stereomicroscopy. Representative stereomicroscopic images are shown in Fig. 5. On the inner surface, scalloped surfaces and fine pits within the larger crevice were observed. These features were characteristic of microbiologically influenced corrosion (MIC). On the outer surface, the perforation measured approximately 973 µm by 517 µm.

SEM examination of the leak location was also conducted. Representative SEM images are shown in Fig. 6. Small pits within the crevice were observed, consistent with MIC. EDS analysis of a tubercle deposit sample removed from the pipe segment inner surface detected the presence of iron, oxygen, chromium, molybdenum, and silicon, consistent with iron oxide. EDS analysis of the adherent material on the pipe inner surface away from the crevice detected iron, oxygen, chromium, phosphorus, and zinc, consistent with iron and chromium oxides.

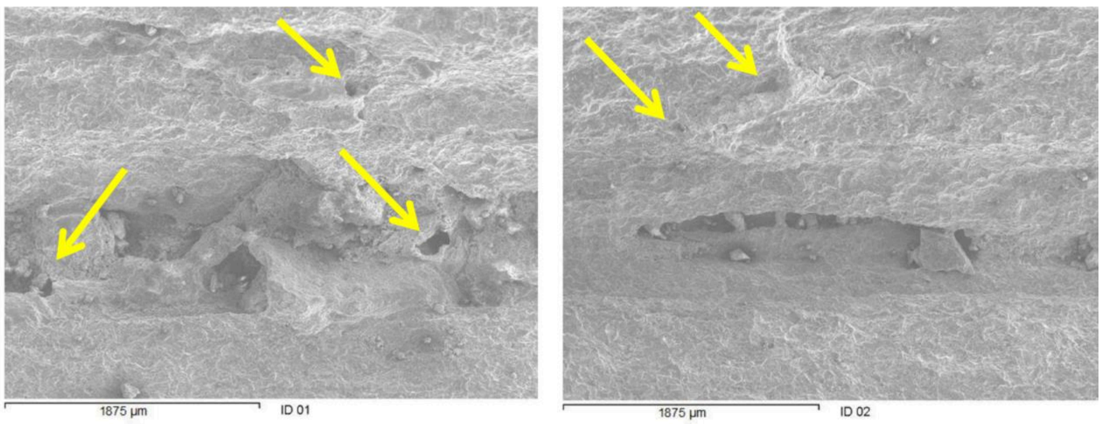

Fig. 6 Representative SEM images of the leak location on the ID surface, with pits observed in the crevice (indicated by arrows).

A specimen sectioned from the subject pipe segment was subsequently submitted for quantitative chemical analysis. The composition of the sample was determined by direct-reading atomic optical emission spectroscopy (OES). The sample composition conformed to the requirements of ASTM A53, "Standard Specification for Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless", for Type E (electric-resistance-welded pipe), Grades A and B.

A specimen at the leak location was cross-sectioned and prepared for analysis using standard metallographic preparation techniques. Within the crevice, irregular-shaped cavities were evident, consistent with MIC (Fig. 7). In the etched condition, the base metal was comprised of a ferrite-pearlite microstructure consistent with plain low-carbon steel (Fig. 8). No evidence of weld metal was observed in the specimen.

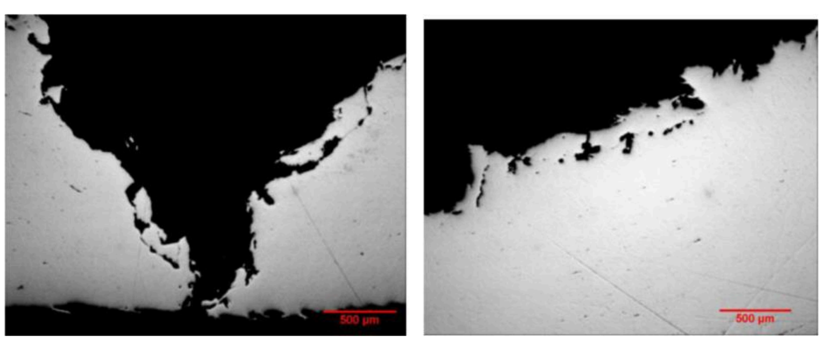

Fig. 7 Metallographic images of the perforation in the as-polished condition.

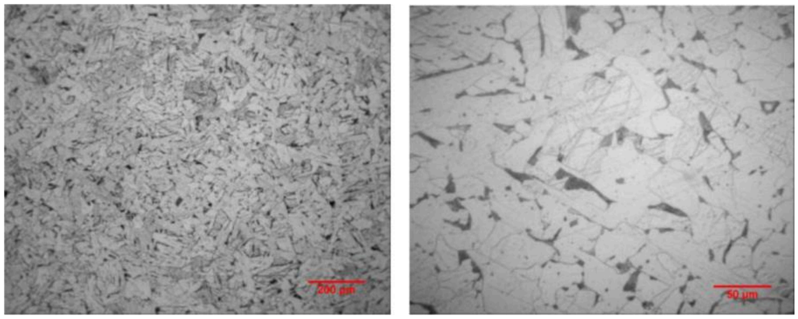

Fig. 8 Representative metallographic images of the pipe segment base metal in the etched condition.

Discussion

Results of the evaluation of the secondary water riser pipe segment indicated that the leak occurred as a result of localized corrosion attack from the inside of the pipe. A build-up of tubercle deposits led to stagnant water conditions that resulted in breakdown of the protective oxide layer at a rough feature created by a defective ERW seam and initiation of localized underdeposit corrosion attack exacerbated by microbiologically influenced corrosion (MIC). The build-up of significant tubercle deposits over time likely created localized stagnant or low-flow conditions that reduced the efficacy of chemical water treatment and intensified the MIC attack.

The corrosion degradation present on the outer surface of the pipe segment was secondary damage caused by the leak saturating the pipe insulation. The continually moist environment provided the conditions for general oxidation and pitting corrosion.

Microbiologically influenced corrosion (MIC) is corrosion caused and affected by the presence and/or activities of microorganisms [1]. Formation of inner surface deposits and localized material loss can occur as a result of the metabolic processes of the organisms, as well as due to underdeposit pitting corrosion beneath a biofilm or tubercle. Once a deposit develops, an oxygen concentration cell forms whereby the oxygen-starved region below the deposit becomes anodic to the oxygen-rich cathodic areas away from the deposit and corrosion attack proceeds at the anode. MIC has been documented to occur on carbon steels, particularly when in constant contact with stagnant, nearly neutral water (pH 4 to 9) between 50°F and 120°F [2]. Biofilms formed by bacteria can create initiation sites for pitting corrosion of carbon steels in the presence of neutral water. When present, sulfate reducing bacteria may flourish in the interior of a pit and further accelerate pitting or crevice corrosion, resulting in irregularly-shaped perforations [2].

The dimensional measurements of the pipe segment conducted away from the areas damaged by corrosion indicated that the pipe was 1-1/4 in., Schedule 40 Nominal Pipe Size (NPS). General corrosion had resulted in an approximately 7% loss of wall thickness. In the absence of the underdeposit pitting corrosion, the general corrosion rate would result in a remaining service life of more than 50 years.

EDS analysis of the adherent material away from the crevice was consistent with iron and chromium oxide corrosion products. It is likely that these oxides were protective in nature since the localized attack was evident only where this material was not present. This indicated the use of chromate corrosion inhibitors, a common method of water treatment during the early service life of the subject riser piping. Subsequent breakdown of the protective oxide layer at the rough longitudinal pipe seam resulted in localized attack of the underlying metal. EDS analysis of the tubercle deposit detected molybdenum, indicative of molybdate corrosion inhibitors typical for current chemical water treatment programs employed after the use of chromate-based regimens was banned.

Documentation provided confirmed that low-flow conditions were present in the secondary water system for more than 20 years prior to the leak. Low-flow conditions promote the formation of inner surface deposits. A pump upgrade had been completed approximately one year prior to the leak. At that time, the secondary water system had shown evidence of deposit build-up during water condition testing, and several “bleed and feed” procedures had been performed.

CASE STUDY #2 – INSULATION DEGRADATION

Experimental Details

Multiple secondary water piping segments reportedly sustained leaks after approximately 60 years in service at a high-rise residential building. The piping was part of the dual-temperature secondary water system that supplies over 1,000 perimeter HVAC fan coil units for the building. More than 100 risers run vertically inside the exterior façade of the building. The risers were reportedly originally insulated in service with fiberglass insulation held by steel tie straps. Facility representatives reported that leaks have typically occurred at steel nipples feeding 5/8 in. copper branch lines off of 2 in. steel risers. Representative samples of piping segments, including risers and branch line joints, were submitted for metallurgical evaluation.

A site inspection included an examination of riser piping and branch line joints in an apartment under renovation, as shown in Fig. 9. Remnants of fiberglass insulation were present on the riser piping, but a general lack of insulation was observed. Extensive corrosion products were evident on the exterior surfaces of the riser piping and branch line tee fittings.

Fig. 9 Riser piping and branch line joints observed during a site inspection.

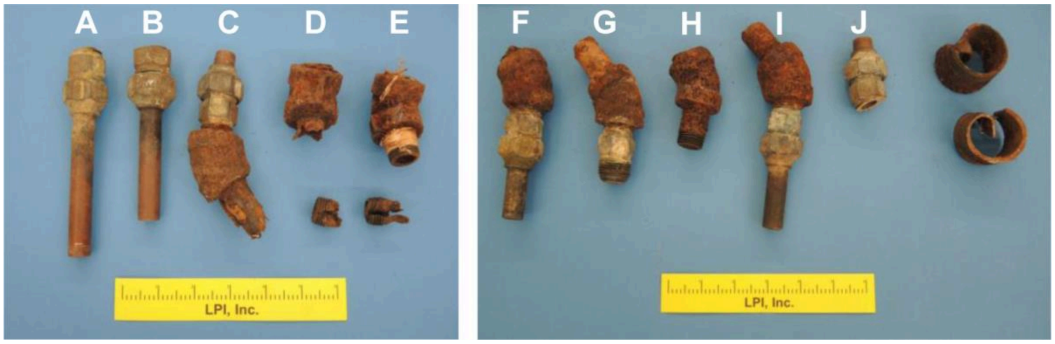

Fig. 10 Submitted branch line joints A through J in the as-received condition.

Fig. 11 Submitted riser pipe segments A through C in the as-received condition.

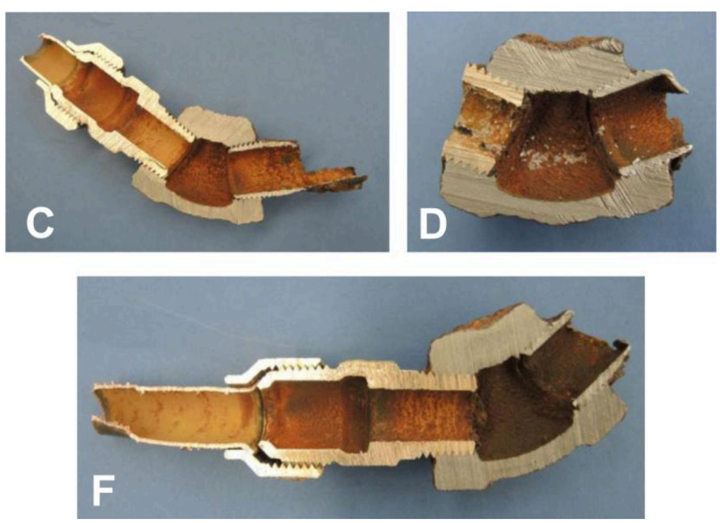

Fig. 12 Branch Line Joints C, D, and F after longitudinal sectioning to allow for examination of the inner surfaces.

The subject branch line joints and riser pipe segments submitted for metallurgical evaluation are shown in Figs. 10 and 11 in the as-received condition. The ten branch line joints were designated A through J, and the three riser pipe segments were designated A, B, and C. No markings were evident on any of the items. No information regarding their service history or location was provided. Five representative branch line joints (C, D, F, G, and I) were selected for evaluation.

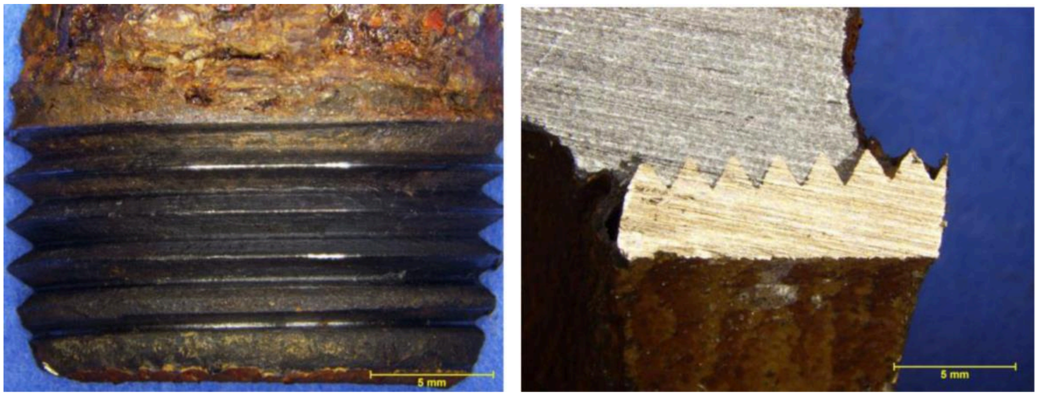

Fig. 13 Representative stereomicroscopic images of the Joint C steel pipe segment (left image) and the Joint D fitting threads (right image).

Fig. 14 Riser pipe segment B after longitudinal sectioning.

Similar conditions were observed on all five branch line joints in the as-received condition. The steel pipe segments had sustained substantial wall thickness loss, pitting corrosion was evident on the elbow fittings, and superficial corrosion was observed on the copper pipe segments and brass fittings. The appearances of the remnant portions of the steel pipe segments suggested that the material loss occurred from the external surface inward.

Joints C, D, and F were subsequently sectioned longitudinally to allow for examination of the inner surfaces. As shown in Fig. 12, the inner surfaces of the pipe segments and fittings were covered with an adherent yellow/tan corrosion product likely consistent with a protective oxide. No evidence of degradation indicative of galvanic corrosion attack was observed at any of the threaded connections. This was confirmed by stereomicroscopic examination, as shown in representative images of the Joint C steel pipe segment and Joint D fitting threads in Fig. 13.

The three riser pipe segments were similar in appearance, with extensive pitting corrosion and corrosion products evident on the external surfaces. Remnant fiberglass insulation material was present on the segments. Some of the corrosion products were friable and flaked off the external surfaces. The riser pipe dimensional measurements were generally consistent with 1-1/2 in. Schedule 80 pipe.

Portions from all three riser pipe segments were subsequently sectioned longitudinally to facilitate examination of the inner surfaces. An adherent yellow/tan corrosion product likely consistent with a protective oxide was present, as shown in Fig. 14. Tubercles were also evident on the inner surfaces of each segment. Reduced wall thickness of more than 50 percent was evident at locations of pitting corrosion attack on the outer surfaces. One half of each segment was then cleaned to remove the corrosion deposits. Evidence of shallow pitting corrosion attack was present on the inner surfaces of all three riser pipe segments, as shown in Fig. 15.

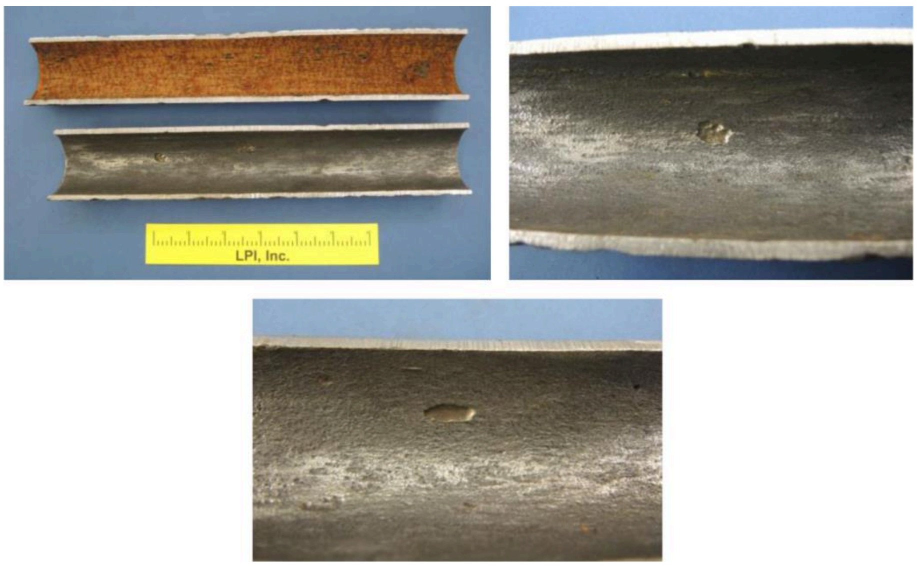

Fig. 15 Riser Pipe Segment C after cleaning.

SEM examination with EDS analysis was conducted on sectioned branch line joint and riser pipe segment specimens. EDS analysis of the adherent inner surface corrosion deposit material on the Joint D steel pipe segment detected the presence of iron, oxygen, chromium, calcium, copper, zinc, silicon, and phosphorus, consistent with iron and chromium oxide corrosion products. EDS analysis of the inner surface corrosion deposit material on Riser Pipe Segment B detected the presence of iron, oxygen, chromium, calcium, copper, zinc, silicon, aluminum, and phosphorus, also consistent with iron and chromium oxide corrosion products. It is likely that the chromium was present from prior chromate water treatment regimens which might have been employed before such treatments were banned.

Specimens sectioned from the three riser pipe segments were submitted for quantitative chemical analysis. The compositions of the samples were determined by OES. The sample composition of all three specimens conformed to the requirements of ASTM A53, “Standard Specification for Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless”, for Type E (electric-resistance-welded pipe), Grades A and B.

Discussion

Results of the evaluation of the submitted branch line joints and riser pipe segments indicated that the degradation observed was a result of general atmospheric corrosion exacerbated by localized pitting corrosion attack initiating on the outer surfaces of the steel riser pipe segments and branch line joints. Based on the appearance of the pipe surfaces, it was apparent that lack of a proper vapor barrier and/or deterioration of the insulation over time had likely resulted in condensation accumulating on the piping outer surfaces throughout the summer months when chilled water was flowing inside the pipes. None of the submitted samples exhibited any evidence of galvanic corrosion between the steel and copper/brass components.

The dimensional measurements of the riser pipe segments indicated that the pipe was 1-1/2 in., Schedule 80 NPS. General corrosion and superficial pitting corrosion of the pipe inner surfaces had resulted in approximately 21% loss of original nominal wall thickness. In the absence of the external pitting corrosion, the internal corrosion rate would result in a remaining service life of more than 50 years.

EDS analysis of the adherent material on the pipe inner surfaces was consistent with iron and chromium oxide corrosion products. It is likely that these oxides were protective in nature since the pitting corrosion observed on the inner surfaces was relatively minor. This indicated the use of chromate corrosion inhibitors, a common method of water treatment during the early service life of the subject piping.

DISCUSSION

Difficulties are often encountered in assessing the state of a secondary water piping system because most branch lines are located in pipe chases with minimal or no physical accessibility. In these cases, facilities only become aware of a problem as a result of a significant water leak. Non-destructive evaluations (NDE) can be utilized to determine if the system piping has expended its useful service life. NDE assessments typically include visual examination and ultrasonic thickness testing (UTT). Through visual examination, locations of insulation degradation can be identified. Ultrasonic thickness testing measures the remaining wall thickness through the use of an ultrasonic probe placed against the exterior surface of the pipe. Both of these assessment techniques, however, require physical access to the exterior surfaces of the piping.

Additional assessment of the piping system can be completed by sectioning and removing representative pipe segments for a destructive laboratory evaluation. This will allow for the determination of the presence and extent of deposit build-up and corrosion damage, and may identify manufacturing anomalies such as defective ERW seam welds and poor fit-up.

Pipe evaluations conducted, such as the case studies above, have definitively shown that water treatments that utilized chromate corrosion inhibitors resulted in the formation of adherent and protective chromium oxide layers that prevented significant general corrosion and localized chloride pitting attack. Condition assessments of pipe segments that had been in service for 40 or 50 years showed little to no wall thickness loss in service.

However, these treatments were banned by the 1980s, and replaced with a combination of chemicals that typically need to be used in concert and on a regular schedule to alleviate different conditions – i.e., corrosion, mineral scale growth, and microbial/biofilm growth. The chemical treatments often include soluble hydroxides, molybdates, and nitrates (as corrosion inhibitors), phosphonates (as chelating agents to remove scale build-up), and glutaraldehydes and sulfamic acids (as biocides to prevent or reduce biofilms and microbiologically influenced corrosion). If these chemicals are not utilized effectively, a relatively significant build-up of corrosion, tubercular, and mineral deposits can form in the system, and create locations of stagnant flow where localized corrosion attack can occur.

The secondary water pipe systems in many buildings are reaching the end of their effective service lives, even with excellent and consistent operation and maintenance. The buildings, however, will remain for decades. As such, decisions will have to be made regarding replacement of these systems. For buildings undergoing full interior renovations, complete replacement is a feasible task. For fully occupied buildings, this undertaking can get considerably more complicated. Abandoning perimeter risers and branch lines, with the installation of new HVAC systems and components between floor slabs, may be required.

CONCLUSIONS

Proper design and water treatment have allowed for decades of service of dual-temperature secondary water piping in commercial office and residential high-rise buildings. Many of these systems, however, have reached the end of their designed service lives as modern water treatment regimens have led to under-deposit pitting corrosion, and as insulation degradation results in the loss of an effective vapor barrier on the exterior surfaces of piping, allowing for significant corrosion attack to occur. As such, facilities will have significant challenges in the next decade as the task of replacing extensive piping systems will be necessary.

REFERENCES

[1] *CorrCompilations: Introduction to Managing Microbiologically Influenced Corrosion*, R.B. Eckert, ed., NACE International, 2015, pp. 1-10.
[2] *Principles and Prevention of Corrosion*, D.A. Jones, Prentice Hall, 1996, pp. 372-387.

Snow Loads on Air Supported Structures

Rahul Ratakonda, P.E., M.ASCE[1]

[1]Managing Engineer, Exponent Inc., 420 Lexington Ave., Suite 1740, New York City, NY 10170. E-mail: rratakonda@exponent.com

ABSTRACT

This paper presents a study of the snow load requirements per governing New York State (NYS) codes since the 1990s to present day (particularly the transition to adapting International Code Council codes in 2003), and discusses maintenance requirements for air supported structures during major snow events as outlined in various standards and by a manufacturer of air supported structures. This paper also presents a case study of a collapsed air supported structure in New York State and the snow loads for which it was designed. The author found that the design snow loads met the manufacturer's requirements and the requirements of an ASCE standard, but that they did not meet the current NYS building code requirements.

1. INTRODUCTION

Air supported structures or domes comprise of an outer flexible membrane that is supported by interior air pressure. The air pressure is regulated by a mechanical inflation system that circulates air in and out of the structure. The membrane is typically held down by reinforcing cables that are anchored to the ground or a foundation system along the perimeter of the structure. Air supported structures have been used for sports facilities and training grounds of varying sizes, from 100' by 100' areas to 500' by 250' and larger areas, in the USA since the 1980s. These structures are typically designed so that the internal air pressure holds up the membrane as well as the environmental loads that act on it (snow and wind). In the past there have been multiple collapses of these types of structures after heavy snowstorms in the state of New York as well as other states with heavy snowfalls. This paper studies the requirement of ASCE standards and NY state codes with respect to the snow load design requirements for air-supported structures, and presents a case study for a collapsed air-supported structure in NY.

2. STANDARDS AND NY BUILDING CODES

The American Society of Civil Engineers (ASCE) published a standard for air supported structures in 1996 (ASCE 17-96). This standard provides minimum criteria for the design and operation of air-supported membrane structures.

Chapter 4 of ASCE 17 states that snow loads shall be accommodated by internal pressure, snow melting, snow removal, or a combination of these methods. This section of the standard indicates that the internal pressure of the dome need not necessarily support the applicable snow loads if there are procedures or protocols in place that allow for either shedding of the snow through snow melt or the snow being removed from the dome. The standard also suggests certain methods for snow removal – water spray, vibrating the structure, scraping with ropes passed over the structure, and shoveling. The standard notes that where it is not necessary for a person to be on the membrane, removal may be the primary method and that if a person must be on the membrane to perform snow removal it shall not be the primary method.

It should be noted that ASCE-17 states that all air-supported structures shall comply with the requirements of the applicable building code(s).

Prior to 2003 the New York State Uniform Fire Prevention and Building Code had a section (803.13) which related to air-supported structures. This section states that loads and designs for air-supported structures shall be in conformity with reference standard “Air structures design and standards manual (ASI-77)” which was published by the Air Structures Institute.

ASI-77 states that snow loads on air structures shall be countered by one of three methods: (a) snow loads are countered by the internal air pressure, (b) snow will melt upon contact with the structure due to heat loss from the interior, and (c) snow accumulation in excess of the structure’s bearing capacity may be removed manually. The standard notes that the primary objective in the design of air structures for snow loads is to prevent the accumulation of heavy snow loads.

Since 2003 New York State has adopted the International Code Council (ICC) codes as a basis for the state building code. This code now governs the construction of every building or structure in New York State. Section 3102.7 of the code provides guidance on the engineering design of membrane structures (including air-supported structures) and notes that the structure shall be designed and constructed to sustain dead loads; loads due to tension or inflation; live loads including wind, snow or flood and seismic loads and in accordance with Chapter 16 of the Code. Section 1608.1 in chapter 16, which deals with snow loads, states that design snow loads shall be determined in accordance with Chapter 7 of ASCE 7 – Minimum Design Loads for Buildings and Other Structures, but the design roof load shall not be less than that determined by Section 1607. Section 1607 (table 1607.1) notes that minimum roof design live load for fabric construction should not be less than 20 psf.

The current NYS code does not use ASCE 17-96 or ASI-77 as reference standards.

3. CASE STUDY

The air supported dome (Dome) being discussed measures 270 feet by 500 feet in plan and is 82 feet tall. The membrane of the Dome is made up of two layers of Teflon-coated polyester fabric separated by a layer of insulation which prevents heat loss from the interior. The membrane is supported by air pressure that is regulated by a mechanical inflation system that circulates air in and out of the dome. The membrane is held down by reinforcing cables that are anchored to a concrete grade beam along the perimeter of the dome. Construction of the Dome was completed in 2015 and collapsed in March 2017 after a snowstorm.

In March 2017 a winter storm impacted the northeast of the United States. Heavy snowfall was recorded throughout the day. Ground snow per the National Oceanic and Atmospheric Administration (NOAA) was measured to be 22”-23” (1.24” liquid water equivalent, which equates to 6.5 psf) at the approximate time of collapse at near the Dome. The maximum and minimum temperatures on the day of the collapse were 24 and 17 degrees Fahrenheit respectively. There were 41 mph wind gusts in the northwest direction around the time of collapse.

Our review of the Dome’s mechanical management system showed that on the day of the collapse the snow mode of the system was engaged and the internal pressure was maintained at 1.9” water column (w.c.), which equates to approximately 10 psf of pressure. The temperature was maintained at approximately 65 degrees F. The graph of the return air (RA) damper, which is the opening that returns air back to the mechanical system from inside the dome, shows that around 4 P.M. the damper started to open past the normal open percentage and gradually increased till about 7:30 P.M., at which point it shut close (See Figure 1). The internal dome pressure and temperature remained at 1.9” to 2” w.c. and 65 degrees F respectively throughout