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Analysis of Failed Dry Pipe Fire Suppression System Couplings From The Filene Center at Wolf Trap Farm Park for the Performing Arts

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J. L. Fink
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Corrosion Group,
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Abstract

A detailed metallurgical analysis was performed on a number of gray cast iron couplings taken from a dry pipe fire suppression system at the Filene Center to verify the source of failure. The results of this analysis indicated that all of the specimens failed in a brittle manner due to the stresses induced by the expansion of freezing water. The available background information indicated that the ambient air temperature on the night of the failures was low enough to induce freezing in a relatively short time period. Based primarily on the appearances of the fracture surfaces provided, no evidence of failure induced by sources other than the formation of ice (i.e. a displacement of the roof support) was apparent on the specimens. Additional information regarding the previous accidental chargings of the system and the actual location of the sample with respect to the collapsed box beam are required before the definitive cause of failure can be determined.

The results of this analysis also indicate that the potential for failure of the couplings may be reduced by replacement of the gray cast iron couplings with a material which is more resistant to brittle fracture.

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Introduction

Ruptured pipe couplings were discovered in sections of a fire suppression system situated in the roof area of the theater located at the Filene Center at Wolf Trap Farm Park for the Performing Arts in Vienna, Virginia during an inspection conducted in April of 1993. The theater, which housed the fractured couplings, is an open structure and, as a result, the piping system, positioned directly underneath a soldered copper roof in the ceiling of the building, was continuously exposed to the ambient, outdoor air.(1) The system was also exposed to the prevailing winds on both the top and bottom surfaces.(1)

In 1985, one of the four major structural components of the roof, a box beam, failed resulting in a permanent displacement of the roof.(1) The magnitude of the displacement, determined by a laser measurement, was on the order of 18 inches (approx. one-half meter). The total effect of that displacement on the roof and the systems housed within remains unknown, however, the structure has since been reinforced and no further displacement of the roof has been observed.(2)

According to the fire codes for open, outdoor structures in regions where the ambient temperatures may induce freezing, suppression systems must be of a dry pipe configuration in order to minimize the potential for failures resulting from the expansion of freezing water.(3) In general, water is not present in the pipes in this type of fire suppression system until a fire is detected by a sensor in the system. When this occurs, water is rapidly introduced into the entire system, under high pressure, and dispersed through outlets in the region where fire has been detected.(3) According to the management of the facility, this particular sprinkler system was charged accidently on several occasions between 1984 and 1993 and because of its closed head design, water was not dispersed but retained in the piping until it was released through drains located throughout the system.(2) Typically, the drains in a system of this type are gravity fed and as a result, residual water may be present at the low points.(3) No information about leaking of the system during these accidental chargings was available.

In January of 1993, the system, once again, malfunctioned and, as in the case of the other accidental chargings, water was held at pressure, approximately 1.7 MPa (250 psi), within the system for a few hours.(2) Prior to draining, water was observed flowing from sections of the piping system.(2) The ambient air temperature during this period was reported to be approximately -9 °C (15 °F).

Failed samples from the fire suppression system were removed and submitted for failure analysis. These specimens included several fractured "T" couplings, elbow joints and random sections of pipe.

Problem Statement

The purpose of this report is to determine the general cause of the failure in the components of the dry pipe fire suppression system located at the Filene Center. Due to the aforementioned environmental conditions, the failures were believed to be the result of stresses induced by frozen residual water present in the system. However, a question remains as to whether the collapse of the box beam, which occurred prior to this failure, produced cracks in the piping system which subsequently led to the ultimate failure. A detailed metallurgical analysis was performed on the failed samples in order to verify the source of failure in the pipe system.

Analysis

The fracture surfaces of the as-received specimens were coated with a heavy layer of surface rust which had to be removed prior to any type of failure analysis. The solution used for this purpose was a buffered descaling solution consisting of 3 ml HCl, 4 ml 2-Butyne 1,4-Diol (35% aq.) and 50 ml H_2O.(4) The samples were immersed in the descaling solution for two minute intervals, removed, and then brushed lightly to remove the surface corrosion. After descaling, the surfaces of the fractured components were analyzed with an optical microscope. Figures 1 and 2 are low magnification micrographs which exhibit the types of failures observed on the coupling sections provided.

Sections were cut from the couplings and prepared for metallographic analysis using standard procedures.(5) The polished surfaces were analyzed in both the "as polished" and the etched conditions. A 2% solution of concentrated nitric acid in methanol (nital) was the etchant used for this analysis. Figures 3 and 4 are representative micrographs of a coupling section in the as polished and etched conditions, respectively. The microstructure is composed of graphite flakes in a pearlite matrix, and on this basis, the material was determined to be a Class 30 cast gray iron.(6,7)

In addition to the metallographic examination, a fractographic analysis was performed on the couplings. This technique was used to verify whether the fractures were ductile or brittle in nature. Figures 5 and 6 are scanning electron micrographs which exhibit the brittle-type features that were observed on all of the coupling fracture surfaces.

The optical analysis of the failed "T" couplings revealed that the stresses which ultimately produced the fractures were purely circumferential. Circumferential, or hoop, stresses are in-plane, principle stresses which occur in thin-walled, cylindrical or spherical pressure vessels.(9) In most cases where water is constricted and allowed to freeze, circumferential stresses result from the expansion of the water and failures from this type of stress generally are symmetrical about the long axis of the component.(9) In the case of the “T” couplings, casting seams were present along the long axis. In general, the seam is the weakest part of a casting and as a result, the principal cracks are believed to have nucleated in this region and propagated along the length, effectively splitting the couplings in two. This type of failure is shown in Figure 1.

The failures observed in the elbow sections were also determined to be the result of the stresses induced by the expansion of water. In these specimens, failures were observed in the “knee” region of the casting as shown in Figure 2. The radius, or knee, is typically the weakest region in an elbow fitting.

The mechanical properties of gray cast irons like the type used in the Filene Center fire suppression system are strongly dependent on the concentration and coarseness of the graphite flakes. While the graphite flakes increase the overall mechanical strength of cast iron, they tend to reduce the fracture resistance of the bulk and also act as internal notches; thereby serving as crack initiation sites.(7) Gray cast irons, in general, possess relatively low mechanical strength due to the interlaced network of graphite flakes. The interfaces between the graphite flakes and the matrix are also very weak, so once a crack has initiated in this material, little or no resistance to propagation is provided by the bulk.(7) This poor interfacial strength generally results in a brittle type of fracture along the network of graphite flakes as shown in Figure 5. Fracture of this type was observed in all of the specimens provided from the Filene Center.

In general, fractures can be classified into two categories, ductile and brittle. A ductile fracture is characterized by an appreciable amount of gross deformation prior to and during the propagation of a crack. Also, evidence of plastic deformation is normally present on the fracture surface.(10) In contrast, brittle fracture in a metal is identified by a separation which occurs normal to the axis of tensile stress resulting from a rapid crack propagation that produced no observable gross deformation.(10) The tendency for brittle fracture in iron alloys is very dependent upon temperature; showing a marked increase with decreasing temperature and in the vicinity of a notch (e. g. the interface between the matrix and graphite flakes).(10) In some materials, brittle fracture occurs along specific crystallographic planes.(10) This particular type of brittle fracture is known as cleavage and the characteristic features of a cleavage fracture are flat facets similar to those shown in Figure 6. The results of the fractographic analysis indicated that the fractures were completely brittle in nature and composed mostly of cleavage. No deformation indicative of a ductile type fracture was observed anywhere on the surfaces analyzed.

Summary and Recommendations

Based on the results of the analyses performed on the failed couplings and on the limited amount of information available, it was concluded that the specimens provided failed by brittle fracture mechanisms caused by stresses induced by the formation of ice. However, more details pertaining to the previous accidental chargings of the system and the actual location of the samples with respect to the collapsed box beam are required before the definitive cause of failure can be determined.

The background information indicated that the ambient air temperature on the night the ultimate failure occurred was sufficiently low to induce freezing in a relatively short time period. After the accidental charging of the system occurred, the combined circumferential stresses induced by the nominal water pressure in the pipe and by the expansion by the freezing water simply exceeded the mechanical strength of the iron castings. This resulted in the initiation of brittle cracks in the couplings. Once initiated, these cracks ran unimpeded through the weakest regions in couplings, resulting in a catastrophic failure of the components. Based on the appearance and location of the fracture surfaces provided, no evidence of cracks induced any means other than those resulting from the freezing of water was observed.

The results of this analysis also indicate that the potential for catastrophic failure of the couplings within this fire suppression system may be reduced by a total replacement of the gray cast iron couplings with a material which is more resistant to brittle fracture. Some carbon steel alloys may be suitable for this purpose. The best recommendation to alleviate this problem is to remove all of the water from the system. More drains located in the key low points throughout the system could reduce the amount of residual water substantially .

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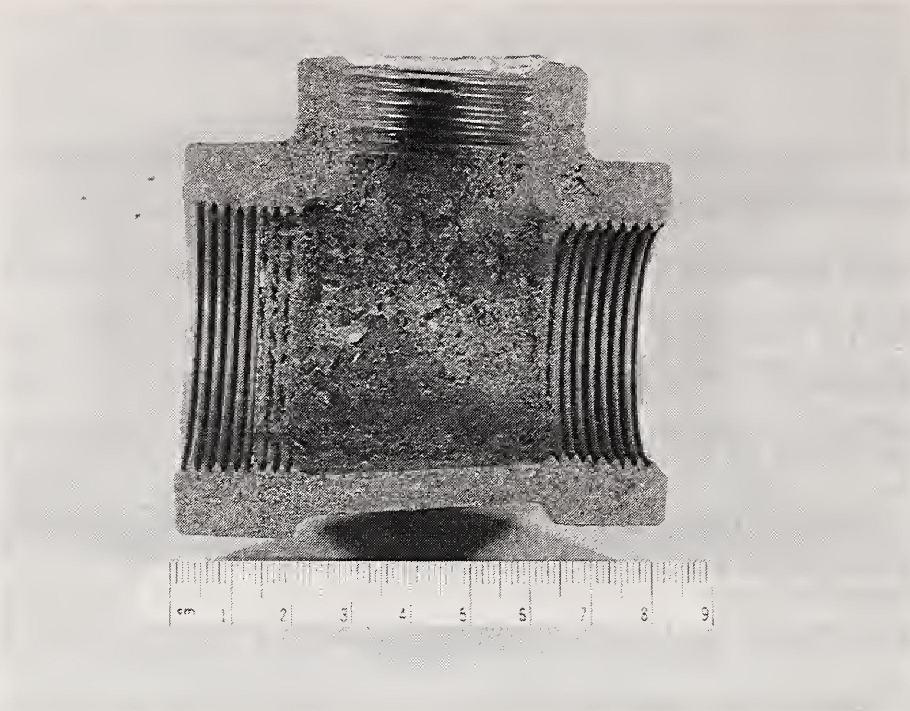

Figure 1 Optical micrograph showing a brittle fracture along the casting seam of a failed cast iron coupling taken from the Filene Center.

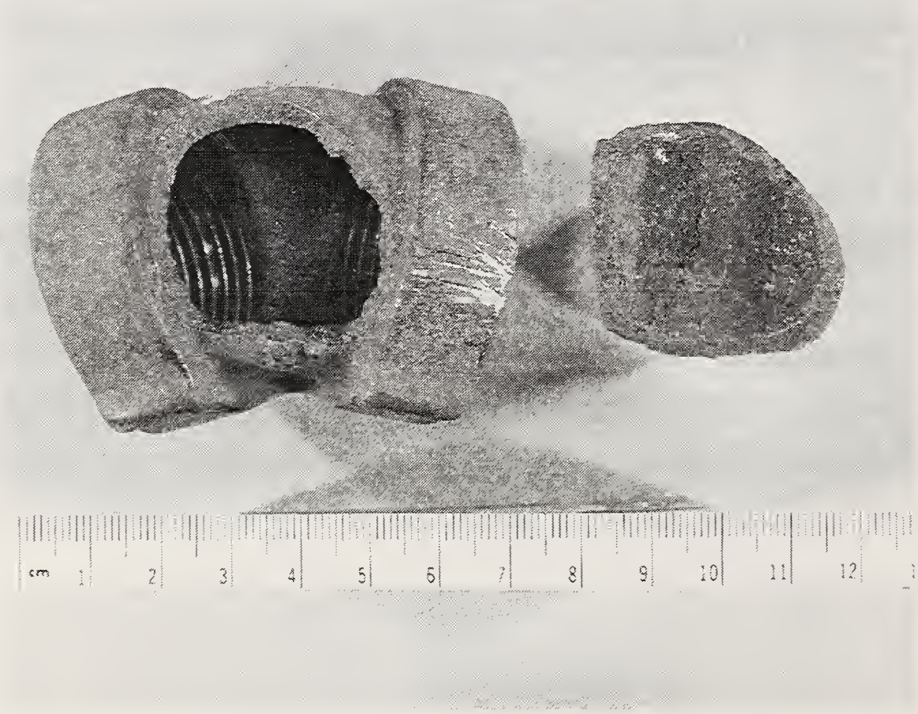

Figure 2 Optical micrograph showing a brittle fracture located in the radius of a failed cast iron elbow taken from the Filene Center.

Figure 3 Optical micrograph in the "as polished" condition showing the microstructure of a failed cast iron coupling taken from the Filene Center.

Figure 4 Optical micrograph showing the graphite flakes in a pearlite matrix microstructure of a failed cast iron coupling taken from the Filene Center . Etchant: 2% nital

Figure 5 Low magnification scanning electron micrograph showing brittle cracking along the graphite matrix interfaces on a fracture surface taken from a failed cast iron coupling at the Filene Center.

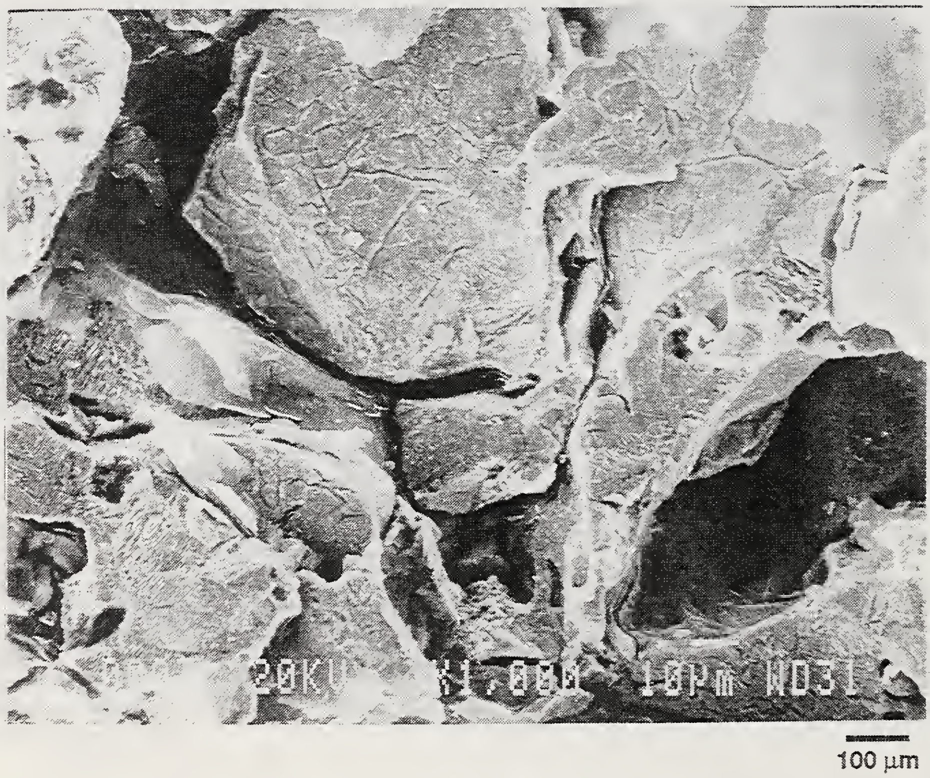

Figure 6 High magnification scanning electron micrograph showing the observed cleavage facets on the fracture surfaces taken from failed cast iron couplings at the Filene Center.