremely expensive, but when you add in possible litigation for third party damages, combined with the potentially **significant value (cost) of the lost water**, you can quickly realize the significance of what may appear simply as “another pipe burst”. It is common for water utilities that serve a typical population base of 1–1.5 million people to quote pipe burst occurrences between 500–1,000 incidents per year. Maintenance repair costs quoted at thousands of US dollars per incident are common.

Surges, or transients, are the result of a rapid change in liquid velocity within a pipeline. This stored energy – released as pressure – can destroy fittings, pipes, valves, instrumentation and pumps. The associated pressure waves travel the length of the pipeline (upstream or downstream), of the offending device (pump, valve, etc.) and then reverse direction. The waves move at a constant speed until they meet a boundary or barrier. The reflected and incident waves superimpose to produce a more complicated wave pattern that includes double-peaks and double-troughs. The consequence of inattention or improper protection from surges or transients could be a “pipe burst” or equipment failure and result in damage, water loss or litigation.

Transients, surges and the resulting pipe bursts can be caused by numerous events. Loss of power at a pump station, pump station PLC malfunction, single-speed pump motors without adequate pump control valves, or the rapid closure of gate valves or butterfly valves within the distribution system are a few of the more common causes.

There are a variety of mitigating solutions that can result in a significant decrease in the number and frequency of pipe bursts within a water utility’s distribution or transmission system. This paper focuses on several solutions and offers a brief explanation of the applications and intricacies of the associated equipment. An overview is also given of non-diaphragm operated control valve solutions, along with background information that includes the advantages and disadvantages of the different types of equipment.

Note: This paper does not deal with the analysis of transients or surges (other than a brief overview), as there are numerous experts in this field and substantial information and engineering expertise available.

Non-diaphragm Operated Control Valve Solutions

- Rupture Discs/Burst Discs
- Surge Tanks or Surge Drums

The core paper focuses on diaphragm operated pressure relief valve solutions and the resulting benefits. The paper removes the guesswork from the selection process and the variety of options.

Diaphragm Operated Pump Control Valve Solutions

- Pressure Relief Valves
- Anticipating Surge Relief Valves
- Surge Anticipating on Rate of Rise Relief Valves
- Surge Anticipating Relief Valves (electrically timed to low pressure reading or power failure at pumps)
- Electronic controls to respond to any out of limit signal

Diaphragm operated pump control valves are briefly included in this paper for situations where pumps operating with single-speed motors are utilized. Pumps that utilize modern VFD (variable frequency drive) motors do not typically require diaphragm operated pump control valves for normal service, but do require careful review and selection of appropriate pressure relief valve protection for power failure incidents.

This paper describes a variety of situations, while citing examples of transients/surges and the resulting damage. The above solutions are reviewed, while discussing the key advantages and disadvantages of each method of pressure relief, as well as key application information and examples of successful applications. This paper clearly presents a variety of pressure relief options for water utilities and educates interested parties on strategies for the overall reduction of pipe bursts and the resulting savings in water. The paper also refers to the associated costs/risks of failures.

Introduction to Transient Behavior

“Water hammer” is a term most of us are familiar with and is the name we often associate with transients. This term is given to the pressure fluctuations that can develop in a pipe when the flow of liquid is suddenly changed. The most common example of water hammer is when pipes in houses rattle when taps are suddenly closed.

The sudden closure of a valve at the end of a long pipeline causes an instant surge at the inlet of the valve. This high pressure expands the pipe and stores energy. This stored energy causes a positive pressure wave that travels upstream. The resulting pressure can be large and can put pipeline integrity at risk. Conversely, a sudden flow stoppage initiated at the upstream end, caused by a pump trip (e.g. power outage) for example, results in a negative pressure wave traveling downstream. The surge then returns as a high pressure wave.

Transients, surges and the resulting pipe bursts can be created through numerous events. Loss of power at a pump station, pump station PLC malfunction, single-speed pump motors without adequate pump control valves, or the rapid closure of gate valves or butterfly valves within the distribution system are a few of the more common causes of transients and surges.

Figure 1: Examples of damage caused by pipe bursts

Consequences of Transient Damage and Pipe Bursts

Transient damage and pipe bursts can be extremely costly and result in excessive water loss. A partial list of consequences could be:

- Inconvenience and interruption of service to customers (no water)
- Disruption of traffic due to road closures
- Water loss and associated costs
- Pump and manifold damage (maintenance and repair costs)
- Damaged pipes within the utility (maintenance and repair costs)
- Litigation from third parties


Figure 2: Service interruption


Figure 3: Road closures


Figure 5: Maintenance and repair costs


Figure 4: Pump and manifold damage

Transient Analyses, Formulas and Modeling

Engineering firms use two key formulas in the review of transients:

1. <u>Surge Formula:</u> (Joukowsky Equation)

$\Delta H = (A/G)\Delta V$
Where ΔH = Surge (feet/meters)
Where ΔV = Change in Velocity in Pipe (fps/mps)
Where G = Acceleration Due to Gravity – Constant 32 ft/s^2 or 9.1 m/s^2
Where A = Wave speed (consult pipe manufacturers for accurate data. i.e. DI Pipe = 4,000/fps or 1250/mps & PVC Pipe = 1,500/fps or 470/mps)

Note: Wave speed is a function of the pipe material.

2. <u>Critical Time Formula:</u>

Critical Time = 2L/A
Where L = Length of Pipe
Where A = Wave speed (see above)

The above formula calculates how long the resulting surge will take to return to the source (cause).

Without "in-house" expertise, it is always strongly recommended utilities retain a qualified engineering firm to provide a professional review of the system in question. A detailed analysis is required to track pressures subsequent to the initial wave interactions with the various boundary elements (reservoirs, pumps, valves, etc.) in the system. In some cases, these wave interactions and the behavior of boundary elements can result in unacceptably high pipe pressures.

The following hydraulic modeling examples were provided by Associated Engineering in Saskatoon, Canada. This project involved an existing water utility pump station and the associated piping network. The figures shown below are not intended to promote various techniques or equipment, as each transient model may have different results and suggest alternative solutions.

The modeling below allowed Associated Engineering to review the existing system during a power failure event. These examples include an existing undersized surge vessel, as well as other options, such as additional surge vessels or pilot operated diaphragm control valves with a surge anticipation function.

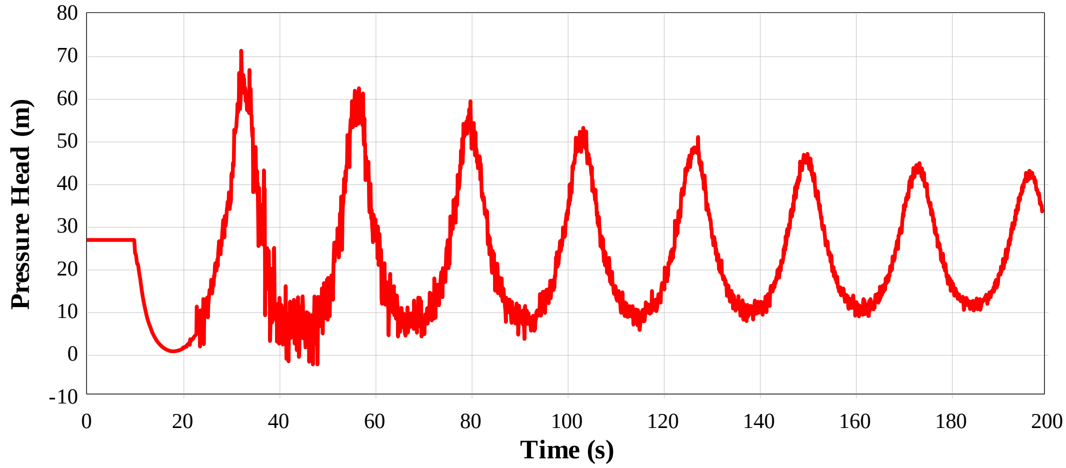


Figure 6: Predicted pump station pressure response for existing system with existing undersized surge tank

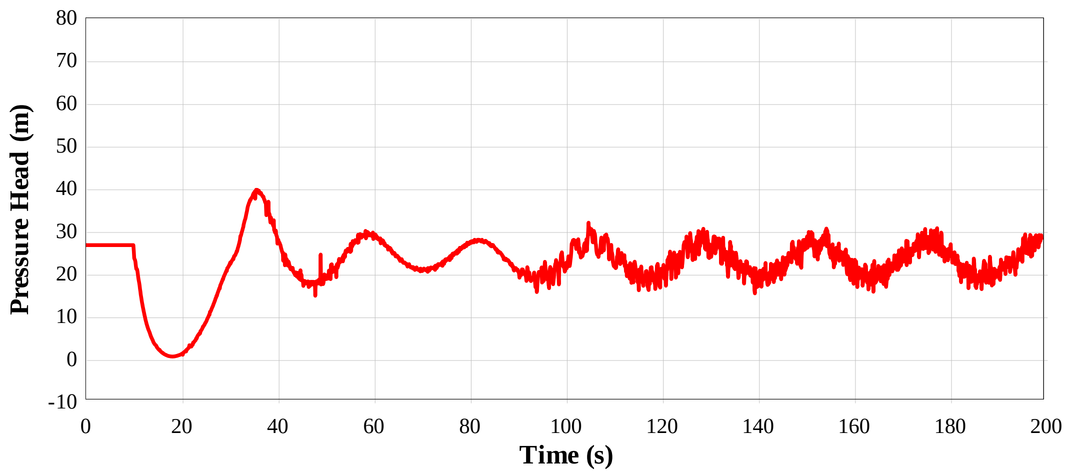


Figure 7: Predicted pump station pressure response with surge anticipating valves option

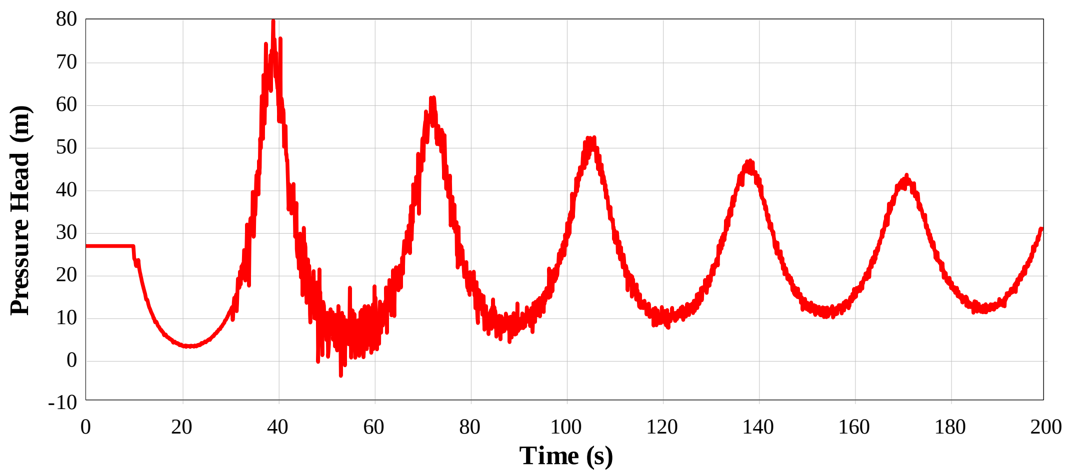


Figure 8: Predicted pump station pressure response with second air chamber option.

Changing Factors & Life of System

Julian Thornton and Alan Lambert have researched and analyzed pipe burst and pressure implications. It is well documented that pressure has a direct influence on water loss, leakage and pipe bursts. As pipes deteriorate through age (and possibly corrosion), and other local and seasonal factors, the "failure" pressure gradually reduces until burst frequency starts to significantly increase. The first step in pressure management (with the aim being a reduction in lost water) is to check for the presence of surges or variations and, if they exist, reduce the range and frequency of both.

The following charts (as supplied by Lambert and Thornton) clearly demonstrate that reducing surges is the first step in a sound pressure management program.

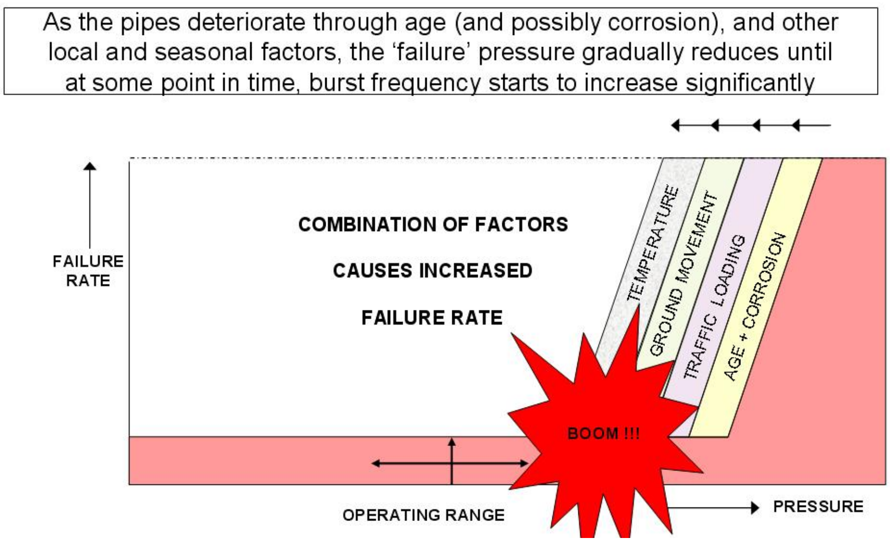


Figure 9: Pressure and Pipe Failure

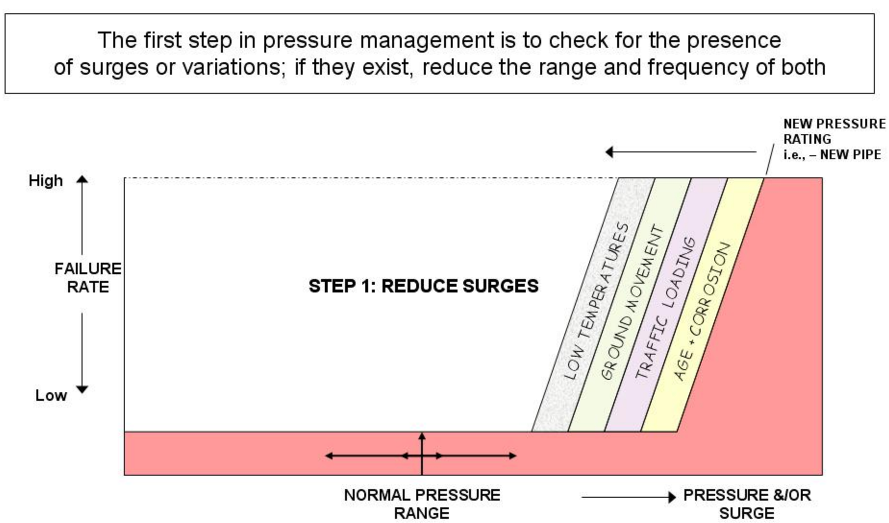


Figure 10: Reduce Surges and Variations

Transient Solution Overview

Figure 11: Example of a pressure transient logger

Numerous devices can be used to mitigate transient pressures. However, without *analysis*, there cannot be a *design*.

The first step is to determine if there is a potential problem of surges in a pipe system that will exceed the pressure limitation. This can be accomplished by numerous means, including the use of a variety of available transient modeling software. If transient problems exist, specifically designed transient data loggers can detect peaks and troughs by logging data in minute timeframes (one second intervals, if required).

Numerous devices can be considered for mitigation of surges. These solutions can also be used in combination. They are not listed in any particular order of effectiveness or cost (see below). Each solution is specific to the system being analyzed in detail by an engineer who is fully qualified in this discipline.

Solutions can be modeled in modern software and will have varying degrees of success in avoiding catastrophic or repetitive damage type scenarios. Some solutions depend on pneumatic, hydraulic, electrical power, or fluids being available to ensure their effectiveness. No solution should be integrated without a detailed analysis of the particular system.

All devices used to mitigate transient surge pressures or vacuum need to be maintained. The devices should be given the same level of attention as safety relief valves. If the surge mitigation device does not perform when required, surge pressure events will occur. The devices and mitigation processes should be fully documented, routinely tested and properly labeled. Examples of devices and strategies are as follows:

- Stronger pipe work to withstand pressure surges
- Reroute piping
- Additional pipe supports
- Change of pipe material to one with a lower modulus (i.e. thermoplastic pipe materials)
- Flow control valves
- Air/vacuum release valves
- Intermediate check valves
- Non-slam check valves
- Bypass valves
- Gas accumulators
- Liquid accumulators
- Surge tanks
- Surge shafts
- Surge anticipation valves
- Relief valves
- Bursting discs
- Increase diameter of pipeline to reduce average velocity
- Variable speed drives
- Soft starters
- Valve closure and opening times

• Increased inertia of pumps and motors (i.e. flywheels or by selection)
• Minimize resonance hazards with additional supports
• Investment in additional engineering

Non-Diaphragm Operated Control Valve Solutions

Rupture Discs/Burst Discs

Rupture discs/burst discs are made from numerous materials; however, graphite and stainless steel sheet are the most common materials. Rupture discs are designed to fail (break or shatter) at a predetermined pressure and are very effective at managing overpressures or transients. Rupture discs are commonly located off a tee and have some form or isolation valve upstream of the tee. An isolation valve is typically manually closed when failure occurs, allowing replacement of the rupture disc. A rupture disc is retained between two flanges and, when it does fail, it normally discharges the water to atmosphere. It is critical that the discharge at time of failure is anticipated and the system is designed for the eventuality. When the rupture disc fails, water is discharged from the ruptured disc.

Figure 12: Examples of rupture discs

Surge Tanks/Surge Drums

Surge tanks, or surge vessels, are typically constructed from steel and are partially filled with air (the balance being water). Normally, the tank is filled with 50% air and 50% water at operating pressure. The air pressure is supplied by an air compressor and associated controls. Water is allowed to freely flow out of the tank to prevent column separation. When the transient returns up the pipeline, the surge tank acts like a relief valve to prevent overpressure. Sizing of flow into the tank is critical and must be accurately controlled and is based on transient modeling.

Often, a properly sized orifice plate is the best solution for the return flow into the surge tank. A surge tank or vessel is a viable solution for the control of transients or surges. However, a few areas of concern must be considered. The space required for a surge tank can be significant, as surge vessels can be very large, unsightly and expensive. Maintenance of surge tanks is also critical, as surge tanks can become waterlogged if they are not properly serviced. For example, if the air compressor and associated air system are not maintained, the tanks can fill with water, rendering them ineffective to counter transients in the system. Other concerns occur in extreme climates that are prone to freezing. In these cases, surge tanks should be located indoors to prevent freezing, which can be cost prohibitive. Theft of air compressors associated with surge tanks and required security are other factors to consider.

Figure 13: An example of an installed surge tank located indoors

Diaphragm Operated Control Valve Solutions

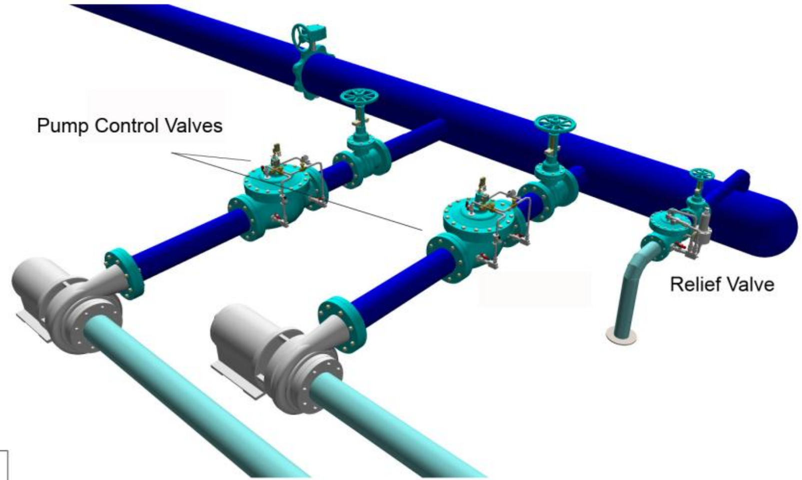
Pressure Relief Valves

A diaphragm style, pilot operated pressure relief valve responds only to a high pressure wave. If the standard operating pressure is 105psi (7bar), you can choose to set the relief pressure on the pilot slightly higher: for example, at 115psi (7.5bar). If an overpressure occurs (fast closing valves, etc.), the relief valve quickly opens and discharges water to atmosphere and reduces the overpressure. When the pressure has stabilized, the pressure relief valve closes and normal operation of the system resumes.

The selection and sizing of pressure relief valves are very important. Generally, a pressure relief valve should be sized for one quarter (25%) of forward flow. This guideline requires a detailed analysis by a transient specialist who looks at all factors before making a final, informed selection. The pressure relief valve is normally mounted off a tee on the header discharging to atmosphere.

A relief valve with an intermittent flow capacity of 25% of the maximum flow in the main pipeline is a good initial selection. If larger valves are needed, surge anticipating or “rate of rise” valves are often a better choice. Pressure relief valves do not have to be limited to pump stations and can be strategically located anywhere in the distribution system to deal with overpressures and transients.

It is also important to consider the discharge that is released from the relief valves when they react to the overpressure. The discharge can often be chlorinated water that poses dire consequences for fish bearing streams, landscaping, etc. A well-considered approach to the proper management of the discharged relief water is always required.



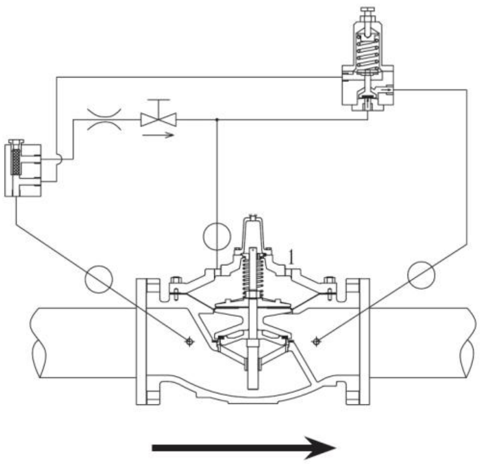
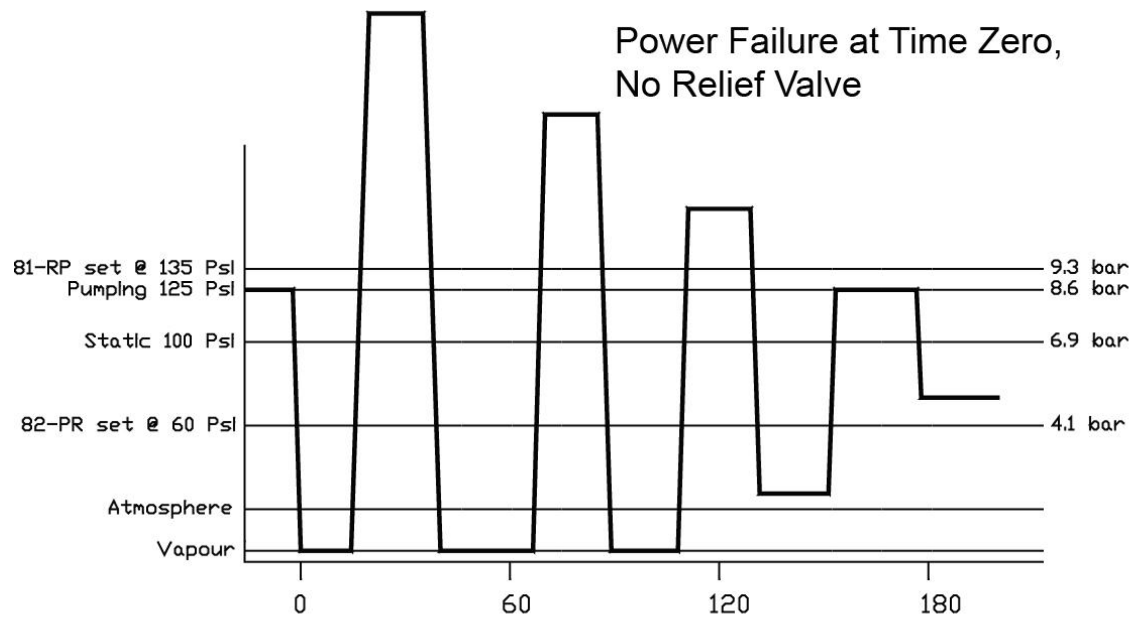


Figure 14: Examples of pressure relief valves, installations and applications

Surge Anticipating Relief Valves

Standard relief valves only start to open when the system pressure exceeds the pilot setting. Should the surge increase rapidly, standard relief valves may not have time to open and will then be ineffective.

Surge anticipating relief valves react to the period of low pressure after a power failure. A second pilot opens the valve whenever the system pressure falls below its set point. How low the second pilot is set should be carefully considered, but it should always be set lower than static less full flow friction. By sensing the dip in pressure, the surge anticipating relief valve has time to be at least partially open when the wave returns, thereby reducing the overpressure. The stable pressure after operation must exceed the pilot setting to ensure the valve closes and does not drain the entire pipeline. Correct sizing of the surge anticipating relief valve is very important and oversizing the surge anticipating relief valve can be a common mistake. Consulting with the valve manufacturer, or working with a knowledgeable surge consultant, is always recommended.



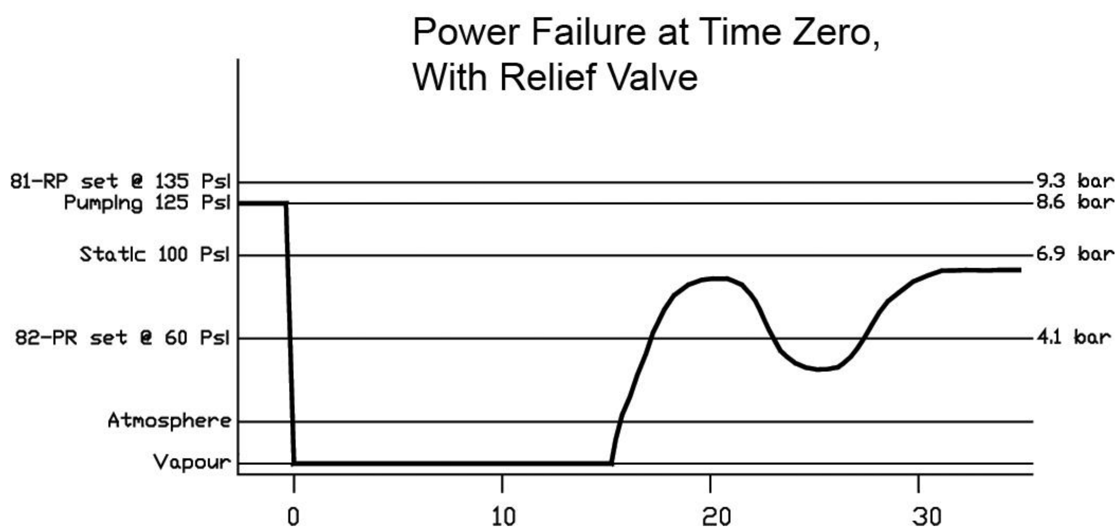
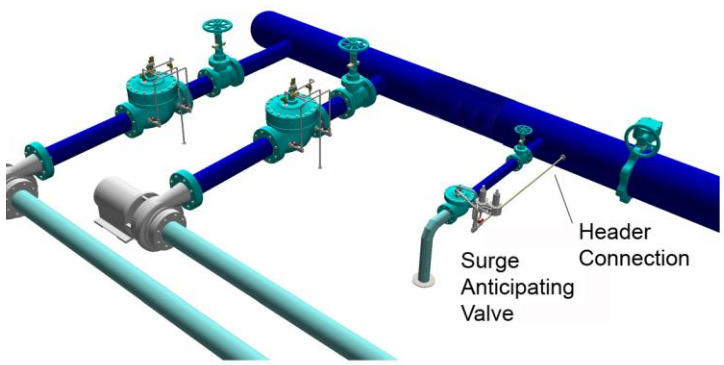


Figure 15: Graph depicting effectiveness of surge anticipating relief valves

Surge anticipating relief valves need significant static pressure to operate properly. A minimum of 100ft (30m) is typical.

Sizing concerns for surge anticipating relief valves are similar to pressure relief valves. Selection and sizing are usually based on one quarter of forward flow. This should be verified by a transient specialist and surge anticipating relief valves must be sized correctly.

Surge anticipating relief valves are often a good selection when design criteria calls for valves 6" (150mm) or larger. This style of valve is often found on larger distribution and trunk mains. One of the most common problems with surge anticipating relief valves is when they are oversized and do not recover or close when the transient is completed. This is caused by friction from high flow returning due to the static head and insufficient header pressure. Bigger is not necessarily better when it comes to surge anticipating relief valves. It is also very important that the sensing line (copper or stainless steel tubing) is routed directly from the header and not from the valve. This ensures accurate header sensing. Surge anticipating relief valves act as an insurance policy by allowing the valve to start opening before a peak on the transient returns. Surge anticipating relief valves can be easily tested and their operation can be replicated in a static condition in the field. This style of valve is very common and reliable.



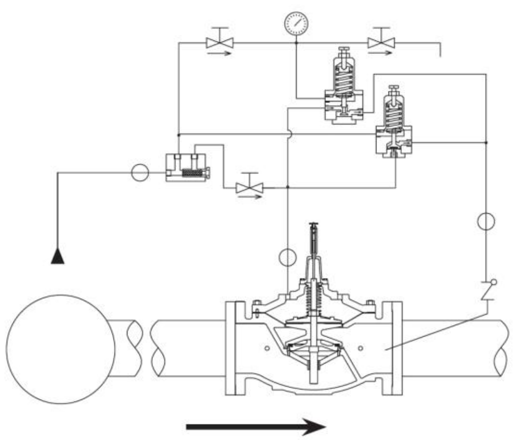


Figure 16: Examples of surge anticipating relief valves, installations and applications

<u>Typical Surge Anticipating Relief Valves Application Case Study – Malaysia</u>

Anticipating Surge Relief Valve: Size 300mm. The valve is installed in Kelinchi Water Pumping Station in Negeri Sembilan, Malaysia. The main header pipeline diameter is 900mm.

Problem:

This pumping station had an unexpected power supply failure, which caused catastrophic damage to the pipeline. Some of the pipeline ruptured as a result of the sudden rise in pressure, causing the entire pump station to be closed down due to flooding. Since the pumps, valves and fittings were all underwater, the water utility had to engage divers to locate and isolate the supply pressure from the suction. After accomplishing this, the water was drawn out of the station, and the crew managed to restore the pumps. After this incident, the water utility took extra measures to ensure that the problem would not reoccur.

Objective:

The water utility studied proposals from consultant firms that examined the surge that was produced by the pumping station when there was an abrupt disruption in the power supply. In the report, the consultants recommended installing a large surge vessel to minimize the effects of a water hammer during power failures. The space required to install a surge vessel was great, and the cost was prohibitive. The utility wanted to know if a surge anticipating relief valve could offer an alternative solution for the system.

Solution:

This water utility had many installations of pilot operated control valves within the network. This included PRV, altitude valves, modulating float valves and surge anticipating relief valves. Some of the reasons for the successful installation of the surge anticipating relief valves are due to the simplicity of the operation, minimal space and, most important, the valve is purely mechanical (without electrical requirements). Based on the effectiveness of the past installations of surge anticipating relief valves within the network, the utility decided to employ a surge anticipating solution.

Conclusion:

Since the installation of the surge anticipating relief valve in June 2005, there have been several power failures in the pipeline. With the presence of the surge anticipating relief valve in the system, the utility has managed to avoid the problems that occurred prior to June 2005.

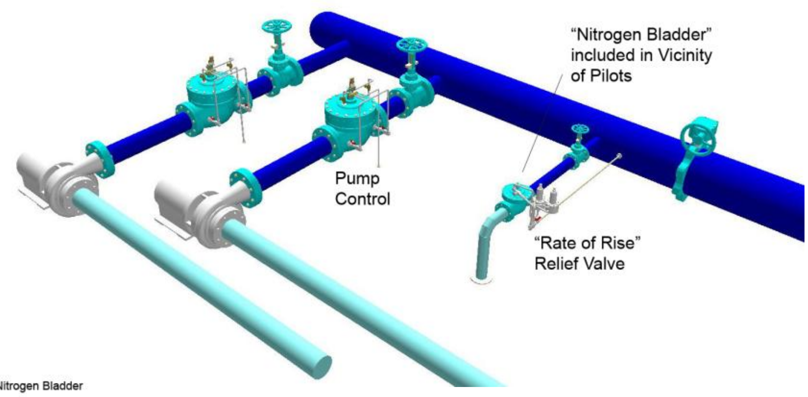
Figure 17: Malaysian surge anticipating relief valve installation

Rate of Rise Relief Valve

Rate of rise relief valves add another safety feature to standard relief valves. The valves open when they detect a sudden change in pressure. On power failure, and after the low pressure interval, the returning wave starts building pressure. The rate of rise pilot senses this and immediately opens. The main valve may be partially open even before the system reaches its normal operating pressure, effectively reducing overpressure to an acceptable level. This valve model is very attractive, as it has positive pressure to force it open and closed. It removes the risk of failure to close, should the pressure not recover.

Rate of rise relief valves are similar to surge anticipating relief valves. The major difference is that downstream static pressure is not required for this valve to operate effectively, so downstream elevation is not required. The other major advantage of this type of valve is that sizing is not critical. If the valve is oversized, it will recover and close on conclusion of the transient. It is still recommended that the valve be sized for one quarter of forward flow. However, if oversized, the valve will still function as required. The rate of rise relief valve starts opening immediately when pressure begins to rapidly rise. This valve utilizes a nitrogen bladder that allows very accurate sensing of pressure rise. This is an excellent selection if the local topography has minimal static pressure available, or if oversized valves may be specified knowingly or unknowingly. Again, it is always recommended to get a transient specialist to assist in valve sizing, location and selection.

"Rate of Rise" Relief Valve



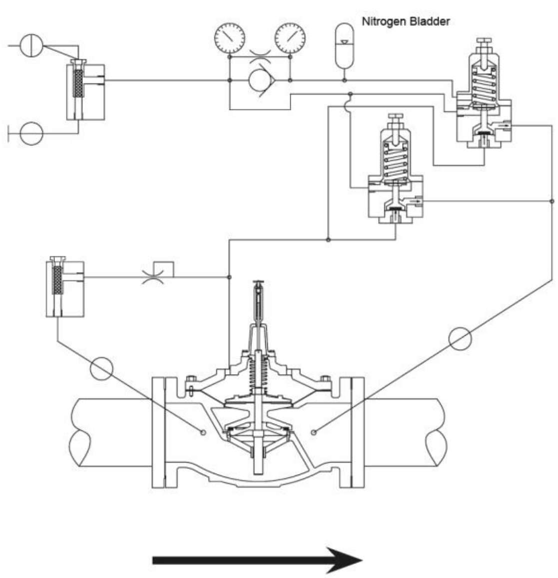
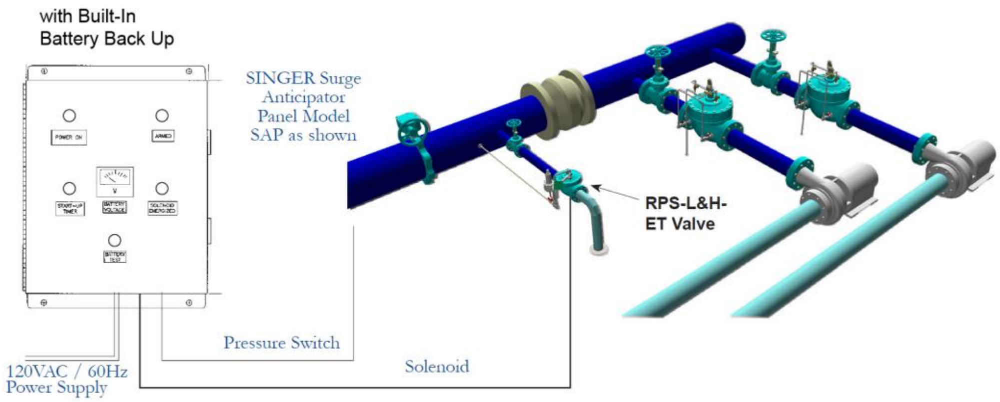


Figure 18: Examples of rate of rise relief valves, installations and applications

Surge Anticipating Relief Valve (electrically timed closure after power failure at pumps)

This valve is similar to the surge anticipating relief valve, with the exception that the low pressure pilot is replaced with a solenoid valve. All other sizing protocol and design criteria remain the same. No static pressure is required, because the valve closes on a timer. The valve opens on either power loss, or by way of the high pressure pilot. If power loss is the major concern, then this style of valve can be an excellent selection. Timing for the solenoid to close is normally coordinated with the critical period – the time it takes for the surge return. Always consult with a transient specialist for sizing and selection concerns.



SAV–ET (Surge Anticipating Valve Electrically Timed)

SAV–ET (Surge Anticipating Valve Electrically *Surge Anticipating Panel*

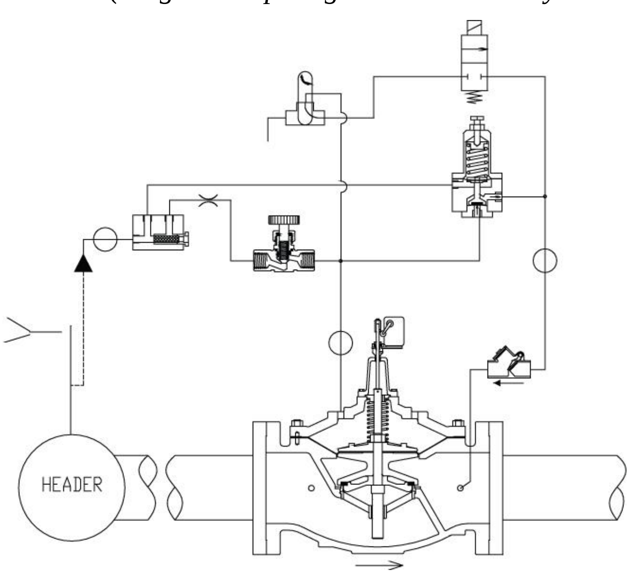


Figure 19: Examples of surge anticipating relief valves (electric), installations and applications

Electronic Control to Respond to Any Out of Limit Signal

Any diaphragm operated control valve can be designed to respond to any out of limit signal. A battery and timing device are required. These valves can respond to flow or pressure transmitters utilizing 4–20 mA signals or switches (either ON or OFF). There are numerous variations depending on the application.

Pump Control Valve Solution Overview

While virtually all pump stations require some form of surge/transient protection, pump stations may also require some form of diaphragm operated control valves for actual pump control at start up and shut down. When pump stations utilize variable frequency drives (VFD), then this technology adequately controls flows and pressures at pump start up and shut down. If the pumps in question are operated by single-speed motors, careful analysis should be made, as the resulting transients at start up and shut down can be catastrophic, or the piping system may be unnecessarily stressed, resulting in pipe bursts.

Booster Pump (Inline) Control

Booster pump control (BPC) valves are located in line, downstream of the pump. When started, the pumps turn on against a closed valve. The solenoid is then energized, opening the BPC. At pump shut down, the solenoid valve is de-energized by the system control to put the valve into closing mode. There is an electronic limit switch located on the stem of the BPC, so when the valve is almost fully closed, a signal goes back to the pump control panel (or relays) to shut the pump down. The opening and closing speeds are adjustable. This is a very efficient way to manage pump control and do not require any static pressure in the piping system downstream. When sizing BPC valves, consultants often prefer to oversize the valves to minimize pressure loss through the valves. The dilemma is that when selecting pumps, efficiency is always a concern in the design. When a BPC valve is utilized, if sized too small, pressure loss or lack of efficiency may be of concern.

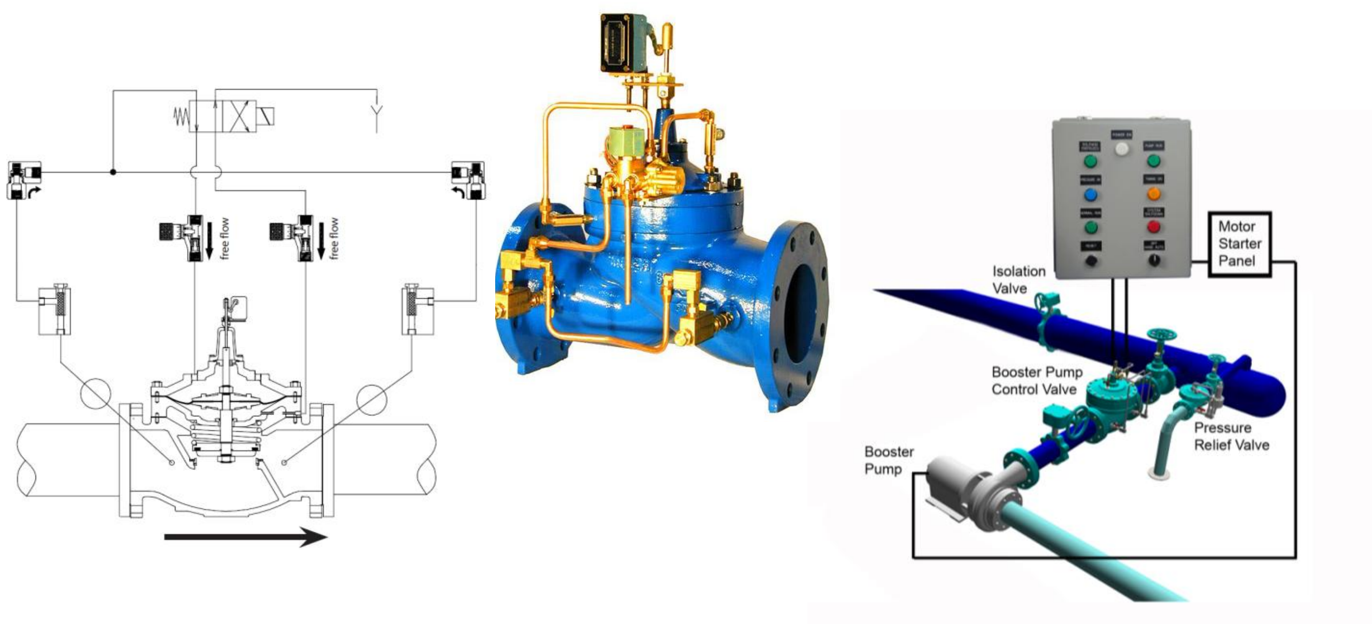


Figure 20: Examples of booster pump inline control valves, installations and applications

Deep Well (By Pass) Pump Control

If site conditions permit, deep well (DW) pump control valve solutions can be a very economical practical solution to pump control. This type of valve requires some static pressure downstream to work effectively. Elevations are the best method to ensure the static condition, which should be a minimum of 100ft (30m). This static pressure applies pressure to an inline check valve until pump pressure overcomes this check valve and allows flow into the distribution pipe.

When the pump starts, it starts against a fully open DW valve. This valve is located off a tee and discharges to atmosphere (back to sump). Again, a pump control panel, or series of relays, are required. When the pump starts, a signal is sent to the solenoid on the DW valve, which starts the closing process of the DW valve. The speed of closure can be selected by adjustments to the manual needle valve (slow is the goal). As the pressure builds in the manifold, it eventually overcomes the static pressure holding the check valve closed and water commences flowing to the system. At pump shut down, the solenoid on the DW valve is de-energized, which causes the DW valve to start opening. The opening speed can be manually adjusted using the needle valves.

When the valve is almost fully open, a limit switch (mounted on the stem of the DW valve) sends a signal to the pump control panel to shut the pump down. If site conditions are correct, this can be a very efficient way of managing pump control for single-speed motors for the following reasons:

- The DW valve selected is always smaller than the header size, so it is very economical.
- When the DW valve is fully closed, there is no flow through the valve; This is a great method with respect to pump efficiency, as there is no pressure loss through the DW valve.
- When a deep well pump starts, initially you can have sand, air and other components that would be pumped into the header and piping system. As the DW valve closes at start up, these components are dumped back to sump and are not discharged into the piping system.

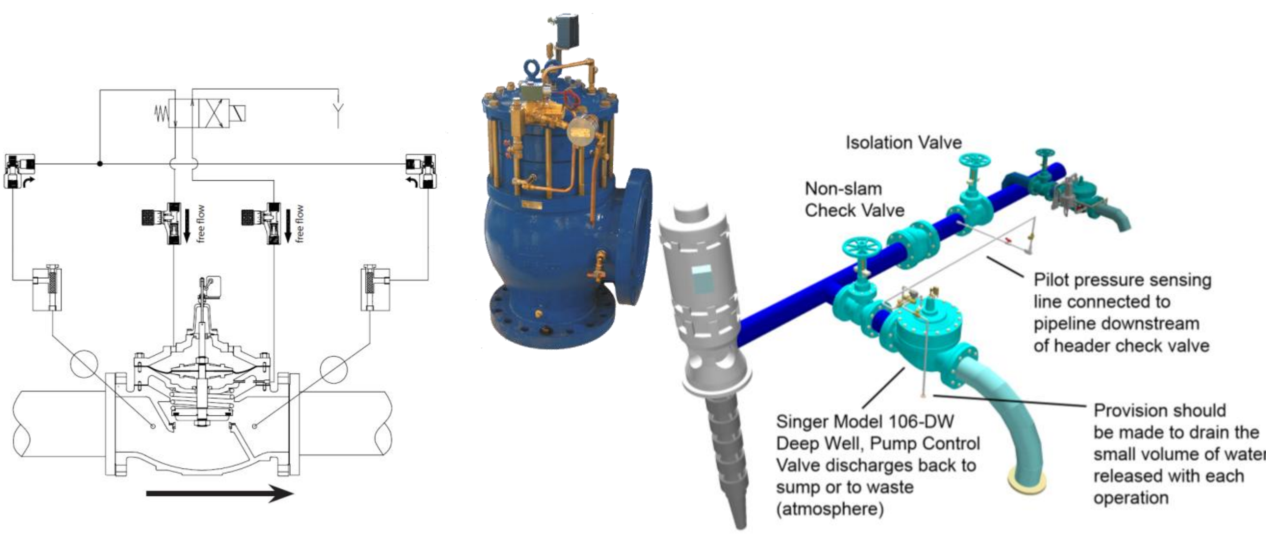


Figure 21: Examples of deep well pump control valves, installations and applications

Conclusion

Transients and surges are a worldwide problem with enormous consequences. Water loss, litigation, disruption of service and maintenance costs are only a few of the resulting issues. Transient analysis experts are employed by engineering firms around the world, and it is always advisable to consult an expert who can review specific modeling and make informed product selection and decisions. There are many factors to consider when designing water utility distribution systems to ensure good design. There should always be some form of surge or transient protection at every pump station. Diaphragm operated control valves are often a cost effective and practical solution when combined with other sound design practices. Should surge or transient protection be overlooked, resulting loss of power can have devastating effects.

If pumps are utilized in a system (and they are VFD designs), pump control valves are usually not required. If single-speed motors are used on pumps, some form of diaphragm pump control should always be used. Depending on site conditions, booster pump control valves or deep well control valves can be excellent choices. Every pump station requires some form of pressure or transient relief to protect the investment of the pump station and distribution system.

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