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Anatomy of Surge Analysis for Industrial Firewater Systems

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Anatomy of surge analysis for industrial firewater systems — “we never have problems with firewater systems!”

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ABSTRACT

When confronted by a recommendation for a surge analysis of a firewater system, Fire Protection and Process Safety Engineers’ first response is often “we haven’t done that before, why do we have to do it now?” Firewater systems for industrial plants, airports and process systems are significantly larger than in the past, and (happily) there is relatively little experience with system performance under design conditions. We present a case in which the analysis of the sudden activation of firewater monitors predicted a piping failure which was subsequently (and unintentionally) confirmed by field testing together with some issues with a major addition to the existing system. We hope with this paper to provide some guidance through the labyrinth of codes and often conflicting requirements that must be traversed in order to achieve a robust design. Problems are reviewed with respect to discerning what design codes may apply and establishing permissible transient pressures for hydrants, monitors and valves for which manufacturers offer no surge-related criteria.

1 INTRODUCTION

The refrain “why do we have to do this transient analysis now, we haven’t had to do this before?” is all too familiar. The short answer is that times change. Industrial firewater systems have become much larger involving multiple firewater pumps, flow demands in excess of 2000 m^3/hr (8000 gpm), firewater mains more than 800 mm (30 inches) in diameter, and distances more than 3 km (1.9 mi) between the pump station and the location of the fire event. In general, it seems that the principal focus of the design of a firewater system is a steady-state problem in getting the requisite demands to the fire area at a pressure sufficient to satisfactorily operate the firewater sprays, monitors or hydrants (10). Hydraulic transients are not foremost; a quick review of problems on the Internet reveals many studies of systems to correct deficiencies in the steady state performance but virtually nothing on problems with hydraulic transients.

Here we discuss the analysis of a large industrial firewater system with a presentation of some pitfalls we stepped into (and should have known better), some choices made in the input data, results, and issues with code requirements and design criteria. The system presented in this paper was constructed in several phases. The original system analysis identified a potential problem with the firewater monitors. Firewater monitors, as illustrated on Figure 1, are located 20 to 30 m (65 to 100 ft) above grade so that the throw of the jet from the monitor provides coverage over a fairly large area. There is a deluge valve located upstream from the monitor that opens rapidly when a fire is detected. Since servicing a deluge valve 20 or 30 m off the ground is problematic, the deluge valves were located near plant grade for ease of access, and not adjacent to the firewater monitor as shown on Figure 1. For purposes of minimizing instrumentation and control installations the valves were also located some distance upstream of the actual monitors. The hydraulic transient analysis showed that if there were no water between the deluge valve and the firewater monitor, then there was a very significant pressure rise that occurred when the water filled the dry pipe, expelled the air, and suddenly encountered the resistance afforded by the discharge characteristics of the firewater monitor nozzle. The effect is similar to filling an empty garden hose after suddenly turning on the water, but on a considerably larger scale.

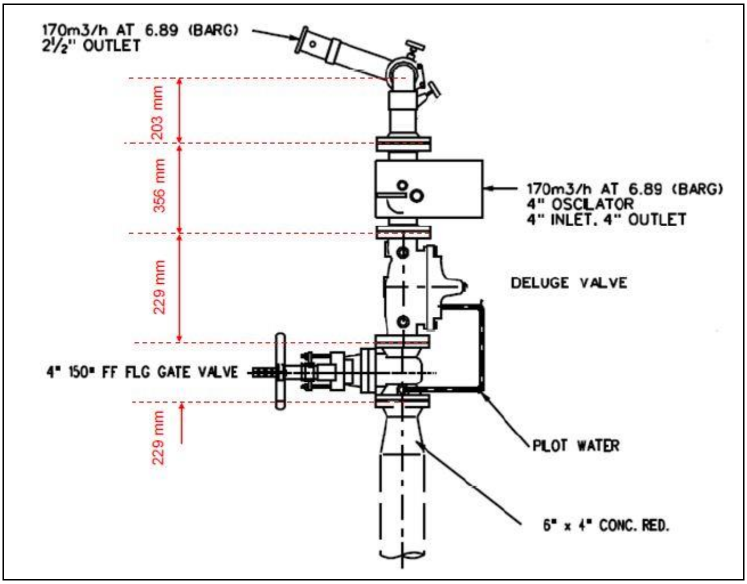

Figure 1 Firewater monitor and deluge valve

The hydraulic transient report recommended that the pipe between the deluge valve and the monitor be kept full of water to preclude excessive transient pressures and forces which, in fact, predicted a piping failure. Unfortunately, this requirement was not communicated to the start-up test team, with the result shown in Figure 2. A second start-up test the same day also with a dry pipe between the deluge valve and monitor confirmed the results shown in Figure 2. This incident did lend some credence to the necessity for a hydraulic transient analysis of firewater systems. When the industrial facility underwent design of a major expansion, a hydraulic transient analysis of the complete firewater system was undertaken without the familiar refrain quoted above.

Figure 2 Result of dry pipe start-up test

2 SYSTEM DESCRIPTION

A schematic layout of the firewater system is shown in Figure 3. The drawing is deliberately obscure for possible proprietary reasons. The principal components of the firewater system consist of a firewater storage pond, a pump station containing a Jockey Pump and three diesel firewater pumps, an underground distribution system, and branches from the distribution system that supply firewater to firewater monitors and hydrants. In addition, two booster pumps, one operating on demand and the other standby, are provided to boost the pressure at the elevated tank-top firewater monitors located on top of the storage tanks. The hydraulic transient analysis was conducted in two phases, an original plant layout that was already built, and an expansion of the original system. The original system and hydraulic transient model contained the pump station, process area, utility area, three storage tanks and two jetties for shipment of product. For final analysis, the original model was expanded to include the two additional storage tanks and four process trains and associated facilities.

The firewater pump station is composed of a Jockey Pump and three Main Firewater Pumps. The three Main Firewater Pumps are diesel-driven and rated at 909 m^3/hr (4000 gpm), 115 m (377 ft) Total Dynamic Head (TDH) and 1760 rpm. The Lead and Secondary Firewater Pumps are sufficient to meet all of the required firewater demands. The Tertiary Main Firewater Pump serves as a standby pump. Each Main Firewater Pump is equipped with a pressure relief valve. When the Main Firewater Pumps are not in operation, system pressure is maintained between 1100 and 1172 kPa (160 and 170 psig) at the pump station by the Jockey Pump.

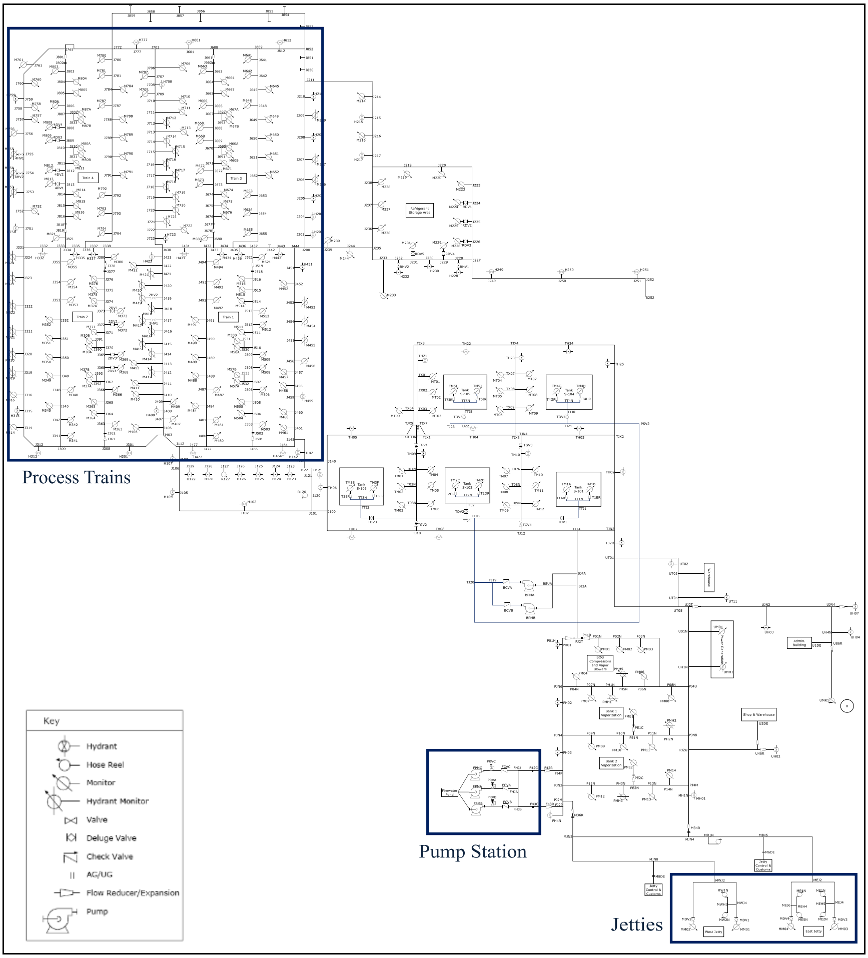

Figure 3 Firewater system layout drawing

The control logic for operating the firewater pumps used in this analysis is based on a combination of manual and automatic operation. A fire event activates alarms in the control room. The deluge valves required to supply the firewater monitors must be activated manually from the control room. The firewater pumps may be operated manually, or will auto-start on the basis of detected low pressures at the pump discharge. The set pressures for auto-start of the main firewater pumps are:

1. Lead Firewater Pump: 1034 kPa (150 psi)
2. Secondary Firewater Pump 965 kPa (140 psi)
3. Tertiary Firewater Pump 896 kPa (130 psi)

Two possible sequences for operating the main firewater pumps were investigated:

1. Operating Sequence 1. As soon as the alarms in the control room have been activated, the operator manually starts the Lead Firewater Pump and then opens individually the deluge valves that serve the alarmed fire zone. It was estimated to take 0.5 seconds to activate each deluge valve in sequence. Any additional firewater pumps required to meet the firewater demand will be activated by auto-start of the firewater pump on the basis of detected low pressures at the pump discharge. A 10-second delay is required between the receipt of the signal to start the third pump (if required) and the actual start of the third pump. This was found necessary to prevent spurious surge-initiated starts of the standby pump, which for lesser overall system demands, could have led to sustained operation of three pumps below their manufacturer's recommended minimum operating point.

2. Operating Sequence 2. This sequence was the same as Sequence 1 except without the manual starting of the Lead Firewater Pump. As soon as the alarms in the control room have been activated, the operator manually opens the deluge valves. It was again estimated to take 0.5 seconds to activate each valve in sequence. The main firewater pumps are then activated by auto-start on the basis of detected low pressures at the respective pump discharge. A 10-second delay is required between the receipt of the signal to start the Tertiary (third pump) (if required) and the actual start of the third pump.

In some cases, the deluge valves are opened simultaneously to be conservative or to accommodate possible simultaneous activation of a set of firewater monitors. Pressure relief valves for each main firewater pump have been incorporated into the computer model. The set pressure for these pressure relief valves is 175 psi at the pump discharge.

3 CASES INVESTIGATED

Six cases involving flow demands from 450 m^3/hr to 1800 m^3/hr (2000 gpm to 8000 gpm) were studied. In each case, scenarios were investigated using Operation Sequence 1 and Operation Sequence 2 that considered the consequences of detection of a fire and subsequent response of the Main Firewater Pumps and the Booster Firewater Pumps (if required) to the fire event. These scenarios also considered cases in which the firewater system was supplying the required firewater demand and then one of the operating firewater pumps failed, followed by start-up of a second pump or the third pump as required.

One of the principal concerns is the potential for column separation and rejoining in the system. The firewater monitors are located on towers 20 to 30 m (65 to 100 ft) above grade as indicated by Figures 1 and 2. As Figure 3 shows, there are a large number of firewater monitors located throughout the plant area. The Jetty Area, for example, is located more than 1.6 km (1 mi) from the Main Firewater Pumps and the Process Train Area is located about 2 km (1.2 mi) from the pump station. Under Operating Sequence 2, activating the firewater monitors results in a negative pressure wave that will travel to the pump station and start the Main Firewater Pumps when the pressure at the pump station drops below the set pressure for the pump. There is a possibility that the pressure at some of the firewater monitors in the system could drop below vapour pressure, resulting in column separation at the firewater monitor. Subsequent rejoining caused by starting the Main Firewater Pumps could then lead to excessive transient pressures.

Keeping the initial pressure high with the Jockey Pump can mitigate this problem, but when the system is in operation during a fire event, the operating pressure in this system is below the Jockey Pump Set pressure. Consequently, if one of the Main Firewater Pumps trips out during the fire event, the trip-out and subsequent start of the standby firewater pump may also result in column separation at the high points, i. e. the firewater monitors. It therefore becomes important to consider transients during system operation for a fire event, and not just the start-up conditions. There was also a major concern that operation to meet demands in the expanded system could result in excessive transient pressures in the existing system.

The six cases were selected on the basis of the magnitude of the firewater demand and the distance from the Main Firewater Pump Station. A detailed description of these cases will not be presented since it is the results that are of interest here.

4 DISCUSSION AND RESULTS

4.1 Computer model

4.1.1 Setting up the computer model – getting the correct data

The Bechtel Standard Computer Program, CE099, was used to simulate the hydraulic transient conditions in the firewater system. This proprietary program was developed originally by Bechtel with the assistance of Prof. V. L. Streeter and Prof. E. B. Wylie and has been modified and expanded by Bechtel engineers to meet the ever-changing needs for analysis of practical systems with special conditions. It uses a standard Method of Characteristics (MOC) solution. The analysis of the original system was done under the direction of the senior author and the analysis of the expanded system was done by the first and second authors in consultation with the senior author. The project directed that the analysis of the expanded system start with the original analysis and simply add the system expansion to the original computer model to expedite the analysis. The second author takes full responsibility for the gaffe that followed. All of the authors requested that the project confirm that the as-built system reflected the original computer model and report (the way things were). Project understood this to mean that “the way things were” was the way the system had been built, but our author understood “the way things were” to be as in the report for the original computer analysis. After more than 40 years of experience in hydraulic transients, we should have known better than to take the understanding for granted, particularly since most of the contact with the project was with personnel who had not worked on the original part of the system.

In spite of intermediate reports and reviews, it was not until the report for the final system analysis was in preparation that we discovered that 1), the pump data and characteristics used in the original report were for a preliminary pump that ended up differing considerably from those that were eventually installed, and 2), the control logic for operating the pumps was completely different from what was assumed and recommended in the original report. The second author had violated Rule No. 1: Verify, verify, verify. When someone tells you to use this past study, and it is your starting point (with the implication that you should have started yesterday), you know this is a prescription for disaster. Communication in this age of computers is not always easy.

The computer model was rebuilt several times to accommodate the changes, including one or more iterations after it was determined that the first description of the revised control logic for the pumps as obtained from the client was not entirely correct either.

Adding the expansion to the existing computer model was reasonably straightforward, and depended on obtaining the correct drawings from the project to incorporate the new piping into the computer model. We kept having a problem with a small gap between the High Density Polyethylene (HDPE) underground piping and the above-ground steel piping. The major purpose of our analysis was, of course, to assure that transient pressures will not exceed the allowable pressures for the various components. It was only at the very end of the analysis that we finally got the missing link for the "allowable pressures" – and it was the only ductile iron (DI) piping in the entire system we were analysing. Project had assumed that the amount of ductile iron piping was so minimal that we did not really need that information for the analysis. However, DI has its own very limiting design allowances for surge, and is often the weakest link in a firewater (sub-)system. Clearly there is room for improvement in communication; at least we had persevered until we did get the correct data.

4.1.2 Considerations for wave speed, pump moment of inertia, firewater monitors

More time and effort can be spent worrying about selection of wave speed than it really warrants. Air content, for example, is an unknown, and from an engineering viewpoint, we want conservative results. Therefore, wave speeds were calculated using standard equations and no attempt was made to include any effects of air content. The underground HDPE pipe also presents uncertainties in estimation of wave speed (7). Here, we simply used conservative estimates for the wave speed in HDPE.

The Main Firewater Pumps are diesel pumps. It was assumed that a pump trip during system operation was the result of sudden interruption of fuel. Given the extreme rotational resistance of a fuel-deprived piston engine, coast-down of a diesel-driven pump cannot be computed like the classic loss of power for an electric motor. Therefore, to be conservative, we assumed that the pump speed would decrease linearly from full speed to zero speed in 2 seconds. On the basis of discussions with operators, the start-up time from zero speed to full speed was taken as 10 seconds.

The firewater monitors were modelled using a creative approach with a surge tank boundary condition as described in (8) to simulate filling of the dry pipe between the deluge valve and the firewater monitor. In all cases, the piping downstream from the deluge valves was assumed to be full of water to within 1 meter (3 ft) of the firewater monitor. (The deluge valves open so fast that larger air gaps would risk the system by letting flow accelerate too much before creating the waterhammer due to suddenly engaging the restrictive monitor nozzles themselves.)

4.2 Results of the analysis

4.2.1 Pressure transients and control logic

The principal focus of the analysis was to determine if the control logic for activating the Main Firewater Pumps and subsequent operation of these pumps would lead to excessive transient pressures and recommend any protective facilities or operational changes as necessary to mitigate excessive transient pressures. The control logic was particularly difficult. When the operation of the pumps depends on what happens after the deluge valves are open, it was found to be virtually impossible to determine a series of set pressures for the pumps that provides satisfactory operation in all cases. The postulated fire events occur in different parts of the system at differing distances from the Main Firewater Pump Station, and with differing demands. This means that the pressure drop at the pump station, which is the signal that is used to start the Main Firewater Pumps, is different for different fire events.

Operating Sequence 1 was the recommended operating procedure. Operating Sequence 2 was found to result in numerous cases in which more than the required number of Main Firewater Pumps would be put into service. The pressure relief valves at the Main Firewater Pump Station then operate and remain in operation during the fire event. The pressure relief valves were found to "hunt" because the operating pressure falls below the 175 psig set pressure for the PRV, but the pressure then rises again and re-opens the valve. This pattern continues almost indefinitely and is not considered a desirable condition for a fire event. If the set pressure for the PRV were higher, then several cases with all three pumps in service led to pump operation below the manufacturer's limit for Minimum Continuous Stable Flow.

There were several scenarios for fire events involving the trip-out of an operating Main Firewater Pump and subsequent start of either the second or standby pump that caused excessive transient pressures in the system due to dead-end reflections of the transient pressure waves. The most critical case resulted in excessive transient pressures in a firewater line located in the original system piping. There is no flow in this line during the fire event, but the dead-end reflections of the transient waves caused by the pump trip did result in high transient pressures at the end of one firewater line in the original system. The results of a series of runs showed that a 10-second delay between the start-up of the Secondary and Tertiary Main Firewater Pump would mitigate the excessive transient pressures. With this delay, the maximum transient pressure was 2200 kPa (319 psig) and the transient pressure was above 1725 kPa (250 psig) for less than 2 seconds. There was no column separation and rejoining anywhere in the system.

The results of numerous runs showed that excessive transient pressures could occur if the active Booster Firewater Pump trips during a fire event and the standby Booster Firewater Pump is started immediately. On the basis of a series of runs, we recommended operational procedures or a time delay relay to prevent the standby booster pump from starting within 10 seconds of the trip-out of the active Booster Firewater Pump. This time delay prevents the pump start pressure wave from adding to the pressure wave caused by the pump trip, a condition which we found could lead to excessive transient pressures in the system.

Additional cases were run with the piping between the deluge valves and the firewater monitor dry. These results confirmed those in the original study, with a very firm admonition to make sure that the piping between the deluge valve and the firewater monitor be kept full of water at all times. (Were this a cold-weather region, heat-tracing would have been the price of keeping the deluge valves remote from the monitors.)

4.2.2 Considerations for determining allowable transient pressures -

The question now was what were the allowable transient pressures for the piping and components. Herein lies a very tangled tale having to do with code requirements and design criteria. The design code specified for this project was NFPA 24 (9) (National Fire Protection Association), which is the bible for firewater system design in the United States as well as on many international projects. This document does not specifically address hydraulic transient pressures, but provides prescriptive guidance for system design. FM (Factory Mutual) approved pipe is generally a means of satisfying requirements for performance, safety and quality for firewater piping. FM Approvals Class Number 1613 (5) states that "WPR [working pressure rating] should be determined in accordance with AWWA C906 Polyethylene (PE) Pressure Pipe and Fittings, 4 in. through 63 in. for Water Distribution." The WPR as determined in AWWA C906 (4), includes allowance for transient pressures. For recurring transient pressures, defined as surge pressures that occur frequently and are inherent to the design and operation of the system (such as normal pump start-up and shutdown, and normal valve opening or closure) the maximum allowable pressure is 1.5 times the nominal Pressure Class (PC). For occasional transient pressures, defined as surge pressures caused by emergency operations (such as equipment failure), the maximum allowable pressure is 2 times the nominal Pressure Class. A word of caution: some international projects are governed by in-country codes. For example, HDPE pipe design in Australia usually refers to AS/NZS2566.1 Supplement 1:1998 (1), which allows a maximum transient pressure of 1.25 times the allowable working pressure for hydraulic transient conditions. A very thorough review of applicable codes and standards is therefore an essential part of the design process.

The design pressure for the HDPE pipe for this project was 1200 kPa (175 psig) at a temperature of 32 °C (90 °F). The governing case of transient pressures in the dead-end line occurred for a pump failure with the system in operation after the fire event had occurred. Clearly this is an occasional condition, and the allowable transient pressure for HDPE pipe is therefore 2 x 1200 kPa = 2400 kPa (350 psig). This is less than our calculated 2200 kPa (319 psig). Furthermore, the duration of the maximum transient pressure is short, and we conclude that the HDPE pipe is therefore satisfactory.

The design pressure for the above-ground carbon-steel piping is 1725 kPa (250 psig) and the design code is ASME B31.3, Process Piping" (2). That code's allowance for pressure variations above design conditions is discussed in Paragraph 302.2.4(f). Since the pressure variations are of short duration, with owners approval, the allowable pressure variation is 1.33 times the design pressure or 2290 kPa (333psig). All transient pressures obtained in this analysis were below 2290 kPa (333 psig) so the carbon steel pipe is satisfactory. It should be noted that ASME B31.3 does not allow pressure variations above design conditions for non-metallic piping. The underground piping (the HDPE) for the firewater system is not part of the industrial process piping, and the AWWA code is applicable.

The valve manufacturer does not specifically address transient pressures, but refers to the requisite Factory Mutual (FM) test requirements. The valve is solenoid-operated, with the body FM rated at 2068 kPa (300 psi) and the solenoid operator rated to 1200 kPa (175 psi). The FM Approval Standard for Deluge and Preaction Sprinkler Systems, Class Numbers 1011/1012/1013 dated September 2009 (6), requires that the solenoid valve body be subject to a hydrostatic test pressure of 4820 kPa (700 psi) or four times the rated working pressure, whichever is greater, for a duration of 5 minutes. There shall be no visible rupture, cracking, or permanent distortion to the valve body as a result of this test. In view of the rigorous testing requirements, we concluded that the valve would perform satisfactorily as part of a system whose maximum design pressure is only 1.33 times the rated pressure.

Other appurtenances such as hydrants also did not have manufacturer's specific recommendations for allowable transient pressures. The hydrants were rated at 250 psig and met the requirements of ANSI/AWWA C502-05 "Dry-Barrel Fire Hydrants" (3), and can also be ordered in configurations that are listed by Underwriters Laboratory and approved by FM Approvals. The FM Approvals are more stringent than the AWWA standard. After review of the test requirements for the AWWA and FM Approvals we concluded that the hydrants would perform satisfactorily. Specifying FM Approvals would be conservative.

5 CONCLUSIONS

Hydraulic transient analyses of industrial firewater systems are not trivial exercises. The sudden occurrence of locally high demands and subsequent start-up of firewater pumps in response to the demands can lead to excessive transient pressures in parts of the system not in service due to dead ends, or in some cases, due to column separation and rejoining at elevated firewater monitors or sprays not in service which act as local high points in the system.

As shown by the analysis (and unintentionally confirmed by field tests), hydraulic transients at the operating firewater monitors or sprays can lead to high pressures and loads on equipment, with failure of the equipment.

The hydraulic transient analysis assisted in establishing recommended control logic for operating the system to avoid potential problems with activating more pumps than necessary to meet the firewater demands. It also established operating sequences for starting the firewater and booster pumps to avoid excessive transient pressures.

Hydraulic transients that occur after the system has responded to a fire event must also be considered. Accidental trip-out of one or more of the operating firewater pumps during the fire event can result in excessive transient pressures that should be addressed in all analyses of firewater systems.

The prescriptive guidance of NFPA 24 places the responsibility for establishing design requirements directly on the design engineering team, which in the authors' view is exactly where is should be. It is the design engineer who must exercise due diligence and provide the client with a robust design. Which codes and requirements should apply have to be tailored to the specifics of each project. There are no general solutions. The analyst therefore cannot work in isolation, but must be familiar with the myriad of design codes and standards as well as different types of equipment and how these apply to the analysis of hydraulic transients. Although it is patently obvious that communication among specialists and the design team is essential, e-mail and computers are not a substitute for old fashioned face-to-face conversation.

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