PRACTICAL CONSIDERATIONS FOR PREVENTION OF FLOW ACCELERATED CORROSION DURING REFURBISHMENT

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Abstract

With the increasing number of nuclear power plants entering periods of extended operation, more and more refurbishment and plant life extension efforts, such as component replacement and pipe system modification, are being undertaken. From the past experience in various nuclear plant maintenance and refurbishment projects, the authors encountered situations where modifications for maintenance and capacity improvement of piping systems affected the riskofFlow Accelerated Corrosion (FAC), and provided appropriate solutions. This paper presents an industry example of implementation of FAC prevention and mitigation during a replacement of a pressure reducing valve and associated piping in a steam line, and suggests practical considerations for effective management of FAC risks and improved project performance for future refurbishment efforts.

1. Introduction

With the recent announcements of Bruce Power's plans for the six-unit refurbishment in 2020 and Ontario Power Generation's plans for the Darlington Station's four-unit refurbishment in 2016 and continued operation of the Pickering Station until 2024, all of Ontario's nuclear power fleet are preparing to ensure safety and efficiency in their extended operations. In addition, other CANDU plants, such as New Brunswick Power's Point Lepreau Station, and the majority of nuclear plants in the United States and around world have been in service for severaldecades,constantly undergoing various maintenance work and modifications.

A major portion of the upcoming refurbishment and maintenance work at Bruce, Darlington and Pickering will involve modifications to the nuclear class piping in the reactors and turbines, as well as the non-nuclear class piping in various balance-of-plant pressure boundary systems.One of the common mechanisms historically known to cause degradation and even failure in these piping systems is Flow Accelerated Corrosion (FAC) ([1]-[8]). FAC is a chemical mechanism that leads to wall thinning of steel pipes exposed to flowing water or wet steam. The rate of metal loss due to FAC depends on several parameters such as water chemistry, material composition, and hydrodynamics[2]. In severe cases, FAC could lead to complete failure of the affected line,causing costly outages and repairs, as well as impacting plant reliability and personnel health and safety. For example, on December 9th, 1986, a severe elbow rupture in the feedwater piping occurred in Unit 2 of Surry Nuclear Power Station in Virginia, USA, resulting in four fatalities and extensive plant damages[2]. Since this incident, the nuclear power industry has been developing extensive inspection and monitoring programs for detection of FAC risks, and guidance and criteria for mitigating and preventing FAC related degradation and failures.These recommended practices are available in piping codes such as American Society of Mechanical Engineers (ASME) B31.1 Power Piping [9]and technical reports such as Recommendations for an Effective Flow-Accelerated Corrosion Program (NSAC-202L-R4)[1]. Other organizations such as Nuclear Energy Agency (NEA) have also published reports presenting various FAC management and mitigation strategies employed worldwide[2].

There have been several researches conducted by scientists showcasing the fundamentals behind therecommended practices for FAC prevention ([3]-[6]). Muhammadu et al. reviewed available literatures for the flow accelerated corrosion of mitred bends, andhighlighted details of experimental data and methodologies that can be a good benchmark for related numerical analyses[3].Homicz demonstrated the occurrence of maximum shear stress and turbulent kinetic energy, which are contributing factors to increased FAC risks, in a flow through an elbow using the RNG k-ε and realizable k-ε turbulence models in the FLUENT commercial software [4].Pietralik presented the proportional relationship between the local mass transfer of ferrous ions from the oxide-water interface and the FAC ratethrough computational fluid dynamics calculations for short-radius and long-radius bends [5].Schefski et al. demonstrated the application of CHECWORKS™at Darlington Nuclear Generating Station to improve the existing FAC program by providing ranking of components by predicted wear rate [6].

Although there are extensive studies about the FAC phenomenon, its initiation, and prevention methodologies, industrial and practical examples of such recommended practices are not as readily available. This paper presents an industry example of implementation of FAC prevention and mitigation during replacement of a pressure reducing valve and associated piping in a steam line in a nuclear power plant. It also suggests practical considerations for effective FAC risk management and improved project performance for future refurbishment efforts. For contractual reasons, certain specifics of the project such as the name and location of the plant will remain undisclosed.

2. Flow Accelerated Corrosion (FAC)

Flow Accelerated Corrosion (FAC, sometimes also termed “Flow Assisted Corrosion”) is a wear mechanism that results in wall thinning of steel piping exposed to flowing water or wet steam. The wall thinning occurs due to the dissolution of the normally protective oxide layer present on the surface of carbon and low alloy steel piping. The rate at which the metal loss occurs is dependent on a complex interplay of several parameters such as water chemistry, material composition, and thermal hydrodynamics. Based on operating experience, it has been shown that wall thinning rates can be as high as 3 mm/yr in carbon steel piping components exposed to wet steam([1], [2]).

In order to apply correct mitigation methods, it is crucial that FAC degradation be diagnosed correctly. FAC is a chemical mechanism and should not be confused with cavitation or erosion where the oxide is broken down mechanically by impingement of particles, solids or gaseous bubbles. The following variables are known to have the most dominant impact on the degree of FAC degradation([2],[6],[7]):

- Temperature – Most of the reported cases of FAC damage on carbon and low alloy steels occurred within the temperature range of 80°C to 260°C. While the exact temperature at which maximum wear rate occurs varies with pH, oxygen content, and other environmental variables, operating experience has shown that wear rates are highest at around 150°C.

- Flow velocity – Flow velocity has a linear effect on the FAC wear rate as the enhanced mass transfer associated with higher flow velocity accelerates the dissolution of the pipe wall protective oxide layer.

- Fluid pH – The FAC wear rate has been shown to increase rapidly in the pH range of 7 to 9, and drops sharply above 9.2. As the fluid becomes more acidic, more pipe wall losses are experienced. It should be noted that magnetite solubility, which is directly proportional to the FAC rate, is dependent on both the temperature and the pH level. While the FAC risk is reduced with high pH at lower temperatures, pH greater than 9.8 has been shown to result in increased dissolution of the magnetite at higher temperatures [3].

- Oxygen – The amount of dissolved oxygen in the fluid inversely affects the FAC wear rate. When the fluid contains more than 20 ppb oxygen, the FAC rate decreases rapidly.

- Alloy additions – The presence of alloying elements such as chromium, copper and molybdenum, even at low percentage levels, significantly reduces the FAC rate. A chromium content of 0.2% is known to reduce the relative corrosion rate by 80%, and austenitic stainless steels are virtually unaffected by FAC.

- Piping material composition – An FAC wear effect known as the entrance effect occurs when an FAC-resistant material is joined with a non-resistant material downstream of the flow. The non-resistant material experiences a locally increased corrosion rate.

- Piping geometry – Elbows, tees, reducers, orifices,and regions where the inner surface or geometry changes over short distances are all contributing factors to the occurrence of FAC [5].

Failures and accidents resulting from FAC degradation have been reported at nuclear power plants around the globe since 1981. Some of the significant FAC events include the main feedwater line rupture at Surry Unit 2 in 1986 and the condensate system pipe rupture at Mihama Unit 3 in 2004. The 18" (450 mm) elbow, located in the suction line to the main feed pump at Surry Unit 2 (Figure 1), experienced a substantial loss of wall thickness from a nominal 13 mm to 0.38 mm at the thinnest point[2]. As a result, when a main steam isolation valve failed closed, the elbow ruptured from the increased pressure causing four fatalities. Similarly, the ruptured condensate pipe located downstream of an orifice at Mihama Unit 3 (Figure 2) went through a loss of wall thickness from 10 mm to 1.5 mm[8].

Figure 1 A Ruptured Elbow in Feedwater Line at Surry Unit 2(W. H. Ahmed [8])

Figure 2 Ruptured Condensate Pipe at Mihama Unit 3(W. H. Ahmed [8])

Since the tragic 1986 Surry pipe rupture event, several recommendations and guidelines for an effective program to detect and mitigate FAC risks have been developed. Non-mandatory Appendix IV of ASME B31.1 Power Piping code provides a set of parameters to consider in order to minimize the FAC risk. For example, it is recommended that the flow velocity is kept below 10 ft/s (3.0 m/s) for water and 150 ft/s (45.7 m/s) for steam[9]. Other recommended practices include detailed FAC analysis using a predictive methodology such as the

CHECWORKS^{TM} computer software developed by EPRI,and periodic inspection of components and systems. Furthermore, long-term strategies for reducing the plant FAC susceptibility include replacing FAC-susceptible materials to carbon steel components containing minimum of 0.10% chromium, improving the water chemistry by increasing the pH level or the amount of dissolved oxygen, and changing local designs such as pipe diameter to reduce the flow velocity[1].

3. Industry Example involving a Steam Piping System in a Nuclear Power Plant

3.1 Background

At a power plant that has been operating for over four decades, an oil-fired standby boiler, originally installed to provide heating to miscellaneous facilities and systems such as laundry and showers, had a change in its design requirements to also provide heating steam in certain emergency scenarios to prevent equipment freezing in the plant powerhouse.

In preparation for the changes, a thorough assessment was conducted of the existing system piping and components including the standby boiler itself and the 10" (250 mm) pipe line from the boiler all the way to the 12" (300 mm) station steam header. It was determined that the 4" (100 mm) pressure regulating valve (PRV) located immediately upstream of the tie-in point to the station auxiliary steam header was undersized to deliver the required mass flowrate, and that the steam flow from the standby boiler at full capacity would cause the PRV to choke. Subsequently, the standby boiler capacity improvement project was initiated to address the issue.

3.2 Initial Approach and Discovery of Increased FAC Risks

The scope of the standby boiler capacity improvement project included the solution to the choking 4" (100 mm) PRV as well as the necessary piping modifications to accommodate the solution. Based on operating experience and the field test conducted before the project, the standby boiler was known to have a net capacity of 47,000 lb/hr (21,300 kg/hr). However, the full amount of steam could not be delivered to the station steam header through the existing 4" (100 mm) PRV at 100% valve opening before tripping several pressure sensors at the boiler. As a result, roughly 28% of the total steam had to be discharged through a blow-off valve resulting in the delivery of only 37,000 lb/hr (16,800 kg/hr) of steam to the station header. The 3D piping system model of the PRV and the associated piping is shown in Figure 3.

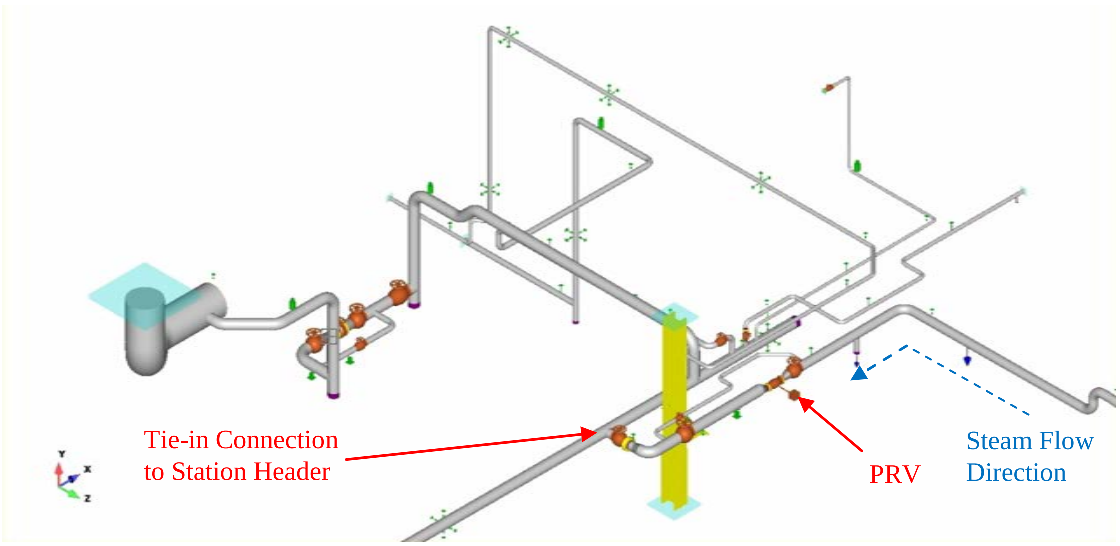

Figure 33D Model of the Affected Steam Piping System

In order to verify the field test resultsto conclude that it was indeed the existing 4" (100 mm) PRV that was causing the chocked flow,and to determine the proper sizing of a replacement PRV, several mathematical models of the steam piping system covering different case scenarios were developed using Applied Flow Technology (AFT) Arrow[10], a computer software designed to perform compressible pipe flow analysis.

Upon confirming the existing 4" (100 mm) PRV as the cause of the choked flow, the model shown in Figure 4was developed to determine the appropriate size for the PRV. The model successfully confirmed a new 6" (150 mm) PRV as the suitable replacement, and the full steam flow of 47,000 lb/hr (21,300 kg/hr) was shown to be delivered to the station steam header.

During the review stage, however, it was highlighted that the flow velocity had increased significantly in the pipes downstream of the new 6" (150 mm) PRV due to the its increasedcapacity. In the worst case, the flow velocity reached approximately 214 ft/s (65.2 m/s), which far exceeds the maximum steam velocity of 150 ft/s (45.7 m/s) recommended by ASME B31.1 for minimizing the risk of FAC for wet steam.

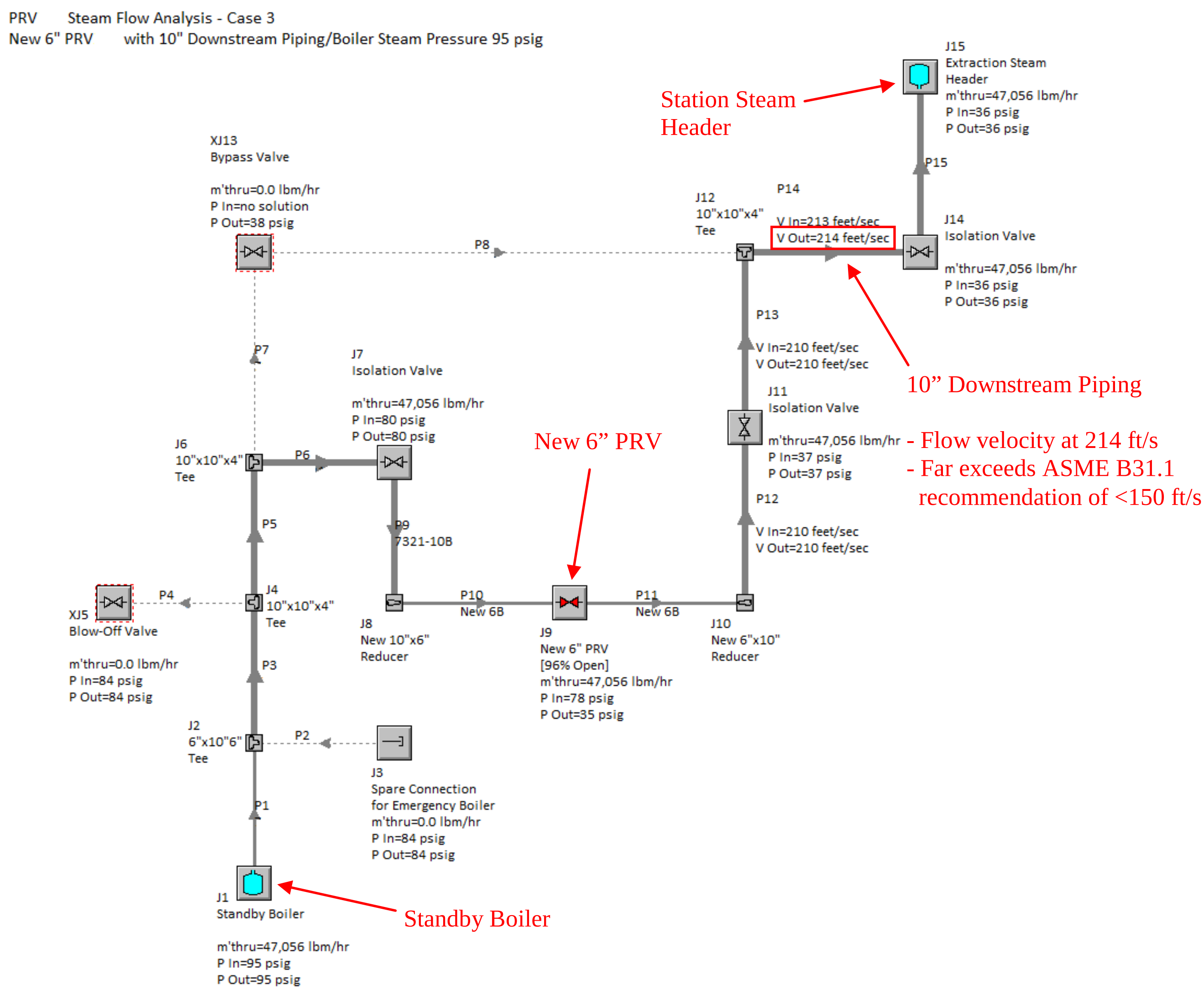

Figure 4 Initial Model and Output from the Flow Analysis performed using AFT Arrow

3.3 Mitigation of FAC Risks

According to Table IV-5.2 of ASME B31.1, the FAC rate for steam increases when the fluid velocity, fluid temperature, and steam quality are higher than 150 ft/s (45.7 m/s), between 200°F and 500°F (93.3°C and 260°C), and less than 100%, respectively. As these parameters were directly applicable to the affected system conditions, the following measures were taken to reduce the FAC risks as best possible.

3.3.1 Flow Velocity

As identified in ASME B31.1 Non-mandatory Appendix IV, the FAC rate increases when the steam flow velocity is higher than 150 ft/s (45.7 m/s). At the flow velocity of 214 ft/s (65.2 m/s), the affected steam system would experience a very high FAC rate with the new 6" (150 mm) PRV.

Coincidentally, the very case of the increased FAC rate due to locally increased flow velocity in a control valve station is presented in Section 5.4 of EPRI Recommendations for an Effective Flow-Accelerated Corrosion Program (NSAC-202L-R4)[1]. As suggested in the EPRI recommendation, the pipe diameter downstream of the 6" (150 mm) PRV was increased from the original 10" to 12" (250 mm to 300 mm).

Although the increased weight and thermal loading on the pipe supports and the station steam header introduced additional challenges to the design, they were appropriately managed and, as shown inFigure 5, the flow velocity in the model was successfully reduced belowthe threshold of 150 ft/s (45.7 m/s).

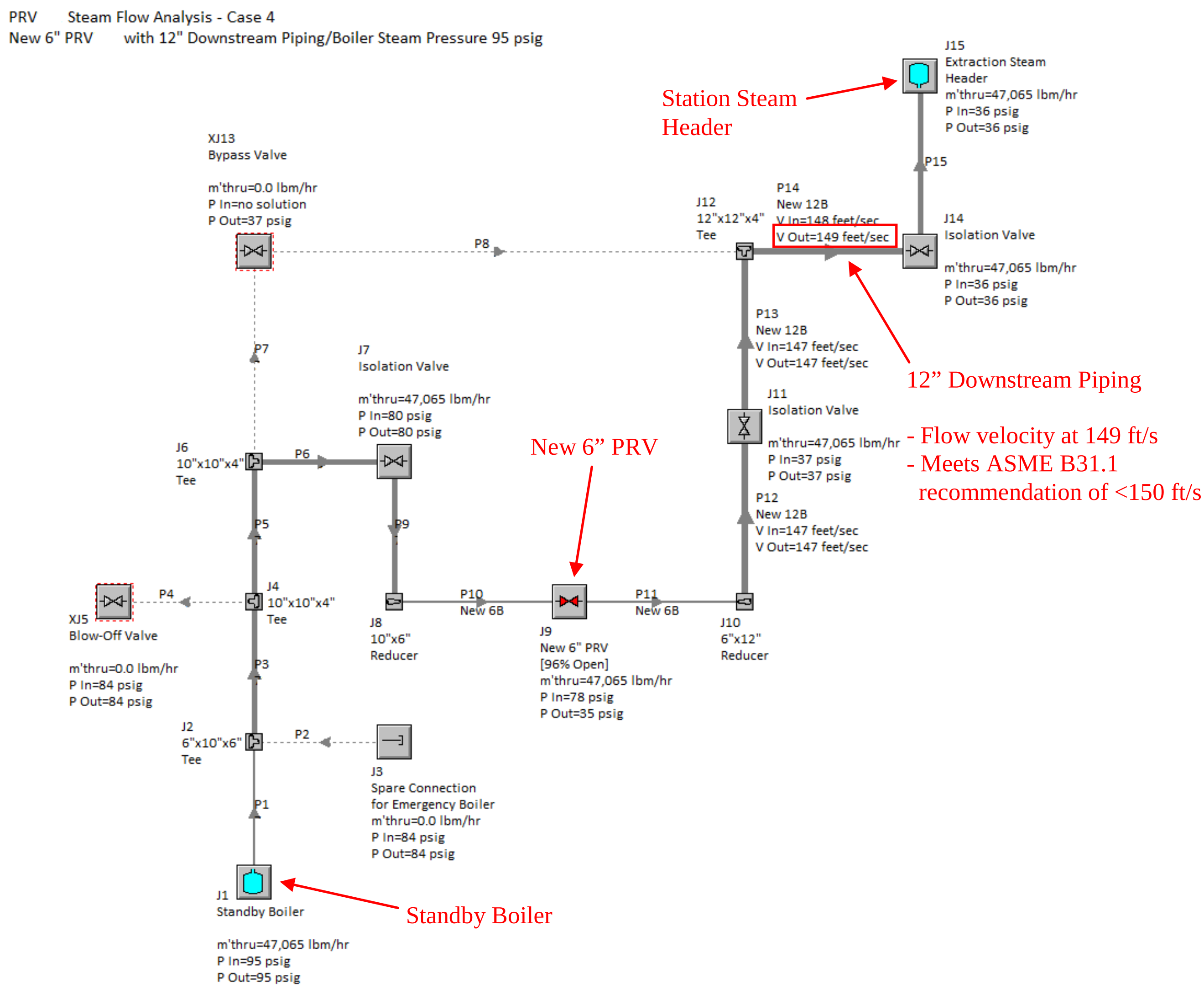

Figure 5 Final Model and Output from the Flow Analysis performed using AFT Arrow

3.3.2 Steam Quality

Another concern for potentially increased FAC risk was the quality of steam generated from the standby boiler. The boiler itself had been in service for several decades and measurements to determine the steam quality were not readily available. In order to gauge the steam quality that could be expected at the PRV, a site inspection of the system was performed, assessing the condition of the existing pipes andcomponents. Through examination of the existing system configuration such as pipe lengths, sizes of headers and branches, number and sizes of drip legs, and condition of the boiler drums, it was determined that the steam quality based on the original system condition would range between 99.0% and 99.5%.

To improve the steam quality at the PRV, the original 4" (100 mm) drip leg of 12.5" (317.5 mm) length, which was located immediately upstream of the PRV, was replacedwith a larger 6" (150 mm) drip leg of 18" (457.2 mm) length as part of the standby boiler capacity improvement project. Additionally, recommendation to re-tube and refurbish the boiler to bring it to near new performance was given to the station. After the replacement of the drip leg and refurbishment of the boiler, a steam quality in excess of 99.5% would be anticipated.

3.3.3 Inspection and Replacement of Existing Piping and Components

Before the installation of the new 6" (150 mm) PRV and associated piping, ultrasonic Non-Destructive Testing (NDT) was performed on the nearby piping, including the 12" (300 mm) station steam header, to measure the wall thickness. As recommended by Section IV-5.4 of ASME B31.1 and ASTM standards for the piping system material, the pipes were checked for having existing wall thickness of no less than 87.5% of their nominal wall thickness.

While there were salvageable portions of piping surrounding the PRV, such as the 4” (100 mm) bypass line and 1” (25 mm) condensate line, like-for-like replacement of the entire lines with new materials was performed. This practice, typically employed by utilities, would ensure that the old piping and components are not exposed to locally increased FAC rates [8].

3.4 Considerations for Project Performance

The standby boiler capacity improvement project adequately exemplifies the case of unknowingly increasing the FAC risks while trying to improve the system performance. Although the risks were appropriately managed eventually, they were discovered laterin the project, and design changes had to be made causing anincrease in project budget and delays in schedule. Also, additional analysis had to be performed and the scope of piping modification had to be expanded.

For future projects involving various carbon steel piping systems, where FAC is a concern, it is recommended that considerations be given as early as possible in theproject to minimize the FAC risks and associated impacts. Following the recommendations and guidelines discussed in this paper from the beginning of the design phase will help avoid potentialschedule delays and rework.

4. Conclusion

Flow accelerated corrosion is a chemical wear mechanism that results in wall thinning of steel piping exposed to flowing water or wet steam. Several parameters including temperature, flow velocity, material composition, and pipe geometry affect the FAC rate. In case of the aforementioned steam piping modification project, the increased FAC risks wereprimarily the result of increased flow velocity due to increased overall capacity of the system by incorporating a larger PRV. Following the recommendations from ASME and EPRI, as well as goodindustry practices, larger downstream piping was used to reduce the flow velocity.In addition, surrounding piping and components such as bypass lines, condensate lines, and drip leg were replaced with new materials of the same or higher capacity and size to improve the steam quality and to control locally increased FAC rates.

5. Acknowledgements

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