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Monitoring for Transient Pressures in Pipelines

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Abstract

A change in the flow rate in a full pipeline will cause a change in the pressure within that pipeline. These changes are given careful attention in the well-designed pipeline; however, in the past it has been difficult to accurately measure these transient pressures after the pipeline is constructed and placed in service. Transient pressures exceeding the structural strength of the pipeline will cause damage in the form of rupture or, as is more frequently the case, in the form of latent damage that results in failure at a later date. Advances in digital data processing systems have significantly improved our ability to continuously monitor and record even the very-short waterhammer event. These improvements have facilitated monitoring for transient pressures under a wide variety of circumstances. Early detection of damaging transient pressure events is now more practicable, thus permitting the reduction of damage to pipelines resulting from these events.

Introduction

Pipeline failures are occasionally traced directly to the occurrence of transient pressures that have caused damage. Among the more familiar ruptures in this category are the failures in Dallas, TX; San Juan, Puerto Rico; Metropolitan Water District of Southern California; Houston, TX, Oigawa Penstock, Japan; and Bartlett Dam, AZ. The last mentioned caused catastrophic rupture at the outlet of the hydro generator, with fatal injuries to the operator. Countless other failures are believed to have resulted from transient pressures, but the evidence is not conclusive. In many cases the transient pressure events occurred repeatedly without detection prior to the failure. This paper will briefly describe the causes of transient pressures and improvements in tools available to detect transient pressures. It will conclude with suggestions to civil engineers and pipeline owners regarding what we can do to reduce damages from transient pressures.

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Figure 1 – Transient-caused failure, Superaqueduct of Puerto Rico

A transient pressure in a pipeline is a generic term for a wave phenomenon that accompanies a sudden change of the velocity of the fluid in the pipeline. Authors variously use the term "surge" pressure to denote a transient pressure that has no detrimental effect, whereas the term "waterhammer" may be used to denote a transient pressure that will have serious consequences if not properly addressed and mitigated. Pressure transients can be positive or negative. The magnitude of these surges is independent of the operating pressure, and can be many times normal operating pressure.

Any event that causes a sudden change in the velocity of fluid in a pipeline will generate a transient pressure. The most common sources of transient pressures are

- Pump operation
- Pump power failure
- Control valve operation
- Sudden changes in demand
- Air release valve operation
- Pressure reducing valve operation
- Pipeline rupture
- Filter flushing operations

Most transient pressures are repetitive and predictable. Examples include opening and closing an in-line valve, starting and stopping a pump, and operation of an air relief valve. Because these transients are predictable, they are readily accommodated in the pipeline design. A variety of methods are available to mitigate transient pressures, generally falling into three categories – alteration of pipeline profile and diameter, valve and pump control procedures, and surge control devices. For instance, a main-line butterfly valve may be designed to close over a period of minutes to minimize the transient. Pump motors are designed to start against a closed valve, and that valve is gradually opened to minimize the transient pressure. Combination air valves are included in the pipeline design to discharge accumulated air pockets and to minimize the effects of negative pressures. Care is taken in the selection of the proper orifice size for air valves, to avoid the damaging "air slam" that may result from an improperly designed air valve, causing a transient pressure as much as 500 times the pressure before the slam. Often the most severe transient will be the sudden power outage in a pumped pipeline system, which will cause the abrupt cessation of flow in the pipeline and a large transient pressure. When this scenario results in cavitation within the pipeline, true waterhammer events may be generated that are very brief but very damaging.

Hydraulic engineers have long understood the transient pressure phenomena and surge wave theory, and the pipeline designer will accommodate these events in the design. Great strides in hydraulic modeling have significantly facilitated the analysis of complex pipeline systems and the propagation of transients.

Some transient pressures are the result of an abnormal and unpredicted condition, and they are not so readily accommodated in the pipeline design. These transients may also be more difficult to detect and measure. Several examples from case studies include improper installation of valve actuators during construction, improper placement of combination air valves, installation of unstable pressure relief valves, and the installation of unanticipated water diversion flows by pipeline customers.

Figure 2 –Surge Event Physical Model, Advantica

Some transients are cyclic in nature, for example those caused by unstable pressure reducing valves, unsuitable pressure-relief valves, and reciprocating pumps. These transients may cause fatigue damage and should be eliminated or reduced to non-damaging pressure changes. Figure 3 is a pressure reduction valve that proved to be unstable at certain flows. It is imperative that these pressures be measured to assure design pressures are not exceeded.

Figure 3 – Pressure Reduction Valve

So a strong case can be made for monitoring pressures carefully – whether it is on a continuous basis, or in response to some particular need. Even the most rigorously modeled pipeline would warrant carefully monitoring of pressures immediately after construction – if for no other reason than to confirm that it was built according to the designer's intent.

Traditional Pressure Measurement Methods

The most traditional method of method of measuring and recording transient pressures is a dial gage and a notebook.

Figure 4 – Typical pressure gauge with no negative pressure capability

Mechanical pen-and-chart recorders have been in use for decades, and offer a good solution to many pressure-recording needs. They are relatively inexpensive, easy to use and continuously monitor all pressures. The disadvantages of the mechanical recorders are that they need to be manually reviewed and the charts need to be changed every day or every few days, are not typically designed for negative pressures, and they are not capable of providing detailed information on the duration of a transient since the width of the line drawn by the pen may cover up to 60 seconds of time.

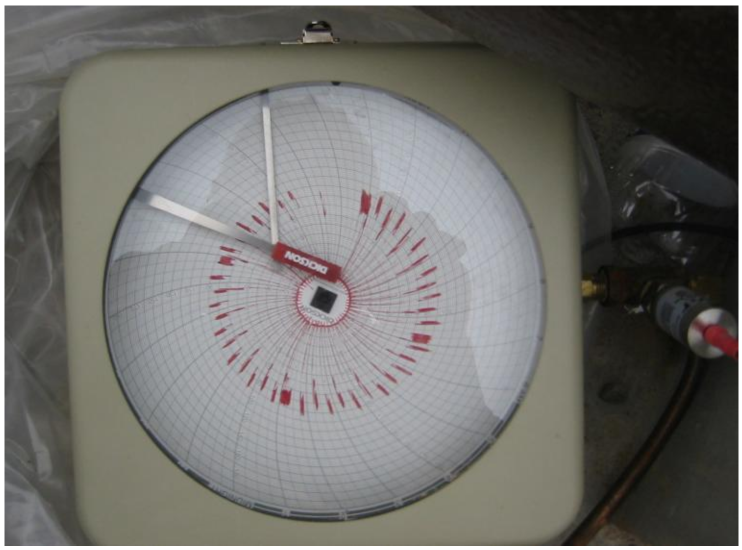

Figure 5 – Circular graph recorder, with no negative pressure capability

Several portable high-speed electronic data loggers are available. These do record negative pressures, and if set to record frequently enough can record the details of a specific surge event over a period of seconds to minutes. So if you know when the transient will occur and can set the data-recording rate accordingly, and can upload the data from storage immediately after the event, these devices may fulfill the need. Data recording intervals of 0.05 seconds (20 Hz) are available.

Figure 6 – Digital data logger for pressure measurement

On the other hand, if there is a need to monitor over longer periods of time, the data interval will have to be set at a longer interval to stay within the memory capacity of the device. An interval of once per minute might be selected, which would provide 1440 pressure readings per day. Surely this would convince a pipeline owner that the pressure is rigorously and carefully monitored. But is this sufficient? Not necessarily, because many of the most damaging transients may last only a fraction of a second, and would not be detected at all. It has been difficult to detect and measure an unexpected transient that may last a fraction of a second, and that may be 100 times the operating pressure or more. Not only are these events difficult to detect, they may be the most damaging of all and may go unnoticed for long periods of time. Mathematicians will recognize this as the Nyquist principle.

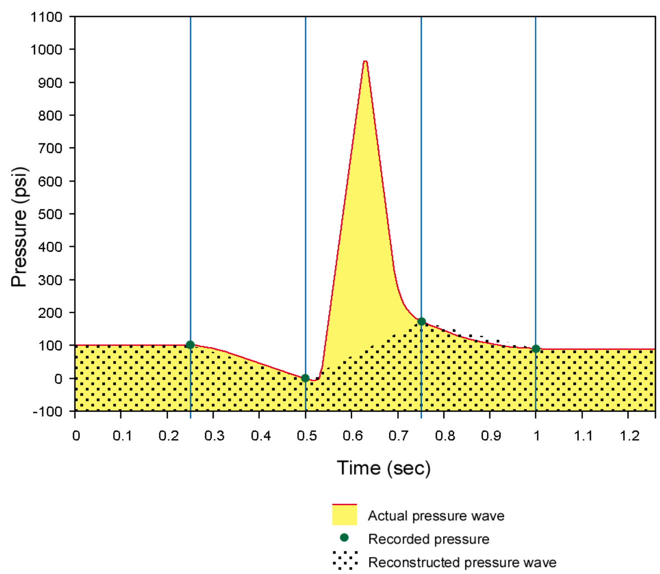

Figure 7 – Digital data collection with insufficient sample rate

A New Method of Pressure Measurement

Within the last year, a system has been devised that overcomes several of the limitations of previous systems. It is capable of monitoring over extended period of time in a "snoozing" mode, recording background pressure at a user-set interval between once per second and once per day. Although the system appears to be snoozing, in reality it is very busy. It continuously samples the pressure 1000 times per second and computes a running average. Effectively the system algorithm has a built-in alarm clock that goes off when a pressure is detected that differs significantly from the average – in other words when a transient is detected. When this occurs, the system "wakes up" and records all data at another user-set rate up to 100 Hz. This continues until the transient has passed, at which time the system goes back to the "snoozing" mode. The scheme is shown graphically in the figure below.

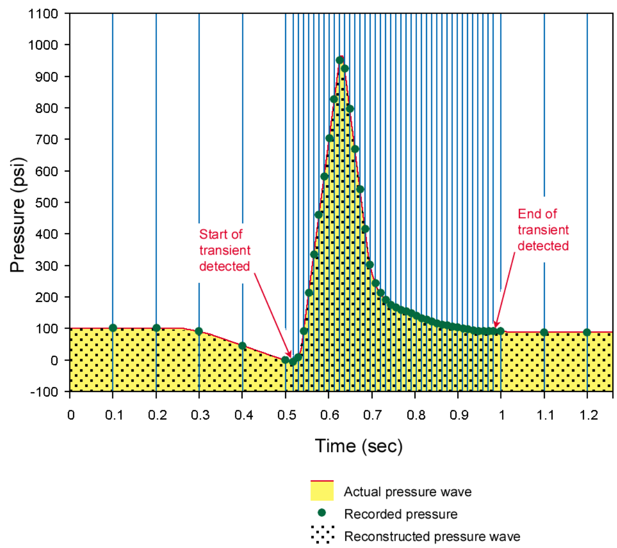

Figure 8 – The TP1 Transient Pressure Monitoring System algorithm

The so-called TP-1 Transient Pressure Monitoring System is comprised of the following components:

Personal Digital Assistant (PDA)	A Pocket PC PDA is the primary device for the user interaction. A laptop with a WiFi card can also be used. (Any desktop or laptop on a wired LAN can also be used, if the Controller is connected to the LAN.)
TP1 Controller	The Controller processes all of the input signals, and performs all of the logic in the system. It also stores all of the historical data until it is retrieved using the PDA.
Communications	WiFi is the primary communications mechanism. (A wired LAN can also be used.)
Sensors	Depending on the operating mode, 1 or 2 pressure sensors are used to measure the pressure in the pipe.
Data Analysis Programs	PC programs that retrieve the stored data files from the PDA, and convert and display the data. The data is also stored in a database for analysis by other programs.

Figure 9 – TP1 Transient Pressure Monitoring System components

The TP-1 has been under development for nearly 2 years, undergoing extensive bench testing and modification. One of the early examples of data recorded with the TP-1 include the acceptance testing of a new Wastewater Treatment by the City of Glendale, AZ. They had experienced the rupture of several 8” (20.3 cm) ductile iron pipes in the course of testing, and had attempted to diagnose the problem with a chart recorder. The test data from the chart was not very revealing.

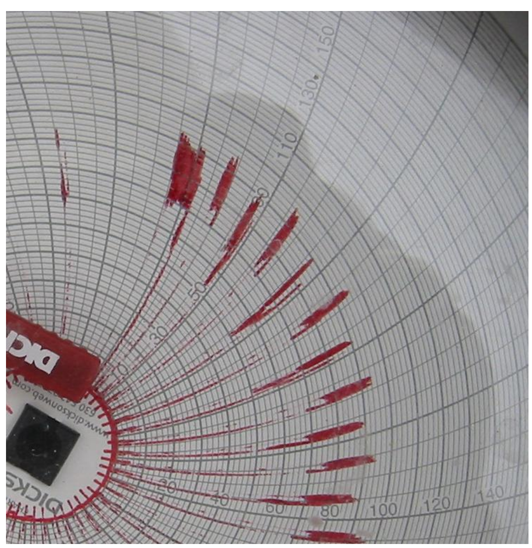

Figure 10 – Circular graph of sewage lift station discharge pressure

They asked to install my demonstration model of the TP-1 to see if it could detect the transients at the discharge line of the lift pump station.

Figure 11 – TP1 installed at sewage lift station

The results were such that when the City Engineer visited during the TP1 demonstration, his remark was “Will, I’m sorry, but I will not let you remove that system from City property. Send me a bill.”

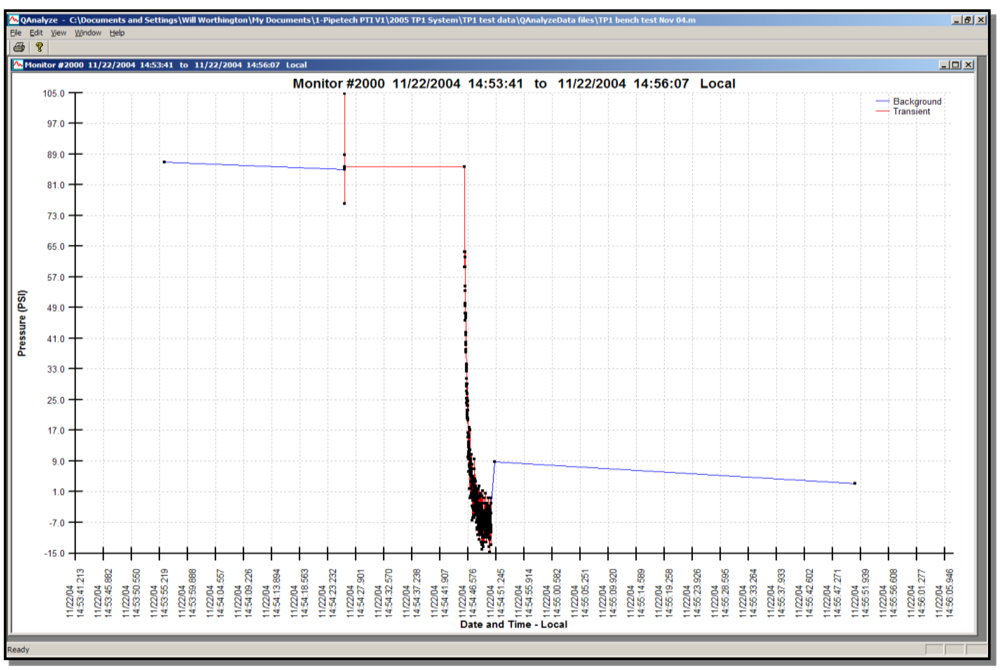

Figure 12 – TP1 graphic depiction of the lift station pump shutdown sequence pressure (Note negative pressures to -14.5 psi)

The data collected at the sewage lift station showed negative pressures approaching the cavitation range during the pump shutdown sequence. The system allowed the careful evaluation of surge reduction measures, and continues to monitor the dynamic pressures at this $30 million facility during its early months of operation as this is written.

Reducing Transient Pressure Damage

So, what can we do with this new technology? I suggest this technology opens the door to several testing programs that would benefit owners and engineers alike. And for the sake of discussion, I share the following observations and ideas:

<u>Who</u> should require the testing? The transient pressure monitoring system is not difficult to learn to use. The system is available for lease or purchase from the developer. An hour of demonstration and a few hours getting familiar with the operation manual will be sufficient for an operator to learn to conduct valid tests. Whoever performs the testing should be familiar with the transients that might be expected in the pipeline, as there are several user-set parameters that will need to be tailored to the pipeline system. These parties might have a vested interest in having the test performed, and require the test

- The owner of the pipeline system
- The ENGINEER or hydraulic designer
- The contractor who constructs a new pipeline
- A manufacturer of critical components of pipelines, such as manufacturers of the pipe itself, control valves, valve actuators, and pressure tanks

The testing could be done by any of the above parties, or it could be a third-party engineering firm. The advantage of third-party testing is gaining popularity in construction contracts because of the independent, unbiased nature of the test results.

<u>What</u> testing should be done? The testing should be of sufficient detail to permit the detection and recording of the shortest duration and highest pressures that are reasonably characteristic of the pipeline system.

- For an acceptance test of a new facility constructed in a design-bid-build delivery system, I suggest a clause in the construction specification that might read, in so many words:
    - *Hydrodynamic Pressure monitoring - The CONTRACTOR shall engage the services of a THIRD-PARTY ENGINEERING FIRM to conduct pressure monitoring of the pipeline at the points designated below. The pressure monitoring shall be continuous during the initial filling of the pipeline, and throughout the acceptance test, and for period of 30 days following substantial completion of the project. Pressure shall be recorded not less*

frequently than once every minute throughout this period, except that any transient pressures shall be recorded not less than 50 times per second. A transient shall be defined as any sudden departure of more than 10 psi from the running 5-second average pressure. The THIRD-PARTY ENGINEERING FIRM shall submit interim reports following initial filling, and following the simulated power failure of the XYZ pumping plant; and a final report of all recorded pressures in graphic and tabular form. The graphic presentation shall depict a separate graph for each recorded transient in sufficient detail to observe each data point. The report shall compare the recorded pressures to the design pressures specified by the ENGINEER. The final report shall include calibration curves for the pressure transducers used in the test before the initiation of testing and upon completion of testing, and a certification that the equipment used is capable of meeting the requirements of this paragraph, and shall be sealed by a registered engineer. One copy of the final report shall be submitted to each the CONTRACTOR, the OWNER, and the ENGINEER. Points to be tested are:

  - *Pumping station discharge line at station __+__*
  - *Combination air valves located at stations __+__, __+__, and __+__*
  - *Butterfly valves located at stations __+__ and __+__*

- For new facilities constructed in design-build delivery systems, I suggest a similar clause should be included in the contract between the owner and the builder.
- Maintenance testing should be performed to the same criteria, and should be recorded for future reference.

<u>Where</u> should this monitoring be done? The hydraulic designer should specify which points are most critical. Depending on the hydraulics of the system, these points might include:

- For a new pipeline, at multiple points such as pump discharge lines, on both sides of control valves, and at selected air release valves.
- On any new delivery lines near the connection to an existing line
- At selected air release valves following maintenance and during refill if the pipeline has been emptied
- At other locations identified by the hydraulic designer as being particularly prone to transient pressures

<u>When</u> should transient pressure monitoring take place? Transient pressure monitoring should be accomplished:

- As part of the initial acceptance test of every new pipeline, beginning with the initial fill, during all maximum performance tests including simulated power failure, and for at least 30 days of normal operation
- Upon the completion of any modification to an existing pipeline, such as the addition of a new delivery point, or pressure booster station

- Upon completion of any transient pressure mitigation measures
- Upon completion of any significant maintenance programs, such as air valve or blowoff valve maintenance
- Annually, at selected critical points in a pipeline system, as part of a routine maintenance program
- During any periods when temperatures may cause air release valves and pressure relief valves to freeze and malfunction

How should the testing be performed? The testing should be done with advanced notice to any interested parties, and with ample opportunity for them to observe the testing. There should be opportunity to review the method of performance of the equipment, to ask questions, and to observe installation and establishment of test parameters. The ENGINEER responsible for the design of new facilities should be present during the initiation and critical points in the testing.

Why should this be done?

- To prevent failures such as those described above.
- To protect the interests of owners, engineers, suppliers, and contractors who are interdependent on the performance of each other to construct our vital pipeline systems.
- To confirm that a pipeline system is fully functional following significant maintenance activities
- To identify negative pressures that may result in contamination of potable water mains
- To identify negative pressures that may result in collapse or partial collapse of flexible pipelines
- To extend the useful life of our pipeline infrastructure. And finally
- To protect the public interest and investment.

Conclusion

Advances in digital technology and equipment have opened the door to improved monitoring of hydrodynamic pipeline pressures. Owners, engineers, contractors, and operators no longer need to wonder whether phantom transient pressure events are plaguing their pipeline facilities; it is possible to continuously monitor, detect and record these events. The greatest benefit of this capability may be through the implementation of a hydrodynamic pressure test, in addition to the standard hydrostatic pressure test, as part of the acceptance testing for new pipeline facilities.

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