ABS Consulting
RISK CONSULTING DIVISION

Report No.
1763931-R-001
December 18, 2007

July 18, 2007
Steam Incident Investigation at East 41st Street and Lexington Avenue New York, NY

Prepared for:
Consolidated Edison Company of New York, Inc.
New York, NY

Prepared by:
ABS Consulting
Northeast Area Office
Stratham, NH

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EXECUTIVE SUMMARY

The cause of the steam pipe rupture that occurred on July 18, 2007 at East 41st Street and Lexington Avenue (the Incident Site) was an excessive internal pressure that resulted from a waterhammer. A waterhammer is a rapid pressure shock inside a pipe caused by violent interaction of steam and cooler water.

Small amounts of water are normally present in the pipe as steam condenses into water from heat losses to the surrounding environment. The water formed inside the pipe is called condensate. Condensate is removed from the steam pipe by devices called steam traps. Drain piping removes condensate from specific sections of the steam network to the steam traps. Condensate from the steam traps is discharged to the sewer system. For the section of piping associated with the Incident Site, condensate from approximately 912 feet of steam main drained to a low point on the west side of Lexington Avenue. A drain pipe removed condensate to a steam trap station, consisting of two steam traps, which provided redundancy and additional margin above the expected condensation rates during normal operation.

A heavy rain occurred on the morning of July 18 in Manhattan, with a peak rain intensity of approximately 0.85 inches/hour as measured at Central Park for the period from approximately 7:00AM to 8:00AM. Total accumulation was 1.59 inches during a five-hour period from 6:00AM to 11:00AM. At the intersection of 41st Street and Lexington Avenue on the morning of the event, water accumulated beneath the street outside the pipe. It flooded the manholes and steam pipe housing across Lexington Avenue and west of the intersection, where the low-point drain was located.

A post event investigation revealed that the pipe housing at the 41st Street and Lexington Avenue intersection had exhibited a history of flooding during periods of heavy rain. External water sources were investigated. Potential flooding sources were identified as direct and in-direct infiltration from the adjacent northwest catch basin, a rise in the local water table during the rain event, possible pressurization of the sewers under heavy rain conditions, and potentially leaking water mains, increasing the elevation of the water table.

The external housing and manhole flooding caused very rapid condensation inside the pipe. The condensate that formed built up and filled the pipe. This eliminated steam flow in the pipe at this location in the steam distribution network. The condensate remained inside the pipe below the intersection until late in the afternoon, during which time the condensate temperature dropped below the temperature of the steam.

Just before the pipe rupture, routine system adjustments, including the movement of valve CV-3 and a reduction in steam output to match demand, resulted in the steam flow in this region entering the cooled condensate that had collected in the pipe at the Lexington Avenue intersection. This initiated a condensation induced waterhammer.

A condensation induced waterhammer occurs when a steam bubble enters a region of somewhat cooler condensate and becomes trapped. The steam in the trapped bubble condenses to water very rapidly and creates a void — a space where the bubble previously existed. The normal pressure of the steam causes the surrounding condensate to rush to fill the void left as the steam bubble collapses. The rushing condensate mass impacts itself and creates a large pressure pulse in a fraction of a second. The steam's normal pressure is approximately 160 pounds per square inch (psig). The pressure pulse resulting from a waterhammer can be as large as 1,000 to 2,000 psig.

The pressure pulse was transmitted through the condensate filled portion of the pipe with a pulse velocity equal to the speed of sound in water, which is approximately 4,000 feet/second. As the pressure pulse traveled through the condensate, the pipe was pressurized and stresses were induced into the pipe wall. The combination of internal pressure loading and stresses generated as the pressure pulse traveled through the bend region at the east side of the intersection resulted in the pipe stress exceeding the strength of the material. This caused the pipe to rupture.

After a monitored cleanup and evidence gathering process, the failed section of piping was removed for detailed examination. The examination confirmed that the rupture resulted from over pressurization of the pipe. Tests also showed that the piping had appropriate strength for normal operation, with appropriate safety margins, per industry piping design standards. The pipe was in good condition with only superficial corrosion of the pipe outer and inner surfaces. The age of the ruptured pipe, which had been installed in 1924, did not contribute to this event. Based on metallurgical tests to determine the actual pipe strength, coupled with the results of detailed pipe stress analysis, the magnitude of the pressure pulse needed to cause the rupture was a minimum of 1,060 psig. This pulse is above the normal operating pressure of approximately 160 psig, resulting in a total applied pressure of approximately 1,200 psig.

Both steam traps removed and examined after the event were substantially clogged with debris. This blockage reduced the traps' ability to remove condensate from the steam main. Debris material from one of the steam traps draining the pipe was identified as predominantly a Phenolic resin material with small quantities of iron oxide corrosion type products.

Phenolic resin was the main constituent of the compound used for sealing steam leaks at gasketed joints such as pipe or valve flanges. A steam pipe flange approximately 20 feet east of the drain line had been sealed in the past to control steam leaks. The last time the flange was leak sealed was March 14, 2007. Leak sealing can be performed either with the steam main in operation or shut-down and depressurized. The leak sealing operation that took place in March 2007 was performed with the steam main shut-down. During the subsequent turn-on, blow-off and trap bypass valves were opened, purging the steam main and trap lines to clear condensate and debris. It is likely the Phenolic resin debris was pumped through the flange and migrated from the flange location to the steam traps at some time after the March 14 leak sealing operation.

Post-event review of security camera images on the morning of July 18 show vapor was visible from a steam flange manhole located within the Lexington Avenue intersection. This indicates the pipe was hot, steam was flowing in the pipe, and external water was contacting the outside of the hot pipe. Vapor was not visible after approximately 10:05 AM, indicating the pipe was full of water and that steam flow had stopped.

A Con Edison "vapor patrol" surveyed the intersection at approximately 11:30 AM. Con Edison identifies external water in contact with steam mains by observable vapor at the street level. When the vapor patrol surveyed this location, no vapor was observed nor was flooding identified. Con Edison did not receive any notification of vapor issues from the public for this location on the day of the event.

An extensive evaluation of condensate generation and cooling, system flows, waterhammer pressures, and the resulting pipe stresses was performed to define the conditions needed to produce this event. The primary causal factors that contributed to this event were:

1. Flooding of the steam pipe at 41st Street and Lexington Avenue occurred due to heavy rain and external water infiltration, which resulted in significant condensate generation exceeding the steam traps' capability.
2. Leak sealant application in the adjacent pipe flange resulted in the sealant material migrating and compromising the steam traps' ability to remove condensate.

The combination of these two primary causal factors produced the conditions that led to the waterhammer and subsequent pipe rupture.

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1.0 INTRODUCTION

A steam main rupture occurred on July 18, 2007 at approximately 5:56 PM at the intersection of East 41st Street and Lexington Avenue in New York City. The steam main at this location is a 20-inch diameter pipe running east-west along 41st Street, incorporating a lower elevation section as it crosses beneath the Lexington Avenue intersection ("Incident Site"). The steam main rupture created an approximately 32 foot by 32 foot by 16 foot deep crater in the intersection, sending steam, water and debris into the intersection and surrounding area. The rupture occurred in a rising pipe bend section on the east side of Lexington Avenue. The steam distribution piping at the intersection is depicted as Figure 1-1 [1][1].

Consolidated Edison Company of New York, Inc. (Con Edison) owns the system, which contains 105 miles of steam piping, extending from Manhattan's southern tip to 96th Street and 89th Street on the west and east side, respectively. The system is networked, with steam supplied from seven available steam generating stations; individual customers receive steam from the network through steam mains and smaller piping located beneath city streets. An elevation view of the piping beneath the Lexington Avenue intersection, including an approximate profile of the crater, is included in Figure 1-2; a photo of the crater debris follows in Figure 1-3.

This report investigates the sequence of events leading up to the incident and develops the causal factors precipitating the steam pipe rupture.

[1] Numbers appearing in brackets [xx] refer to numbered reference items in Chapter 6.0

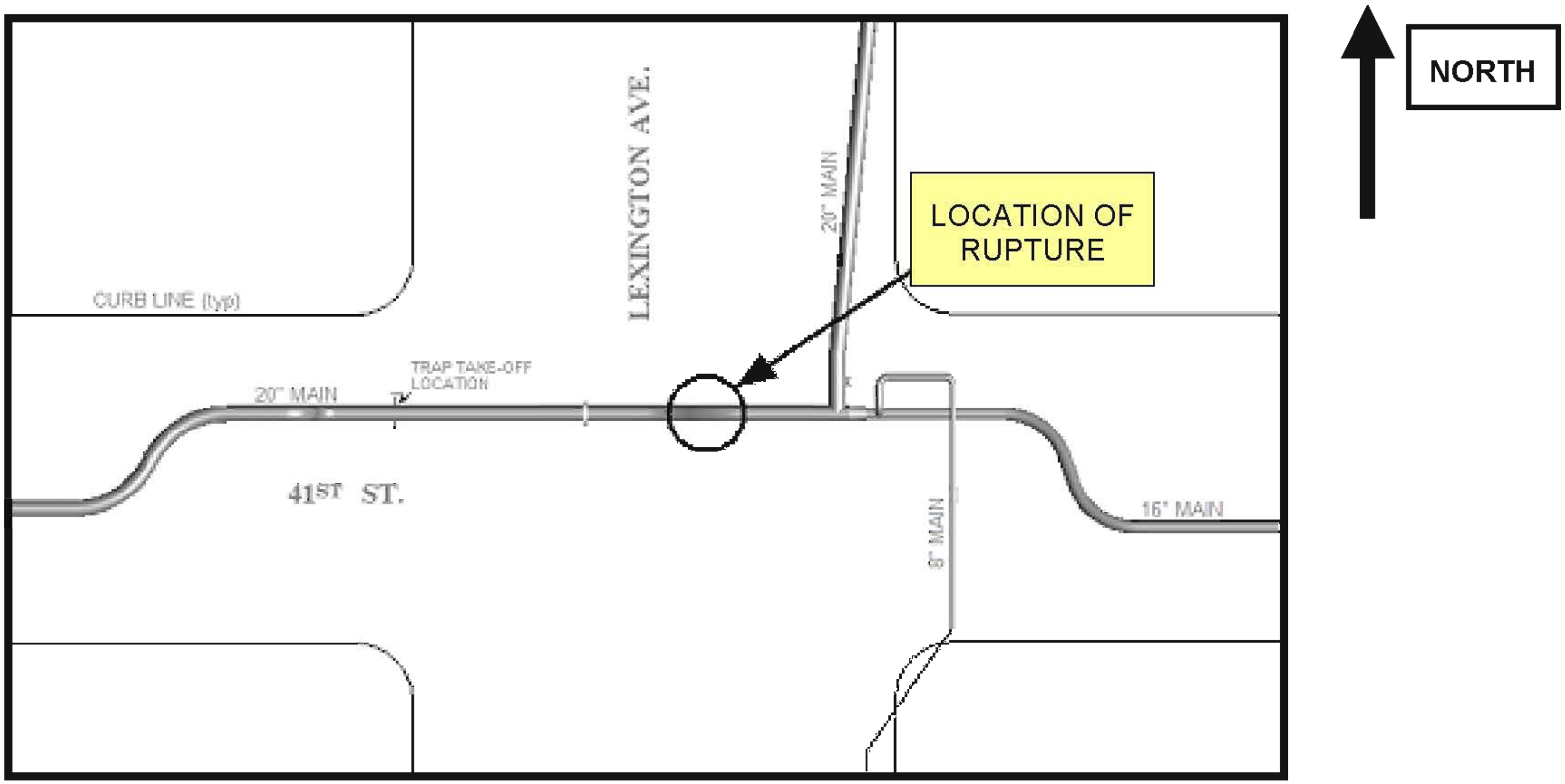


Figure 1-1: Plan View of Steam Main Configuration at Incident Site

(Rupture location is in a vertical plane bend; referred to as a "File 3 bend", see Figure 1-2 for elevation view)

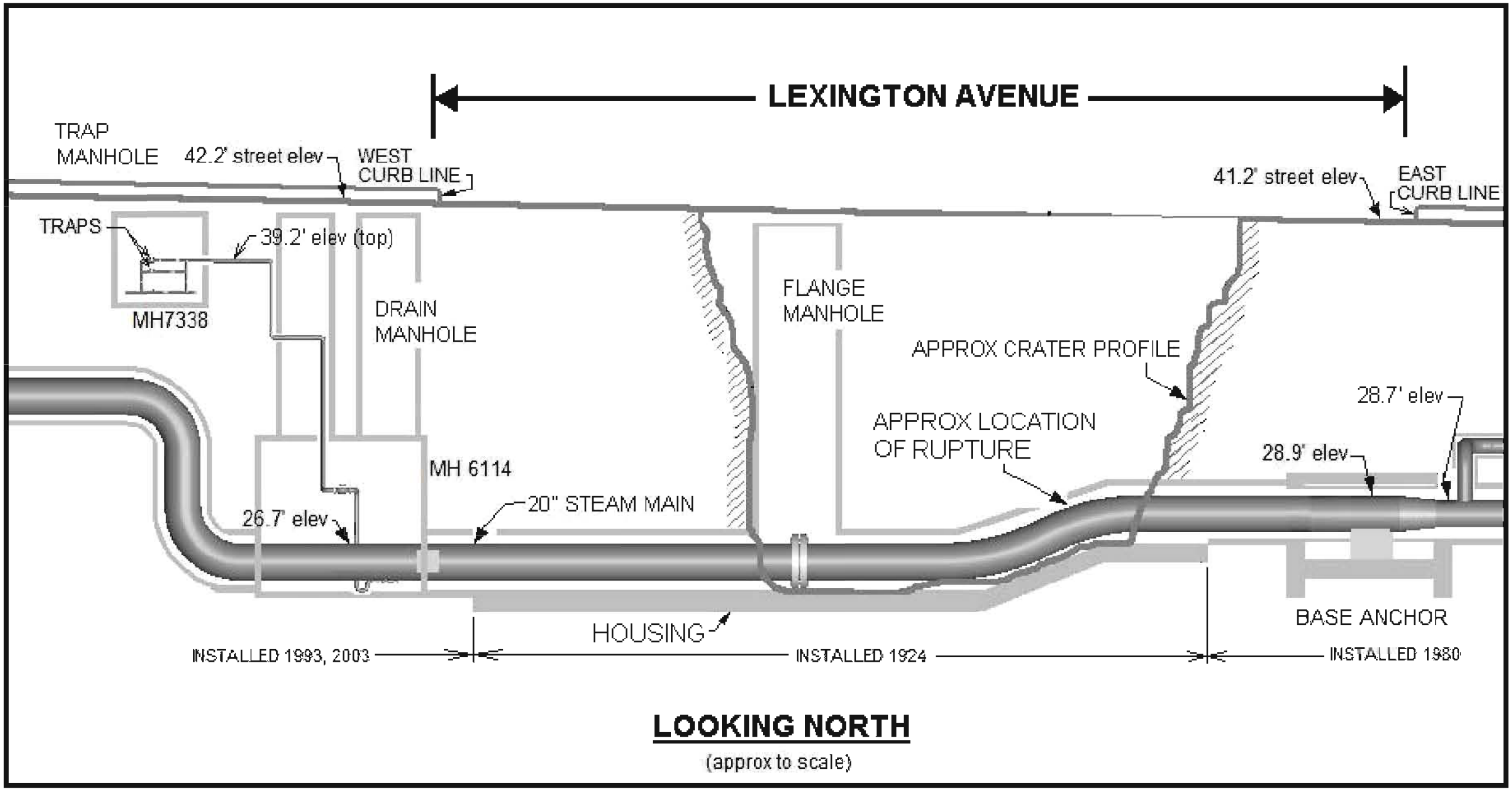


Figure 1-2: Elevation View of Steam Main Beneath Lexington Avenue
(Identified elevations are based on Manhattan datum)

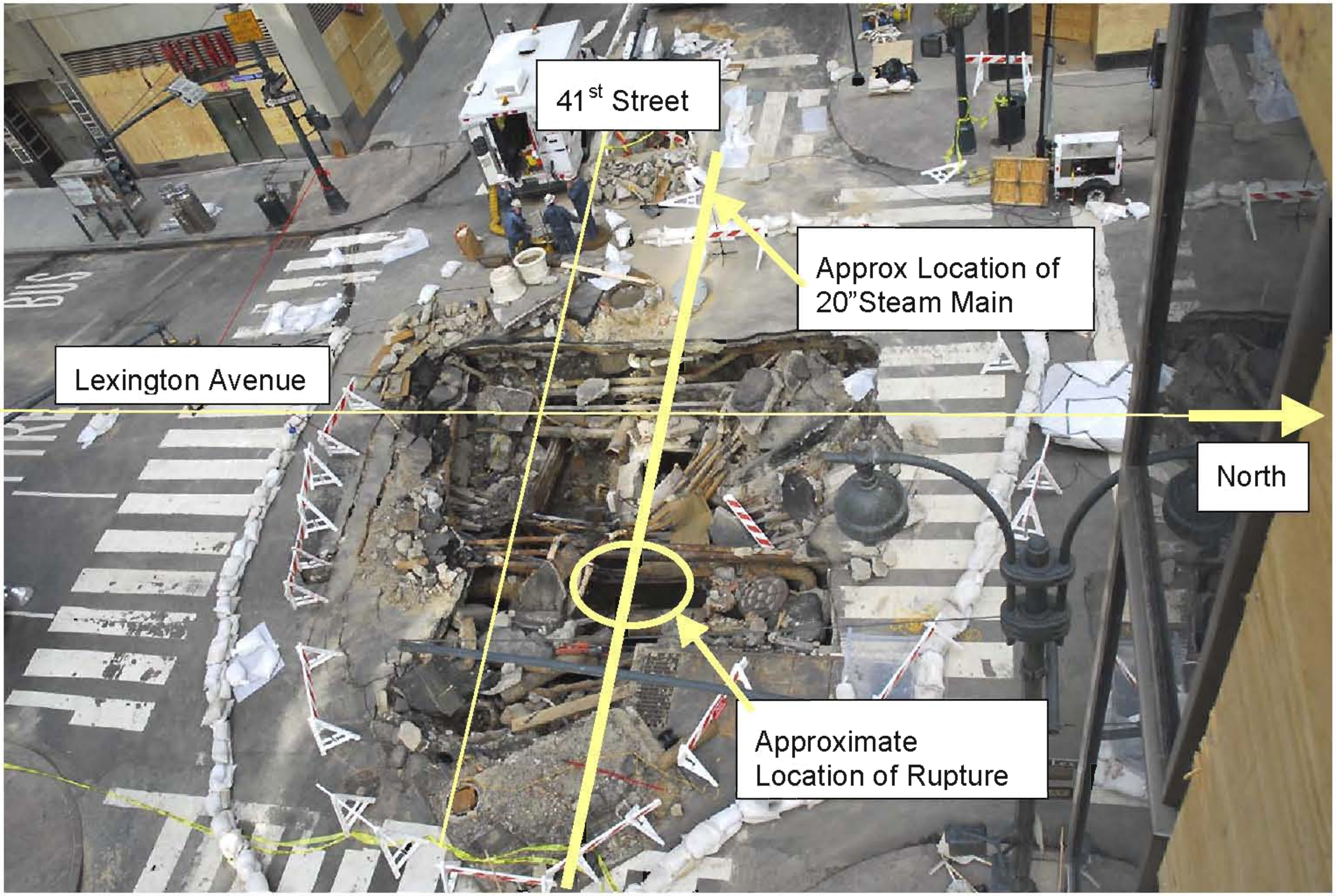


Figure 1-3: Image of Crater During Debris Removal

2.0 DESCRIPTION OF THE INCIDENT AREA AND PRE-EVENT CONDITIONS

This report section provides details of the steam distribution system's construction, the steam main piping, condensate drainage methods and steam system flows.

2.1 Steam Main Housing Construction

The steam distribution piping within Manhattan is generally constructed within a concrete, steel pipe or clay-tile housing and is buried below street level (see Figure 2-1). Clay tile housing surrounded the steam main at Lexington Avenue and 41st Street.

An air gap surrounded the insulated pipe within the housing. Insulation thickness for the 20" diameter steam pipe at the Incident Site was 1.5" to 2". Between housing runs, reinforced concrete manholes accommodate steam main drainage locations, system valves, flanges and expansion joints. A flange manhole was located approximately mid-point within the Lexington Avenue intersection, and twenty feet west of this manhole was drain manhole #6114, where the low point drain was located (see Figure 1-2).

2.2 Piping Physical Description

Piping across the Lexington Avenue intersection was installed in 1924. Modifications in 1980, 1993 and 2003 replaced portions of the system east and west of the intersection as identified on Con Edison steam plate drawings [1], and depicted in Figure 1-2.

The 1924 steel piping utilized flanged end fittings to enable field connections during original steam main construction. As sections of the steam mains were replaced, flange connections were removed and pipe section connections were made using a pipe butt-welding process. The east end of this section was welded when a newer pipe was installed in 1980.

A remaining flange connection was located in a manhole near the center of the intersection, as shown in Figure 1-2. This flange connection had experienced steam leakage and was previously repaired by injecting leak sealant (described further in Section 2.8).

A drawing of the failed pipe bend is shown in Figure 2-2. This type of pipe bend is referred to as a File 3 bend, based on the drawing identification numbers for these components. The typical manufacturing method in the 1920's for this pipe bend type is a seam-welded pipe. Two seam welding methods were typically used: lap welding and butt-welding. Lap welding was commonly used for piping greater than 2" diameter and butt-welding for smaller diameter pipes. The lap-welded method was used for this piping. Few standards existed at the time for steel pipe properties, but the pipe material metallurgical properties were consistent with 1920s and current day pipe materials such as the ASTM A-53 pipe standard [8, 13].

2.3 Pipe Drainage

The local low point under Lexington Avenue (at the drain manhole location as shown on Figure 1-2) provided a collection point for steam pipe condensation for a piping region encompassing portions of 41st Street to the east and west and Lexington Avenue to the north and south.

Steam main service plates [1] and other drawings [2, 3] for the intersection area were reviewed to determine the pipe lengths draining into the intersection. Figure 2-3 provides an elevation of the piping for 41st Street, looking north, and Figure 2-4 provides a view for Lexington Avenue, looking west. The elevations (with the vertical scale exaggerated relative to the horizontal scale) show the piping high points (crown points), near the Incident Site. These crown points define the flow direction of the condensate generated in the pipe.

The total length of pipe draining to this location was 912 feet [1]. Most of the piping was 20" diameter but also included 16" (to the east), and 8" and 6" pipe (to the south).

The pipe drain location was within drain manhole #6114 on the intersection west side. Condensate was collected in a configuration typically referred to as a “fish-mouth” type drain, consisting of a 3″ pipe cut horizontally into the bottom of the 20″ steam main and oriented perpendicularly to the main pipe. A 2″ diameter pipe carried condensate through a small loop-seal and then up to trap manhole # 7338A (See Figure 2-5). Two 1″ Gestra model DK-57H steam traps were installed in this trap assembly.

The pipe’s condensate generation rate draining to these traps under normal conditions was approximately 400 lb/hour of condensate [4].

2.4 Trap Capacity, Testing and Replacement

The two installed traps were designed to remove up to approximately 3,700 lb/hour of condensate (two traps combined) at 160 psig steam main pressure in the as-installed piping configuration. This provided a significant margin of safety (nearly ten times) for condensate removal under normal conditions.

These traps operate by water flashing to steam as it passes through the trap. The only moving part is the disc above the flat seating face inside the cap (see Figure 2-6). On start-up, incoming pressure raises the disc, and condensate is immediately discharged from under the disc, and out through three outlet ports. Steam flowing through the inlet passage into the chamber under the disc drops in pressure and moves at higher velocity than the condensate. This high velocity creates a low-pressure area under the disc, drawing it towards its seat. At the same time, the steam increases the pressure inside the chamber above the disc, forcing it down against the ring below it until it seats. At this point, the steam is trapped in the upper chamber, and the pressure above the disc equals the pressure being applied to the underside of the disc from the inner ring. However, the top of the disc is subject to a greater force than the underside, as it has a greater surface area. Eventually the trapped pressure in the upper chamber decreases as the steam condenses. The now higher system pressure below the disc raises the disc and the cycle repeats.

The traps at this location were replaced with new traps in December 2006 following an inspection that found the prior traps "blowing" or freely passing steam [9]. The new Gestra traps replaced two Sarco model TD-52, 1" thermo-dynamic steam traps. Gestra model DK57H were the traps utilized at the time of the replacement.

Based on a review of Con Edison's Steam Operations Mapping Information System (SOMIS) records for work on the trap assembly at 41st St. and Lexington Avenue, the traps were inspected on June 8 and again on June 10, 2007, following a Main Shut Off (MSO) (See Section 2.9). These inspections were "functional tests", in which trap cycling was verified by listening for the noise of disc movement (a "clicking" sound produced as the disc lifts into the cap and reseats) [10]. The next prior trap test was on April 9, 2007 and was called an "efficiency test" [10]. This test involved opening of the trap downstream outlet valve to observe steam and condensate flow as the trap cycles. While not quantitative, these tests both indicated that the traps were operating and passing condensate prior to the event.

2.5 System Flows

Depending on customer demand and steam send-out operation, the piping segment under Lexington Avenue can experience steam flow in either a west to east or east to west direction.

A steam main network arrangement plan, local to the Incident Site, is shown in Figure 2-7. On a typical day, steam from the intersection west side was provided primarily from the East River Generating Station, located at East 14th Street, with steam traveling up along Park Avenue. Steam from the east and north can come from various east side locations. Steam piping to the south of the intersection consists of 8" and 6" diameter piping supplying two customers.

The steam distribution system utilizes a number of pressure sensing telemetry stations to record pressure at various locations in the steam network. These pressure telemetry data points were evaluated for July 18, 2007. System pressures for the entire day of July 18 up to the time of the event varied between approximately 150 psig and 170 psig. This is within the normal operating pressure ranges, and there were no unusual pressure excursions.

Pressure indication also is available at specific customer locations local to the Incident Site, shown in Figure 2-7. These data were used to evaluate differential pressure (DP) across the 41st Street and Lexington Avenue intersection. System differential pressures between 10:00 AM and 5:56 PM are shown in Figure 2-8. From approximately 10:00 AM through 5:30 PM, the DP between the pressure gauges bounding the intersection was below approximately plus or minus 1 psi (the largest pressure differential was east to west with a magnitude of approximately 1.2 psi). Within the one-hour period prior to the event, normal steam operational changes were occurring with a control valve repositioning (designation CV-3 approximately 30 blocks south). This valve position change would send more steam from the East River Generating Station to uptown locations. As this valve was closing, between approximately 5:15 PM and 5:45 PM (refer to valve position on Figure 2-8), a differential pressure of approximately 3 psi was generated across the intersection, with higher pressure on the west side.

The steam customer on Lexington Avenue, south of the intersection, was interviewed to determine if the customer had a steam supply interruption during the afternoon of July 18, 2007. This customer, who receives steam through the 8" steam take-off on the east side of Lexington Avenue as shown in Figure 1-1, reported no interruption [5]. This was confirmed based on a review of the customer's pressure chart, Figure 2-9, which shows normal system pressure up to the time of the incident. This confirms Lexington Avenue customers south of the intersection did not lose steam through the time of the event.

2.6 Rain Information

During the morning of July 18, 2007 a heavy rain occurred in Manhattan, with a rain intensity of approximately 0.85 inches/hour for the hour period from approximately 7:00AM to 8:00AM and an accumulation of 1.59 inches for the five-hour rain duration as measured at Central Park (see Figure 2-10). Rainfall data for the incident date were assessed relative to similar rainfall intensity and accumulation over the preceding 3-1/2 year period. The data is depicted in Figure 2-11.

For this period, there are only ten days with similar or higher rainfall intensity and accumulation, as summarized below [6, 7]:

Date	Rainfall Intensity (inch/hr)	Rainfall Accumulation (inches)
07/18/2007	0.85	1.59
04/27/2007	0.79	2.04
04/15/2007	1.19	7.57
08/10/2006	1.9	2.51
07/21/2006	0.84	1.95
06/02/2006	1.46	2.79
10/8/2005	0.89	4.26
08/14/2005	1.73	3.01
07/06/2005	1.33	1.52
09/18/2004	1.15	2.19
09/08/2004	1.76	3.77

2.7 Manhole Pumping and Vapor History

A history of vapor and pumping occurrences at the 41st Street and Lexington Avenue intersection was developed based on a review of SOMIS. Review of these records over an approximate four year period indicate vapor was detected and the intersection manholes were pumped 3 to 9 times per year corresponding with high rain accumulation days.

2.8 Flange Leak Seal Injection History

The flange located in the manhole at the mid-point of the Lexington Avenue intersection has experienced steam leakage and had been sealed approximately ten times by injection of a leak sealant material since July 2005. An assessment of the number of leak seal activities and the corresponding amount of injected material was developed from invoices from the vendor performing the work and through a review of SOMIS entries. Leak sealing is a technique used by many industries as a method to seal leaks at flange gasketed surfaces. A specialty vendor is utilized to perform these activities.

A variety of products were used to seal this flange. The base of all the products used was a Phenolic resin material.

The last flange leak sealant injection was performed on March 14, 2007 with the steam main depressurized. During the subsequent turn-on, blow-off and trap bypass valves were opened, purging the steam main and trap lines to clear condensate and debris.

2.9 Recent Relocation of 8" Customer Main

A recent steam main modification in the rupture vicinity was relocation of the 8" customer main providing steam to customers on Lexington Avenue, south of the Incident Site. The new and revised piping configuration is shown in Figure 2-12. This work was completed and the main re-pressurized on June 10, 2007. Before the traps were placed into service, the blow-off and trap bypass valves were also used to purge condensate and debris from the steam main and trap lines.

2.10 Infrastructure in the Region of the Incident

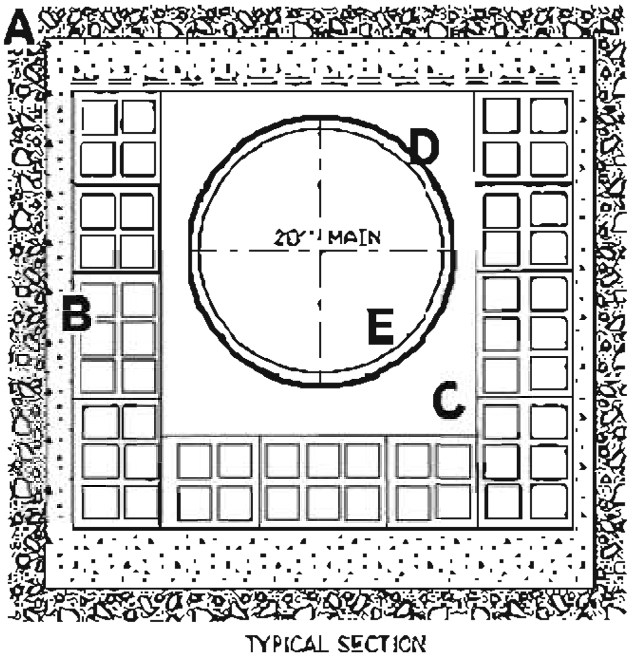
The as-found condition of the Incident Site was surveyed using a laser on July 23, 2007 and again on August 2, 2007. The purpose of the laser survey was to locate items in the crater as accurately as possible, in their as-found position, in order to identify infrastructure in the incident region. An initial survey was performed when only minimal debris had been removed from the Incident Site. A later survey was performed when the steam main rupture site was exposed.

The Light Detection and Ranging (LiDAR) or laser scanning process was used. This involves aiming a light beam at a target and having it bounce back to the source. The instrument measures the time it takes for the light to travel from the instrument and reflect off of an object (time-of-flight). Using this data, the system calculates the target's distance. The instrument also uses beam direction; by aiming millions of light beams at the remaining crater, the distance and direction of many million data points (cloud of points) are calculated, mapping the surfaces of the crater objects.

Data from the laser survey, together with available infrastructure drawings, helped locate the utilities at the intersection. Composite utility plots are shown in Figure 2-13, through Figure 2-15.

The infrastructure contained two 12" diameter water mains. Within the intersection were two 4 ft by 3 ft sewers, one running west to east, the other running south to north. A deeper 8 ft by 8 ft intercept sewer, also running west to east across the intersection, was approximately 12 feet below the steam main.

Several boreholes were drilled on the intersection's east and west side to identify the intersection's rock and water table depth (refer to Section 4.1.2 for further discussion). The bore hole locations are shown in Figure 2-15.



A. Soil

B. Clay-tile Housing

C. Air gap

D. Insulation

E. Pipe

Figure 2-1: Typical Steam Main Housing Construction

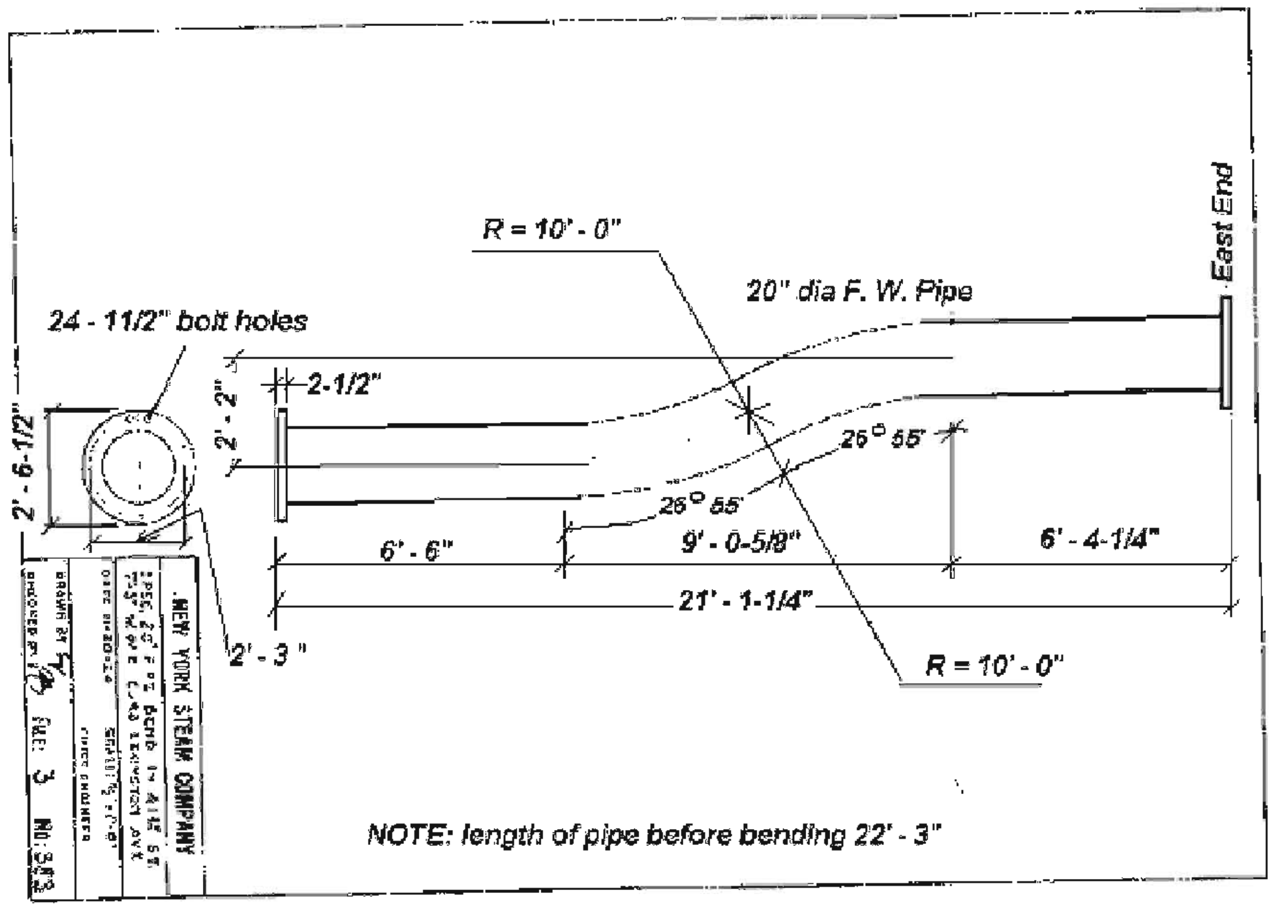


Figure 2-2: Drawing of File 3 Bend Utilized on East Side of Lexington Avenue

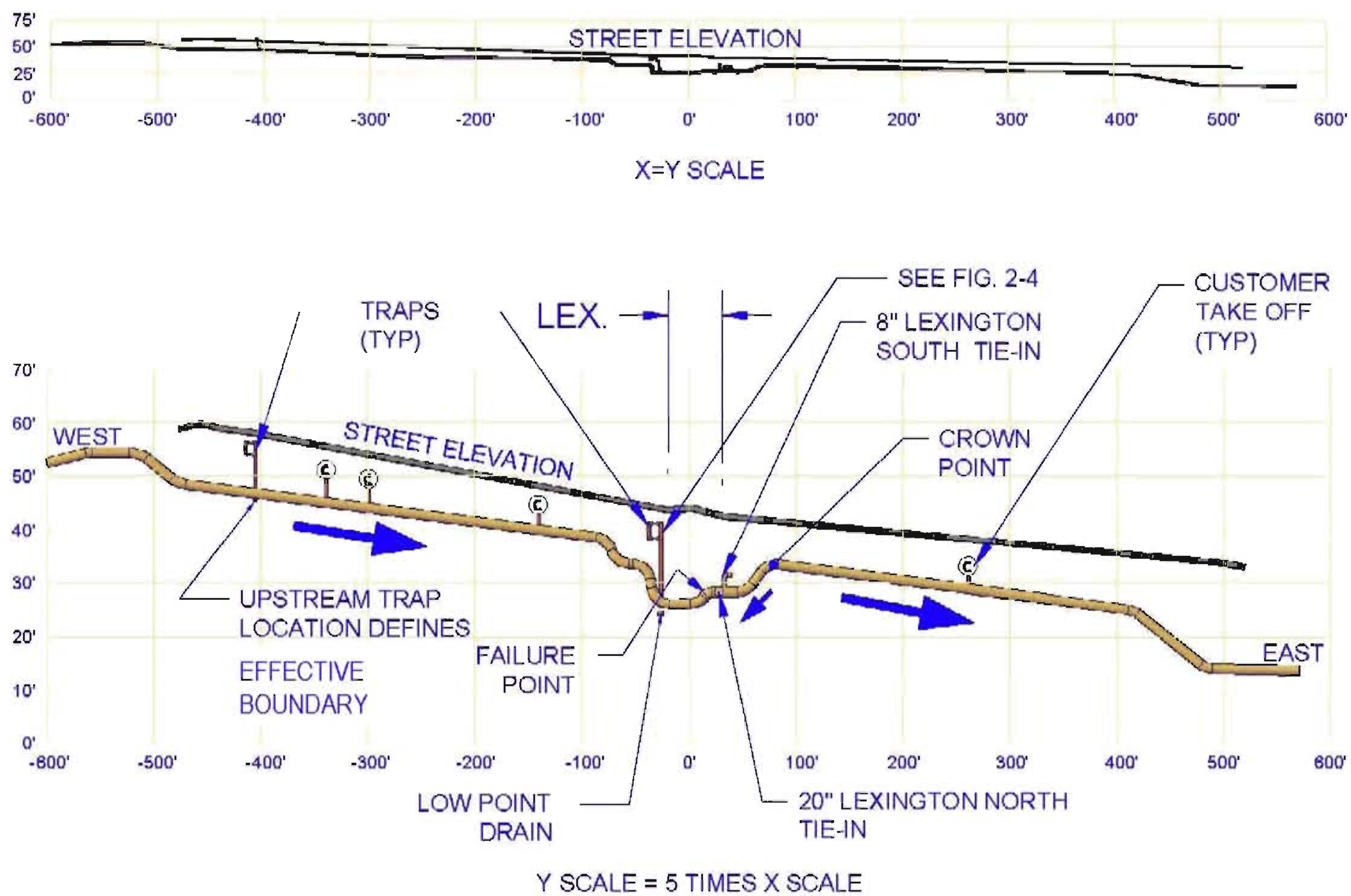


Figure 2-3: Pipe Elevations along 41st Street Looking North

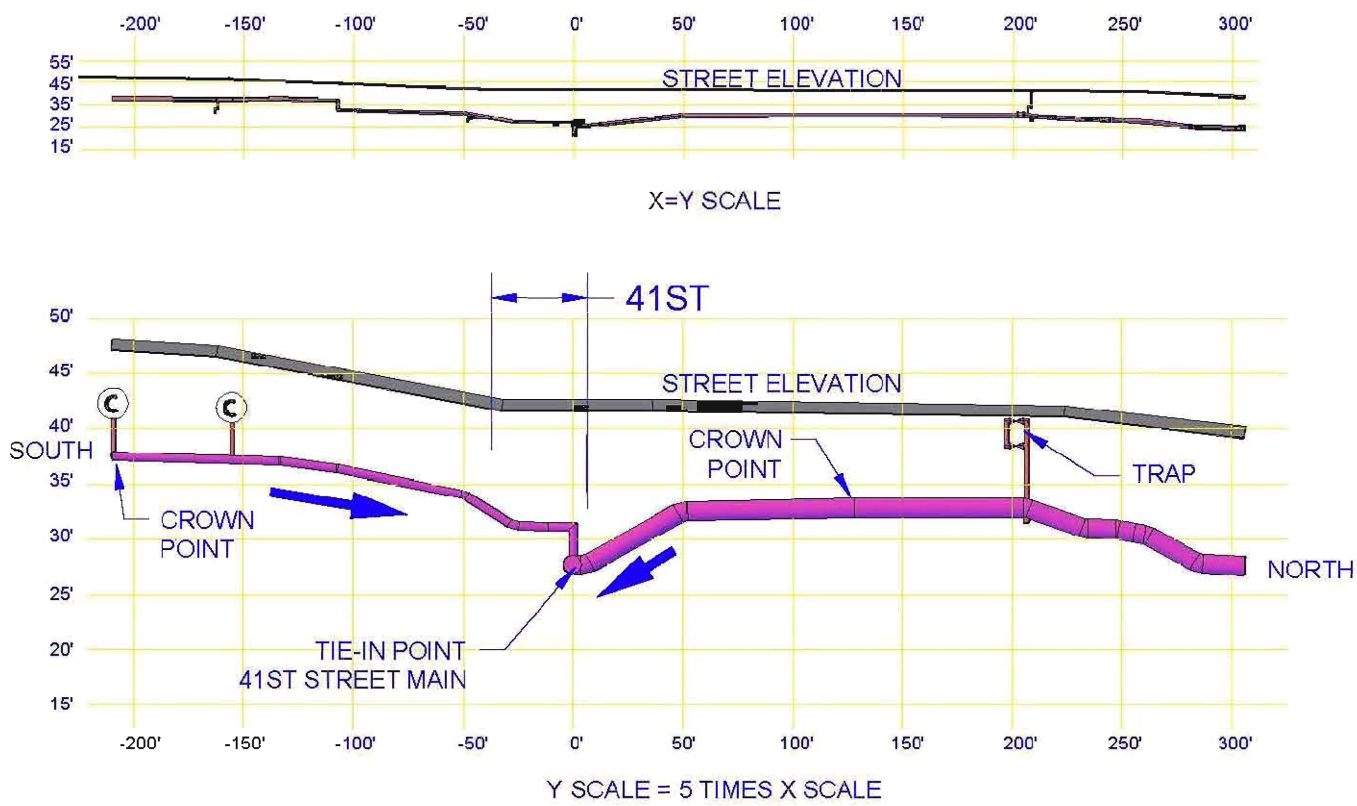


Figure 2-4: Pipe Elevation Along Lexington Avenue Looking West

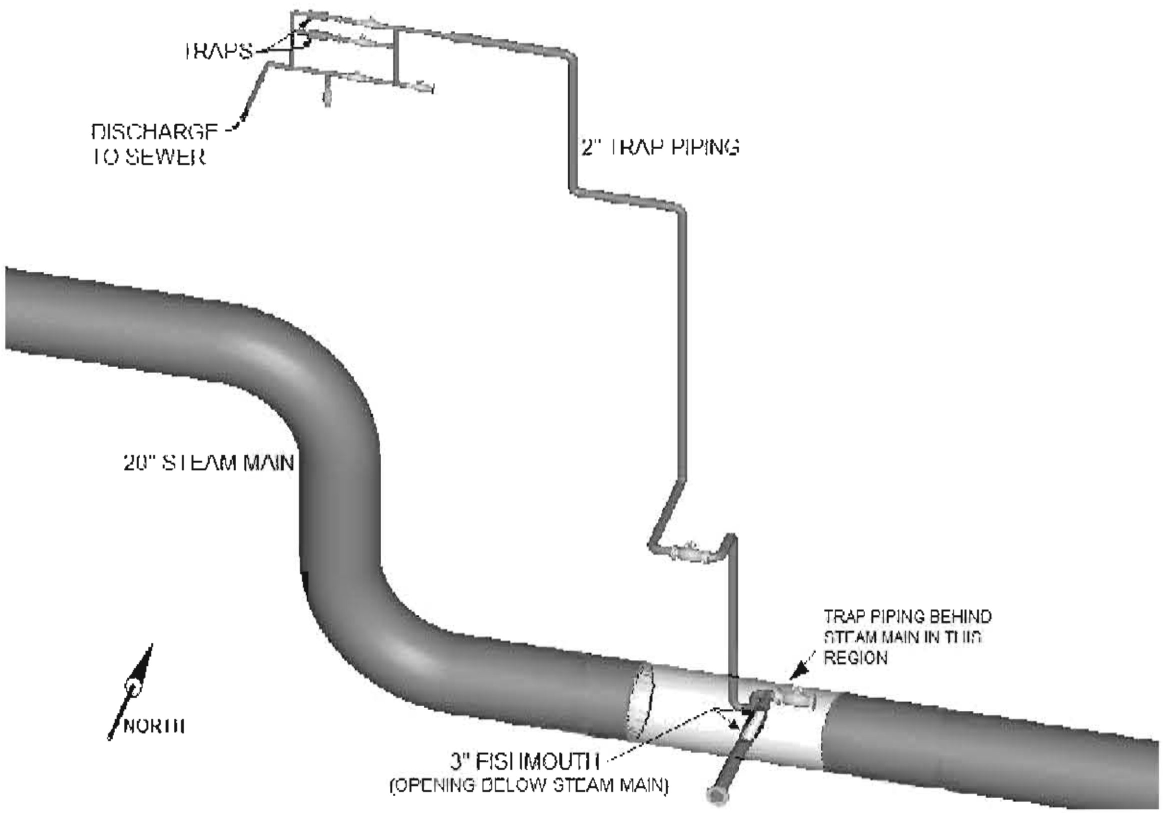


Figure 2-5: Trap Line Layout (Looking North)

(The trap line take-off point at the 3" fish-mouth drain was located within the drain manhole as shown on Figure 1-2)

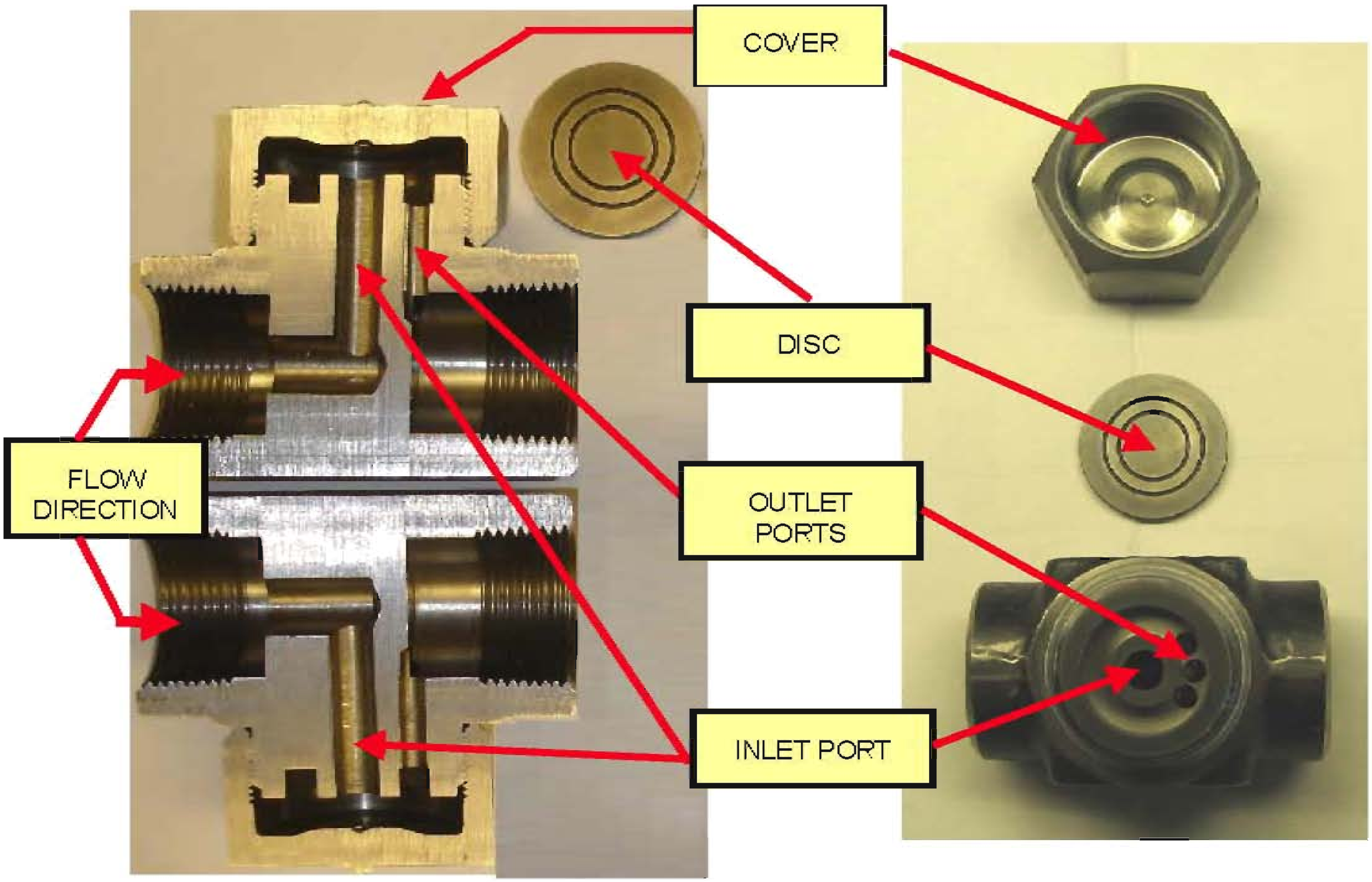


Figure 2-6: Trap Internals (Sectioned on left, Top View on right)

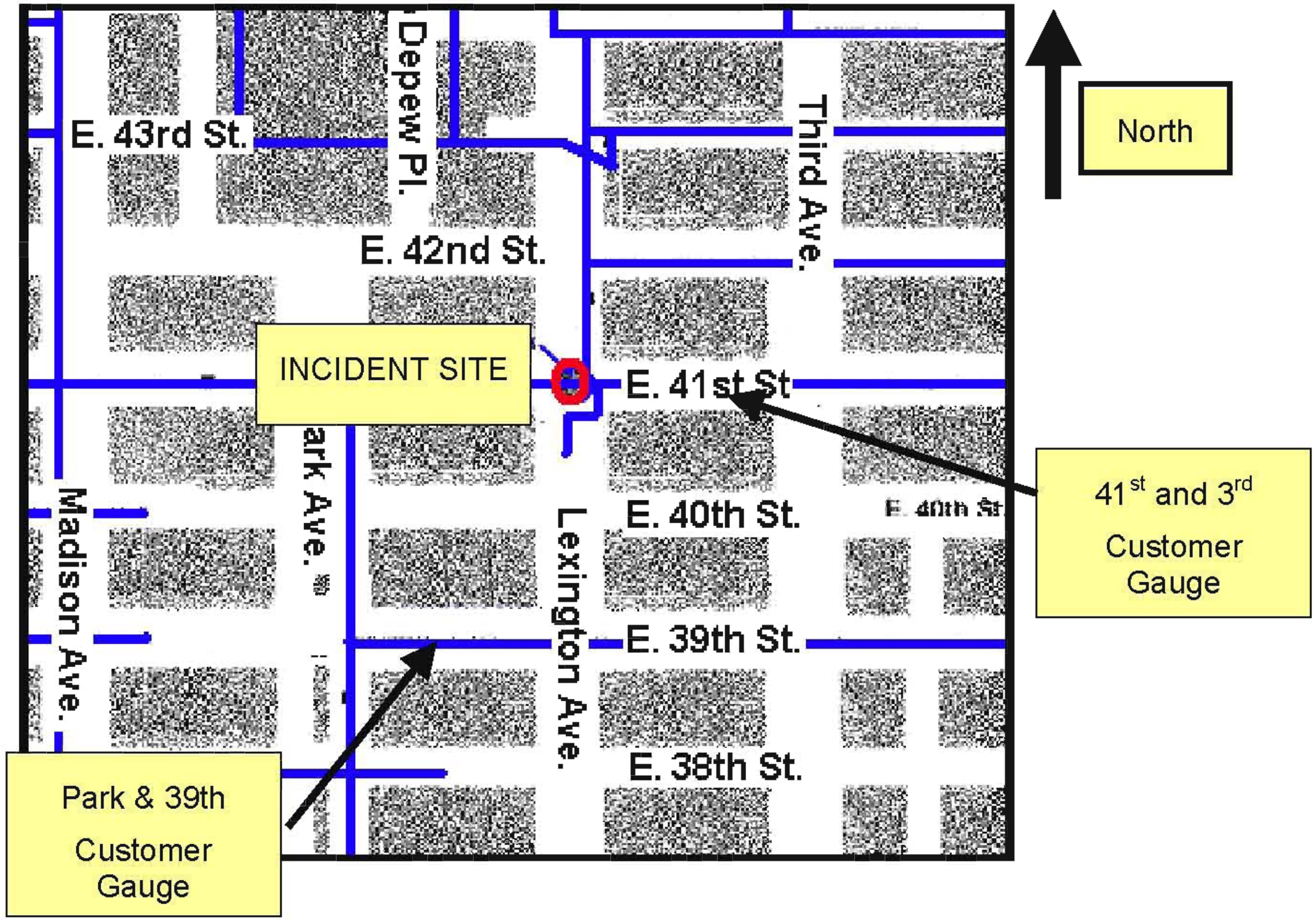


Figure 2-7: Steam Main Plan Local to Incident Site

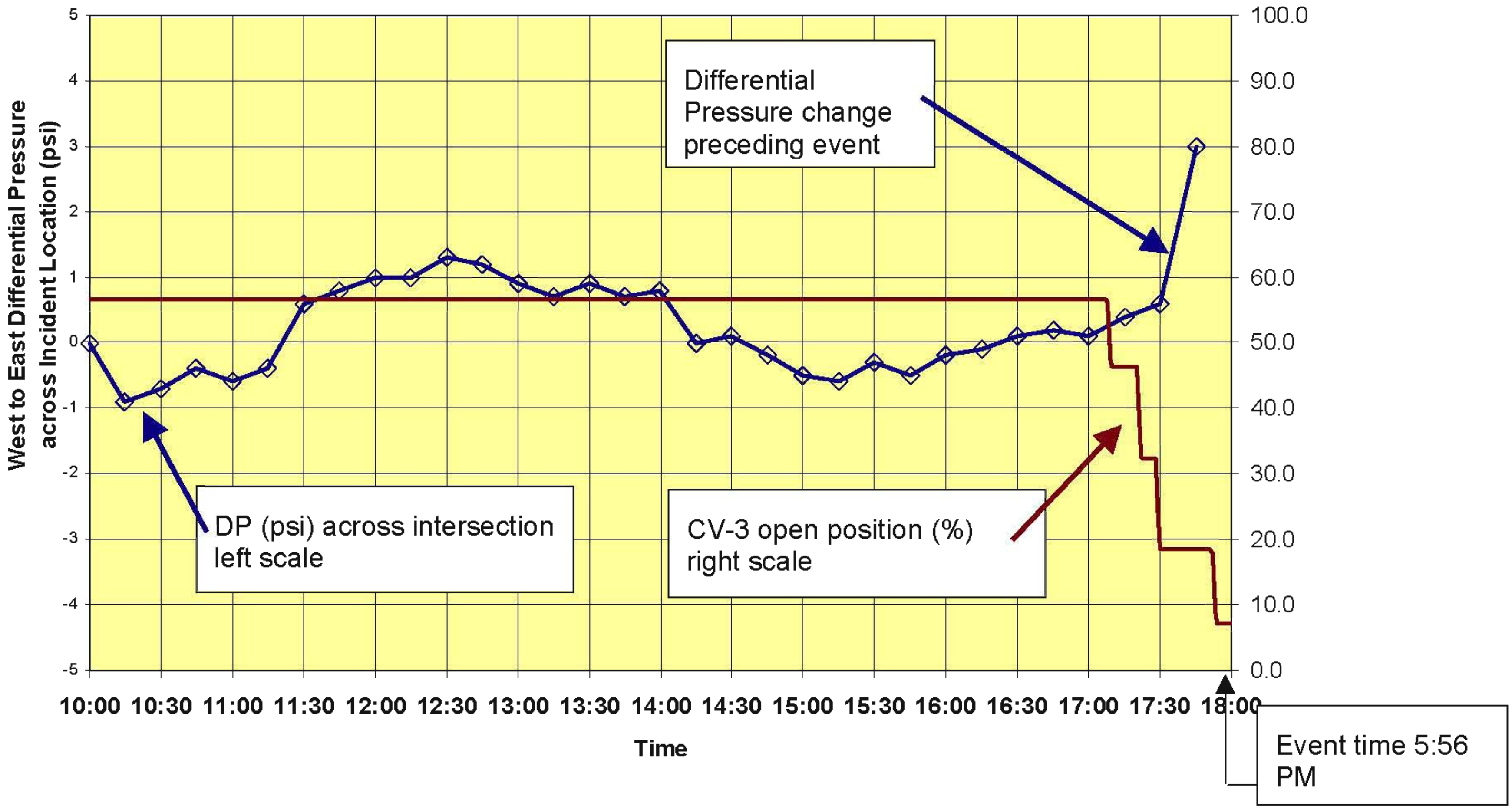


Figure 2-8: Differential Steam Main Pressure Across Incident Site

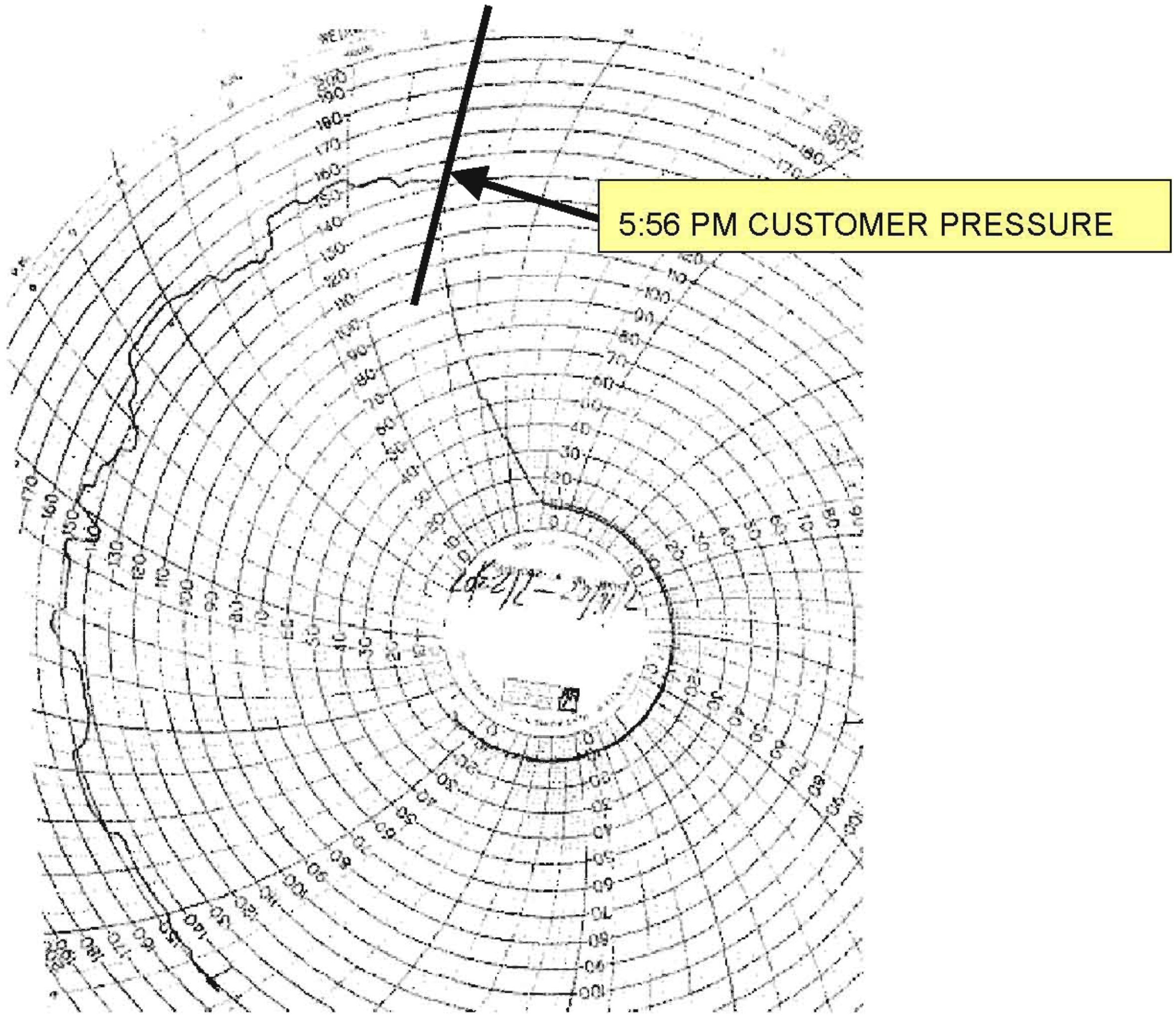


Figure 2-9: Pressure Chart Lexington Avenue Customer South of Intersection

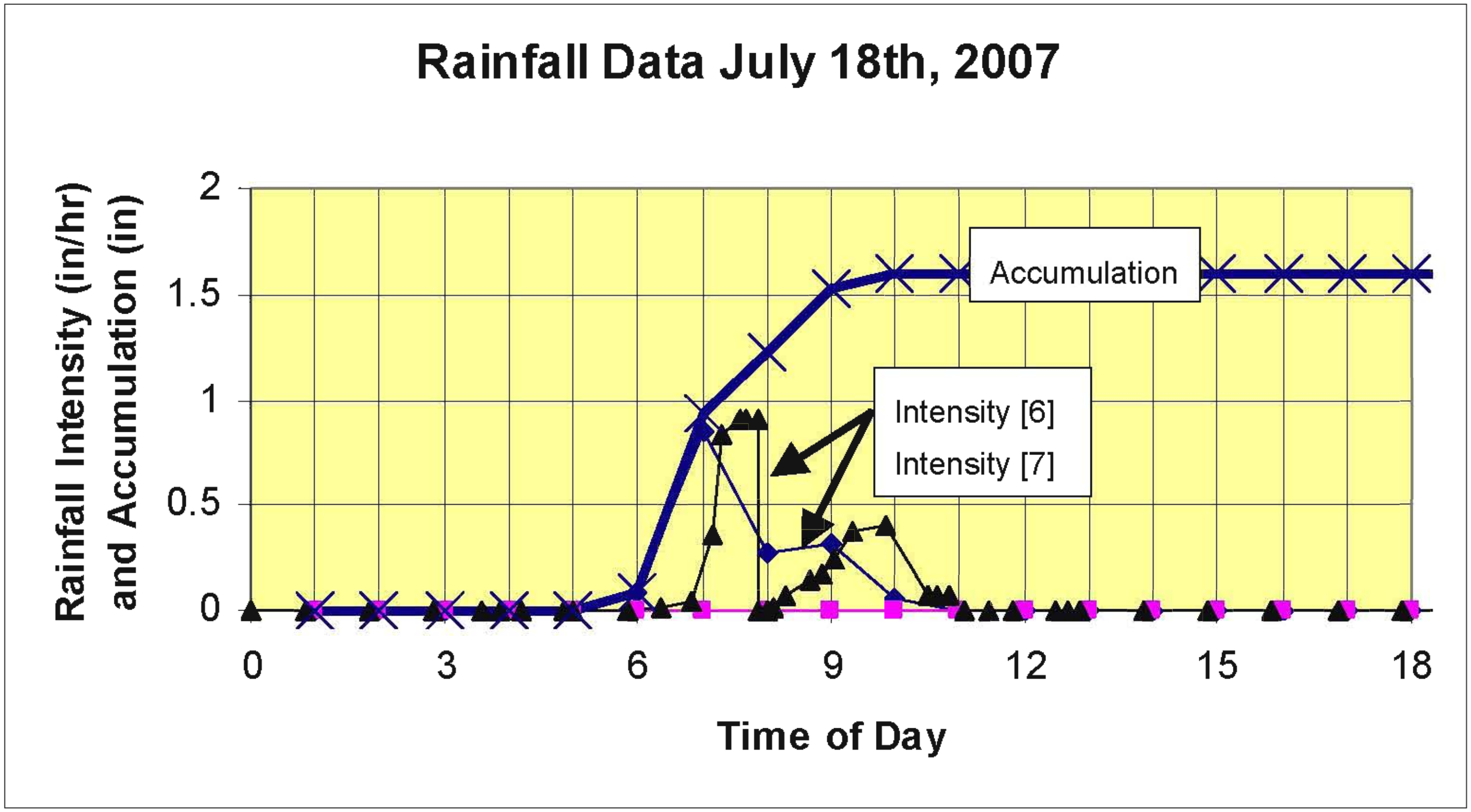


Figure 2-10: Rainfall Intensity (inches/hour) and Accumulation (inches) on July 18, 2007

(Data based on [6] and [7])

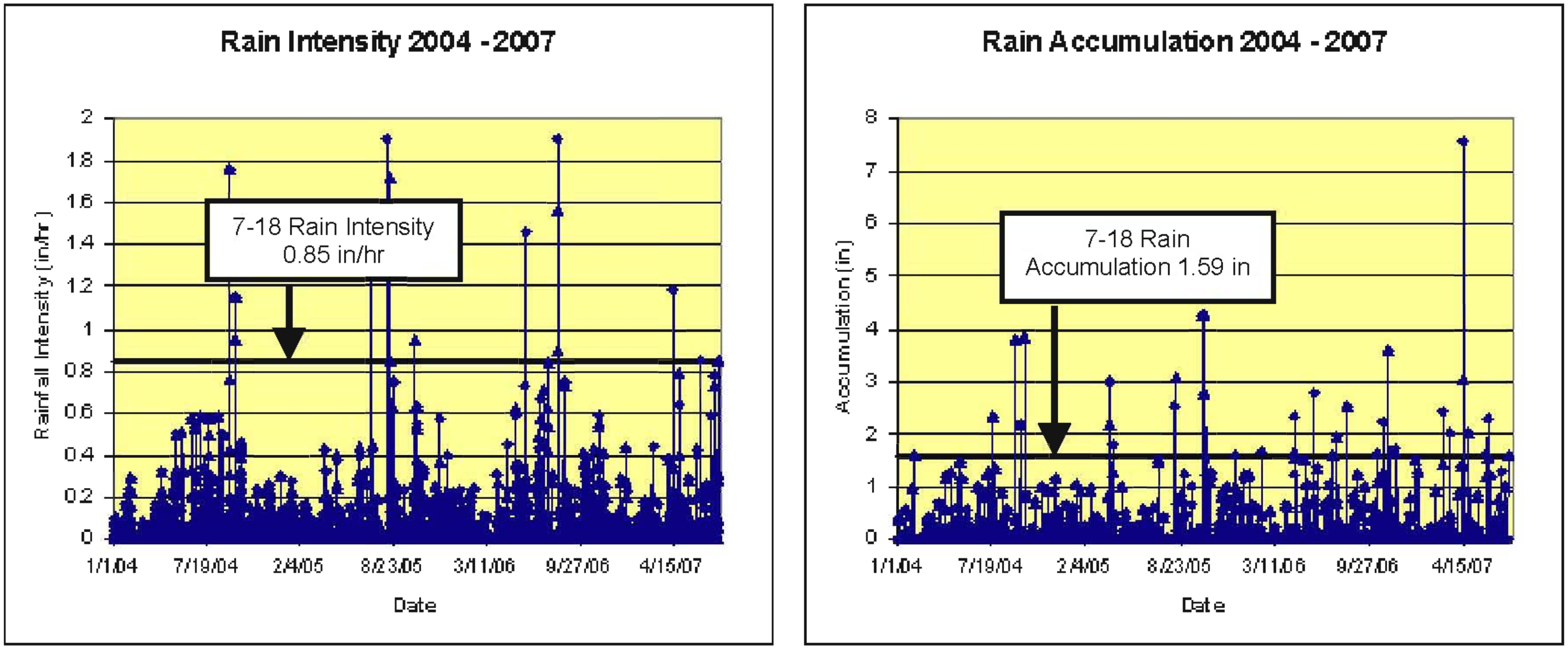


Figure 2-11: Comparison of July 18, 2007 Accumulation and Rainfall Intensity to Historical Data [6, 7]

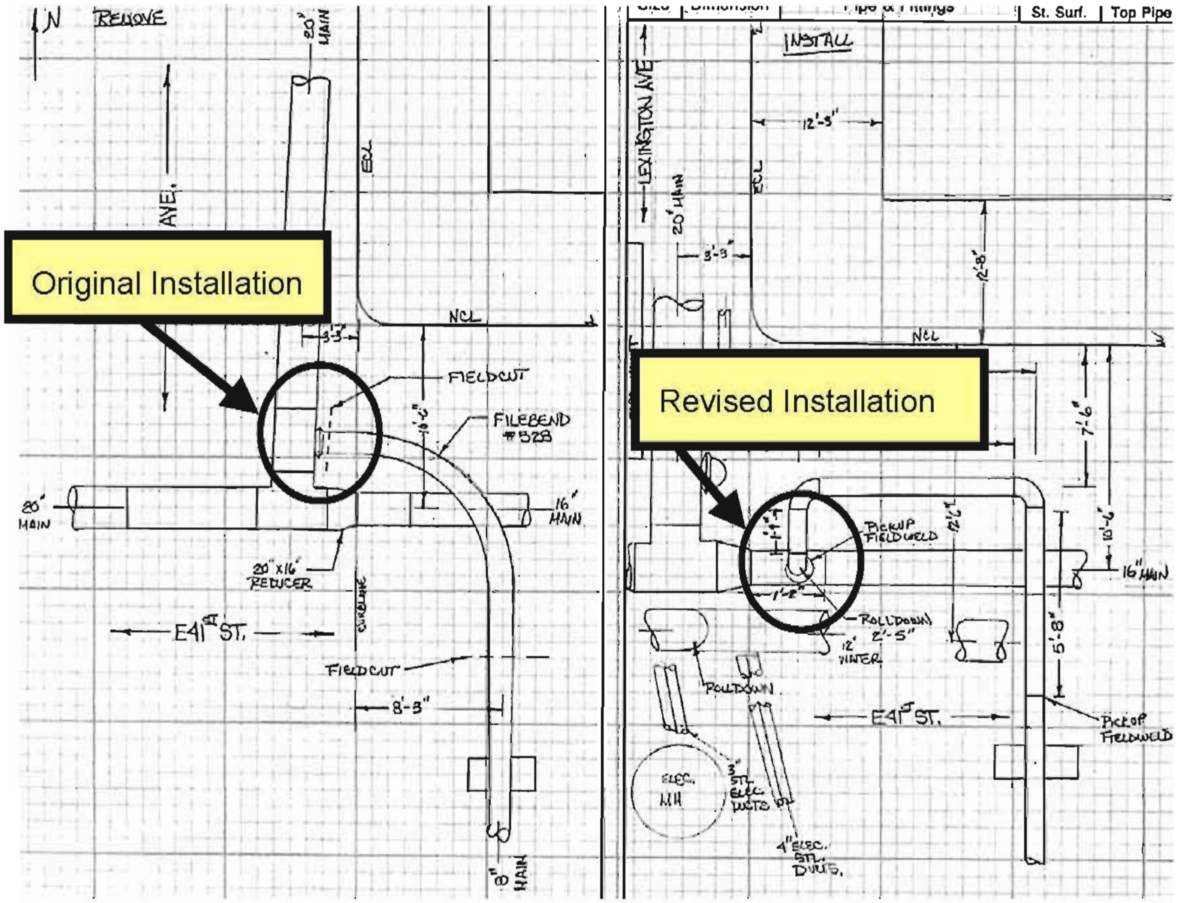


Figure 2-12: Revised Piping Configuration at 8" Connection to Lexington South Customers

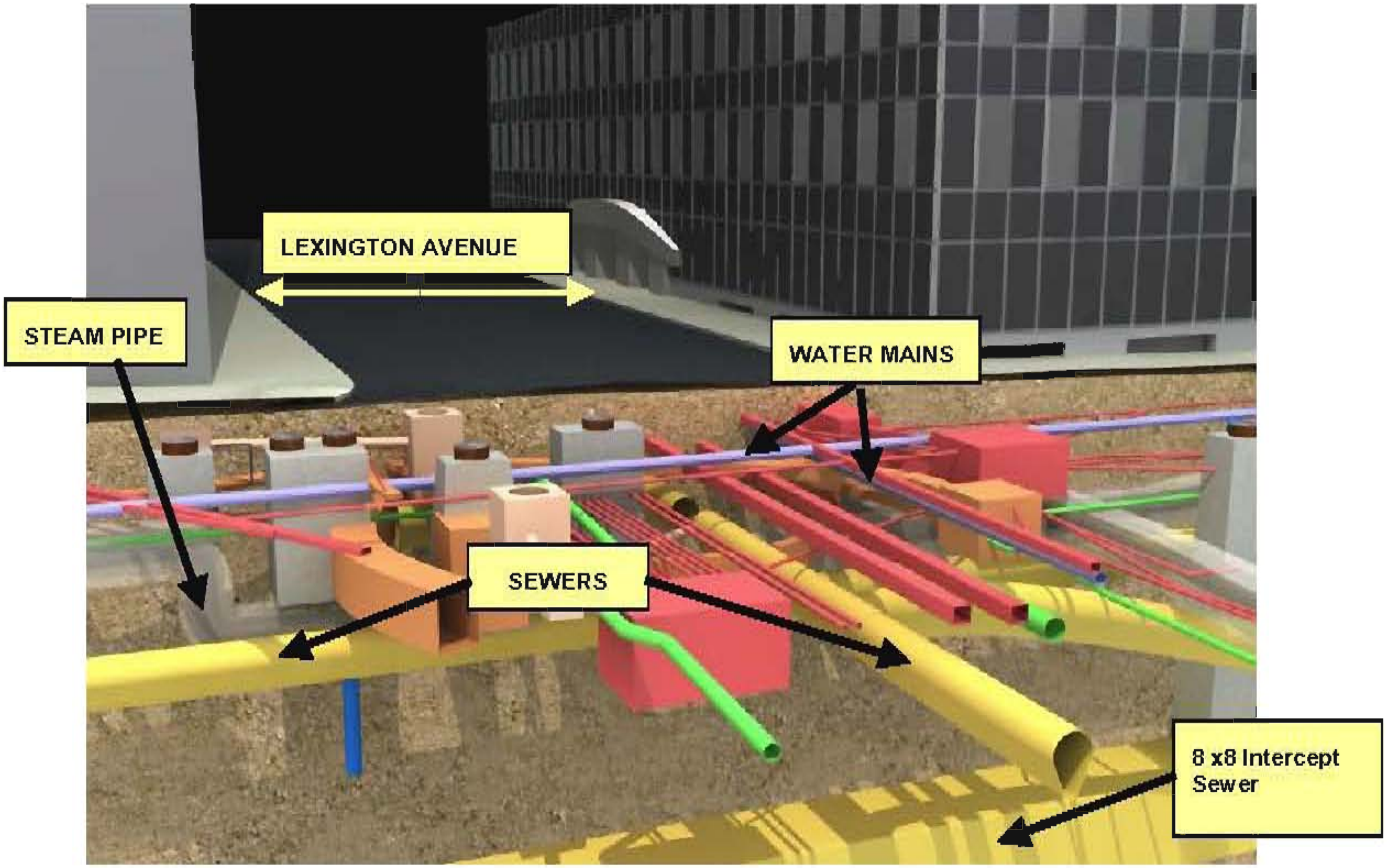


Figure 2-13: Composite Section of Intersection Utilities (Looking North)

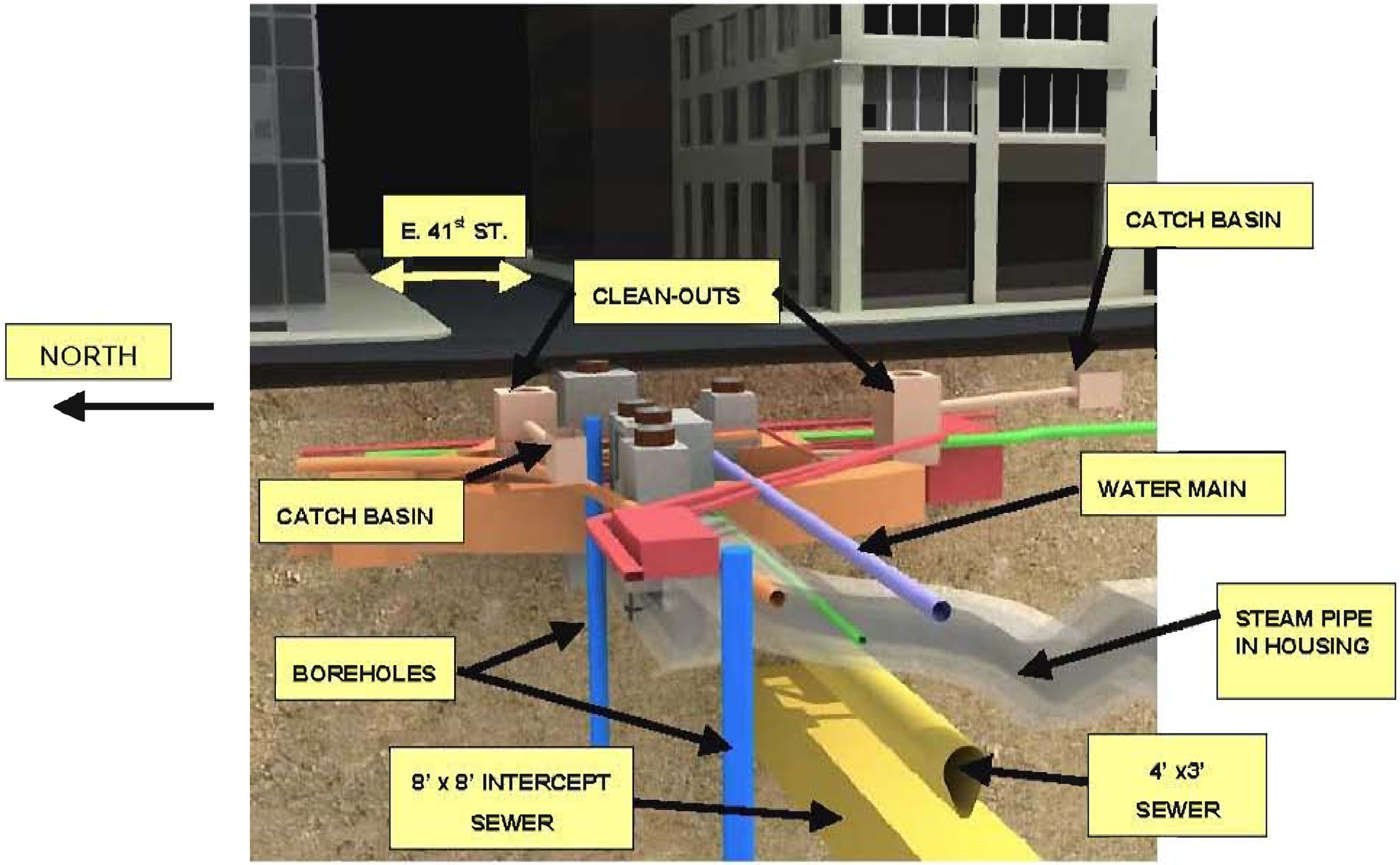


Figure 2-14: Intersection Utilities Looking East

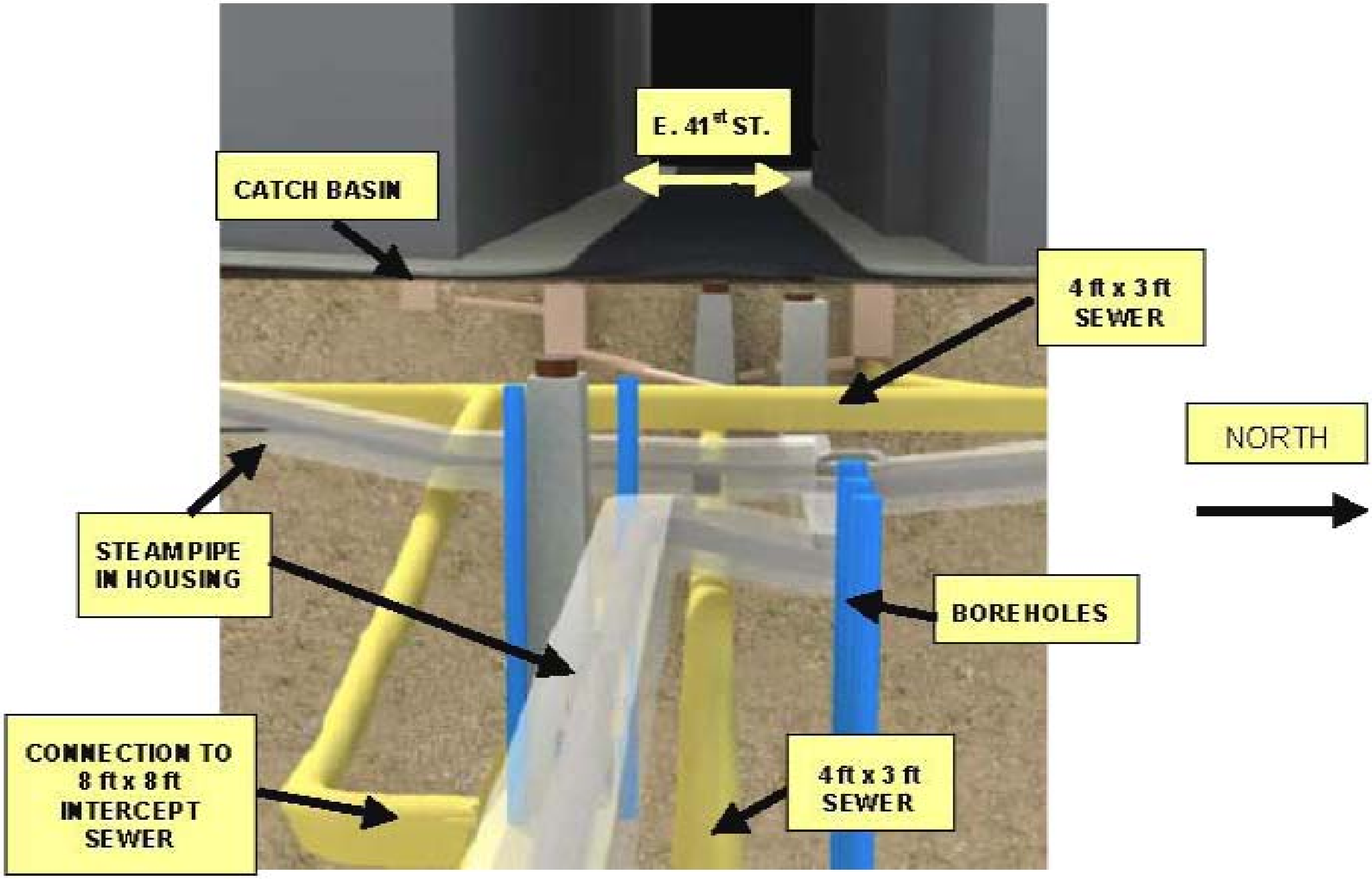


Figure 2-15: Intersection Utilities Looking West

3.0 SEQUENCE OF EVENTS CAUSING RUPTURE

Based on the post-failure examination of pipe materials and rupture characteristics, the piping failed from a rapid dynamic overpressure [8] not associated with normal system pressure conditions (see Section 2.5). The overpressure transient leading to component rupture was caused by a waterhammer, which is a rapid pressure shock created inside the pipe caused by rapid steam bubble condensation in accumulated condensate.

For a waterhammer to cause the rupture, the following conditions were needed:

1. Condensate, the water that is generated and accumulates in the pipe due to condensing of the steam on the pipe wall from heat loss to the surrounding environment, had to have filled the pipe at the rupture location. The pressure pulse from waterhammer will only exert internal pressure on the pipe where it is filled with condensate. The pressure pulse is not transmitted into the steam region.
2. The temperature of the accumulated condensate inside the pipe had to cool to a minimum of approximately 35 to 40 degrees Fahrenheit (°F) below the saturation temperature. The saturation temperature is the temperature at which water will boil to steam or steam condenses to water.
3. Steam distribution system operating conditions had to cause steam to enter the region of accumulated subcooled condensate. This will create the waterhammer.
4. The pressure resulting from waterhammer must be large enough to induce a stress in the pipe that exceeds the pipe's strength, causing the rupture.

Each of these is described below.

3.1 Condensate Accumulation and Subcooling

Condensate normally accumulates in the steam piping as heat is lost to the environment surrounding the pipe. The drains and their associated steam traps located at the system low points normally remove this condensate. If more heat than normal is removed from the pipe exterior, the condensate formation rate inside the pipe will increase.

On the day of the event, the housing surrounding the pipe flooded due to intrusion of external water as a result of damaged sewer infrastructure and possible water main leaks. This greatly increased the pipe heat losses and the condensate generation rates.

Floodwater sources were investigated and potential sources were identified as: 1) direct infiltration from the adjacent northwest catch basin; 2) potential pressurization from the local sewers running full under heavy rain conditions, and ; 3) potential leakage from a water main.

The flooding of the steam pipe housing and intersection manholes has been identified as a Causal Factor to the incident and will be described in detail in Section 4.1.

Condensate accumulation was calculated with consideration of external flooding. Depending on the external water flood depth, the inside of the pipe beneath Lexington Avenue could have filled with condensate in approximately one hour.

Debris had entered the steam traps and reduced their ability to remove condensate. Debris transport most likely occurred during a time the housing was flooded, corresponding to vapor emissions since the March 14, 2007 leak seal injection, when higher condensate flows occurred in the drain line to the steam traps.

Condensate generation and removal are described in the next sections.

3.1.1 Condensate Generation Rates

Condensate will accumulate in steam piping due to heat losses to the pipe exterior. A range of insulation conditions (wet, dry, missing) and steam pipe housing conditions (dry or externally flooded to various elevations) was evaluated to determine the potential for condensate accumulation within the steam pipe. These pipe and housing conditions can be postulated based on the potential for external water to flood the steam main housing and manholes with water.

The calculation of condensate accumulation is based on a steady state, radial heat transfer model and provides condensate generation per linear foot of 20" steam piping. Figure 2-1 shows the pipe and housing cross section. The pipe contains saturated steam at approximately 160 psig and 370 degrees Fahrenheit and is insulated with approximately 1.5" to 2" of insulation. The pipe conditions assessed ranged from dry insulation with a dry air space to a flooded condition with missing or separated insulation and boiling on a percentage of the pipe's exterior surface. Condensate generation for differing conditions is summarized below:

Normal Operating Condensate Generation. Condensate is generated based on normal system heat losses and is removed by the traps. For the steam pipe draining to the Lexington Avenue intersection low-point drain, normal condensate generation was assessed by considering the pipe and insulation dry and in good condition. Natural cooling of the system will produce approximately 0.5 pounds of condensate per foot of 20 inch diameter pipe (0.5 lb/ft of 20" pipe) or approximately 400 lb/hr of condensate for the total length of pipe draining to the drain manhole at 41st Street and Lexington Avenue. This calculation was confirmed by measurements of condensate generated in the region of steam pipe draining to this location following steam main restoration across Lexington Avenue [4].

External Flooding at the 41st Street and Lexington Avenue Intersection. The rate of condensate generation is a function of flooding elevation, water level inside the pipe, and the condition of the pipe insulation. Forty seven feet of horizontal piping crossed beneath Lexington Avenue at a low elevation (top of pipe elevation 26.7 feet, Figure 1-2). If the housing for this pipe section was flooded and the pipe steel was directly exposed to the surrounding floodwater, boiling heat transfer on the pipe exterior would produce approximately 323 lb/ft/hr of condensate for the 47 feet of 20" diameter pipe, or 15,000 pounds of condensate per hour.

These condensation generation rates occur if 100% of the pipe's circumference is exposed to the external floodwater. This accumulation rate will diminish, depending on the external floodwater depth, the condition of the exterior pipe insulation, and as the pipe interior fills with condensate. As shown in Figure 3-1, condensate filling inside the pipe reduces the available surface area inside the pipe for condensing to occur as the difference between flooded elevation and condensate height diminishes. Thus, as the inside of the pipe fills with condensate, the condensate generation rate for external flooding conditions diminishes.

External Flooding Away From the Intersection. Condensate generation due to external water coming in contact with the steam main such from a leaking water main, sewer or hydrant, could create additional condensate generation. Condensate generation is not limited by accumulation in the pipe since it drains away to the low-point. After the event, piping to a fire hydrant on Lexington Avenue north of 41st Street, adjacent to the steam main (within approximately 10 feet), was found to be leaking. It was reported [11] that the hydrant was struck during reconstruction after the incident; however, pipe joints of the hydrant water supply exhibited signs of corrosion, indicating that leaking may have occurred for a period prior to the event.

3.1.2 Condensate Removal from the Pipe

The trap capacity was calculated to be 3,700 lb/hour for the installed configuration (see Section 2.4). Normal condensate generation for the piping draining to the low point drain at the Lexington Avenue intersection was 400 lbs/hr (Section 3.1.1). The full trap capacity exceeds this value by nearly a factor of ten.

In other words, if 11% of the total trap capacity was available, condensate would not accumulate in the pipe under normal conditions. If the trap capacity fell below 11%, condensate would accumulate in the pipe. This is shown in Figure 3-2. For a trap combination with no capacity to remove condensate and no external flooding, approximately twenty-four hours would be required to accumulate sufficient condensate to fill the pipe to a level to encompass the rupture location.

Following the event, the traps were removed and found to contain debris. The traps' compromised condition has been identified as a Causal Factor to the incident and will be described in detail in Section 4.2.

3.1.3 Level of Condensate in the Pipe

The condensate within the pipe accumulated to within a specific elevation range. As a minimum, condensate needed to fill to the rupture for the pipe to fail. As a maximum, the condensate did not reach an elevation where the customers on Lexington Avenue south of the Incident Site lost steam supply (Section 2.5). It is possible to consider analytically the combination of housing flooding elevations, insulation condition and trap capacities that produced condensate accumulation within this range. Figure 3-3 shows the relationship between the housing flooding elevation and compromised trap capacity required for condensate to reach the rupture location but not flood the customers considering 50% of the pipe steel surface exposed to the external flooding (average insulation conditions) for a nine hour period. Nine hours was selected as the approximate time span from 9:00 AM (when external water first contacted the steam pipe, Section 4.1.6) to 5:56 PM when the rupture occurred.

The conclusion drawn from this envelope of possible scenarios is that the flooding was at least to an elevation of 26 feet 10 inches but not higher than 28 feet 10 inches with trap function between zero and 100% (see Figure 1-2 for elevations – based on Manhattan Datum).

3.1.4 Condensate Subcooling

Condensate subcooling (the temperature of the condensate below the steam saturation point) is based on the balance of heat flow from steam into accumulated condensate, compared to heat flow out to the flooded air space surrounding the pipe. Thermal stratification (the formation of hotter layers over cold) will occur due to the lower density of hotter water. This will form an insulating layer on the top of the water, limiting heat transfer into it. Subcooling occurs over a shorter time in a flooded horizontal pipe with vertical or vertically inclined ends (see Figure 3-4) as the area exposed to steam is small.

For condensation induced waterhammer to occur, subcooling of approximately 20 degrees Celsius or 36 degrees Fahrenheit is required [12]. A temperature range of 35 to 40 degree Fahrenheit was used to determine the time to reach potential waterhammer conditions. The results of the subcooling evaluation show that if the pipe is undergoing active boiling on the exterior, then heat transfer is rapid, and the required sub-cooling can occur in minutes. If free convection is occurring on the exterior of the pipe, then the time required to reach 35 to 40 degree Fahrenheit sub-cooling would be on the order of several hours. The subcooling required can be obtained in the nine hour time available.

3.2 Waterhammer Evaluation

Condensation induced waterhammer resulting from the steam contact with subcooled condensate was investigated to determine pressure magnitude and time history of the pressure pulse as it traveled through the accumulated condensate in the pipe.

3.2.1 Waterhammer Mechanism

Waterhammers are fluid pressure transients caused by rapid changes in fluid velocity. The change in fluid velocity produces large pressure shocks and unbalanced pressure loads on piping and components.

In steam systems, the most powerful waterhammers typically result from steam interaction with subcooled condensate and are referred to as condensation induced waterhammers. Steam and subcooled condensate conditions can result in the trapping of a steam bubble within a mass of condensate. The very rapid condensation heat transfer within the steam bubble creates a void in the condensate, collapsing the steam bubble in a nearly instantaneous manner. The resulting pressure pulse occurs as the in-rushing condensate fills the void and impacts onto itself.

In this event, the steam's introduction into accumulated condensate resulted from operating changes in the system, inducing a pressure differential across the accumulated condensate in the pipe. As described in Section 2.5, negligible differential pressure existed across the accumulated condensate mass until shortly before the rupture. This allowed the accumulated condensate to remain in a relatively stable condition during the day. The data shows that just prior to the event, the differential pressure increased to approximately 3 psi higher on the west side, containing the partially filled vertical piping leg (see Figure 2-8). This higher pressure would push the condensate mass down the vertical leg approximately 2.6 feet per psi of differential pressure. A diagram of this process is provided in Figure 3-5.

In diagram (A), an initially stable mix of hot steam over a stratified column of condensate exists until the steam/condensate interface position changes due to an increase in steam pressure on the intersection west side. In (B), the hot steam is exposed to the sub-cooled condensate as the interface transitions from the vertical to horizontal pipe. In (C), a bubble is formed and trapped due to steam and condensate movement behind the bubble. The steam in the bubble condenses very rapidly because of the subcooled condensate. This creates a void in the condensate where the steam bubble had existed.

The system's normal operating pressure (approximately 160 psig) caused the condensate surrounding the void to rush into this space, impacting the condensate mass rushing in from the other side. The magnitude of this impact is primarily a function of system pressure, the size of the bubble, and bubble pressure, which very quickly approaches the saturation pressure of the sub-cooled condensate.

3.2.2 Calculation of Waterhammer Pressure

The waterhammer pressure pulse is calculated using the Joukowski equation [12] and the impact velocity from simple kinetics of the pressure differential across a water mass. The Joukowski equation is defined as follows:

$$\Delta P = \frac{1}{2}\, \rho\, c\, \Delta V$$

Where: ρ = condensate density (approximately 55 lb/ft^3 at 370°F)

c = sonic velocity (approximately 4,000 ft/sec for condensate in pipe)

ΔV = fluid velocity change resulting from impact

The waterhammer pressure magnitude (ΔP) is determined using the system pressure of 157 psig when the pipe ruptured and the void pressure based on 36°F subcooling, or a saturation pressure of 94 psig. The resulting waterhammer pressure is dependent on the bubble size. For bubble sizes of 5% to 25% of the 20" diameter pipe, the resulting pressures will be approximately 1,000 to 2,800 psi. However, tests to determine waterhammer pressures show a large variation in pressure magnitudes based on the dynamics of bubble collapse, the amount of non-condensable gases in the steam and condensate, and other variables.

3.2.3 Forces on the Piping System

The waterhammer pressure pulse travels at sonic velocity (approximately 4,000 ft/sec) through the condensate filled portion of the piping system, creating a region of elevated pressure and generating a hoop stress in the pipe wall. As the leading edge of the pressure wave reached the changes in direction (90 degree bend – on the west side of intersection, File 3 bend (Figure 2-2 – on the east side of intersection), the pressure acting on the piping walls creates unbalanced forces. These unbalanced forces generate additional membrane and bending stresses in the pipe wall.

From the initiating location, the pressurization wave traveled both east and west. The steam boundary or free surface at the west side elbow reflects as a rarefaction or inverse wave, i.e. it reduces the elevated pressure back to the normal system pressure. This rarefaction wave then traveled to the east following the pressurization wave, providing a finite duration of the pressure pulse loading. The resulting forces at piping locations A, B, and C are shown in Figure 3-6. This figure shows a specific bubble collapse location, although the initiation location could have varied along the length of the horizontal pipe. This variation would not have affected the waterhammer pressure generated and would have a small and inconsequential effect on the forces calculated on the pipe.

3.3 Impact of the Waterhammer on the Pipe

The waterhammer pressure pulse loaded the pipe with both pipe circumferential direction (hoop) loads from internal pressure rise and pipe axial direction loads from internal unbalanced pressure loading at changes in direction. The resulting stresses exceeded the pipe ultimate stress as outlined below.

3.3.1 Pipe Stress

A detailed piping stress analysis investigated the effects of waterhammer transient loading and determined the likely minimum value of internal pressure generated from a waterhammer rupturing the pipe. Details of the stress evaluation are summarized below.

The pipe was stressed from normal operating loads and dynamic loads caused by the waterhammer. Normal operating loads occur from the following conditions:

(1) Deadweight of the pipe;

(2) Operating Pressure, including unbalanced pressure loads that are caused by expansion joints;

(3) Temperature (the pipe in the steam environment was at a temperature of 370 degrees Fahrenheit).

The pipe rupture occurred as a result of the above conditions occurring simultaneously with a waterhammer event.

With the steam bubble collapse somewhere along the lower elevation portion of the horizontal steam main, a shock wave was initiated that progressed rapidly both east and west of the collapse location as outlined in Section 3.2.3. The resulting pressure from the shock wave created both internal pressure and unbalanced forces acting on the pipe at changes in direction.

Although an assumed location of the bubble collapse was utilized, a bubble collapse anywhere along the lower horizontal portion would produce similar differential pressure loading in the File 3 bend. Only timing of the stresses would differ from the case evaluated. An assumed pressure pulse of 1,000 psi was initially utilized for the evaluation, and the pipe stress results from this loading were then adjusted to determine the approximate pressure pulse magnitude to result in rupture of the pipe.

A detailed time history analysis of the piping was performed considering the internal pressure rise from waterhammer, together with the application of the unbalanced pressure forces outlined in Figure 3-6. A plot of the resulting hoop direction stress is shown in Figure 3-7. The maximum hoop stresses occur at the sides of the File 3 bend (the 3 o'clock and 9 o'clock positions). This location coincides with the orientation of the pipe weld.

A worst-case region of pipe stresses was identified as occurring between 0.012 seconds and 0.027 seconds after the initial waterhammer bubble collapse initiated. The maximum stresses from this evaluation were as follows:

σ_{memb} = 30,490 psi

$\sigma_{memb+bend}$ = 53,742 psi

These represent the maximum principal stress in the pipe wall from membrane direction stress (σ_{memb}) and membrane plus bending stress ($\sigma_{memb+bend}$), respectively under the assumed 1,000 psi internal pressure pulse.

3.3.2 Pipe Strength

The pipe material was tested after removal from the Incident Site. The pipe materials were tested and the results are described in the LPI report [8]. The information from the LPI report showed that the pipe strength is typical for carbon steel piping material such as ASTM A-53 for the year of fabrication. Only superficial external and internal corrosion exited and both surfaces were covered with a thin film of red-brown corrosion products. The pipe did not exhibit any gross mechanical defects and there was no significant service induced degradation that could have affected the pipe's structural integrity. Pipe wall thickness was measured by ultrasonic techniques (UT) along the full length of the ruptured pipe section. Based on conclusions reached in the LPI report [8], the pipe sustained wall thinning away from the fracture as a result of the overpressure. Using the overall UT results, the pipe was concluded to be within pipe specification requirement tolerances suitable for a 3/8-inch-thick pipe.

The strength of the pipe was tested [8]. The lowest yield strength and ultimate strength test values for the seam weld were used for this evaluation. Those values are:

Yield Strength = 27,600 psi

Ultimate Strength (UTS) = 43,800 psi

These values are approximately 9% below the average values measured for the base metal away from the weld [8]. This reduction in value is consistent with the reduction allowed by industry standards used then and now [13, 20]. Based on the measured material strength properties, no age related strength reduction is apparent.

3.3.3 Rupture Pressure Calculation

The distortion energy failure prediction methodology [14, 15] used failure criteria limits of approximately 90% of the pipe material's ultimate tensile strength to predict membrane failure (a stress of 39,900 psi) and 1.5 times the membrane limit to predict membrane plus bending stress rupture (a stress of 59,800 psi). Using these rupture criteria limits the ratios between the stress values calculated at 1,000 psi internal pressure and the derived rupture limits were:

σ_{memb} = 30,490 psi calculated membrane stress

$\sigma_{memb+bend}$ = 53,742 psi calculated membrane plus bending stress

$ratio_{memb}$ = 30,490 psi/39,900 psi = 0.764

$ratio_{memb+bend}$ = 53,742 psi/59,800 psi = 0.899

As described above, these results were developed for an assumed pressure pulse loading of 1,000 psi. The pressure pulse magnitude was then factored such that the calculated stress matched the rupture criterion.

This means that the rupture pressure (based on waterhammer alone) would be the lesser of the following values:

$P_{failure\_memb}$ = 1,000/0.764= 1,309 psig

$P_{failure\_memb+bend}$ = 1000/0.899 = 1,112 psig

An additional adjustment was made to include the effect of normal operating stresses. Based on the large contribution from hoop stress from the waterhammer and small (in comparison) stresses from normal operating conditions, an adjustment ratio was based on the maximum hoop stresses given in Figure 3-7 and calculated as follows:

Adjustment factor = 76,292 psi/80,003 psi = 0.954

Therefore, the pressure to cause rupture was estimated to be (based on lower bound of material test results):

$P_{failure}$ = 0.954 x 1,112 psig = 1,060 psig

Based on this assessment, the magnitude of the waterhammer pressure pulse from the steam bubble collapse was expected to be a minimum of 1,060 psig. The actual pressure pulse could have been higher. This pulse is above the normal operating pressure of approximately 150 to 170 psig, resulting in a total applied pressure of approximately 1,200 psig.

A similar stress evaluation was performed considering a similar waterhammer pulse loading only along the section of straight pipe beneath the Lexington Avenue intersection. The straight section also would have experienced the same pressure pulse. The pipe stresses in the straight pipe were insufficient to result in pipe rupture, since this portion of pipe was subjected to internal pressure loading only, and stresses from unbalanced pressure loads for these sections were not significant.

3.3.4 Stress Evaluation of Observed Pipe Indentations

Within the LPI report, examination of the piping adjacent to the pipe flanges identified a section with a weld patch. This is a typical location for a roller type support. Review of SOMIS records [9] indicate that this weld repair was performed on March 24, 2005. Those records also indicate that the roller support was not in place at that time. Two indentations were visible, approximately 1/8" in depth, and when observed from inside the pipe, these indentations exhibited small circumferential cracks at their center, Figure 3-8.

An assessment was performed to determine the impact of pipe deflection in a vertical direction at the File 3 bend, with roller supports located at the flange manhole (at the indentation points). This assessment was performed to investigate the potential causes of the observed indentations in the pipe. A deflection of the pipe could occur from the section across Lexington being full of condensate or from a waterhammer loading at the File 3 bend. The calculated pipe stresses due to the weight of water filling the pipe would be insufficient to create the observed indentations. Pipe stresses at the roller support locations, from waterhammer load deflection at the File 3 bend could result in formation of these indentations.

With consideration of this loading, it is concluded that a prior waterhammer event of insufficient magnitude to burst the pipe likely occurred at the Incident Site prior to the March 2005 weld repair.

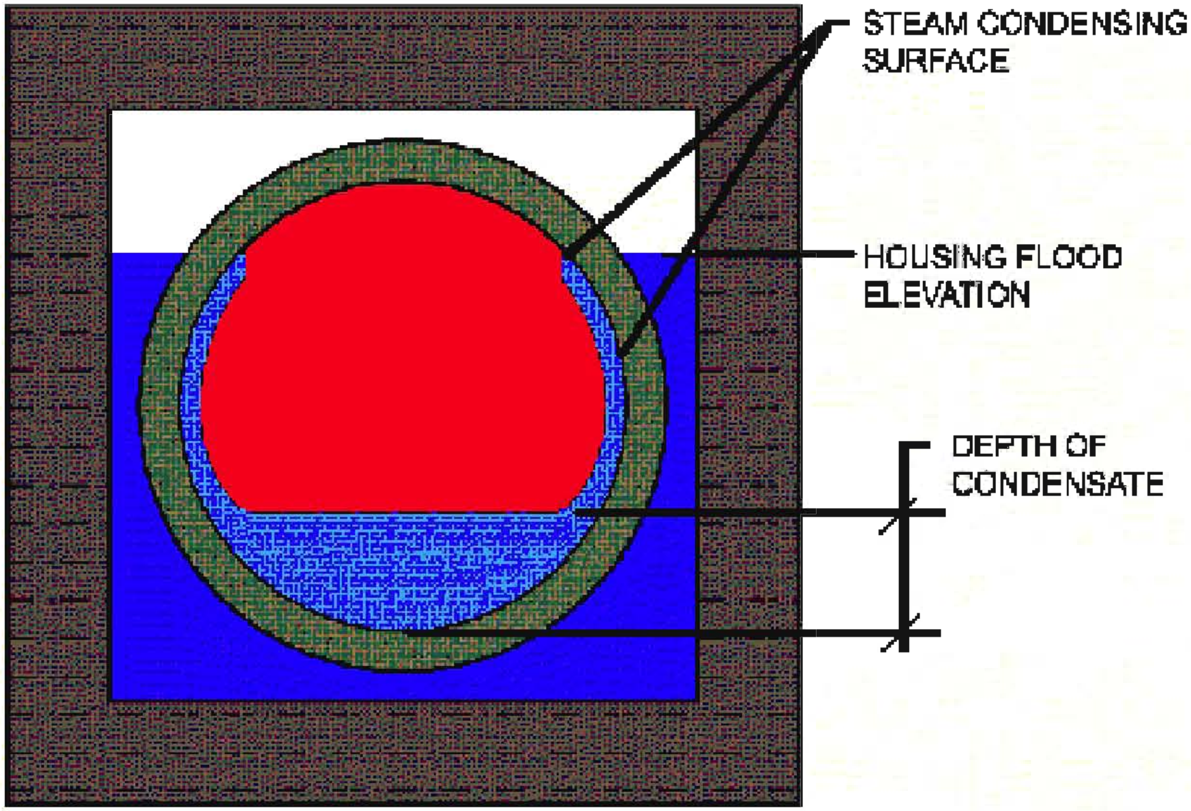


Figure 3-1: Condensate Accumulation from External Flooding in Housing

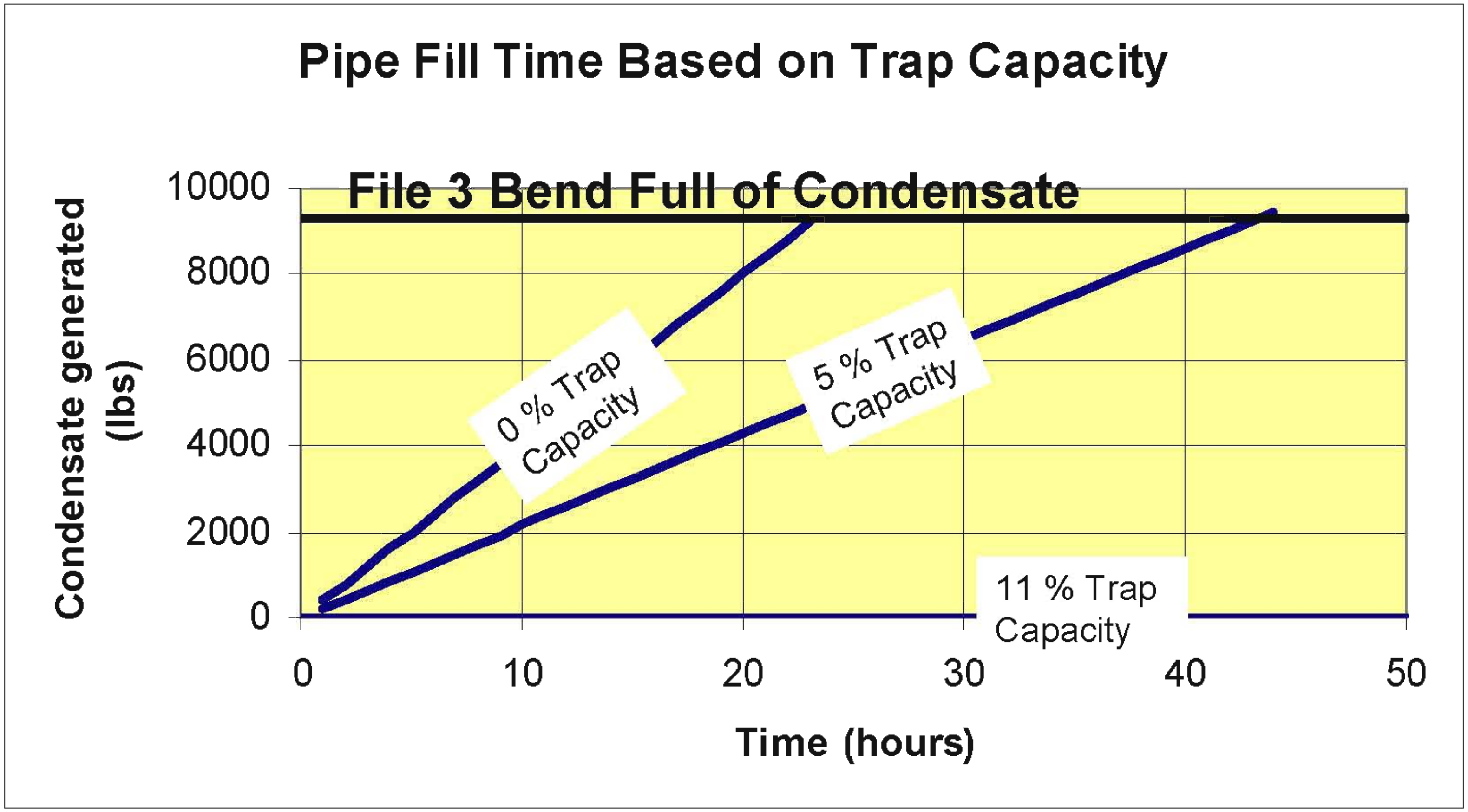


Figure 3-2: Condensate Accumulation for Normal Condition Generation versus Trap Capacity

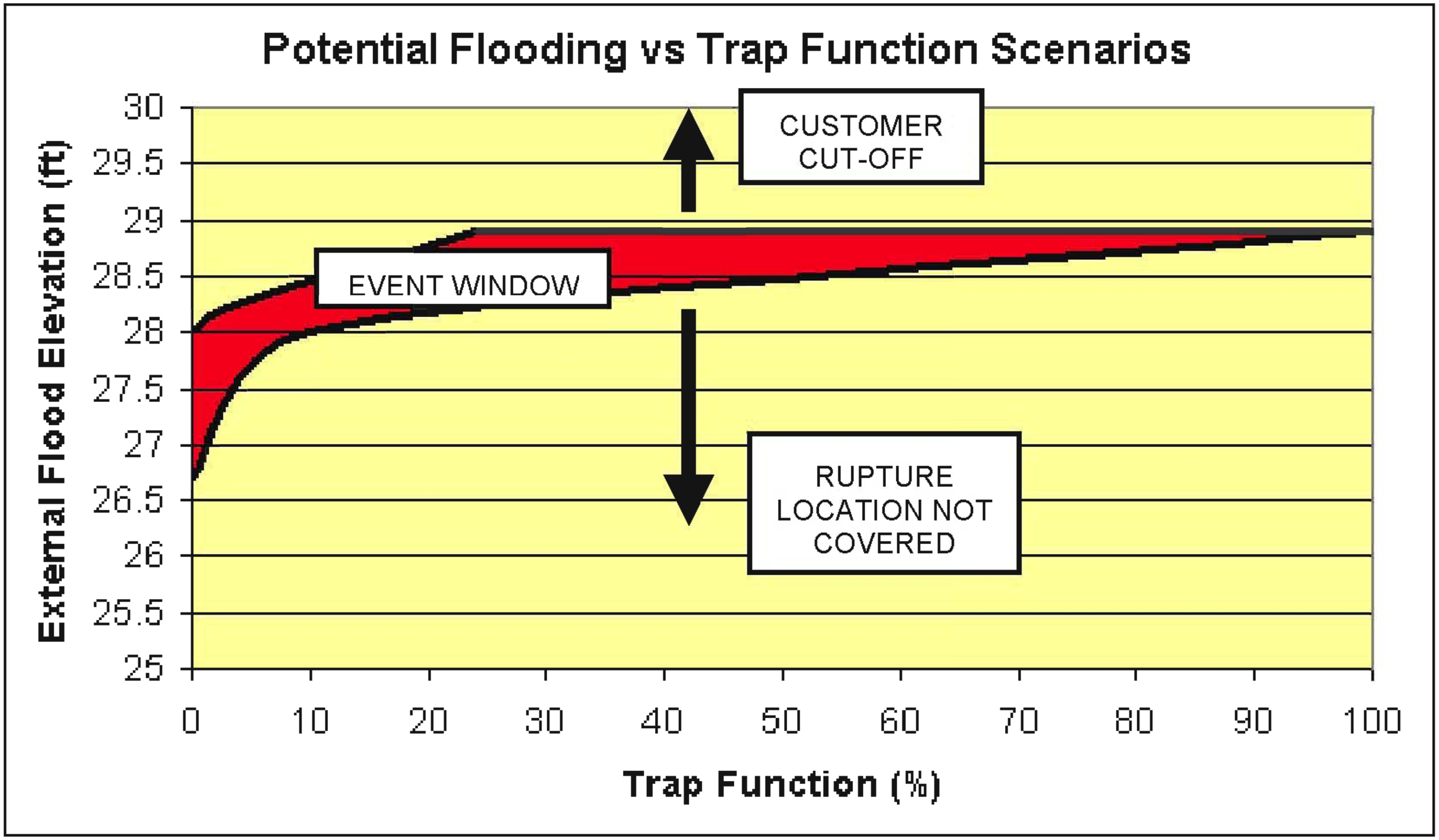


Figure 3-3: Potential Flooding and Trap Function Scenarios (9 Hour Duration)

(Note: Event window is based on range of pipe area exposed to boiling from 25% to 75%)

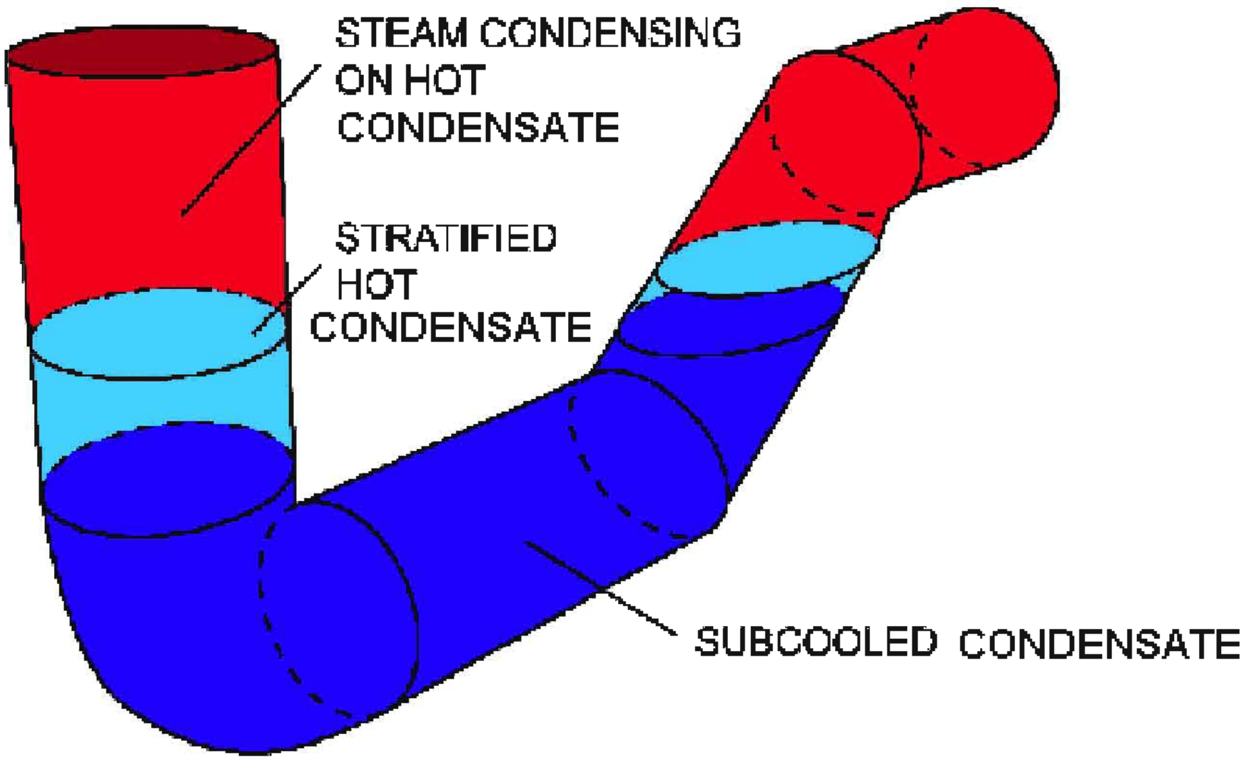


Figure 3-4: Condensate Subcooling and Stratification Scenario

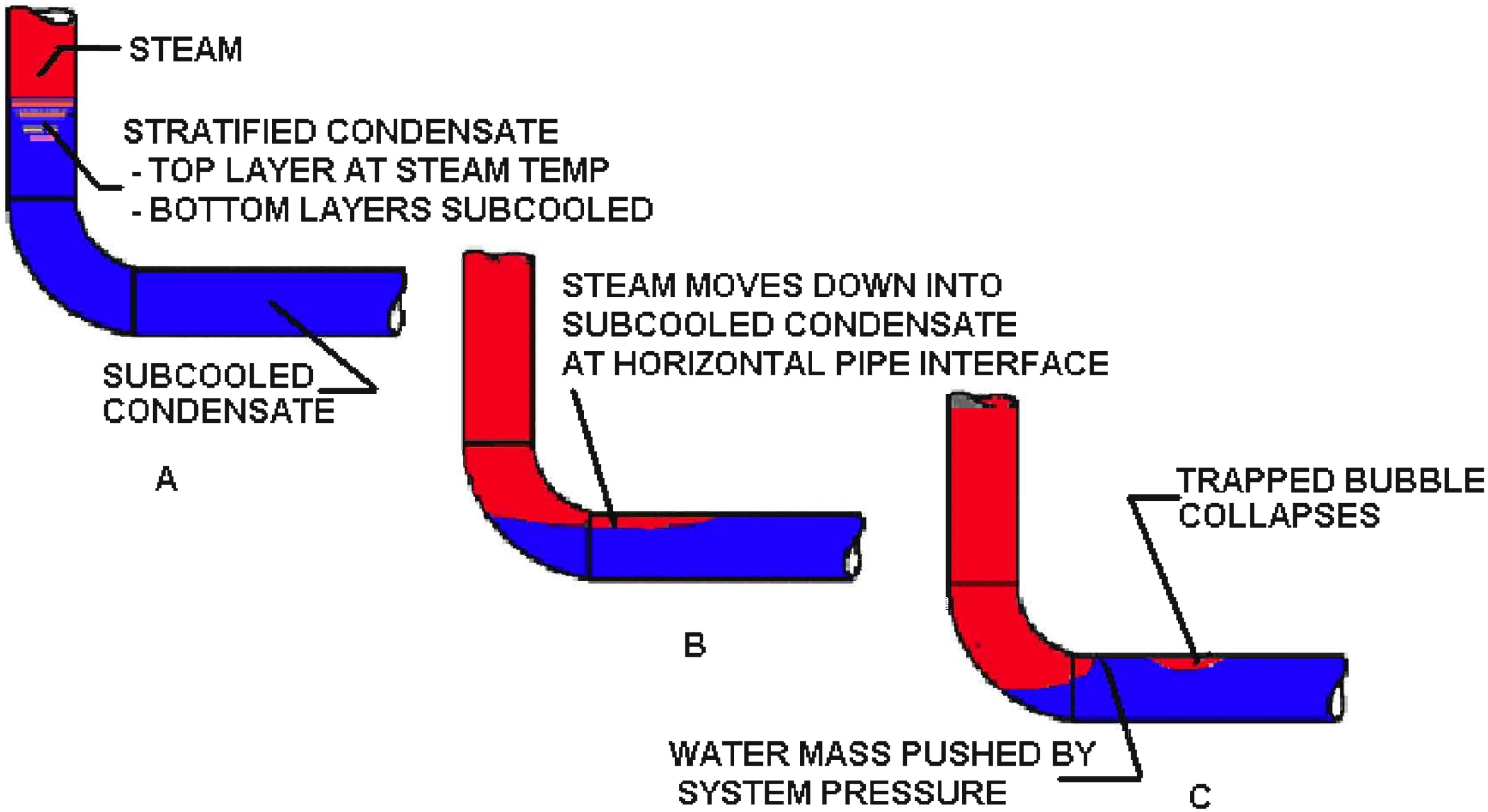
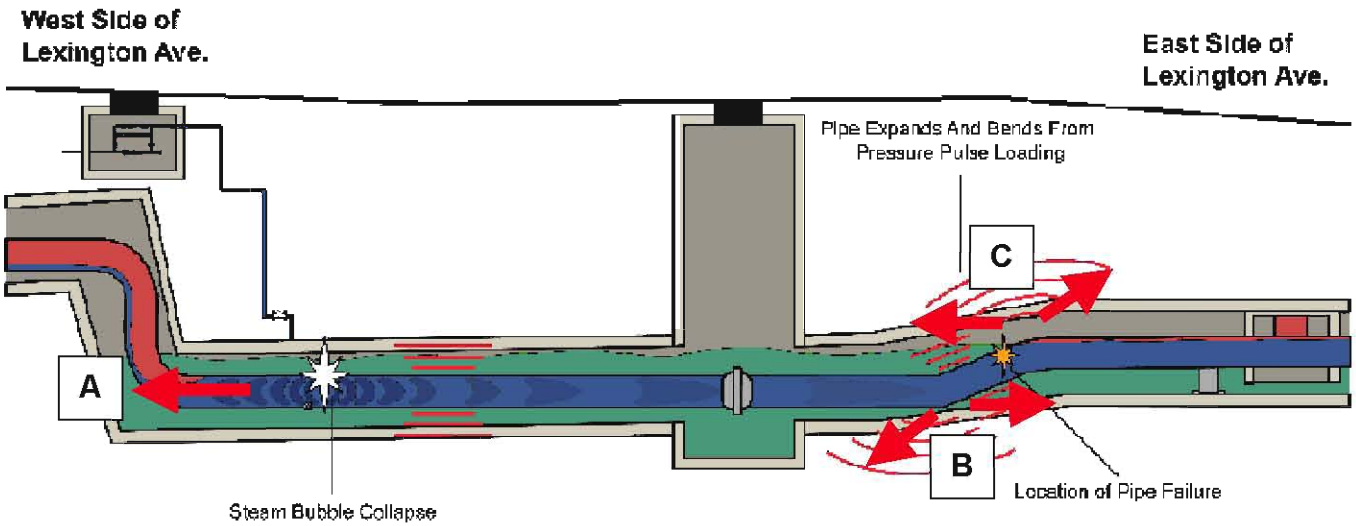


Figure 3-5: Scenario for Bubble Collapse Waterhammer



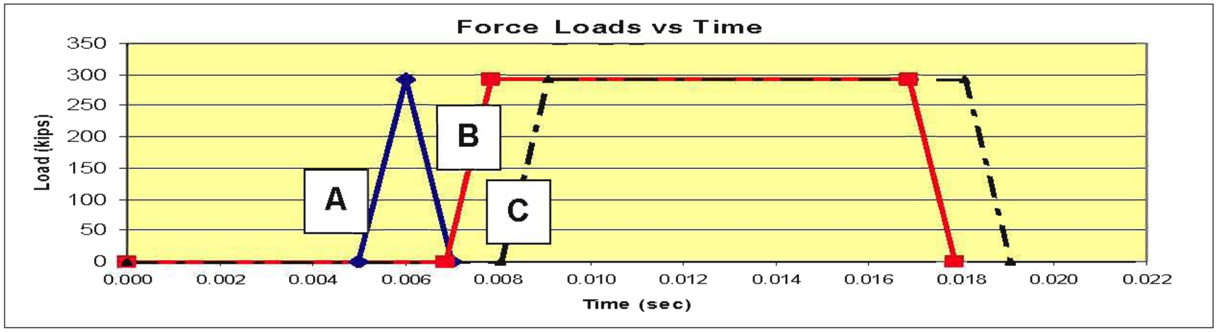


Figure 3-6: Force Time-History Loading Applied to Piping Model

(Assumed bubble collapse location. 1 Kip is equal to a 1,000 lb force)

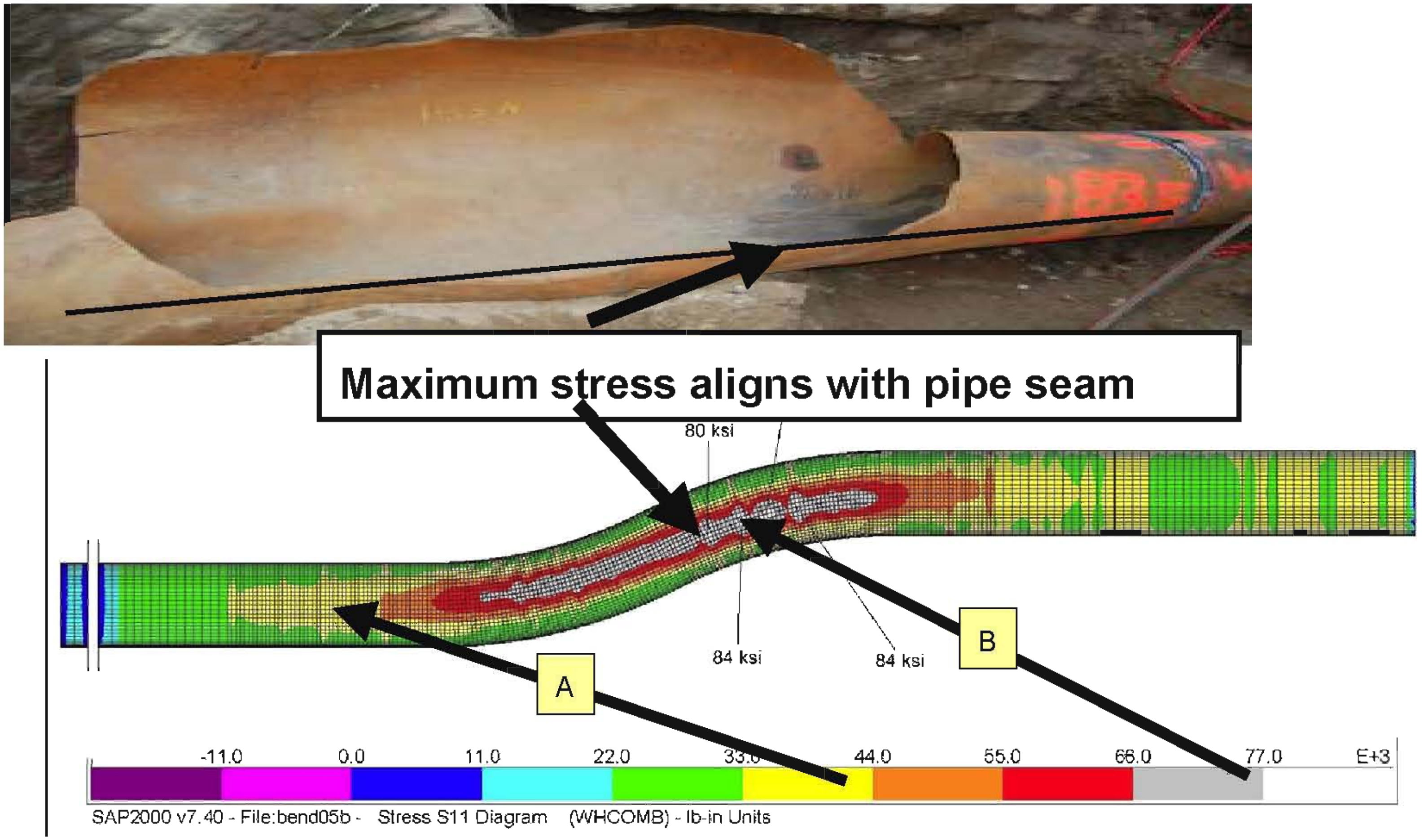


Figure 3-7: Maximum Pipe Stresses

(Stress levels in the horizontal west end of File 3 bend (Pt A above) can be seen to be significantly lower in stress magnitude than in the bend region, (Pt B above)).

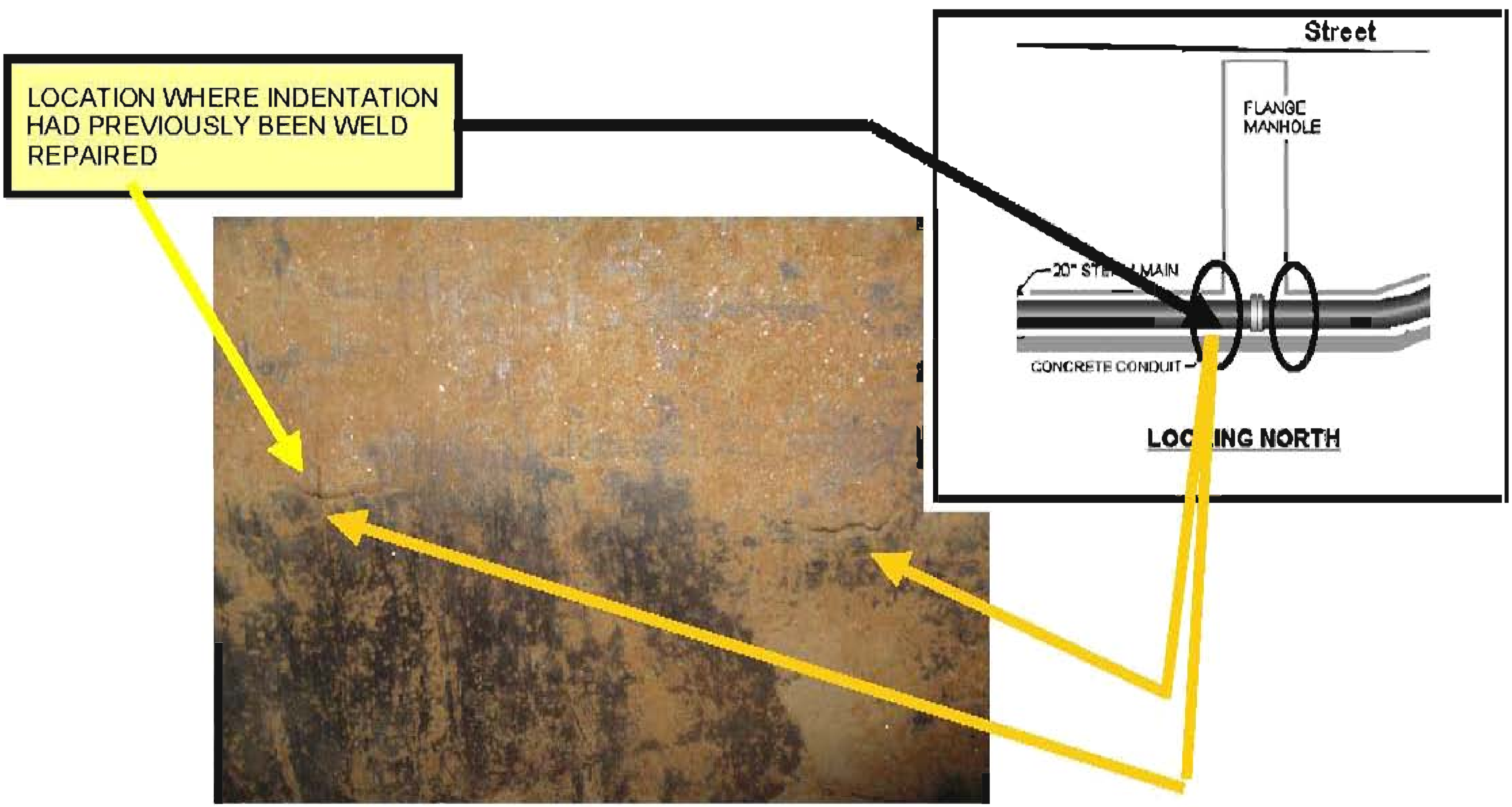


Figure 3-8: Interior View of Indentations Adjacent to Flange Section

4.0 CAUSAL FACTORS

This report section will evaluate the two abnormal conditions – flooding of the steam pipe and the compromised trap condition – that created conditions preceding the rupture.

4.1 Steam Main Housing Flooding

The volume of the steam main housing and manholes beneath the Lexington Avenue intersection for the piping with a top-of-pipe elevation of approximately 26.7 feet was calculated to be approximately 120 cubic feet (see Figure 1-2). The maximum external flood height would be limited by the crown (high) point of the pipe on 41st Street east of Lexington Avenue (see Figure 2-3). If flooding occurred to this crown point elevation, flood water would spill over towards 3rd Avenue, limiting its depth. The housing volume for this maximum elevation of flooding was calculated to be approximately 360 cubic feet.

The following sections discuss infrastructure conditions associated with water infiltration to the steam main housing.

4.1.1 Roadway Surface Runoff

The steam pipe local low point was at the intersection of 41st Street and Lexington Avenue in the drain manhole (see Figure 1-2). This intersection also was a low point for the roadway contours in the immediate vicinity to the south and west of the Incident Site. The numbered streets, from 38th to 41st, on the intersection west side and Lexington Avenue on the intersection south side slope down to this location as shown in Figure 4-1. Based on street slopes, rainwater runoff would drain down to the Incident Site. Con Edison manholes at the intersection had to be pumped out following significant rain events several times during past storms (see also Section 2.7).

Rainwater run-off is accumulated by the street drainage system through curbside gutters, catch basins and a drainage pipe connected to sewers. Two catch basins are located on the west side of the 41st Street and Lexington Avenue intersection, one on the southwest corner, and the other on the northwest corner. The drainage pipes connected to these catch basins cross over the steam pipe housing there (see Figure 4-2).

Using the rainfall data for July 18, 2007, runoff volume to these two catch basins was calculated and it was determined a breach in the chute of one of these catch basins could provide sufficient water to fill the volume of the housing air space. As outlined in Section 4.1.3, the northwest catch basin chute piping to the sewer was damaged, including through wall openings. Under heavy rain conditions, significant leakage to the ground and directly into the housing would occur.

4.1.2 Subsurface Water Level

A series of boreholes were drilled along 41st Street to the east and west of the Lexington Avenue intersection to enable monitoring of the water table local to the Incident Site. The borehole locations are shown in Figure 4-3, enabling the determination of the rock elevation at the intersection. Piezometer instruments were inserted into the boreholes that measure the water table elevation over time. Based on the observed elevation of rock, the steam main housing is likely cut into the rock, and rests on or is close to rock across the intersection (this is at approximately elevation 24 feet at the west side of the intersection, see Figure 1-2). The normal subsurface water level is at the rock elevation, just below the steam main housing. Using the borehole instrumentation in combination with rainfall events, it is possible to interpolate the water table fluctuations (see Figure 4-4). The water table elevations, as influenced by leaking infrastructure, rapidly responds to rainfall over a certain accumulation magnitude, especially at the borehole 5 location on the west side of the intersection, adjacent to the steam main and drain manhole. Based on the observations of the water table fluctuations, small rises in the water table will result in water entering the housing and manholes at the intersection. It is also believed the water elevation in the area is influenced by the 8 ft by 8 ft intercept sewer that runs along 41st Street, with flow from the west to the east. It was observed during a specific rainstorm that the 8 ft by 8 ft intercept sewer was running full and become pressurized. Any cracks that may exist in this sewer have the potential to create a local surge to the water table in the vicinity of the intercept sewer.

4.1.3 Intersection Catch-basins

The 41st Street and Lexington Avenue intersection has three catch basins to assist in drainage: one on the southeast corner, one on the northwest corner, and the other on the southwest corner.

The southeast corner catch basin drains to the north-south 4 ft by 3 ft sewer that is dammed just south of the Incident Site. This sewer bypasses the Incident Site and connects directly to the 8 ft by 8 ft intercept sewer running west to east. These sewers are identified in Figure 2-14 and Figure 2-15. Based on inspection of the sewer and observed condition, this catch basin is assumed to have been in good working condition prior to the incident.

The two west side catch basins were inspected. The southwest catch basin was found to be clear through the clean-out manhole and chute to the 4 ft by 3 ft sewer running north. The connection at the sewer is shown in Figure 4-2. The final connection to the sewer was not in place, however, it is not known if this was caused by the event or if this was a pre-existing condition. This presents an additional possible leakage path for rainwater to enter the steam main housing.

The northwest catch basin was inspected. The pipe from the catch basin to the clean out manhole (Figure 4-5) was in poor condition, and would leak under heavy rain flows, such as those experienced on the day of the incident.

Review of the SOMIS records revealed that in March 2005 where water was entering at the roof elevation of the drain manhole, approximately 11 feet below the street surface elevation. This is indicative of potential catch basin drainage issues.

4.1.4 Intersection Sewer Lines

The sewer lines within this area are shown in Figure 2-14 and Figure 2-15. Three sewer lines are present, consisting of a 4 ft by 3 ft sewer running west to east, a 4 ft by 3 ft sewer running south to north, and an 8 ft by 8 ft intercept sewer running west to east.

The south to north 4 ft by 3 ft sewer was installed circa 1852 and was modified at some point in time with a dam to re-direct flow into the deeper 8 ft by 8 ft intercept sewer, just south of the intersection. Water in this sewer flowing north towards the intersection is diverted into the 8 ft by 8 ft intercept sewer at a connection east of the intersection. Inspection of the 4 ft by 3 ft sewer south of the intersection identified it as in good working order.

The upper portion of the south-to-north 4 ft by 3 ft sewer across the intersection (in the region of the crater) was found to be missing and is believed to have been damaged by the event. This portion of the 4 ft by 3 ft sewer crosses directly above the steam main housing, adjacent to and east of the flange manhole. Based on the construction of the flange manhole, it is evident the manhole was constructed after the sewer.

The southwest catch basin drained into this 4 ft by 3 ft sewer, just south of the steam main, as shown in Figure 4-2. The sewer at the north side of the steam pipe and debris crater was found fully clogged with material. Material to approximately 3 feet deep extended from this location north of the intersection for a distance of approximately 150 feet. A portion of the debris is believed to be a result of the event.

The 4 ft by 3 ft sewer running west to east dates from circa 1863 and was inspected and found to be in good overall condition.

The 8 ft by 8 ft intercept sewer running from west to east was installed circa 1922. This sewer was inspected and was determined to be in good condition. During periods of heavy rain the sewer was observed to run full and pressurized. If cracks exist in this sewer, there is potential to enable the sewer to add to the local water elevation at the intersection.

4.1.5 Intersection Water Lines

The water lines in this area consist of two 12-inch diameter lines running east to west and north to south. The east-to-west lines are connected with “Bell and Spigot” joints and mechanical connectors and was originally installed circa 1929. The north-to-south piping contained “Bell and Spigot” connections. The east to west piping was found broken and laying in the crater. Figure 4-6 shows a disconnected mechanical coupling (Coupling “1”), with one end disconnected from the pipe at the west side of the crater – the coupling located in the crater with a pipe section attached. Another mechanical pipe coupling (Coupling “2”) was also retrieved from the Incident Site, with a manufacturing date of 1989. This coupling is shown in Figure 4-6 and has a longitudinal crack within the component.

As outlined within the LPI report [8], 15 sections of recovered water main piping were examined and tested to determine if the joints in the piping were leaking. One water line joint had indication of corrosion along the bottom of one joint. The fifteen individual pieces were tested under 5 psi internal pressure of which 13 pieces exhibited joint leaks. Leaking water mains would raise the level of external water contacting the steam main.

4.1.6 Vapor Observations

A security camera located at the southeast corner of 42nd Street and Lexington Avenue provided a viewable image of Lexington Avenue south to the 41st Street intersection. The security camera image shows the intersection crosswalk and the manhole cover at the flange manhole location within the intersection. The camera and approximate field of vision of the camera is depicted in Figure 4-7.

Post-event review of the security camera determined rain start and stop times as well as the presence of visible vapor. Visible vapor from the flange manhole was first noted at 8:53 AM. Visible vapor ended at 10:05 AM (See Figure 4-8 – Note the timing/date stamp on the security camera is 54 minutes slow, determined based on observation of the event time on the camera versus known time of the event).

A Con Edison vapor patrol surveyed the intersection at approximately 11:30 AM. Con Edison utilized procedure S-11952 [19] to identify steam pipes with flooded manholes and housings, which would be indicated by observable vapor. When the vapor patrol surveyed this location, no vapor was observed.

4.1.7 External Water Infiltration into Manholes and Housing

External water can infiltrate into manholes and the steam main housing through cracks in the housing or the manhole concrete walls. A review of the SOMIS database identified a report of water infiltration directly into the intersection drain manhole at the elevation of the roof to manhole chimney region, following a rainstorm.

4.1.8 Condensate Accumulation and Past Rain Event Assessment

Within Section 3.1.3 the range of external flooding was presented for the specific July 18, 2007 event, and is depicted within Figure 3-3. This figure shows the "event window" for the range of possible external flood elevation and trap capacity. This is for a given range of insulation conditions (i.e. area of pipe exposed to external boiling between 25% to 75%). Different insulation conditions would shift this curve somewhat in one direction or the other. The condition of the insulation was not known and the range of pipe exposed conditions is considered an assumption. A specific data evaluation of previous rain event days was made to better understand the trap condition prior to and during the July 18, 2007 incident. Based on review of the SOMIS data [9], the Incident Site has been subjected to numerous manhole and steam main housing flooding occurrences, resulting in observable vapor conditions during prior rain events. Vapor at the Incident Site has been observed for long periods of time following previous rain events, indicating that external water does not quickly drain away from this location.

A list of rain dates with similar or higher rain accumulation and intensity than the July 18 2007 incident day is included in Section 2.6. Given the similar or greater rainfall for these dates and the relative lack of rain that preceded the day of the incident, it is reasonable to assume steam main housing and manhole flooding for the listed rain dates occurred. Although event day flooding data are not available, potential flooding was similar in all these cases, and vapor was reported on some prior rain days [9].

The variables that impact the water accumulation inside the pipe and the potential for waterhammer include the external flooding elevation, the area of pipe exposed, and the trap functional capacity.

Given that a rupture from waterhammer did not occur on the earlier dates, although a less severe waterhammer may have occurred, it was likely that the trap capacity was greater at the time. Although this cannot be quantified, a larger trap capacity would result in a lower elevation of condensate accumulating inside the pipe enabling steam to continue to flow. This assessment, coupled with the compromised trap condition found after the event (to be described in the next section) makes it likely that trap capacity on earlier rain days was greater than on the July 18 day.

4.1.9 Summary of Intersection Subsurface Water Issues

The steam main at the intersection was located at a deep location beneath the roadway. Based on rock and water table elevations obtained from the boreholes, the steam main housing is likely located on rock for a portion of the section traversing across the intersection. The normal water table elevation is at the rock elevation, which places it just below the steam main housing. Water levels in the vicinity of the steam main increased as a result of rain and the condition of the sewer infrastructure.

The streets to the west and south of the intersection provide street surface runoff that spills down to the 41st Street and Lexington Avenue intersection catch basins. This street runoff flows into the northwest and southwest catch basins. The northwest catch basin exhibited poor condition between the catch basin to clean-out connection, Figure 4-5; the southwest catch basin was potentially disconnected at its chute connection to the south-to-north sewer, Figure 4-2.

The 8 ft by 8 ft intercept sewer, although approximately 12 feet below the base of the steam main, was observed to run full and pressurized during a post event rainstorm. Any cracks or breaches in this sewer, would allow water to migrate from the sewer, potentially adding to local water level surge during such times.

Finally, testing of water mains removed from the intersection revealed these pipe joints leaked. Although these tests were performed post event, any minor leakage from these water lines would increase the external water level that could be in contact with the steam main.

A summary of the above external water issues is depicted in Figure 4-9.

4.2 Trap Capacity

4.2.1 Testing and Disassembly

The two steam traps and the associated trap assembly piping located in manhole #7338 that drained the section of piping at the Incident Site was removed on July 25, 2007 for examination and testing. The steam traps and associated piping configuration is shown in Figure 4-10. Testing of the traps was performed with steam at typical steam distribution pressure. This testing showed that the traps passed only 1 pint of condensate in 3 minutes [17], or 20 lbs/hour in comparison to the trap capacity for the installed configuration of approximately 3,700 lbs/hour of condensate (0.5 % of the available capacity).

Following this testing, the traps were disassembled at LPI on August 24, 2007. The traps were found to have debris within the inlet orifice [8] as shown in Figure 4-11. Subsequent testing of this material from one trap showed that it was primarily a Phenolic resin with iron oxides [8]. Compositional analysis of the debris from this trap indicated that the material was chemically similar to the leak-seal product injected into the flange 20 feet east of the fish-mouth drain (Section 2.8).

Additional traps were inspected in manholes in the rupture vicinity. These inspections identified some traps with debris present in the trap ports and some traps where the disc did not seat tightly (a blowing trap). A blowing trap will continue to remove condensate. These inspections did not find leak sealant material debris as was found in the traps at the Incident Site.

The traps on 41st Street west of Lexington Avenue were inspected and found to be clear and operating properly.

4.2.2 Debris Transport in Trap Line

As outlined in Section 4.2.1, the steam traps contained debris that was chemically similar to the leak seal product injected into the flange adjacent to the fish-mouth drain. The material used for leak seal injection is primarily a Phenolic resin based material (Section 2.8). Partial trap clogging with the leak seal material may enable corrosion products to further clog the trap ports.

Debris can be moved down the steam main to the trap fish-mouth by the flow of condensate or steam. High steam velocities could sweep resin material down the steam main, and it is likely that debris would collect in the fish-mouth opening to the drain lines. The drain line geometry from the fish-mouth to the traps is shown in Figure 2-5.

Once debris enters the trap line, the potential to be lifted up the vertical legs to the traps is a function of the flow rate in the line and the density of the material. The hydraulic (sinking) forces must be overcome by the drag forces from the upward vertical flow past the particles.

An assessment of the sinking and drag forces was performed. When the drag/lift forces are larger than the sinking forces, the particles will rise up the trap line. A single trap discharging condensate will lift smaller particles and two traps discharging condensate will lift larger particles. The velocity of condensate flow in the 2" trap line is approximately 0.4 feet per second for 1 trap operating and approximately 0.8 feet per second for 2 trap operation. The corresponding ability to lift debris of steel, epoxy, and sand for selected particulate size is shown in Figure 4-12. Epoxy requires the lowest velocity of these materials.

Trap operation during periods of normal condensate generation is intermittent with each of the two traps opening independently of the other. They will each be open for relatively short periods of time. The low velocities with one or two traps operating intermittently makes it more difficult for debris that collects in the fish-mouth and the inverted u-bend to travel to the steam traps. During times of heavy condensate formation, which occurs when the outside of the pipe is flooded, both traps will be constantly open. Two fully open traps under heavy condensate flow conditions could lift larger particles that would be more probable to plug the trap inlet orifice than a single trap with intermittent flow under normal dry conditions. Thus, the traps in this case had greater potential to become plugged with the epoxy resin material given the housing flooding conditions.

Based on the SOMIS information, together with information from the security camera, the days after March 14th, 2007 (the date of the last leak seal maintenance activity on the pipe flange) that had visible vapor identified were April 15, April 27, June 3, June 4 and July 18, 2007. It is likely that the Phenolic material discovered in the traps was transported on one of these days.

4.2.3 Effect of Waterhammer on Trap Debris

The debris found in the trap when the trap was opened was relatively tightly packed. This greatly limited the condensate flow that the traps would pass when tested. It is believed that the debris in the trap inlet port was in the trap prior to the waterhammer occurring. The waterhammer is a very short duration high intensity pressure pulse that would not move debris up the drain line. However, the drain line from the steam pipe all the way to the trap was water solid at the time of the waterhammer. This means that the pressure pulse of at least 1,060 psig would travel up the drain line to the trap. This would reach the debris in the inlet port and compact the material that had collected there. It is very likely that the appearance of tightly packed debris (see Figure 4-11) was an effect of the waterhammer occurrence.

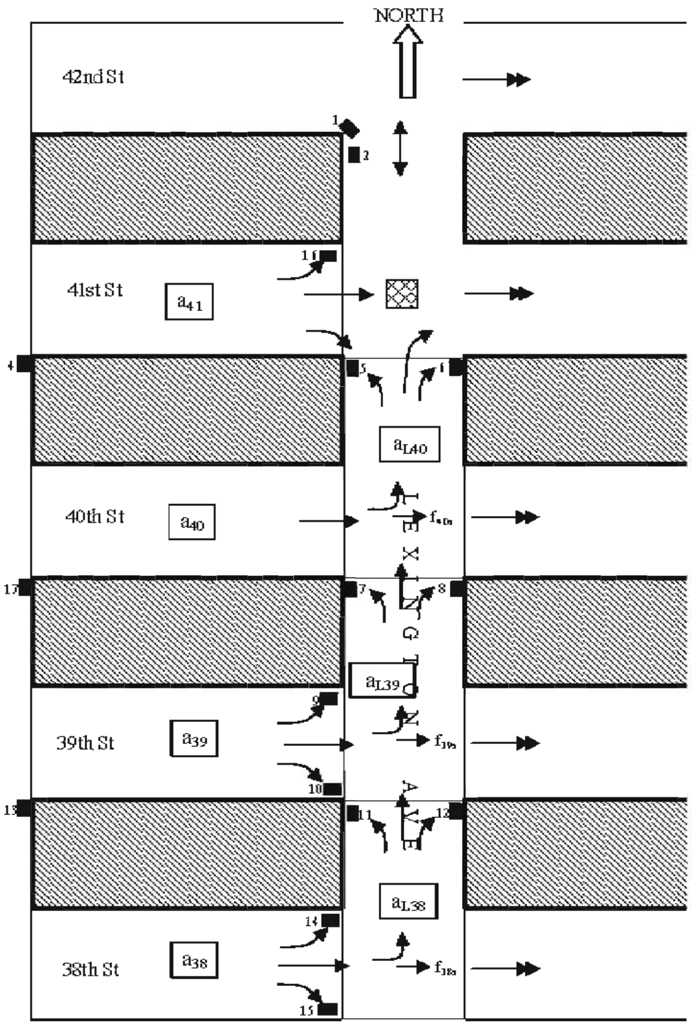


Figure 4-1: Street Drainage and View East on 41st Street

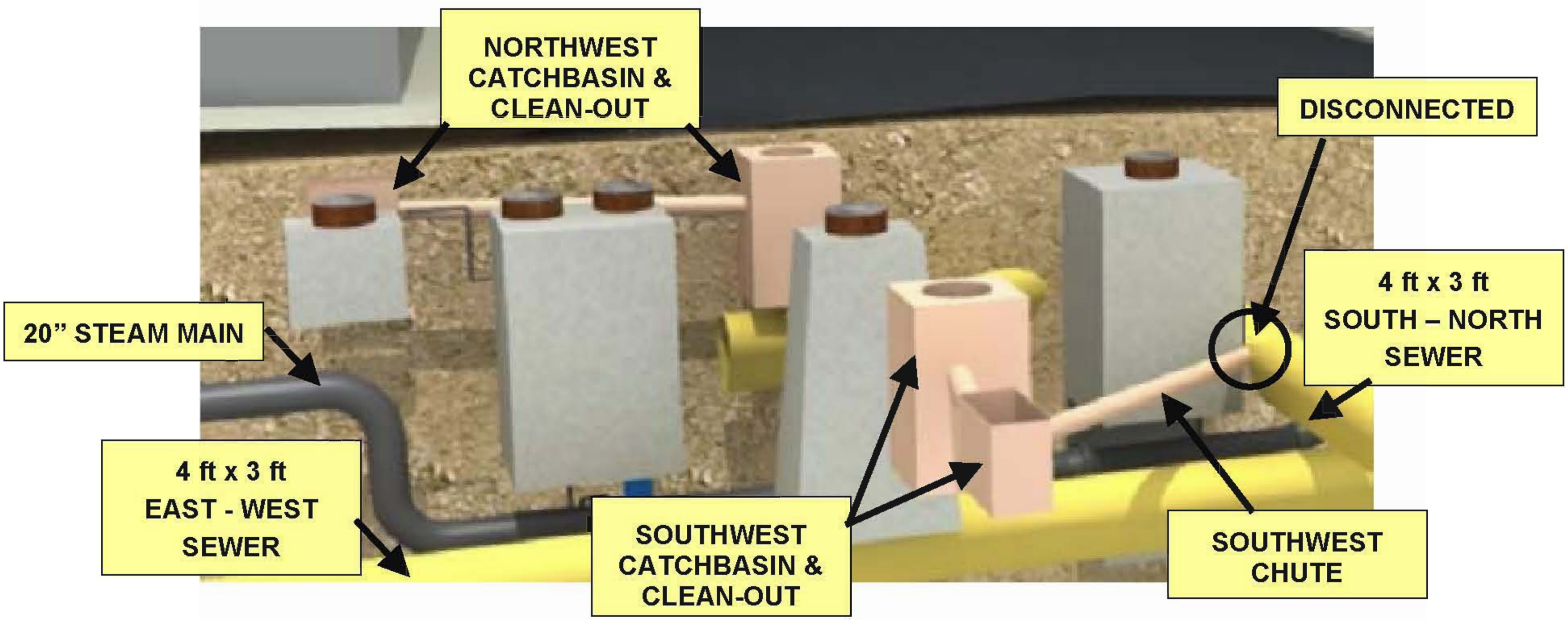


Figure 4-2: Arrangement of West Side Catch Basins Looking North

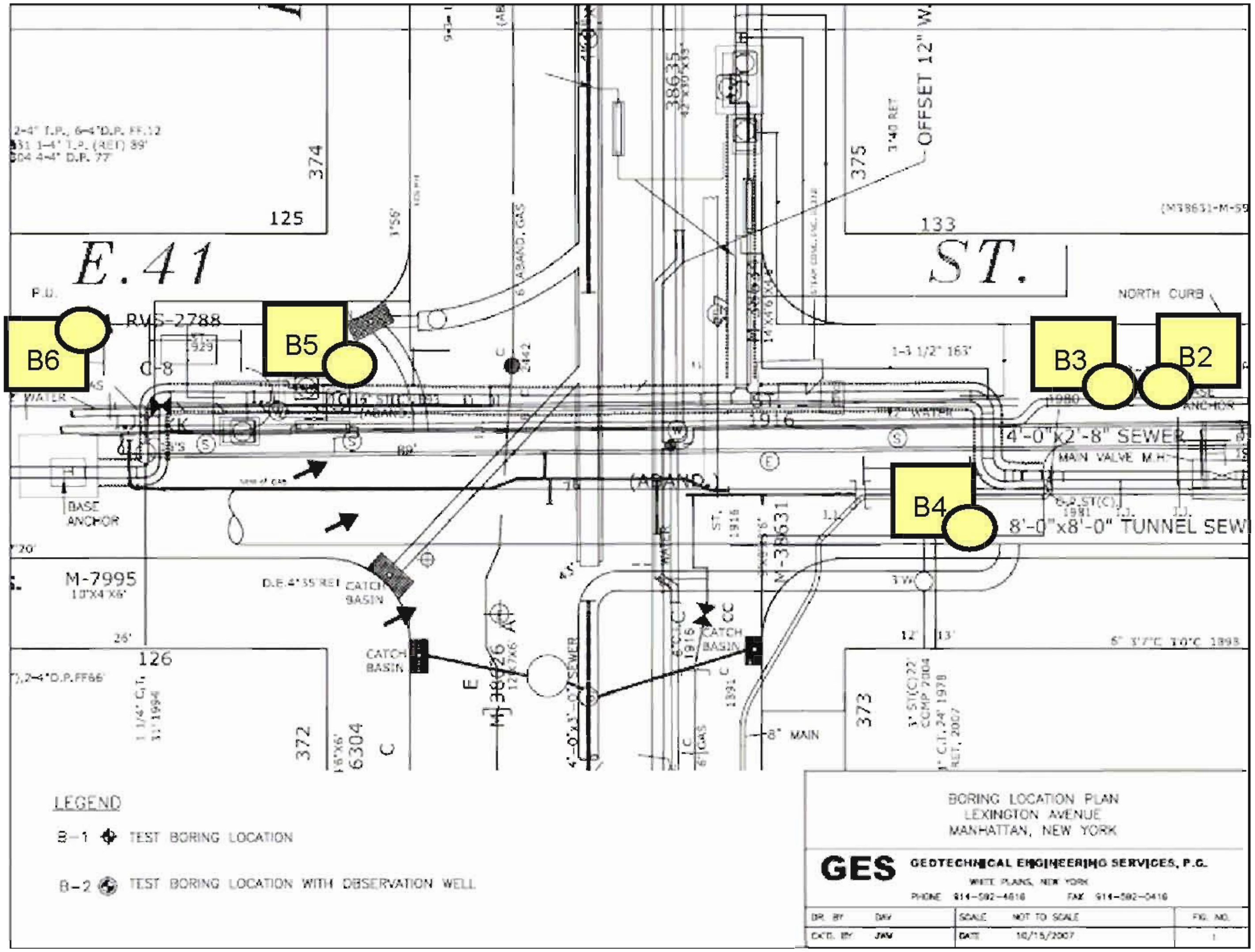


Figure 4-3: Subsurface Water Level Measurement Test Locations

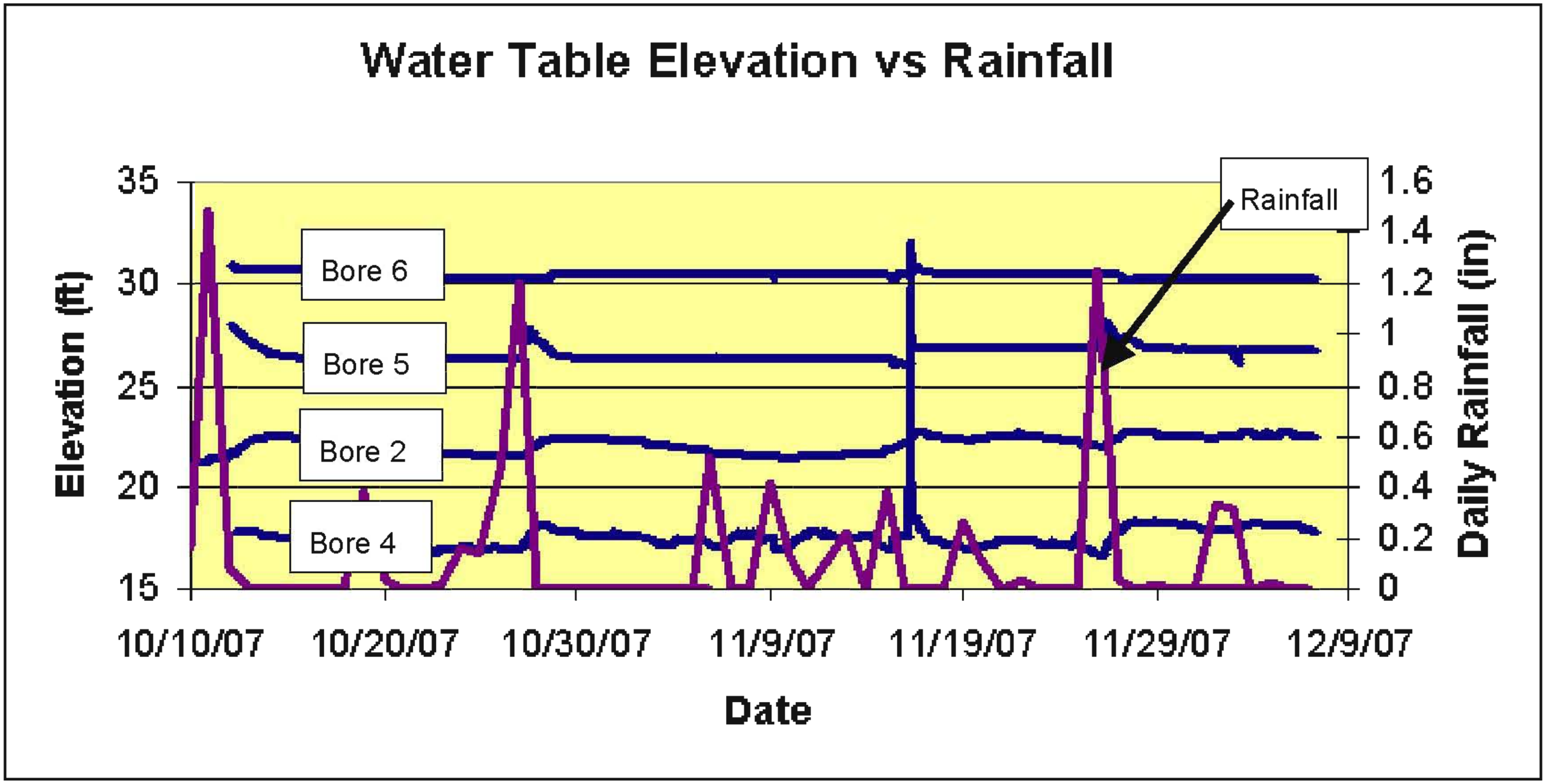


Figure 4-4: Subsurface Water Level Elevation

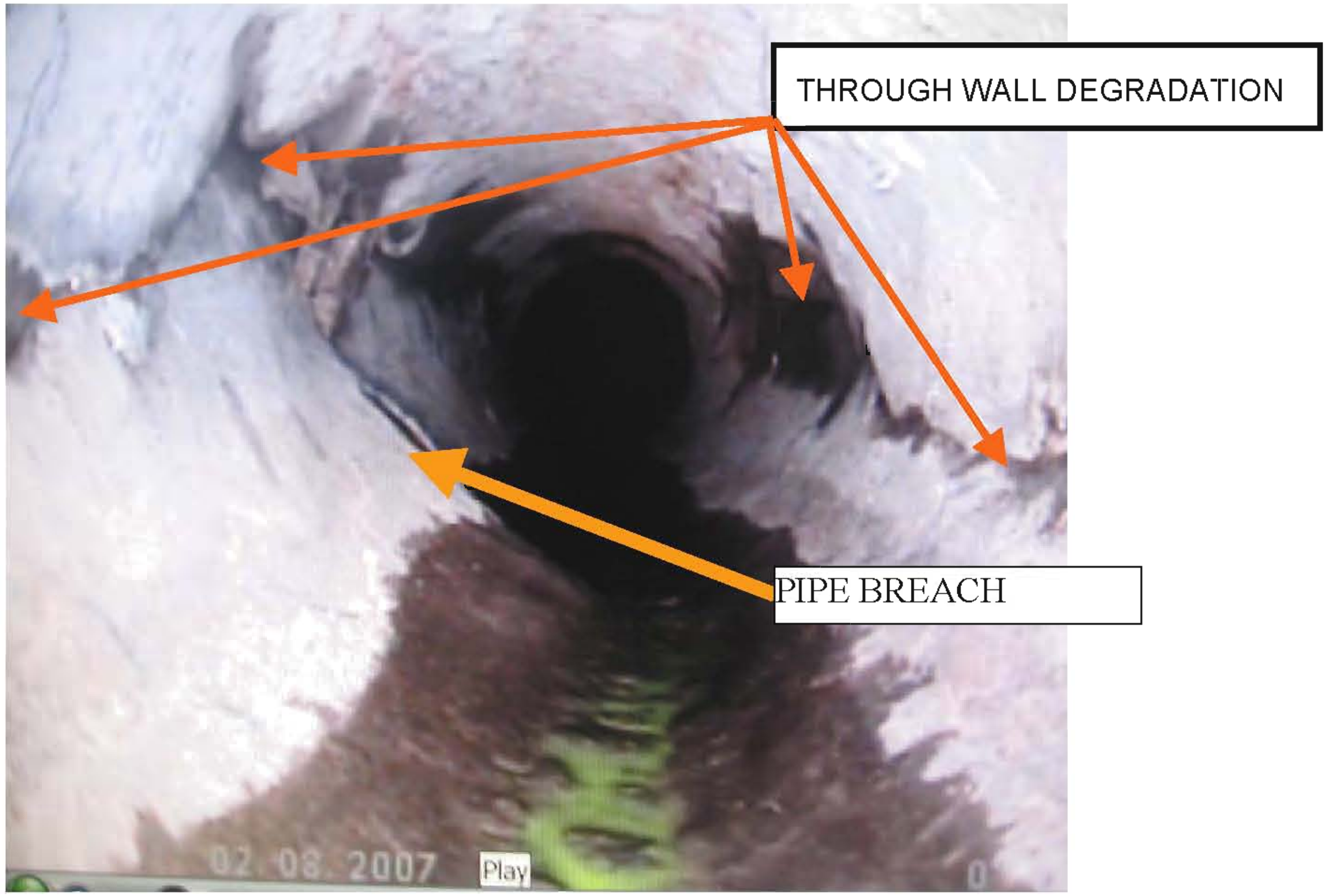


Figure 4-5: Northwest Catch Basin to Clean-out

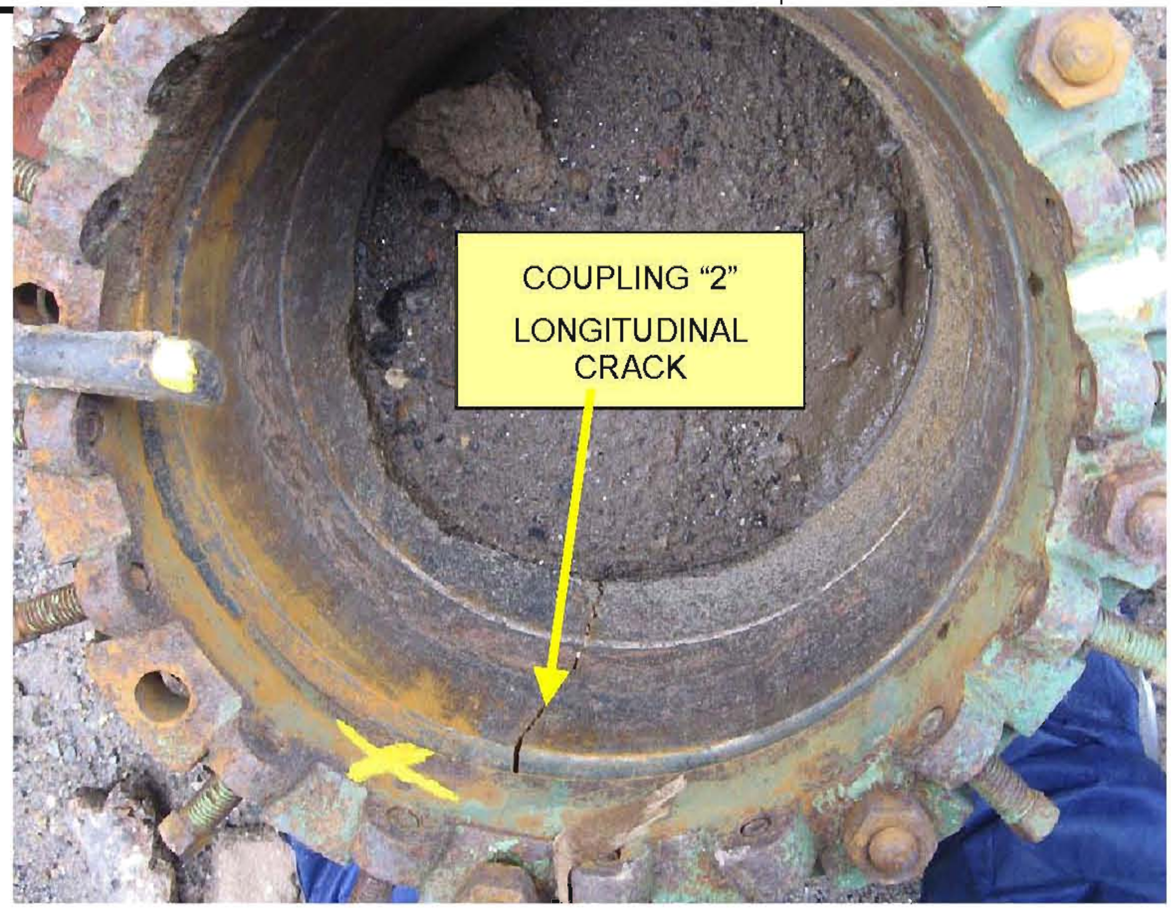


Figure 4-6: 12" Diameter Water Main and Coupling in Crater and A Cracked Coupling Removed from Crater
(Coupling "1" is visible left, and Coupling "2", has a longitudinal crack visible in the coupling (picture on right))

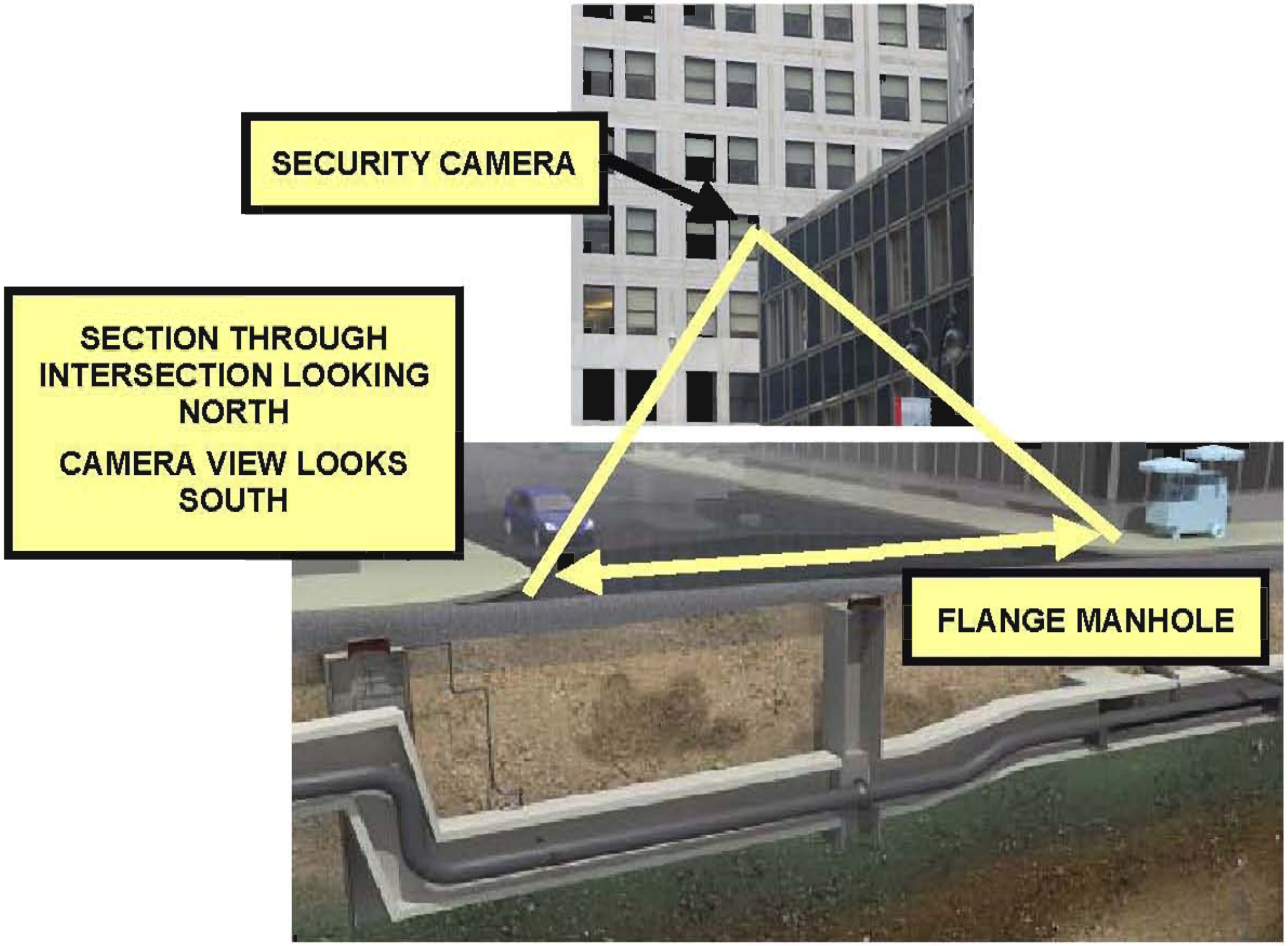


Figure 4-7: Location and Approximate Field of Vision of Security Camera

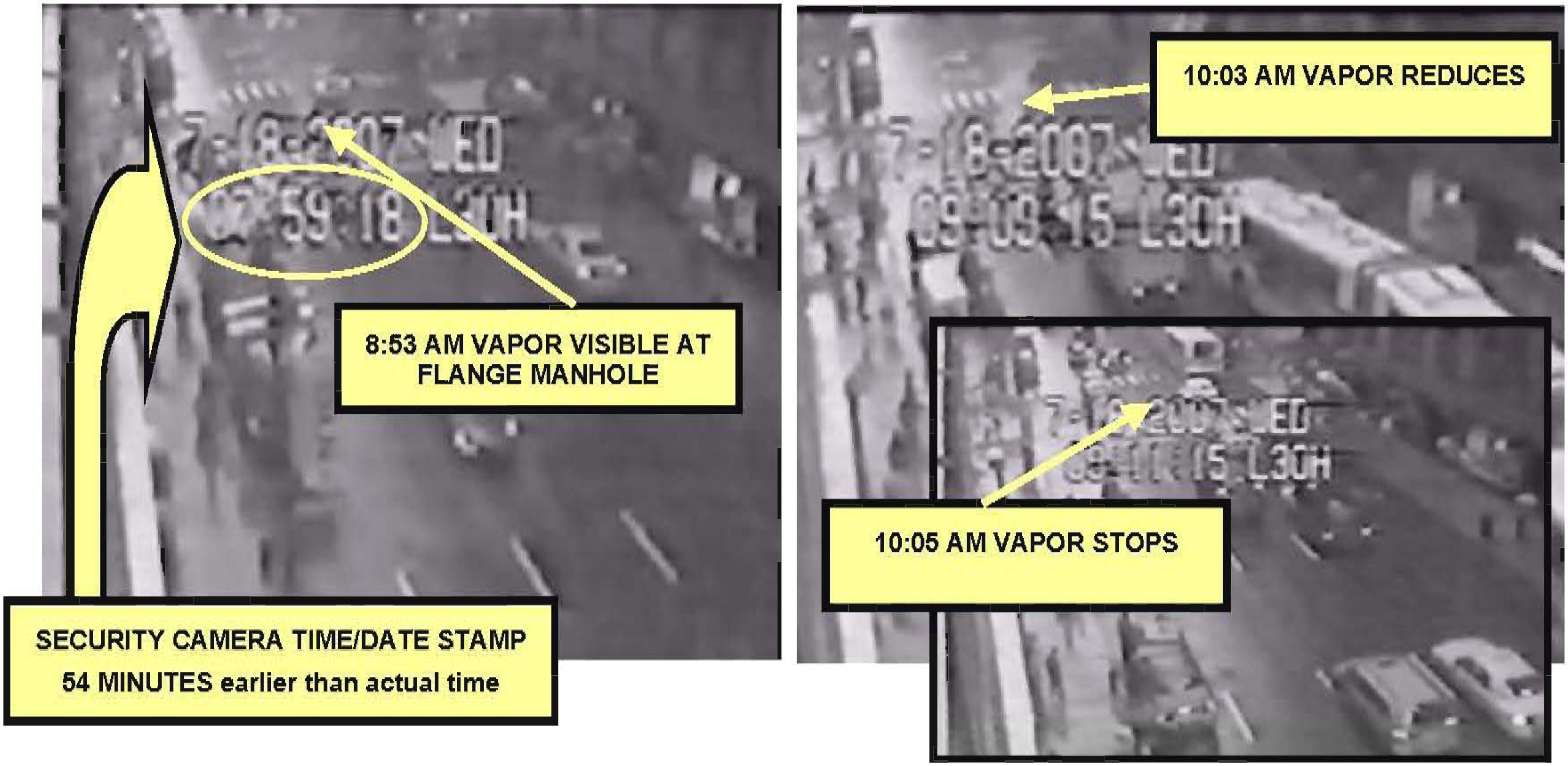


Figure 4-8: Start and End of Observable Vapor From Flange Manhole – Security Camera Looking South

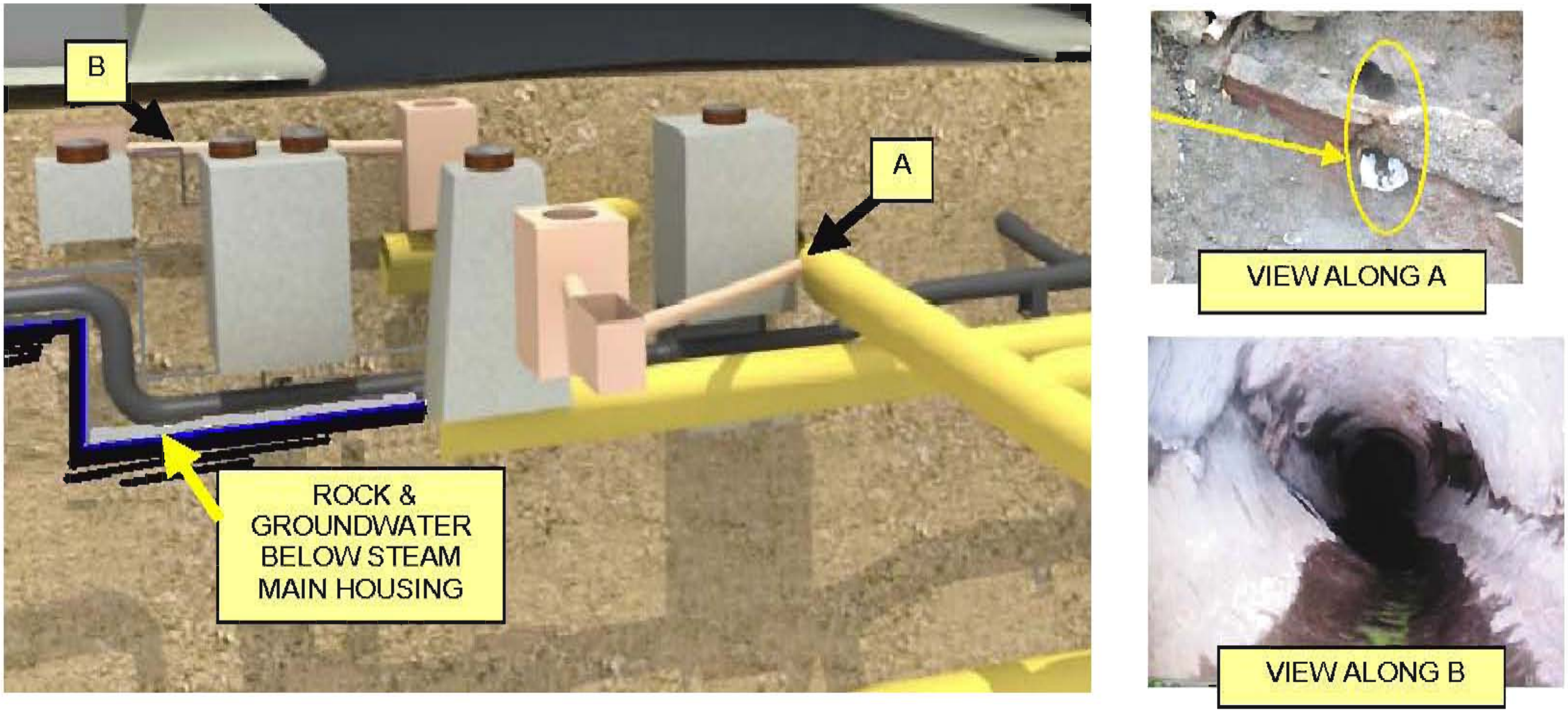


Figure 4-9: Depiction of external water Issues at Intersection

Figure 4-10: Steam Traps and Associated Piping Manifold Removed from Manhole # 7338 for Testing

Figure 4-11: As-found Condition of Upper Trap Following Cap Removal
(Lower trap had similar deposits, refer to [8])

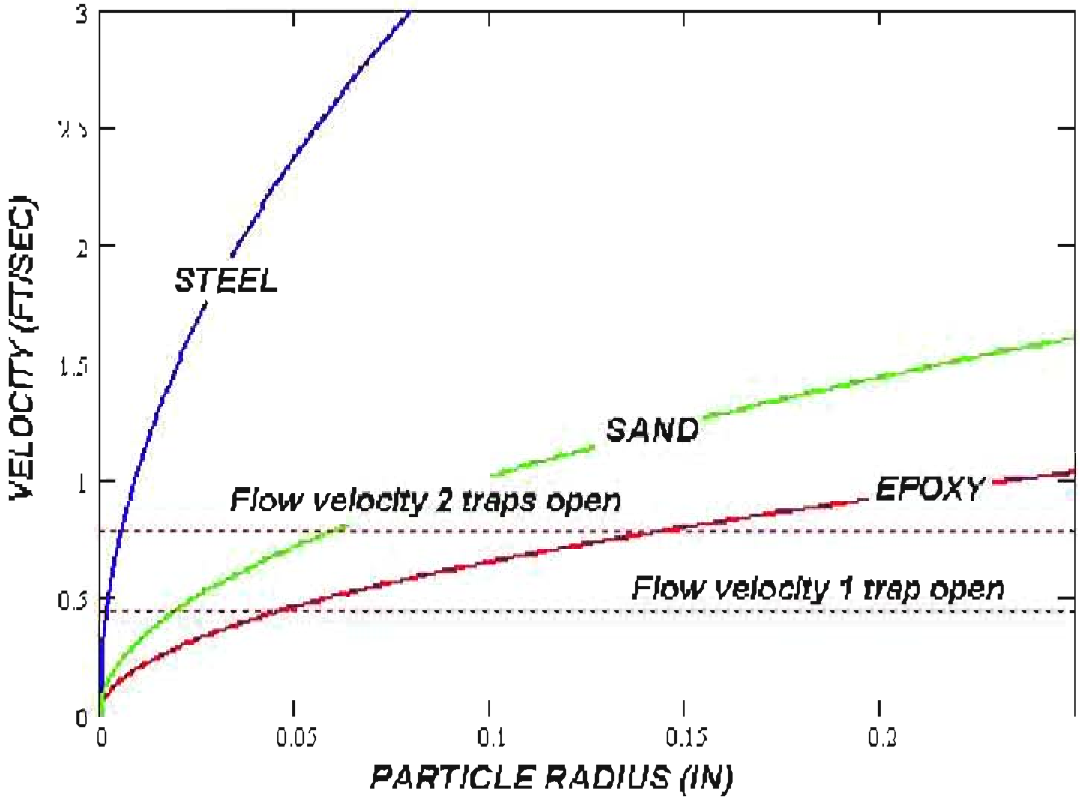


Figure 4-12: Flow Velocity in Trap Line Required to Lift Debris Particle of a Specific Size

5.0 CAUSE OF RUPTURE

The cause of the steam pipe rupture that occurred on July 18, 2007 at East 41 Street and Lexington Avenue (the Incident Site) was an excessive internal pressure pulse caused by condensation induced waterhammer. The required conditions for this waterhammer were collected subcooled condensate in the pipe and a mechanism to enable steam to flow into the condensate. The resulting stress in the pipe from the waterhammer's internal pressure and unbalanced pressure forces must exceed the strength of the pipe.

The evaluation of the rupture cause identified two primary conditions that contributed to the event. These causal factors were:

1. Flooding of the steam pipe at 41st Street and Lexington Avenue occurred due to heavy rain and external water infiltration, which resulted in significant condensate generation exceeding the steam traps' capability.
2. Leak sealant application in the adjacent pipe flange resulted in the sealant material migrating and compromising the steam traps' ability to remove condensate.

The intersection of 41st Street and Lexington Avenue had a history of vapor conditions requiring pumping of the intersection's steam manholes following periods of heavy rain. Vapor conditions result when external water touches the steam main, the heat from the steam main boils the external water, and the resulting vapor is visible at manholes. This is shown in Figure 5-1. During past rain events at this intersection, vapor was observed and remained visible for hours, until steam crews pumped the manholes.

On the morning of July 18, 2007 a heavy rainfall occurred with significant rainfall intensity over one hour. Only ten other days had similar rainfall intensity over a three and half year period. External flooding contacted the steam main and a vapor condition occurred on the morning of the event at approximately 8:53 AM. Rapid condensate generation occurred due to the external floodwater at a time when minimal pressure differential existed across the intersection, and in combination with compromised steam traps, condensate collected and filled the pipe, blocking steam from flowing. With steam flow blocked, condensate in the pipe rapidly cooled, resulting in insufficient heat to boil the external water. As depicted in Figure 5-2, by approximately 10:05 AM, vapor conditions stopped. Con Edison utilizes vapor patrols to identify where external water is touching the steam main. On the morning of July 18, the vapor patrol surveyed the intersection at approximately 11:30 AM, saw no vapor, and was thus unaware of the condition below the street.

Rain should not significantly affect the water table immediately following a rainstorm for this region of the city, with paved streets, sidewalks and minimal exposed ground. This was not the case at this intersection. As a result of monitoring the water table during this investigation, it was demonstrated that the normal water table elevation is just below the steam pipe main elevation on the west side of the intersection. The inspection of the intersection's northwest catch basin identified poor condition of the connection to the clean-out and chutes to the sewer. Both deficiencies add to the local water level during periods of heavy rain and street surface runoff and provide water for direct infiltration into the manhole. The southwest catch basin at the intersection appeared to be in reasonable condition. However, the attachment to the sewer, directly over and adjacent to the steam main, could not be confirmed as being intact at the time of the incident. Additionally, the 8 ft by 8 ft intercept sewer, although lower than the steam main, was observed to run full and pressurized during a rain event, potentially further affecting local water level surge at the intersection location. Water mains recovered from the intersection were tested and were found to leak; one water main connection had indications of significant corrosion at a joint. Leaking water mains also would affect the local water elevation at the intersection.

Post event examination of the steam traps revealed that debris had accumulated in the inlet ports of the traps. The majority of this debris material was chemically similar to a leak-seal product injected at the flange connection approximately 20 feet east of the fish-mouth drain leading to the trap line. The flange connection had been injected with sealant material a number of times, the last occurrence being on March 14, 2007.

At various times between the sealant injection and the time of the event, leak-sealant material migrated to the traps. The debris found in the traps when the traps were opened was relatively tightly packed. This greatly limited the condensate flow that the traps would pass when tested. The debris in the trap inlet port was in the trap prior to the waterhammer occurring. The waterhammer is a very short duration high intensity pressure pulse that would not move debris up the drain line. However, the drain line from the steam pipe all the way to the traps was water solid at the time of the waterhammer. This means that the pressure pulse would travel up the drain line to the trap. This would reach the debris in the inlet port and greatly compact the material that had collected there. A trap capacity of approximately 11% would have been sufficient to handle the normal condensate generation for the steam pipe draining to the trap location. Prior to the morning of the event, trap capacity would have had to be at least 11%.

With condensate collecting in the pipe for approximately nine hours from 9:00 AM until the event time of 5:56 PM, more than sufficient time elapsed to enable subcooling of the condensate below Lexington Avenue intersection by at least 35 to 40 degrees Fahrenheit. With normal operational changes occurring towards the end of the day, pressure increased on the west side of the intersection, enabling the steam to flow into the subcooled condensate, as shown in Figure 5-4. A resulting steam bubble became trapped, creating a condensation induced waterhammer.

The pressure pulse from this waterhammer traveled through the accumulated condensate, inducing internal pressure and unbalanced pressure force loadings at changes in direction. The resulting pipe stresses from this loading exceeded the strength of the File 3 bend component at the intersection east side. This component was the highest stressed portion of the pipe subjected to waterhammer loading. The resulting internal pressure pulse as a result of the waterhammer was calculated to be at least 1,060 psig to result in the rupture of the pipe at the observed location. This pulse is above the normal operating pressure of approximately 150 to 170 psig, resulting in a total applied pressure of approximately 1,200 psig. This internal pressure was insufficient to damage the straight runs of piping across the intersection.

The condition of the material, the fabrication, and the seam weld used to form the File 3 bend was fully adequate for normal operation and did not contribute to the rupture.

The two primary causal factors that resulted in this event have been identified as (1) the external water flooding the housing and (2) leak sealant material compromising the capability of the steam traps to remove condensate. These causal factors in conjunction with other contributing conditions resulted in this event. These primary causal factors together the contributing conditions are summarized as follows:

1. External floodwater surrounded and contacted the steam main across the intersection;
2. Both steam traps that provided condensate drainage for the pipe portion at the intersection were found to contain debris, compromising their ability to remove condensate from the pipe;
3. The steam main at the Lexington Avenue intersection was located deep beneath the roadway, making it more susceptible to housing flooding;
4. The piping configuration and normal flow patterns of the networked steam system that day, allowed condensate to build up and fill the pipe beneath the intersection without affecting pressure or flow to customers;
5. Rapid condensate generation, caused by the combination of flooding and compromised traps, resulted in the cessation of observable vapor at the street. This

sign of water touching the steam main, normally observed by vapor patrols, was defeated by the incident circumstances.

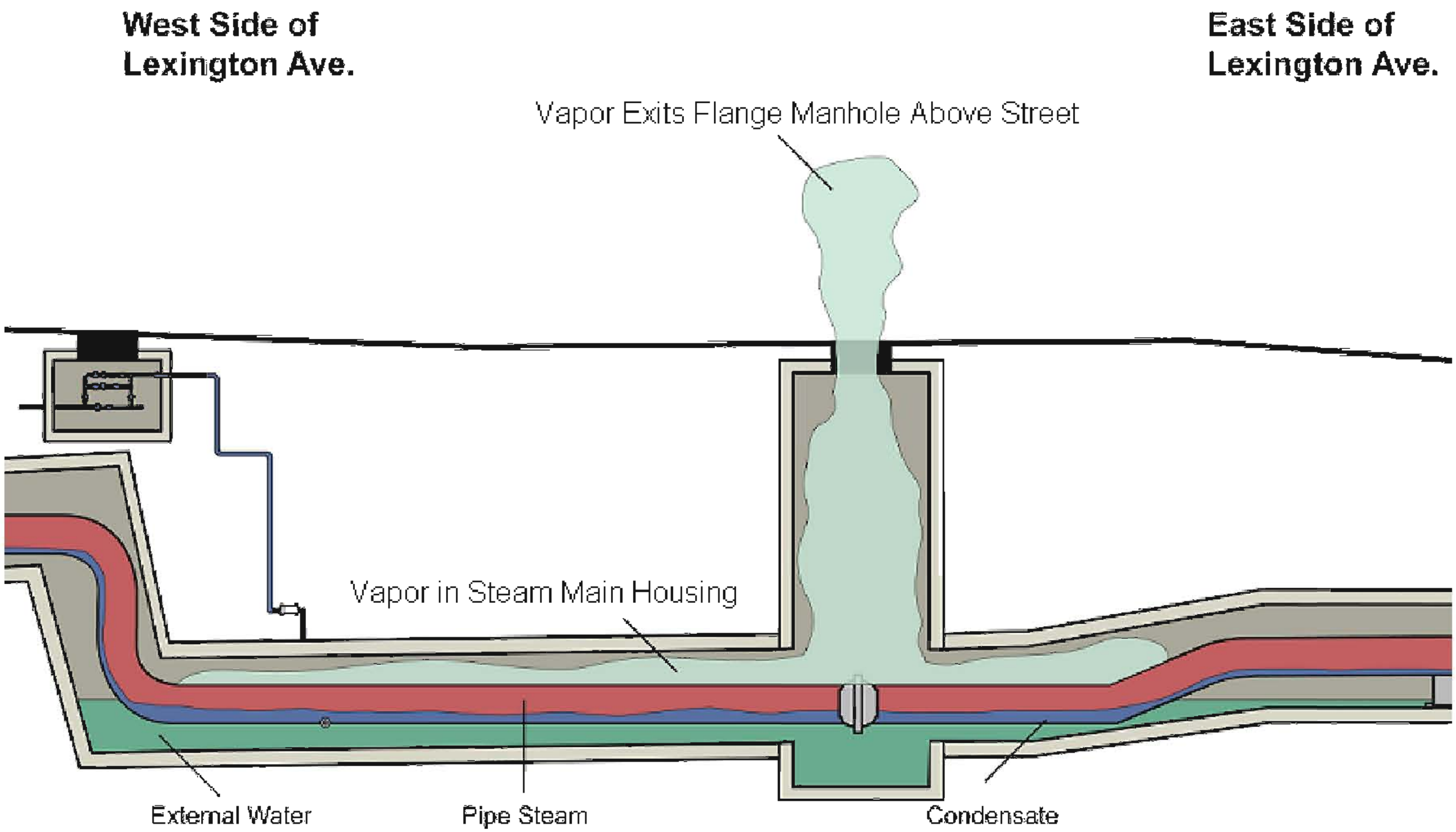


Figure 5-1: Vapor Visible From External Water Contacting Steam Main

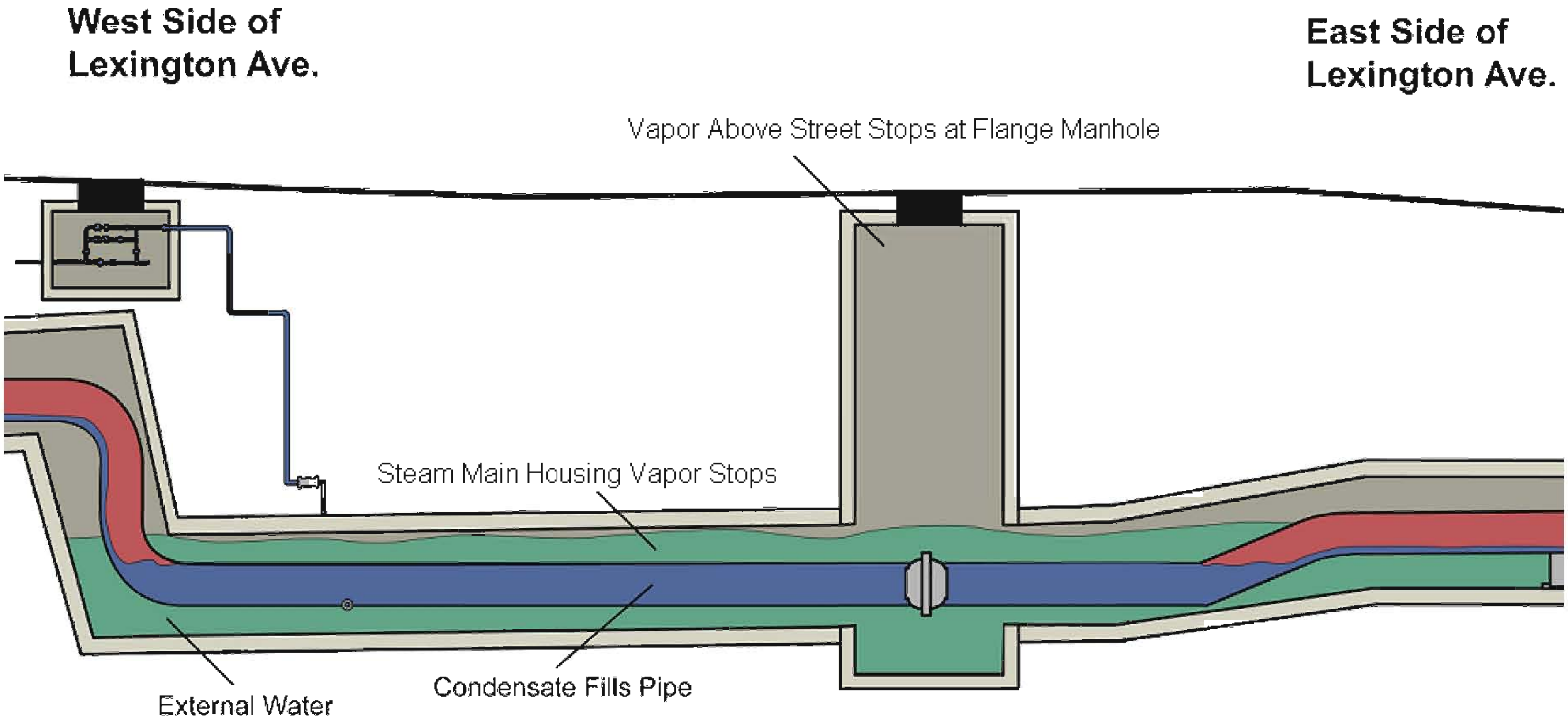


Figure 5-2: Pipe Across Lexington Avenue Intersection Fills with Condensate Stopping Vapor

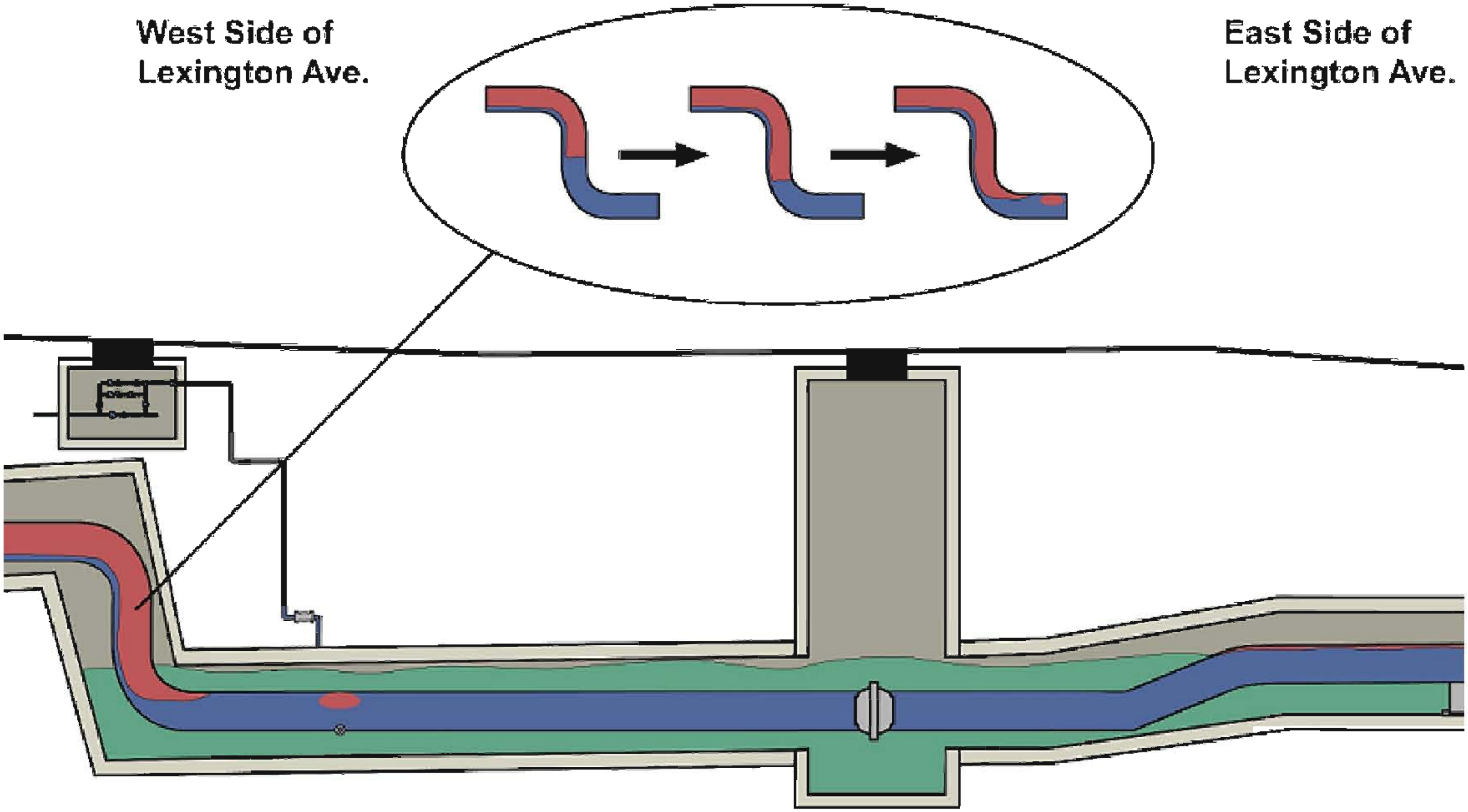


Figure 5-3: Steam Flows into Subcooled Condensate as Differential Pressure Across Intersection Increases

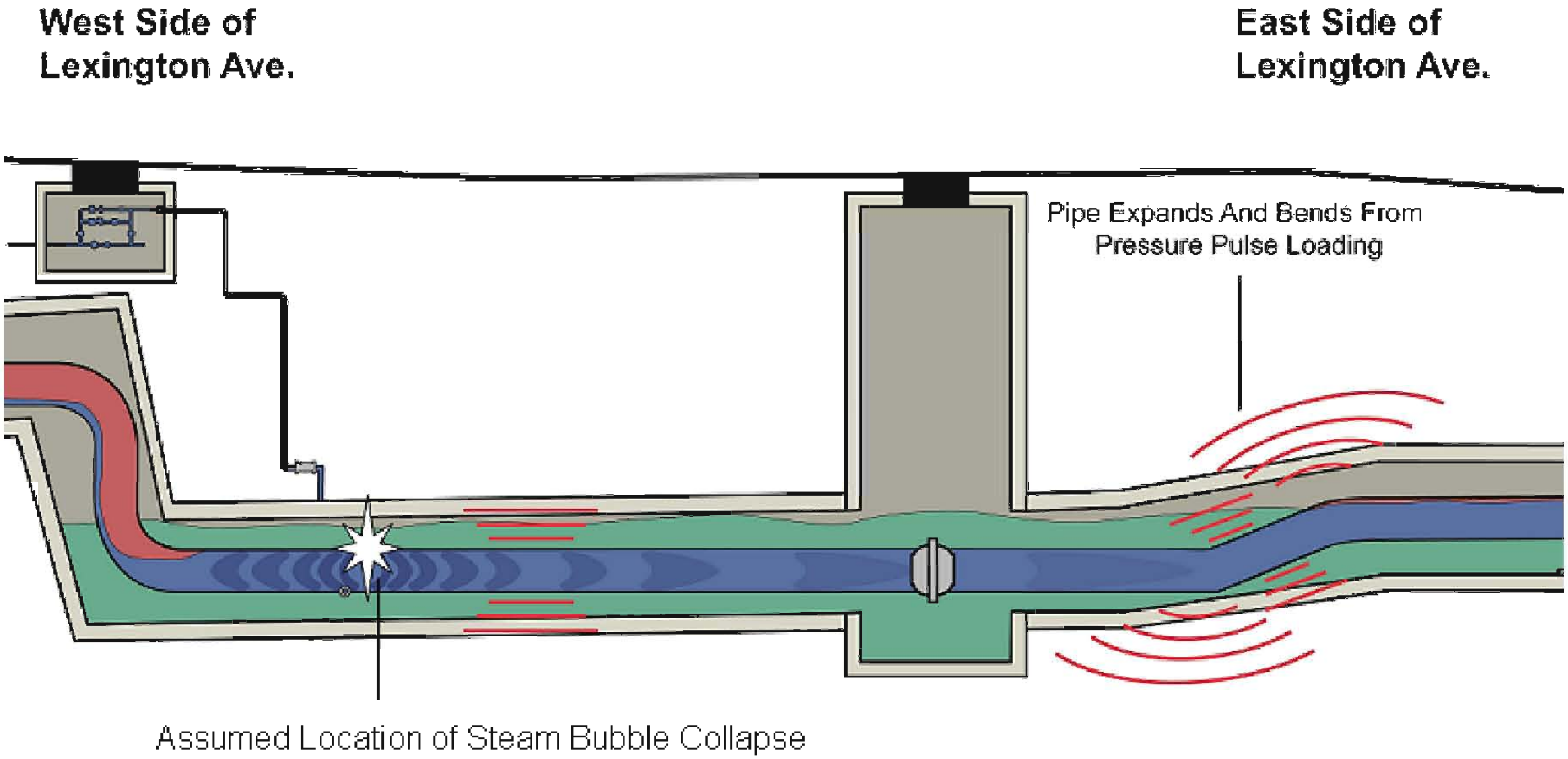


Figure 5-4: Steam Bubble Collapses Creating Pressure Pulse that Ruptures Steam Main

6.0 REFERENCES

1 Con Edison drawings.

a. 18 No. 558-1

b. 18 No. 558-2

c. 18 No. 558-3

d. 18 No. 558-4

2 Con Edison drawings.

a. LL18736

b. LL21775

c. LL24203

3 Con Edison drawings.

a. F30381

b. F30383

4 Con Edison "Measurement of Condensate Accumulation at 41st Street and Lexington Avenue", Dated September 26th, 2007.

5 Con Edison Interview Statement; "Interview with Lexington South customer"

6 Weatherbank Inc, Edmond, OK. Data for Central Park.

7 National Oceanic and Atmospheric Administration (NOAA) NOAA, National Data Centers Local Climatological Data for Central Park, NY.

8 Lucius Pitkin Report No. F-07294, "Evaluation of July 18, 2007 Steam Incident – 41st Street and Lexington Avenue, New York, NY"

9 Con Edison Steam Operations Mapping Information System (SOMIS) Database

10 Con Edison "Trap Testing" per Operations and Maintenance Instructions No. S-11952, Rev. 6 dated April 2007.

11 Con Edison Interview Statement; "Interview with Con Edison Construction Personnel relative to Fire Hydrant on Lexington Avenue, North of 41st Street".

12 Griffith, P., NUREG/CR-6519 "Screening Reactor Steam/Water Piping Systems for Water Hammer" US NRC, September 1997.

13 ASTM Specification A 53 – 1921 "For Welded and Seamless Steel Pipe".

14 Formulas for Stress and Strain, Roark, R.J. and W.C. Young, Seventh Edition, McGraw-Hill.

15 Mechanical Engineering Design, J.E. Shigley and C.R. Mischke, Sixth Edition, McGraw-Hill.

16 Consolidated Edison Company of New York, Inc. 16 NYCRR Part 420 Report, "July 18, 2007 Steam Incident 41st Street and Lexington Avenue", Dated August 17th, 2007.

17 Con Edison "As-found Measurement of 41st St and Lexington Avenue Steam Trap Capacities at 16th Street"

18 Con Edison Interview Documents, "Interview with Steam Crews on general flood depth in Lexington Intersection Flange Manhole"

19 Con Edison "Vapor Patrol" per Operations and Maintenance Instructions No. S-11952, Rev. 6 dated April 2007.

20 ASME B31.1 "Power Piping Code".

7.0 NOMENCLATURE AND DEFINITION

ABS	- ABS Consulting or ABS Group
causal factor	- A condition that, if eliminated would have either prevented the occurrence or reduced the severity
condensate	- Water that accumulates inside the pipe, as a result of heat loss of the steam
conduit	- See housing
Con Edison	- Consolidated Edison Company of New York, Inc.
crown point	- Local high point of steam main, condensate will drain on either side
DP	– Differential Pressure
Efficiency test	- Test of steam trap to ensure trap is passing condensate using visual observation
event	- Pipe rupture that occurred at 5:56 PM on July 18, 2007
File 3 bend	- Con Edison drawing identification for a composite pipe bend
fish-mouth	- Configuration of a drain pipe attached to the steam main
flood water	- Water that collects outside of the steam pipe in the housing and manholes
Functional test	- Test of steam trap to determine trap is cycling using sound
heavy rain	- Rain fall intensity exceeding 0.3 inches/hour
housing	- Concrete, steel pipe or clay-tile housing and is buried below street level steam main running inside
Incident	- The sequence of events that lead up to and followed the event

Incident Site	- East 41st Street and Lexington Avenue intersection
lap weld	- Process used to connect a rolled plate to form into a pipe.
LiDAR	- Light imaging distance and ranging
LPI	- Lucius Pitkin Incorporated.
mainlining	- Injection of leak sealant material into the steam main
MSO	- Main Shut Off
SOMIS	- Steam Operations Mapping Information System
Trap	- Device used to remove condensate from a steam pipe
UTS	- Ultimate tensile strength (breaking point) of a material
vapor patrol	- Procedure whereby employee drives by selected locations looking for steam vapor
waterhammer	- Undesirable pressure pulse, can be caused by mixing of steam and cooler water
yield stress	- Stress at which a material exceeds its elastic limit and will be subjected to permanent strain

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