Waterhammer Simulation and Mitigation for a Fire Protection Network at a Nuclear Power Plant

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ABSTRACT

A waterhammer risk assessment and computer analysis of the fire protection system at the Edwin I. Hatch Power Plant (Plant Hatch) in Baxley, Georgia was performed. The activation of the highest demand deluge system with and without various surge mitigation devices is presented. Vapor void formation and high pressure void collapse can occur at high elevation risers in fire protection loops as a result of the sudden flow demand from the activation of dry pipe fire suppression systems (such as preaction or deluge sprinkler systems). This paper demonstrates that all pressurized piping should be considered in a fire protection system, especially localized high points and longer lengths of piping to dead ends or remote hydrants. This paper demonstrates a comprehensive computer analysis of the entire pressurized fire protection system should be the preferred method of waterhammer risk assessment.

1 INTRODUCTION

Both preaction and deluge piping networks are initially dry pipe and isolated from the pressurized fire protection network by a control valve that is activated from a heat or smoke source. The primary difference between the two is deluge systems have entirely open sprinkler heads and preaction systems limit flow to individual sprinkler heads that have been activated at a specific temperature. Deluge systems are intended to extinguish large scale fires and preaction systems are intended for use in water sensitive areas. Deluge systems typically have higher long term flow demands, but both deluge and preaction systems have a similar initial response as the dry pipe is rapidly filled with water.

During a fire event, preaction or deluge control valves can actuate in less than 0.1 seconds after being triggered by a heat or smoke source to allow water through empty piping and sprinklers to extinguish the fire. The sudden introduction of flow from the pressurized fire protection network into the dry pipe system can drop network pressures significantly. If the pressure drops below the vapor pressure of water, it will result in a localized phase change and the formation of a vapor void or pocket. These vapor voids are likely to form at high points in the system where the local hydrostatic pressure is lower, and within complex network piping with dead end branches where pressure wave reflections are amplified. After a short period of void formation, the dynamic response of the system and the start of the main fire pumps will raise the local pressure at the voids causing them to collapse, potentially resulting in extremely high pressures.

This void formation and collapse behavior was discussed thoroughly in Dr. Samuel Martin’s 2012 waterhammer report on Plant Hatch (1). Dr. Martin concluded severe pressure spikes only occur in risers with preaction valves. However, this study demonstrates a more complete analysis of the entire system is warranted.

The void formation and collapse phenomenon were responsible for a catastrophic valve failure at WNP-2, a nuclear power plant Washington State (now Columbia Generating Station) (2, 3, 4). Activation of the preaction system caused voiding in the reactor risers, and the subsequent void collapse generated a large pressure wave. Repeated waterhammer events lead to weakened supports, and the valve at the base of the riser split in half due to increased force during the final waterhammer event which flooded an estimated 617,000 liters.

Plant Hatch and many other nuclear power plants share a similar fire protection system design to WNP-2. These plants are potentially susceptible to the same void formation phenomenon and should have both testing and waterhammer computer analysis performed to ensure safe operation during the activation of a dry pipe fire suppression system.

2 VOID FORMATION AND COLLAPSE

The phenomenon of vapor void formation and collapse is possible upon the activation of a preaction or deluge fire suppression system. Figure 1, revised from the WNP-2 report (2) demonstrates the phenomenon well.

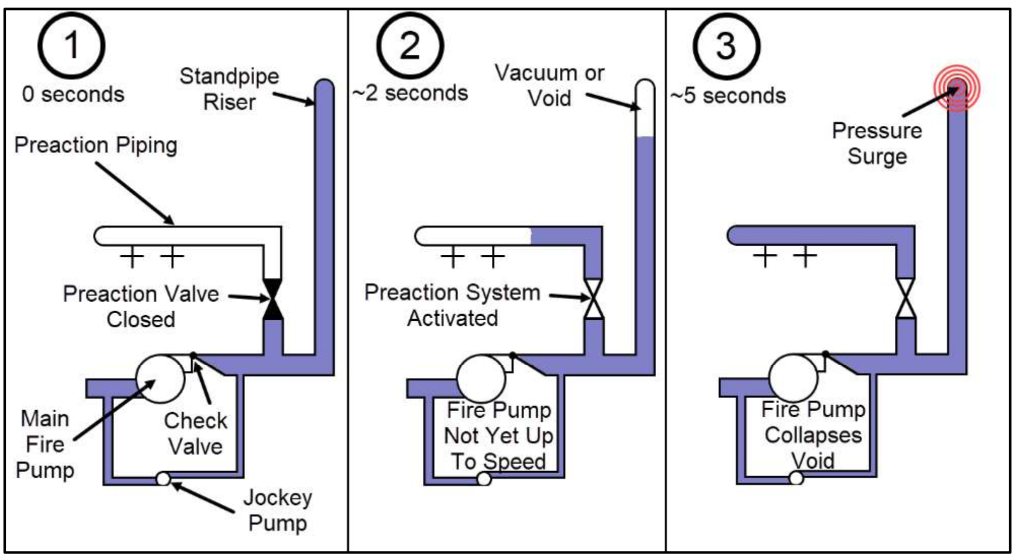

Figure 1: Steps of void formation and collapse during activation of preaction system

Step 1 shows the system at initial conditions, in which it is pressurized by the jockey pump, but there is no flow and the preaction system is closed.

Step 2 shows the system immediately after the preaction system has been activated. Flow is introduced rapidly into the dry preaction piping, causing a pressure drop in the system. The main fire pump is initiated once the local pressure drops and is delayed by the wavespeed, length of piping to the pump, and the rate the pump comes to full speed. Void formation in a nearby standpipe riser occurs during startup delay. The amount of void formation is more significant with increased delay. Although it is possible for void formation to occur in multiple risers or system locations, the worst cases are typically closer to the preaction valve.

Step 3 shows the fire pump providing pressure to overcome the initial pressure drop. The increase in pressure collapses the void with high fluid velocity, and the resulting pressure spikes can be orders of magnitude higher than steady-state pressures.

3 THE FIRE PROTECTION NETWORK

Southern Nuclear Company (SNC) commissioned a study of the fire protection system at Plant Hatch following several piping failures in the system which were believed to be a result of waterhammer. These failures occurred throughout the plant and included several failures in the cooling yard piping. Plant Hatch went online in the 1970s and much of the fire protection system is compromised of the original cast iron piping. The aged pipe and possible corrosion likely contributed to plant piping failures.

A transient hydraulic model of the entire pressurized fire protection system was built by referencing 3D models, plant drawings, and field observations during a site visit. Modeling and simulation were performed in AFT Impulse 8, a Method of Characteristics based waterhammer simulation tool. AFT Impulse 8 uses the methods presented in “Fluid Transient in Systems” (5) as the basis for calculation of general pressure wave response, vapor void growth and collapse, vacuum breaker valves, surge vessels, and pumps.

The fire protection network at Plant Hatch consists of a pump house, hydrants, sprinkler systems, and fire hose stations. The pump house has a low capacity jockey pump that maintains a steady system pressure of approximately 10 barg. Additionally, the pump house has three large capacity fire pumps that turn on sequentially as system pressure drops. The overall network is presented in Figure 2 with the reactor, turbine buildings, proposed surge vessel locations, and an important cooling yard hydrant identified.

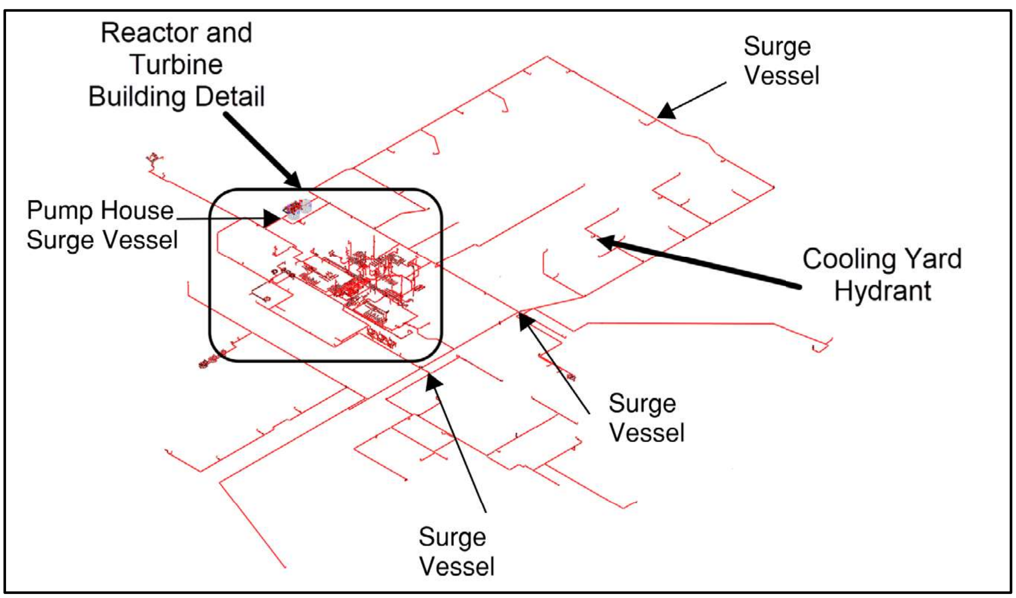

Figure 2: Plant Hatch fire procteciton network

Several sprinkler systems were analyzed including preaction, deluge, and wet pipe systems. The highest flow demand deluge system is considered in this paper and can be seen in Figure 3 with results of the computer analysis shown in Sections 4 and 5.

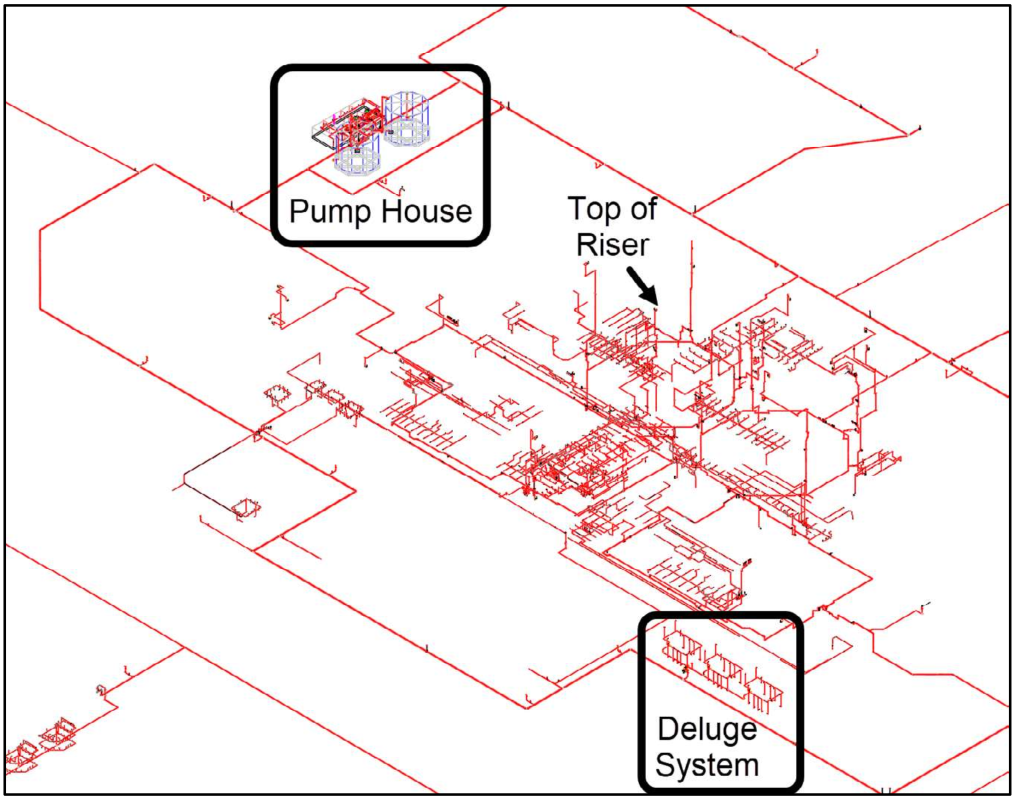

Figure 3: Reactor and turbine building detail

Fire hose stations are also located throughout the facility with many of them located on tall standpipe risers in the reactor and turbine buildings. These hose stations often have small diameter piping which can amplify pressure surges due to more significant velocity changes as compared to larger diameter piping. Figure 4 shows the profile view of the system including the height of the top of the riser and distance between the deluge system and pump house.

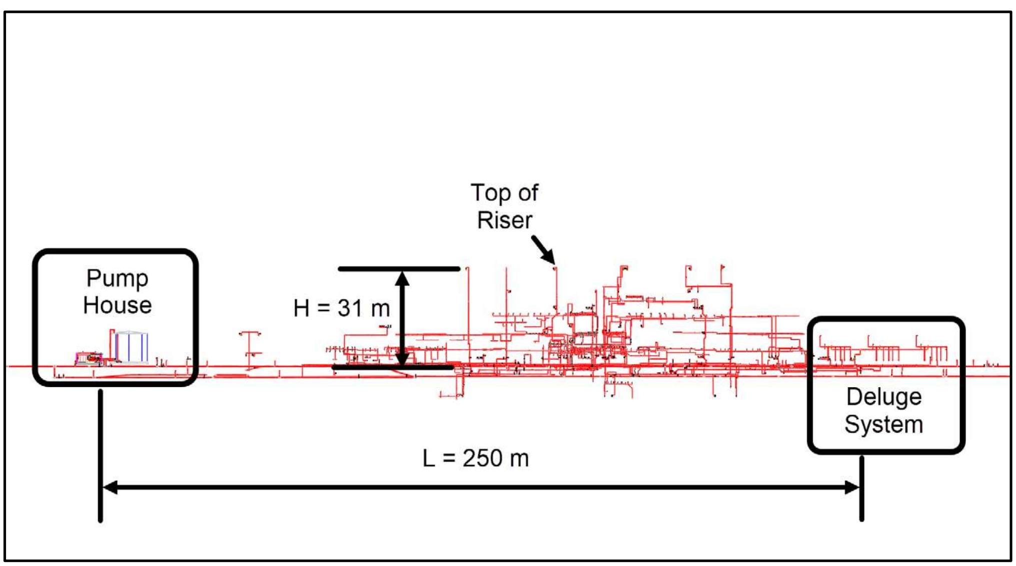

Figure 4: Reactor and turbine building profile view

4 UNMITIGATED WATERHAMMER SIMULATION

The following simulation results consider the activation of a deluge system with a 0.1 second valve opening time occurring 0.2 seconds into the simulation. This valve opening into previously unpressurized and empty pipe creates a sudden flow demand with over 1400 m^3/hr delivered to the system.

When no mitigation is considered, the sudden flow of water into the deluge system drops the network's pressure significantly. The pressure drop is particularly apparent at the high point of a riser. Figure 5 demonstrates the pressure drop and void formation at the top of the riser. The vapor void collapse generates a pressure spike of 100 barg.

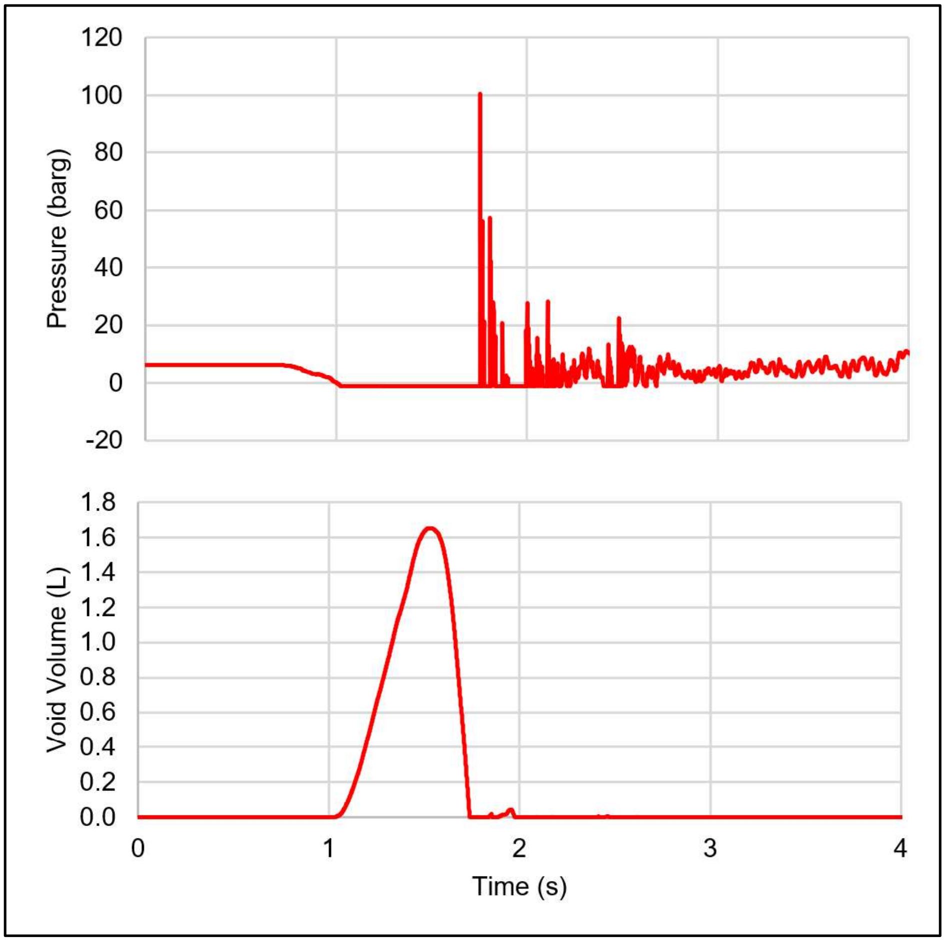

Figure 5: Top of riser pressure and void volume with no mitigation

The low pressures in the network are not limited to the high points of the risers. One location in which vapor voids occur is at a cooling yard hydrant on a branch with multiple dead ends. Dead ends are known to amplify pressure surges and create complex pressure wave interactions that cannot be reproduced without detailed simulation. This hydrant experiences significant void formation and a pressure spike of 55 barg upon collapse of the void as shown in Figure 6.

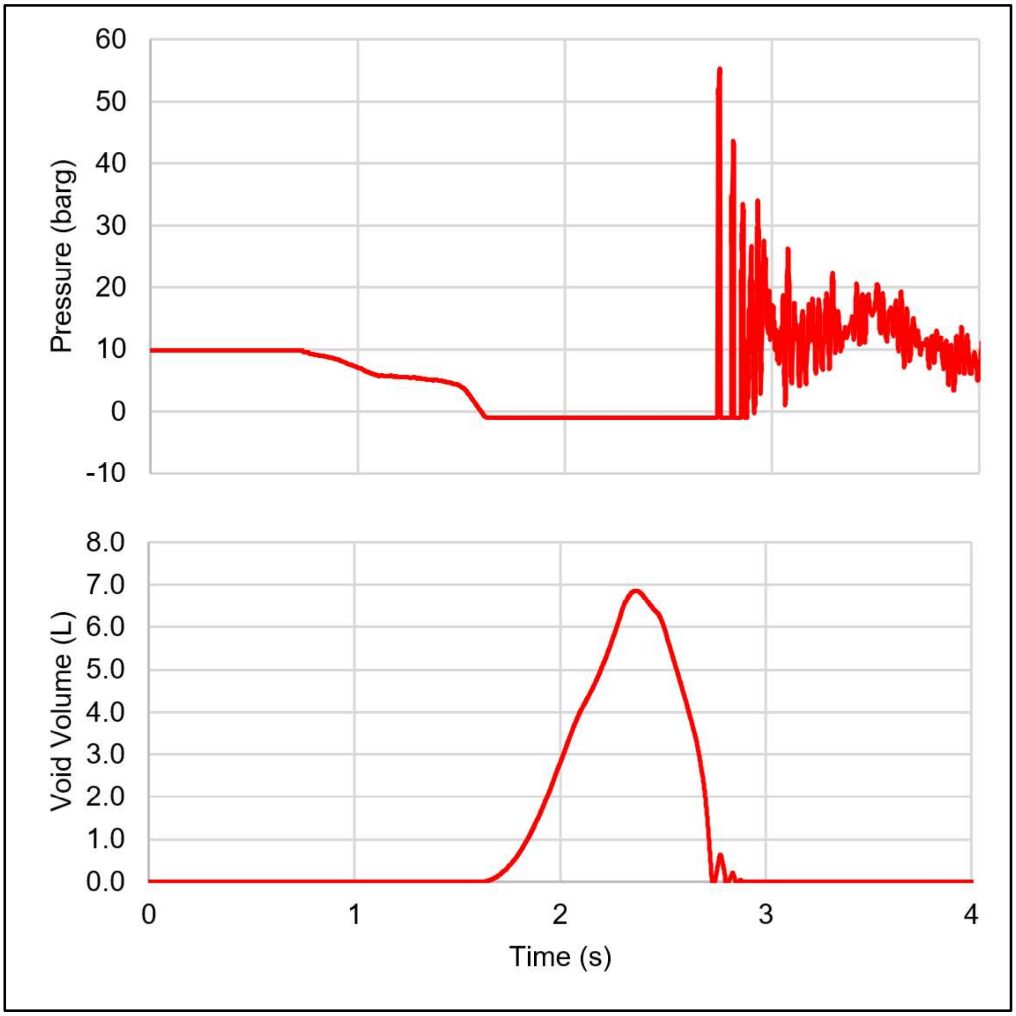

Figure 6: Cooling yard hydrant pressure and void volume with no mitigation

5 MITIGATED WATERHAMMER SIMULATION

5.1 Vacuum Breaker Valve

The inclusion of vacuum breaker valves at the top of the risers was considered as they were successfully used at other plants for mitigation (3, 4). The intended use of these valves is to let air into the high points upon a loss of pressure to prevent vacuum and void formation. As the system repressurizes, the valves release the air back to atmosphere and close. However, if this air release is uncontrolled the valves can close while the water is rapidly moving up the riser. If uncontrolled air release occurs, the resulting pressure spike can be similar to the pressure spike caused by void formation and collapse (6).

To avoid uncontrolled air release, an optional surge protection device was considered in this analysis. The surge protection device has a one-way orifice activated when air is pushed out to create resistance, which limits the rate of air venting, and is intended to mitigate pressure surge when the valve closes. However, the inclusion of a surge protection device is not a guarantee the system will be protected.

This analysis showed a valve with the surge protection device could prevent initial vacuum and void formation in the risers. However, high pressure issues persisted due to rapid air compression during venting (Figure 7). The presence of high pressure air in the piping during air release through small diameter orifices can lead to large amounts of stored energy and the potential for additional pressure vessel codes to be applied to the overall system (7).

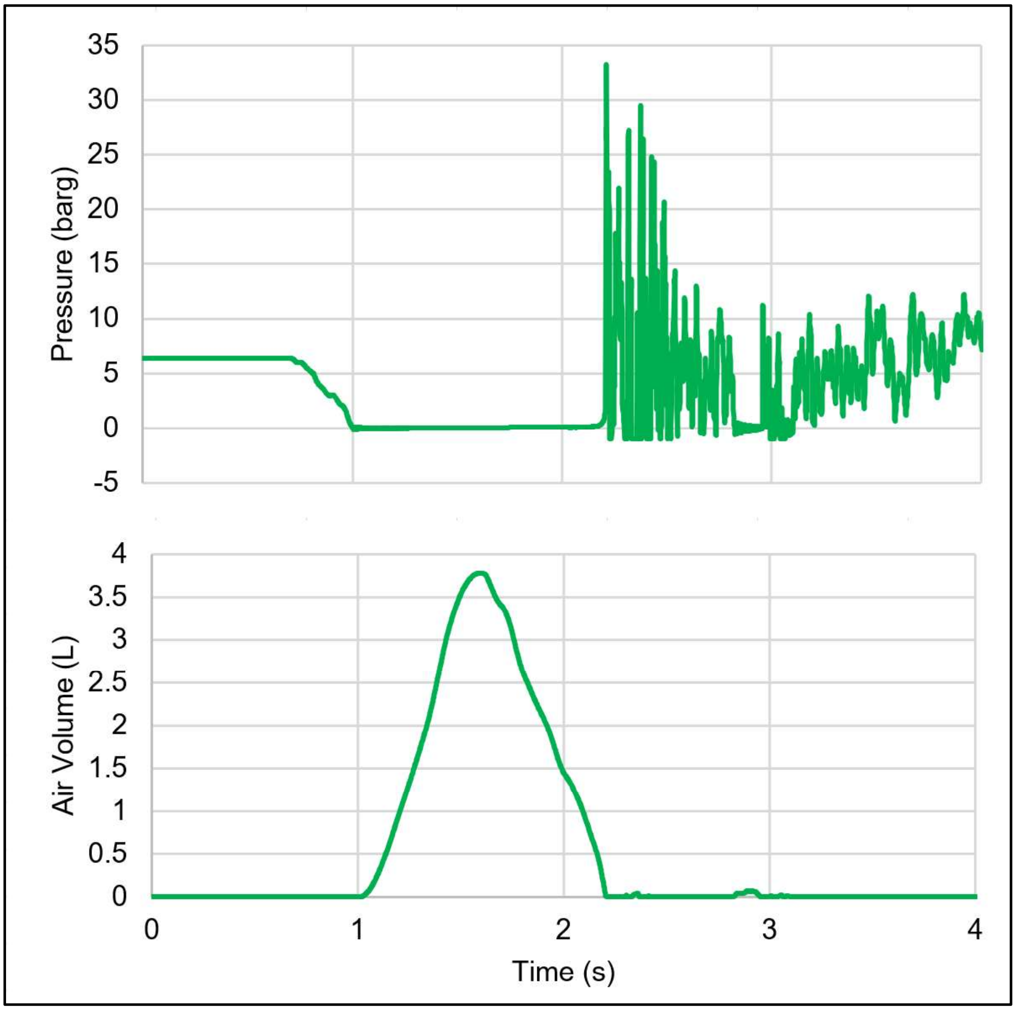

Figure 7: Top of riser pressure and air volume with vacuum breaker valve

Additionally, the vacuum breaker valve does not prevent vacuum formation elsewhere in the system. The cooling yard is an example location where low pressures cause vapor void formation and collapse when vacuum breaker valves are considered as shown in Figure 8. The resulting pressure spike at the cooling yard hydrant is 50 barg with the inclusion of vacuum breaker valves. This pressure spike was 55 barg with no mitigation considered as shown in Figure 6.

While vacuum breaker valves are valuable surge protection devices for less complex systems and in cases where the air can be vented slowly, their poor predicted performance and inability to prevent voiding throughout Plant Hatch led to the conclusion they would be inappropriate for this system.

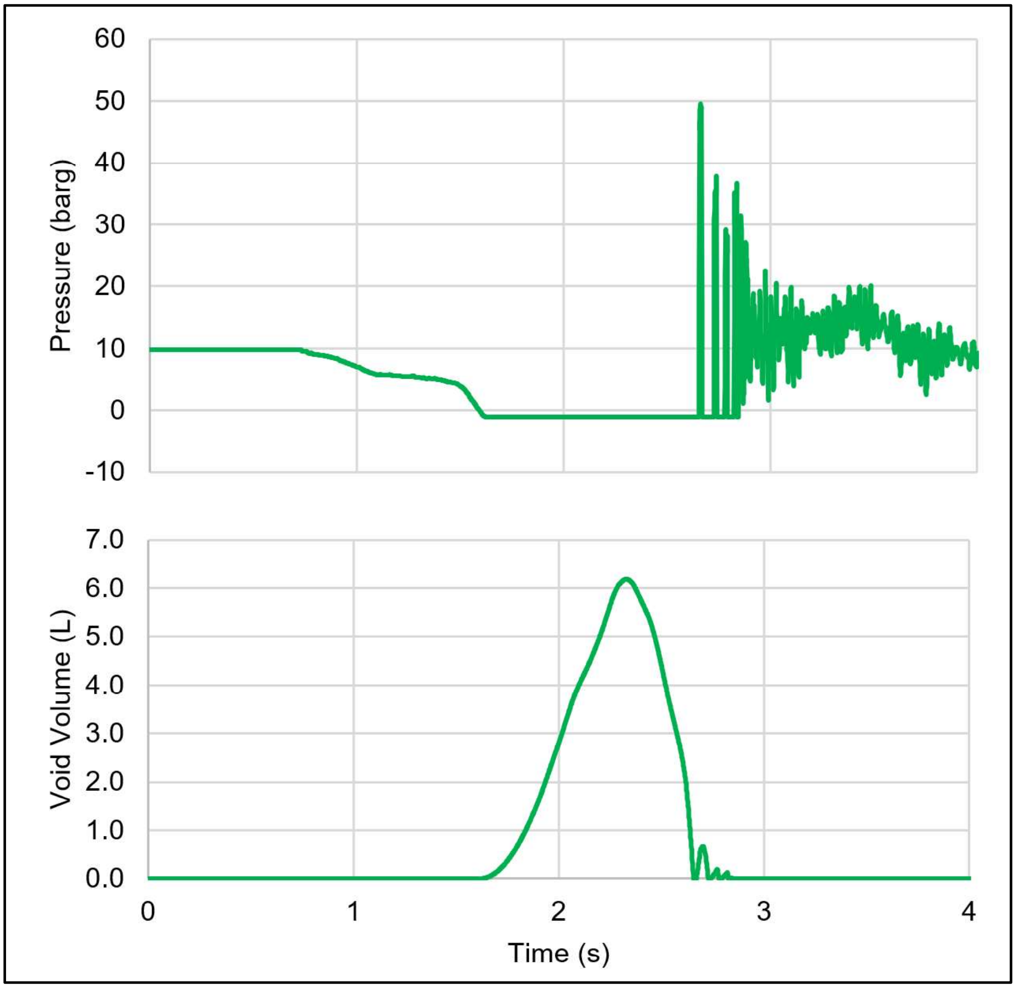

Figure 8: Cooling yard hydrant pressure and void volume with vacuum breaker valve

5.2 Surge Vessels

Surge vessels are passive pressure vessels partially filled with air or an inert gas such as nitrogen. When systems are pressurized, the gas within the vessel compresses and equalizes with system pressure. When a sudden event such as the activation of a preaction or deluge system occurs, the gas within the vessel will expand and compress with system pressure. If properly sized and placed, the vessel will dampen the overall system pressure response. In other words, the vessels give and receive energy to the system to maintain a certain pressure envelope. All vessels were considered initially 50% full of nitrogen gas.

This study considered several smaller surge vessels (95 L) at the top of all standpipe risers that are susceptible to vapor void formation and collapse. These vessels maintain positive pressure at the high points and eliminate the void formation at the risers. 32 mm diameter orifices were considered at the vessels' connection point to the riser to limit the size of the vessels and prevent them from draining during a transient event.

Four additional stabilizing vessels were considered at key points within the fire protection system and locations are shown in Figure 2. The larger stabilizing vessel (1900 L) maintains system pressure at the pump house and helps provide initial flow into the fire protection system before the pumps are up to speed. The vessel also mitigates brief drops in pressure that would result in the second or third pump being started when they may not be required.

Three medium sized stabilizing vessels (950 L) were considered to dampen pressure response in critical areas of the system. These vessels prevent significant pressure surges from propagating towards complex network piping with numerous dead ends which cause significant issues without mitigation.

The inclusion of properly sized and placed surge vessels eliminates the void formation and collapse phenomenon at the top of the riser (Figure 9) and at the cooling yard hydrant (Figure 10).

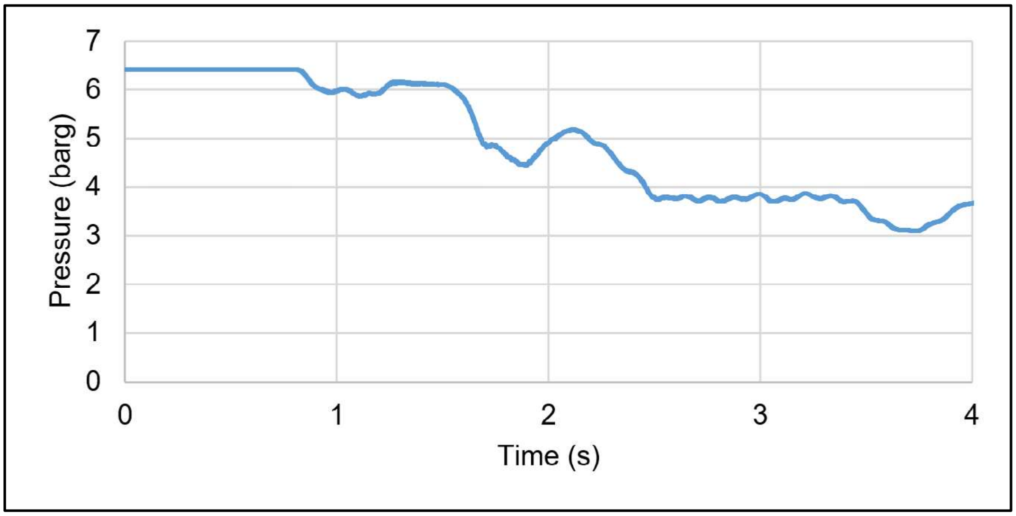

Figure 9: Top of riser pressure with surge vessels

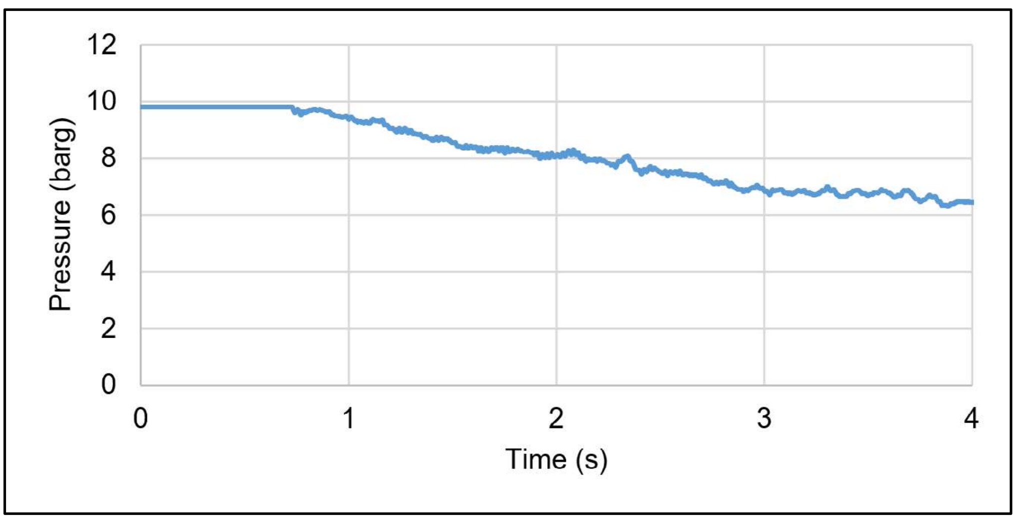

Figure 10: Cooling yard hydrant pressure with surge vessels

6 CONCLUSIONS

Fire suppression systems are dynamic in nature with sudden demand for high flow from previously stagnant conditions. The sudden change from no to high flow will drop pressure and can be significant enough to result in void formation and collapse. Pressure spikes resulting from void collapse can be significant. These high pressures may be of particular concern in aging cast iron pipe which is the majority of fire protection piping at Plant Hatch and many other nuclear plants. Previous studies have reported on this phenomenon but have focused on high elevation risers (3, 4). This study shows that low pressures and significant voids can form throughout the network and are a probable cause of multiple observed piping failures at Plant Hatch. As a result, a more comprehensive analysis that considers the entire fire protection system is required.

Previous analyses have shown vacuum breaker valves to provide effective mitigation against void formation in risers (4) but were demonstrated to be ineffective at Plant Hatch due to poor dynamic response which resulted in significant air compression and high pressures. Additionally, the vacuum breaker valves had little to no effect on remote system pressures where void formation and collapse still occurred.

The addition of surge vessels on the risers and at four critical network locations at Plant Hatch was shown to be an effective mitigation against void formation and collapse within the entirety of the fire protection system. Detailed computer simulations and field testing should be performed at all similar fire suppression systems to ensure their safe operation.

7 ACKNOWLEDGMENTS

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