



# Steam Distribution Pipeline Corrosion Study

Consolidated Edison Company of New York

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**Objective:**

In accordance with the Joint Outage and Regulatory Settlement Agreement in Case 18-S-0448, CECONY hired DNV GL USA, Inc (DNV) to perform a detailed pipeline corrosion study and fracture mechanics assessment on CECONY’s steam distribution system.

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## EXECUTIVE SUMMARY

In accordance with the Joint Outage and Regulatory Settlement Agreement in Case 18-S-0448, CECONY hired DNV GL USA, Inc (DNV) to perform a detailed pipeline corrosion study and fracture mechanics assessment on CECONY's steam distribution system. This report summarizes DNV's findings with respect to the type, extent, causes, and susceptibility of CECONY's steam distribution system to corrosion damage. The report also reviews CECONY's operational history, corrosion control related practices and procedures, and current mitigation methods.

This report concludes that CECONY's steam distribution pipes are seeing three contributing sources to their overall corrosion threat profile: pH based general corrosion, steam condensate localized aggressive pitting, and flow accelerated corrosion (FAC). DNV further concludes that CECONY is limited, based on FDA restrictions placed on end users of CECONY steam, in its ability to mitigate corrosion by adjusting steam condensate pH and must therefore rely on preventative inspection and maintenance of traps, supports and insulation, limiting and effectively responding to drum carryover and limiting contaminants in its steam generation. Additionally, this corrosion is time dependent (with respect to time the material is exposed to the corrosive environment) and is independent of the material type or vintage currently installed within the steam system and only areas of turbulent flow or stagnant condensate have seen internal corrosion which is expected. DNV recommends that CECONY continues its practice of proactively reviewing their preventive mitigation and maintenance procedure and record taking with specific emphasis for compliance to written procedures and internal standards.

As part of its analysis, DNV conducted a Leak Before Break (LBB) study. The LBB study assessed stable flaw sizes for through-wall crack-like features for two types of piping materials in CECONY's distribution system, wrought iron and A53 steel, using conservative material properties and orientations under design pressure and temperature conditions. Stable flaws, if grown through wall, are not expected to result in a pipe rupture, but rather result in a stable leak. Stable crack-like flaw sizes of 6 inches in length for wrought iron material and 7 inches in length for A53 material were calculated in the seam weld under design pressure (200 psig) and temperature (400 °F). For cracks outside the seam weld, stable crack lengths of 14 and 16 inches were calculated for the wrought iron and A53 material, respectively. Flaws smaller than these are not expected to result in pipe rupture. CECONY believes the calculated leak rates associated with limiting flaws to be in a detectable range, allowing for the pipe section to be repaired.



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## 1 INTRODUCTION

On July 15, 2021, the New York Public Service Commission approved a Joint Outage and Regulatory Settlement Agreement between Consolidated Edison Company of New York (CECONY) and the New York State Department of Public Service. Among other things, the Settlement Agreement required CECONY to contract with a third-party to review corrosion on its steam system:

Con Edison will contract with a third-party to study the causes of steam main corrosion and identify mitigation methods. The study will examine the corrosion susceptibility of pipes of varying vintages and include a fracture mechanics evaluation to determine the effect various sized corrosion related flaws have on the structural stability of steam mains. Con Edison will submit the study to the Commission's Secretary or Records Access Officer, as appropriate, by November 30, 2021.<sup>1</sup>

Pursuant to this requirement, CECONY hired DNV GL USA, Inc (DNV) to perform a detailed pipeline corrosion study on CECONY's steam distribution system.

In accordance with the Settlement Agreement, DNV examined the history, extent, causes, and consequences of corrosion on the steam system and identified possible mitigation measures. DNV also conducted a fracture mechanics based LBB study on different pipe vintages to determine the effect various sized corrosion features have on the structural stability of the steam mains.

This report aims to discuss the specific corrosion mechanisms experienced by CECONY's steam distribution system and provide additional material related to mitigation selection, maintenance response and proactive monitoring. The conclusions and recommendations in this report are based on a review of information, data, and reports provided by CECONY and on a LBB assessment conducted by DNV on a representative section of corroded pipe.

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<sup>1</sup> Case 18-S-0448, et al., Order Granting Motion and Adopting Joint Outage and Regulatory Settlement Agreement, Appendix A, Attachment 1, item 11 (July 15, 2021).



## 2 REVIEW OF PROVIDED DATA

To perform a detailed review that captured and summarized the history and extent of CECONY's steam distribution system's wall loss, leak, and failure related damages as they relate to corrosion control, DNV requested and reviewed data in the following areas:

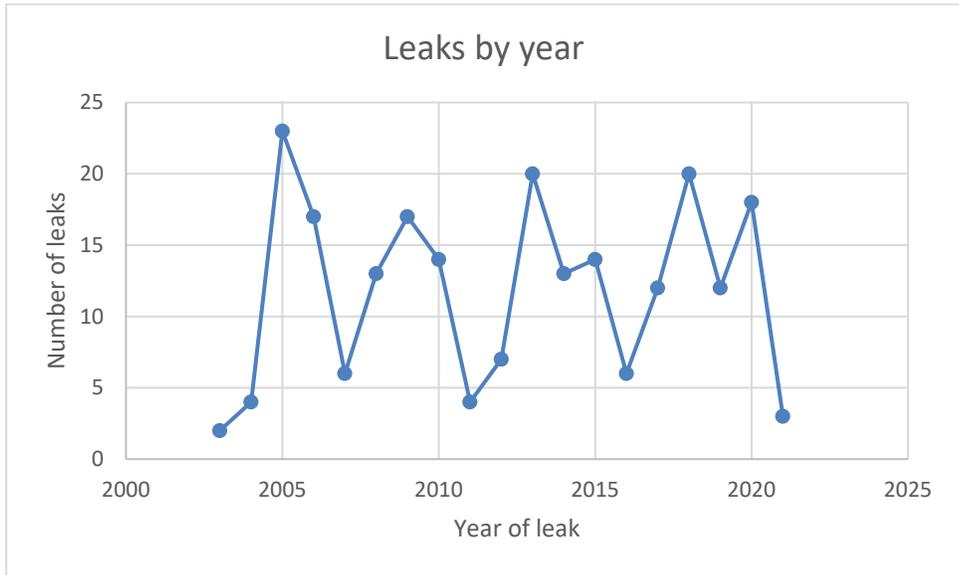
- Chemistry Reports
- Failure Analysis Reports
- Fitness for Service Records
- Inspection Results
- Material Spec History
- Past Events
- Steam Sendout Main Study
- Water Treatment

This data was used to review and identify the specific corrosion related challenges CECONY faces as well as serve as the material basis for setting up the additional Leak Before Break (LBB) study.

### 2.1 History of Corrosion Related Events

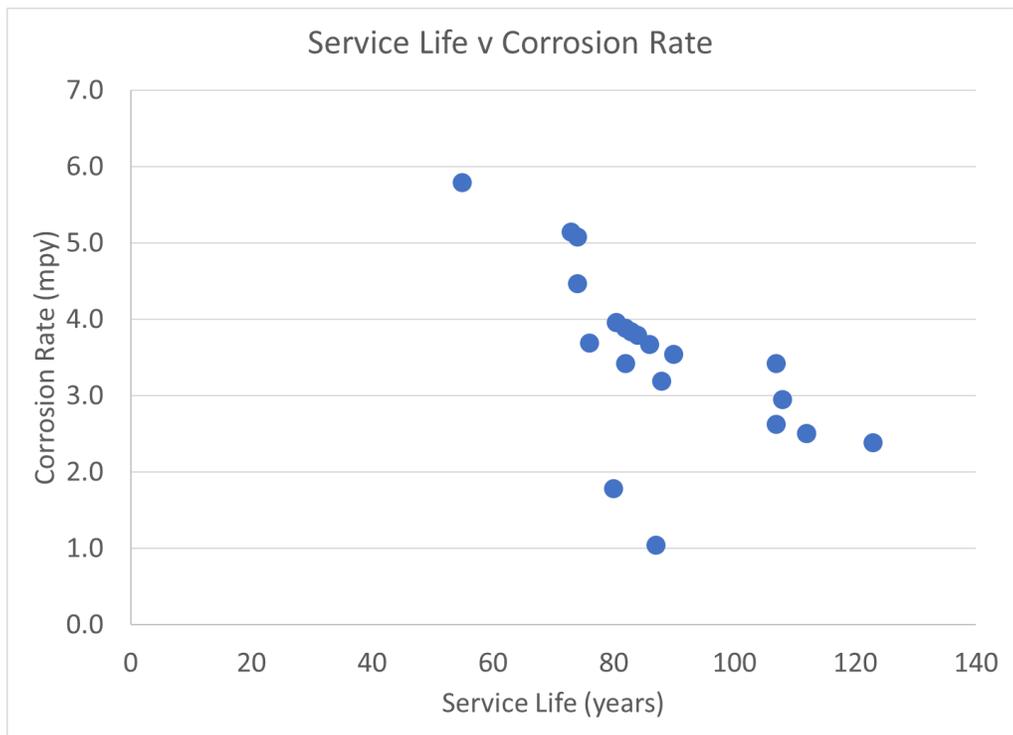
DNV reviewed documents provided by CECONY to gain knowledge and insight into the common degradation and failure mechanisms present in the steam transmission and distribution piping. The files contained information regarding the piping metallurgy, materials of construction, and steam chemistry. In general, the collection of documents indicate that the CECONY steam system is being exposed to general corrosion, pitting, and flow accelerated corrosion. Based upon the provided information and subject-matter-expert testimonial, CECONY has only reported internal corrosion related events and has no reported history of external corrosion on system mains, piping within structures or tunnels, .

The evidence shows that CECONY's steam distribution pipes are seeing three contributing sources to its overall corrosion threat profile, pH based general corrosion, steam condensate localized aggressive pitting, and flow accelerated corrosion (FAC). Each corrosion mechanism will be outlined and an approach to mitigation will be provided as part of this report. To begin DNV reviewed and summarized the history of internal corrosion related events, Figure 1 shows a summary of 6 o'clock related leaks from 2003 to 2021.



**Figure 1 – Count of leaks at the 6 o'clock location by year since 2003.**

The corrosion failures break down as shown in Figure 2.



**Figure 2 - Corrosion rate vs service life for corrosion related features**

Pipe corrosion is a reoccurring process that can never be completely mitigated and an increase in corrosion related leaks is expected over time. In CECONY's case, the fact that reported corrosion related leak frequency remains relatively consistent over time reflects the Company's dedication to controlling corrosion to the best of its ability.

### 2.1.1 Corrosion Basics

There are four requirements for an electrochemical corrosion cell to occur: (1) an anode (where the corrosion takes place); (2) a cathode where chemical balancing reactions take place; (3) an ionic current path (in the case of this study - steam condensate); and (4) an electronic path (in the case of this study - the metal pipe).

The ionic current path (steam condensate) can impact the kinetics of the corrosion reaction by having low pH condensate, dissolved oxygen, carbon dioxide, and/or strong anion contaminants present in the condensate (like chlorides and sulphates). Before a system is in service, design engineers can attempt to minimize future corrosion by their choice of materials, cathodic protection, and linings.

Once a system is operational, corrosion can be minimized by increasing the pH of the solution, managing contaminant ingress into the system, and most importantly ensuring no standing water (condensate) is present in the system. If there is no ionic current path (no condensate present), there will be no corrosion of the piping.

### 2.1.2 General Corrosion

General carbon steel corrosion in the CECONY steam system is caused by the chemistry of the steam condensate, and particularly, the pH level, as shown in figure 3. Typical industry guidance for minimizing carbon steel corrosion due to steam condensate is to maintain the pH above 9.0 during operation and above 10.0 when out of service conditions exist. It is standard industry practice to add ammonia (as ammonium hydroxide) or a volatile organic compound to the cycle at the power station that will volatilize and leave with the steam produced at the station generating sites. The ammonia in the steam will form ammonium hydroxide as the steam condenses and elevate the steam condensate pH, thereby protecting the protective oxide layers formed on the drain lines. The protective oxide layer are primarily magnetite and iron oxy-hydroxides.

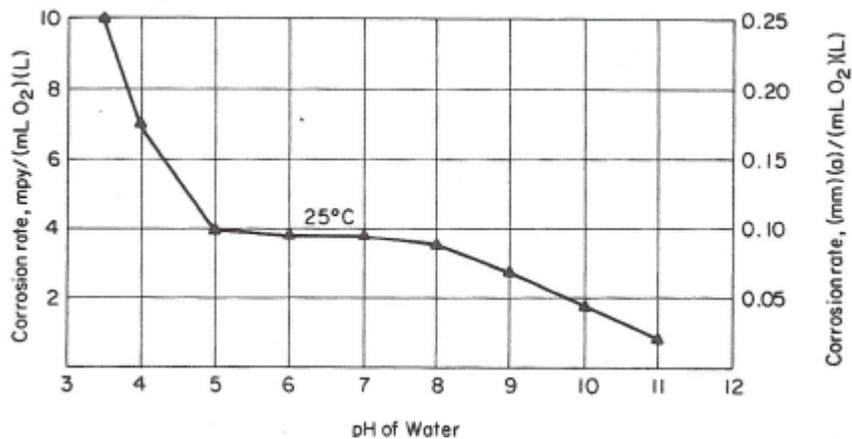


Figure 3 – Corrosion rate by pH. Reproduced from Dillon, C. P., “Corrosion Control in the Chemical Process Industries” pp-145; 1986 McGraw Hill Book Company, New York, New York, USA.



### 2.1.3 CECONY Steam System Comments (General Corrosion)

Based on FDA enforced requirements for end use steam customers, CECONY is prohibited from adding volatile chemicals like ammonium hydroxide or volatilizing amines to the cycle water at its generating stations. Because of these restrictions, CECONY steam system condensate will have a pH as low as 4.74 and as high as 7.96 based on steam generating station pH records for 2019 thru 2021. The average pH for all the stations is typically somewhere between 5.09 to 6.64 (see figures 4 through 6).

Steam Generating Stations	pH	Average											
	Jan-19	Feb-19	Mar-19	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	
59th Street Station - Lower Loop	6.3	5.91	6.04	6.05		6.34	6.33	6.2	5.93	6.04	6.2	6.21	6.14
59th Street Station - Upper Loop	6.12	6.21	6.25	6.27	6.25		6.05				6.16	6.12	6.18
59th Street Station - Package Blrs.	6.49	7.96	6.74	6.55		6.14	6.02	6.55	6.46	6.37	6.38	6.49	6.56
74th Street Station - 74th Main	6.31	6.25	6.27	6.49	6.77				5.66	5.91	5.79	7.4	6.32
74th Street Station - 75th Main	5.37	5.83	5.62	5.76	5.73					5.83	6.16	5.52	5.73
74th Street Station - Express Main	5.41	5.36	5.53	6.49	5.47	5.66			5.31	5.32	5.54	5.4	5.54
East 60th Street	5.3	5.88	5.32	5.44	5.5	5.59	5.71	5.76	5.51	5.66	5.34	5.28	5.52
East River 1st Avenue (South Steam & HRSG)	6.24	5.04	5.22	5.58	5.41	6.47	6.25	6.31	6.65	5.43	6.29	6.26	5.93
East River 11th Street Main	6.19	6.14	6.23		6.25	6.52	6.25	6.92	6.67		6.34	6.31	6.38
East River 14th Street	5.43	5.81	5.65	6.27	5.97	5.88	5.9	5.54				5.82	5.81
East River 15th Street		6.78	6.6	6.83	6.52	6.57	6.63	6.71				6.51	6.64
East River Avenue D	6.32	6.25	6.49	6.67		6.43						6.5	6.44
Ravenswood	5.8	5.18	5.5	5.73	5.22								5.49
Hudson Avenue - Grand Street Main													NA
Hudson Avenue - Water Street Main													NA
York IPP - BNYCP	4.9		5.07		5.12	4.95	5.32	4.98	5.12	5.07	5.21	5.11	5.09

Figure 4 - 2019 Steam pH Values for CECONY Steam Generation Stations

Steam Generating Stations	pH	Average											
	Jan-20	Feb-20	Mar-20	Apr-20	May-20	Jun-20	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20	
59th Street Station - Lower Loop	5.97	5.95	6.09	6.04						6.22	6.36	6.16	6.11
59th Street Station - Upper Loop	5.78	5.72	5.72							6.12	5.42	6	5.79
59th Street Station - Package Blrs.		6.01	6.16	6.26	6.34	6.57	6.15	6.11	6.02	6.47	6.49	6.64	6.29
74th Street Station - 74th Main	5.6	5.96	6.03						6.3	5.77	5.47	6.05	5.88
74th Street Station - 75th Main	5.59	5.78	6.08							5.8	6.79	6.34	6.06
74th Street Station - Express Main	5.16	5.82	5.39		5.25	5.8		5.62	5.44	5.29	5.66	5.66	5.51
East 60th Street	5.18	5.79	5.47	5.4		5.64	5.5	5.54	5.76		5.83	5.74	5.59
East River 1st Avenue (South Steam & HRSG)	6.3	6.31	6.3	6.35	6.34	5.86	5.83	6.01	6.74	5.97	6.35	6.23	6.22
East River 11th Street Main	6.31	6.29	6.25	6.32	6.34	6.5	6.5	7.4	6.12		6.6	5.93	6.41
East River 14th Street	6.25	6.58	6.25	6.15	6.32		6.06	6.05			5.7	6	6.15
East River 15th Street	6.09	6.79	5.89	5.8			6.18				6.01	6.15	6.13
East River Avenue D	6.7	6.63	6.2	6.64							6.07	6.38	6.44
Ravenswood	5	5.67											5.34
Hudson Avenue - Grand Street Main													NA
Hudson Avenue - Water Street Main													NA
York IPP - BNYCP		5.35	5.03	5.13	5.09	5.6	5.56	5.12	5.23	5.62	4.74	7.96	5.49

Figure 5 - 2020 Steam pH Values for CECONY Steam Generation Stations

Steam Generating Stations	pH	Average								
	Jan-21	Feb-21	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21	Sep-21	
59th Street Station - Lower Loop	6.19	5.82	5.86	5.99			5.78			5.93
59th Street Station - Upper Loop	6.12	6.21	6.08							6.14
59th Street Station - Package Blrs.	6.06		7.07	6	5.78		6.69	6.03	5.98	6.23
74th Street Station - 74th Main	5.36	5.79	5.49	5.72		5.34				5.54
74th Street Station - 75th Main	6.34	6.6	5.82				5.82		5.91	6.10
74th Street Station - Express Main	5.84	5.23	5.4	5.08	5.15				6.14	5.47
East 60th Street	6.29	6.06	6.15	5.86		5.98	6.11	5.8	6.17	6.05
East River 1st Avenue (South Steam & HRSG)	5.98	6.05	6.24	5.37	5.57	5.54	5.33	6.43		5.81
East River 11th Street Main	5.73	6.05	6.03		5.78	5.93	5.69	5.67	6.12	5.88
East River 14th Street	6.14	6.07	5.93	4.99	6.23					5.87
East River 15th Street	6.4	6.14	6.18	5.96	5.81					6.10
East River Avenue D	6.57	6.46	6.15	6.21	6.13					6.30
Ravenswood										NA
Hudson Avenue - Grand Street Main										NA
Hudson Avenue - Water Street Main										NA
York IPP - BNYCP	5.27	5.37	5.21	5.83	4.89	5.1	5.22	6.19	5.53	5.40

**Figure 6 - 2021 Steam pH Values for CECONY Steam Generation Stations**

As figures 4,5, and 6 indicate, the average pH of 5.09 to 6.64 corresponds to a corrosion rate of approximately 4 mils/yr to 3.8 mils/yr, respectively. In comparison, if CECONY could chemically elevate its steam condensate pH (9 to 10), it would see corrosion rates of approximately 2.9 mils/year. It should be stated that this corrosion rate estimate only applies to the condensate that is formed in the steam system and not the steam itself. This estimate should only be applied as an approximate average where condensate formation and operation conditions exist to allow for stagnant collection or turbulent transport of fluid condensate. It should be noted that this corrosion projection only occurs when the environmental conditions are present, otherwise this system remains in a low general corrosion state. Additionally this condition is time dependent (with respect to time the material is exposed to the corrosive environment) and is independent of material type currently installed within the steam system and only areas of turbulent flow or stagnant condensate have seen internal corrosion which is expected.

Figure 7 and Figure 8 show some examples of the general corrosion that has occurred in the CECONY steam system in the past.

Altran Corporation  
 Technical Report 05-0523-TR-001  
 Revision 0



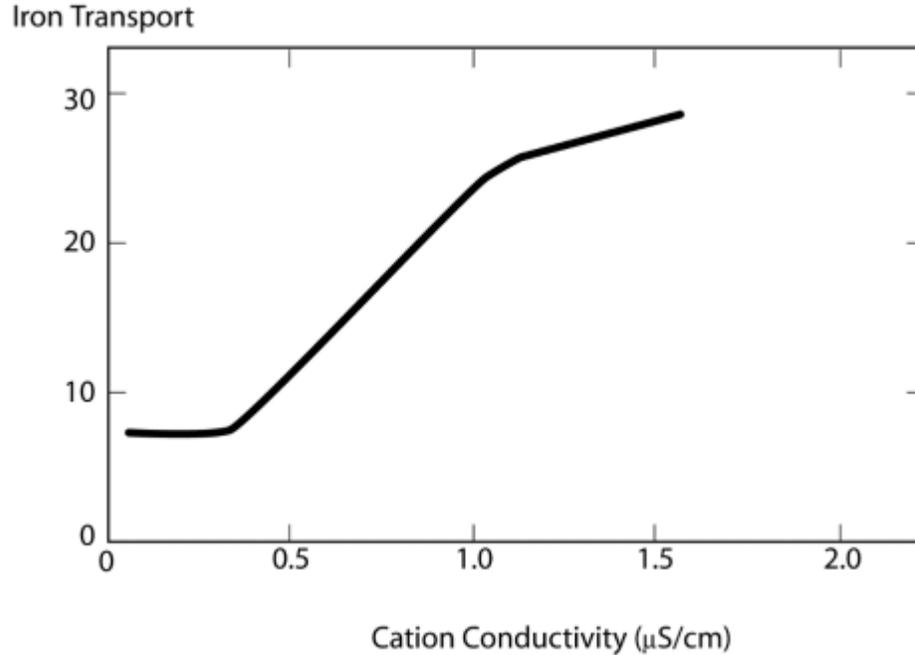
**Figure 7 - 57th Street and 5th Avenue**



**Figure 8 - 57th Street West of Madison Avenue**

The CECONY steam condensate pH can also be impacted by both the carbon dioxide present in the steam condensate along with any contaminants that may be present in the steam leaving the power stations. Ultrapure steam condensate would have a pH of between 6.5 and 7.0. When the measured steam condensate pH is below 6.5 this indicates either carbon dioxide or potentially some acidic contaminant is present lowering the steam condensate pH. Because the steam condensate is so pure, it takes very small amounts of carbon dioxide or contaminant to impact the steam condensate pH. Steam condensate has no buffering capabilities.

If anionic contaminants like chlorides and sulfates enter the steam system, they will increase the conductivity of the steam condensate which will also increase the general corrosion rate of the system. Figure 9 is a generic diagram that shows the relationship between cation conductivity and corrosion (indicated as iron transport) on the corrosion rate of carbon steel. The impact that anions will have on the corrosion rate of carbon steel will be a function of the type of anion present (chlorides and sulfates being the most impactful), the quantity present and the amount of time the material is exposed to the contaminant. It is just important to remember that as steam cation conductivity increase, the steam condensate cation conductivity will increase and thus the corrosion rate of the carbon steel in contact with the steam condensate will increase. It is very difficult to quantify how these contaminants would impact the corrosion rates in the CECONY steam condensate system because of the numerous unknowns. For example, pH levels are collected at the steam generation stations and while this value helps to approximate a general corrosion rate, it does not individually reflect the local corrosion environment. The cumulative effect of temperature, pipe material, flow rate, and accumulation of contaminated condensate ultimately influence both general and localized pitting rate susceptibility and should be considered when reviewing the impact on the measured general corrosion rate within the system.



**Figure 9 – Ion transport based on Cation conductivity. Reproduced from Vasilenko. G. V., “Quality Guidelines and Water Chemistry Control in Supercritical Pressure Units” Proceedings of the Third International Conference on Improved Coal Fired Power plants, EPRI Report TR-100848**

CECONY is monitoring and maintaining steam cation conductivity at the power stations per what is required per the industry. CECONY maintains a monthly report that tallies hours out of limits. This information is reported to the vice president during each station monthly visit. Cation conductivity measurements are necessary to detect the possible ingress of aggressive chlorides and sulfates can enter the steam system when upset conditions (operational and/or mechanical) at the power stations are occurring.

In general, the main source of anions like chlorides and sulfates entering the steam system is when drum carryover occurs at a power station. Each power station has a steam drum where the separation of water and steam occurs. This steam then goes through a series of separators to remove water droplets so that only steam leaves the steam drum and enters the steam system. Contaminants like chlorides and sulfates remain behind with the water in the steam drum. (There can be a very small vaporous portion of chlorides and sulfates laving with the steam, but this is insignificant). When a mechanical issue is noted with either the steam drum separators , drum level upsets alarms, or when the drum level is out of calibration, water droplets can leave with the steam from the power stations. These water droplets will contain quantities of chlorides and sulfates which will contaminate the steam leaving the power stations. This will be detected by steam cation conductivity at the various power stations. Because steam drum separators, drum level control, and drum level indication are all mechanical devices, they will fail periodically causing drum carryover to occur.

At CECONY steam carryover incidents are immediately addressed by operations. Drum carryover is recognized by continuous online measurements of steam sodium, cation and specific conductivity which are all alarmed in the control room. Drum level is also alarmed in the control room. Internal CECONY organizational level and alarm response procedures exist to address drum carryover issues promptly reducing the amount of contamination that enters the steam system when these events occur.

Along with dissolved oxygen in the steam condensate, carbon dioxide will also be present. Carbon dioxide will dissolve in the steam condensate and form carbonic acid. Carbonic acid will lower the steam condensate pH when no neutralizing chemical is present like ammonia or an organic used for pH control. The solubility of carbon dioxide (as carbonic acid) in steam condensate can drive the pH of the steam condensate as low as 4.0. The impact of pH on corrosion of carbon steel is reflected in figure 3 above. CECONY currently aims to address this by phasing out additive water softening treatment by transitioning to demineralization of the feed from their package boilers. This proactive approach would serve to address the main concern of carbonic acid formation while also providing the benefit of reducing the amount of organic material in the system that could eventually breakdown and contribute to corrosive condensate formation.

The CECONY steam condensate general corrosion rate will be driven by both the pH, and the cation conductivity of the steam condensate during operation.

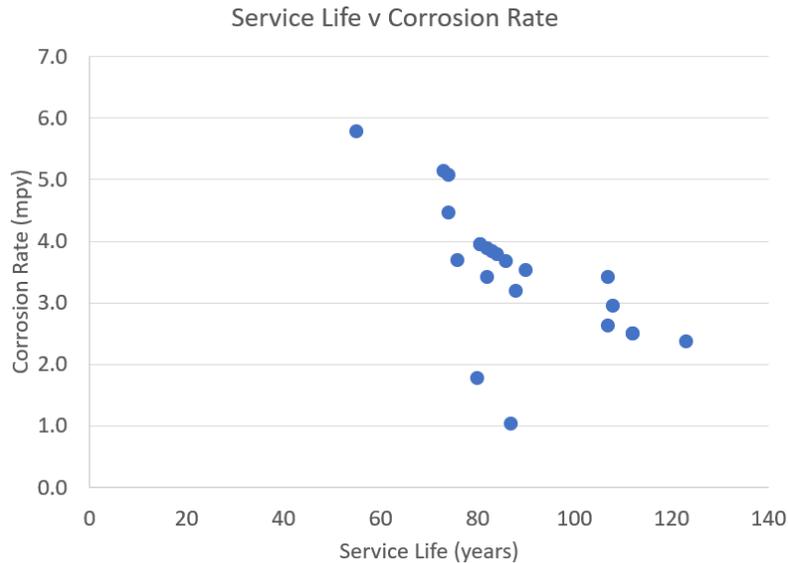
### 2.1.4 Long term and instantaneous corrosion rates

CECONY conducted a corrosion rate study at MIT in 2007. The study reported the corrosion rates of carbon steel in a series of benchtop laboratory experiments in simulated steam condensate with and without flow. The corrosion rates were measured using weight loss and electrochemical techniques. Table 1 is the corrosion rate summary table from the report.

**Table 1 – Corrosion Rate Summary (2007)**

Test Phase	pH	Oxygen Concentration (ppb)	Solution Flow Rate (gph)	Velocity (ft/sec)	Corrosion Rate(mpy) <sup>(1)</sup>	Upstream (non-rotating) Sample Corrosion Rate (mpy) <sup>(2)</sup>	Limiting Corrosion Rate <sup>(3)</sup>
Electrochemical	4	Deaerated	0.25	NA	12.6	NA	NA
Electrochemical	4	2000	0.25	NA	20.3	NA	215 <sup>(4)</sup>
Flow	4	2000	0.25	12	4.3	25.1	215 <sup>(4)</sup> /23 <sup>(5)</sup>
Flow	4	2000	0.25	22	25.6	25.1	215 <sup>(4)</sup> /23 <sup>(5)</sup>
Flow	4	2000	0.25	39	40.0	25.1	215 <sup>(4)</sup> /23 <sup>(5)</sup>
Electrochemical	5	Deaerated	0.25	NA	0.9	NA	NA
Electrochemical	5	200 ppb	0.25	NA	1.3	NA	21
Electrochemical	5	500 ppb	0.25	NA	3.4	NA	54
Flow	5	2000	1.0	12	24.6	17.2	858 <sup>(4)</sup> /93 <sup>(5)</sup>
Flow	5	2000	1.0	22	158.0	17.7	858 <sup>(4)</sup> /93 <sup>(5)</sup>
Flow	5	2000	1.0	39	328.0	17.2	858 <sup>(4)</sup> /93 <sup>(5)</sup>
Electrochemical	5.5	Deaerated	0.25	NA	1.3	NA	NA
Electrochemical	5.5	500 ppb	0.25	NA	1.3	NA	54
Electrochemical	6	Deaerated	0.25	NA	0.003	NA	NA
Electrochemical	6	2000	0.25	NA	1.2	NA	215
Flow	6	2000	0.5	12	9	11.9	429 <sup>(4)</sup> /46 <sup>(5)</sup>
Flow	6	2000	0.5	22	42	11.9	429 <sup>(4)</sup> /46 <sup>(5)</sup>
Flow	6	2000	0.5	39	74.4	11.9	429 <sup>(4)</sup> /46 <sup>(5)</sup>

The study found that carbon steel corrosion rates correlate well with condensate chemistry, namely pH and dissolved oxygen, and flow rate. Notably, the corrosion rates reported by MIT are also quite high given the long service life experienced by the actual steam piping and lack of widespread uniform loss of thickness in the CECONY steam system. Table 2 contains several examples of corrosion rates measured in the steam system. The corrosion rates were estimated using the nominal pipe wall thickness, metal loss, and service life stated in several failure analysis reports provided to DNV. Figure 10 is a plot of the estimated corrosion rates for all corrosion mechanisms (Pitting, FAC, and uniform wall loss) versus service life. The data was extracted from CECONY reports; however, some data points were estimated from average service lives and corrosion rates for similar pipe diameters.



**Figure 10 – Linearized corrosion rate by service life**

The MIT laboratory data tend to overpredict internal corrosion rates evident in CECONY’s piping, which is expected because the laboratory work measured instantaneous corrosion rates on coupons. In the field, a short-term chemistry upset, pooled condensate, and flowing condensate likely act together to create locally high corrosion rates that persist during the upset condition. The corrosion rates likely diminish inside the steam piping once the corrosive condition moves downstream, is corrected by condensate evaporation, and evacuation of the condensate from the piping system. It is clear from the laboratory and field experiences that if an aggressive corrosion mechanism remains relatively stationary on the internal surface of the steam piping, corrosion rates can create the condition for a through wall penetration and loss of steam containment.

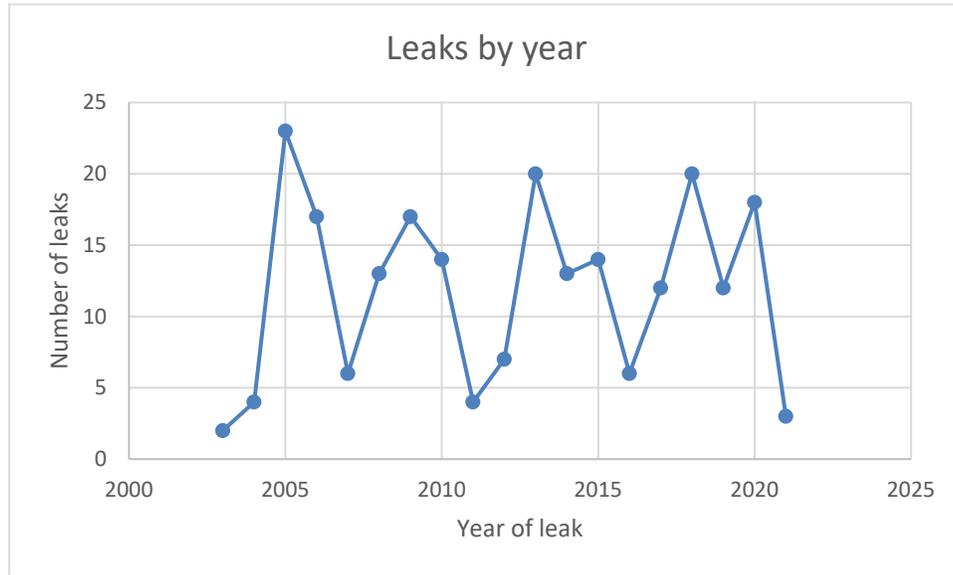
### 2.1.5 Mitigating Techniques for General Corrosion

To reduce internal uniform corrosion occurring because of general chemical factors the steam condensate that forms needs to have an elevated pH of greater than 9.0, be oxygen and carbon dioxide free, and contain no aggressive anions like chlorides and sulfates present.

As discussed CECONY’s ability to reduce general corrosion is hampered by restrictions on its ability to chemically adjust steam condensate pH. In addition, contamination of the steam condensate by aggressive anions like chlorides and sulfates will occur when steam drum carryover occurs putting contaminated water into the steam. As discussed, CECONY has appropriate processes and procedures in place to minimize steam contamination. Even with the best managed program, however steam contamination will periodically occur. This contamination along with the lower pH of the steam condensate will increase the corrosion rate of the piping in the area where these conditions occur.

The surest way to eliminate general corrosion of the distribution piping by the steam condensate is to have no standing steam condensate present in the system.

Figure 11 shows the number of corrosion related leaks that occurred on the CECONY distribution system at the 6 o’clock position (bottom of pipe).



**Figure 11 - Corrosion relate leaks at 6 o'clock position by year**

Six o'clock leaks are areas where steam condensate collected in the bottom of the pipe. This steam condensate would consist of a low pH (between 4.89 and 7.96 based on the information in figures 4 through 6 above). If carbon dioxide or contaminants are present the pH and the overall local corrosion rate would also be impacted negatively. A combination of these conditions would lead to accelerated corrosion at these locations. If pooling of the steam condensate in this location could be avoided, the corrosion failure would not occur.

Because CECONY is restricted in its ability to add chemicals to the system to elevate steam condensate pH, it must focus on preventing standing condensate in its pipes to the extent practical. Ensuring that traps are kept functioning, supports are maintained, and insulation is maintained can help in this effort. When portions of the steam system are removed from service, it is important to ensure the lines are drained completely. Any standing condensate in the system will increase corrosion rates. It is also important to ensure piping has not sagged in certain areas causing steam condensate to possibly collect in these areas. Any place where the steam condensate is present general wall thinning will occur (see figure 8). In addition, if this steam condensate has chloride sulphates or dissolved oxygen present further localized aggressive pitting will occur (See figure 7).

### 2.1.6 Pitting

Pitting corrosion is an aggressive form of steel metal loss in which very localized cavities are formed in the material. Anodes (site of iron dissolution) and cathodes (site of cathodic reduction reactions) are mobile on the steel surface when uniform corrosion occurs, but anodes are stationary when pitting corrosion occurs. Pitting is an out of service phenomena, which occurs when stagnant condensate exists in the steam system. Any dissolved oxygen present will locally setup a corrosion cell to start the pitting process. Dissolved solids like chlorides and sulfates will also drastically increase the risk of pitting in quiescent or stagnant water.

Operating with low steam condensate pH as shown above, along with dissolved solids of chlorides and sulfates entering the steam system from drum carryover, places the steam system at risk for pitting. For pitting to occur, however, water must form in the steam system and become stagnant in non-flow areas or when a part of the steam system is removed from service. Figure 12 shows an example of pitting in the steam system at CECONY.

The ID surface of the pipe segment showed pitting and material loss along the bottom, indicating that condensate was present and eroding and/or corroding the pipe wall locally, (Photo Nos. 27 – 28).



Figure 12 - From CECONY steam pipe rupture 20th street and 5th avenue 2018 Report No. LM-4213

### 2.1.6.1 CECONY Steam System Comments (Pitting)

Pitting should be expected on CECONY's system because of how long it has been in service. Drum carryover, steam condensate pH, and dissolved oxygen could also contribute to the aggressiveness of the pitting. It should be noted that when pitting occurs, it allows for concentrating aggressive contaminants within the pit. When chloride contamination enters the steam system, these contaminants will drop out of the steam onto the pipe surfaces. When these systems are removed from service, and steam condensate is formed, the chlorides will redissolve in the steam condensate. If the condensate is in a non-drainable section of the piping system, the water will remain, and a pit can be established. When the system is placed back into service, the condensate will become steam and the chlorides present in the condensate will deposit back out and the process will repeat itself. As this process repeats itself, the chloride concentration in the steam condensate at this non drainable section will continue to increase causing more and more aggressive pitting.

Pitting typically will cause leak before break type failures, subject to two caveats. The first caveat is that CECONY can discover pitting leaks in the steam piping before regions of aligned pitting and significant metal loss form in the piping. Widespread deep pits can coalesce for a large region of metal loss, which can promote the condition for a propagating failure under certain non-normal conditions, such as a pressure spike from water hammer. The second caveat is if aligned pitting exist within the system. A typical place for aligned pitting is at an area where a water air interface exists when part of the system is removed from service. Aligned pitting can lead to crack formation if there are some existing stress (seam welded piping) present or being applied (thermal or mechanical stress) to the region between the pits. This crack formation and linking up of the cracks between pits can lead to a crack that is longer than the critical flaw size for the pipe at that location and promote conditions that could lead to a propagating failure.

### 2.1.6.2 Mitigating Techniques for Pitting

The most effective way to mitigate pitting is to eliminate areas where stagnant condensate can be present. Increasing condensate pH (CECONY is restricted in its ability to raise pH as describe earlier) and eliminating drum carryover (elimination is impossible but CECONY has appropriate processes and procedures in place to reduce the impact of carryover when it occurs) will help mitigate the aggressive pitting that can occur when chloride and sulfate contaminants are present.

Nitrogen blanketing when a system is removed from service can reduce the risk of oxygen pitting (but it should be noted that nitrogen blanketing will not stop pitting from sulfates and chloride contaminants that maybe present in the steam condensate). Nitrogen blanketing is not practical for the CECONY steam system because the steam is always in service. The only time it is removed from service is to perform repairs in which case nitrogen blanketing could not be used.

Because CECONY is restricted in its ability to add chemicals to the system to elevate steam condensate pH, it must focus on preventing standing condensate in its pipes to the extent practical. Ensuring that traps are kept functioning, supports are maintained, and insulation is maintained can help in this effort. When portions of the steam system are removed from service, it is important to ensure the lines are drained completely. Any standing condensate in the system will increase corrosion rates. It is also important to ensure piping has not sagged in certain areas causing steam condensate to possibly collect in these areas.

### 2.1.7 Flow Accelerated Corrosion (FAC)

Flow accelerated corrosion is a very aggressive form of general corrosion. There are two types of flow accelerated corrosion (FAC): single phase and two phase.

Single phase FAC occurs when only water as a liquid is present, and the proper conditions exist for single phase FAC to occur. Single phase FAC can be completely mitigated by ensuring that the right combination of pH and dissolved oxygen are present so that a combination of magnetite and hematite are formed on the carbon steel pipe surface. If the system is a mixed metallurgy system (both carbon steel and copper alloys used) then single phase FAC cannot be mitigated by chemistry because copper alloys and dissolved oxygen will lead to unacceptably high copper corrosion rates.

Two phase FAC occurs when a two-phase system (water and steam) is present at the proper conditions. It is likely that two phase FAC is a contributing corrosion mechanism affecting CECONY's steam transmission and distribution piping.

#### 2.1.7.1 pH

The lower the steam condensate pH, the higher the corrosion rate and the higher the risk for two phase FAC. Figure 12 shows the relationship over the pH range of 8.5 to 9.6. As stated earlier, CECONY steam condensate typically has a pH between 4.89 and 7.96. This steam condensate pH significantly increases the risk of two phase FAC occurring in the CECONY steam system.

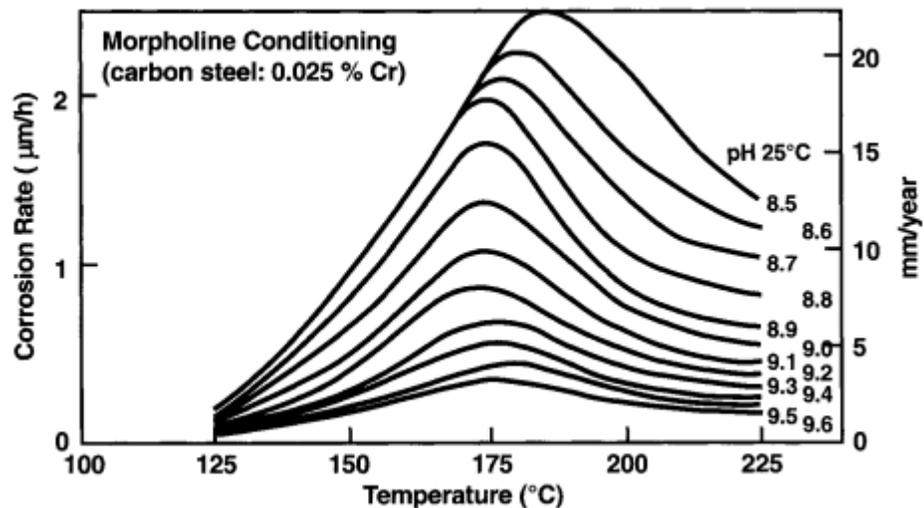


Figure 13 - Flow Accelerated Corrosion in Power Plants, pp - 3-30, EPRI, Palo Alto, CA: 1998. TR-106611- R1

### 2.1.7.2 Temperature

Two phase FAC can occur in the temperature range (See figure 14) of 122 F (50 C) to 437 F (225 C). This temperature range helps pinpoint the areas of concern for two phase FAC in the CECONY steam system.

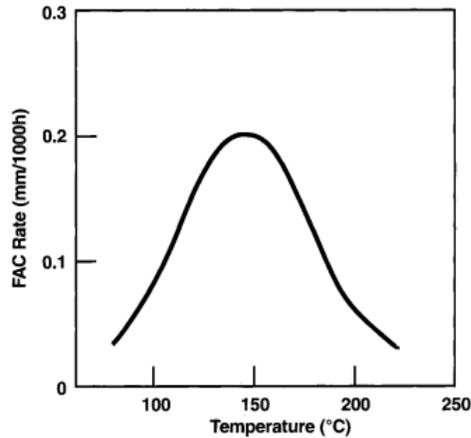


Figure 14 - Flow Accelerated Corrosion in Power Plants, pp - 3-30, EPRI, Palo Alto, CA: 1998. TR-106611- R1

### 2.1.7.3 Chromium Concentration

To mitigate two phase FAC it is typically recommended<sup>2</sup> that susceptible areas be replaced with material that has a minimum of 1.5 % chrome. Figure 15 shows the relationship between Cr content and relative corrosion rate. It should be noted that while the standard industry recommendation is 1.5% Cr content, this figure shows that Chromium concentrations as low as 0.3% will drastically reduce the risk for two phase FAC.

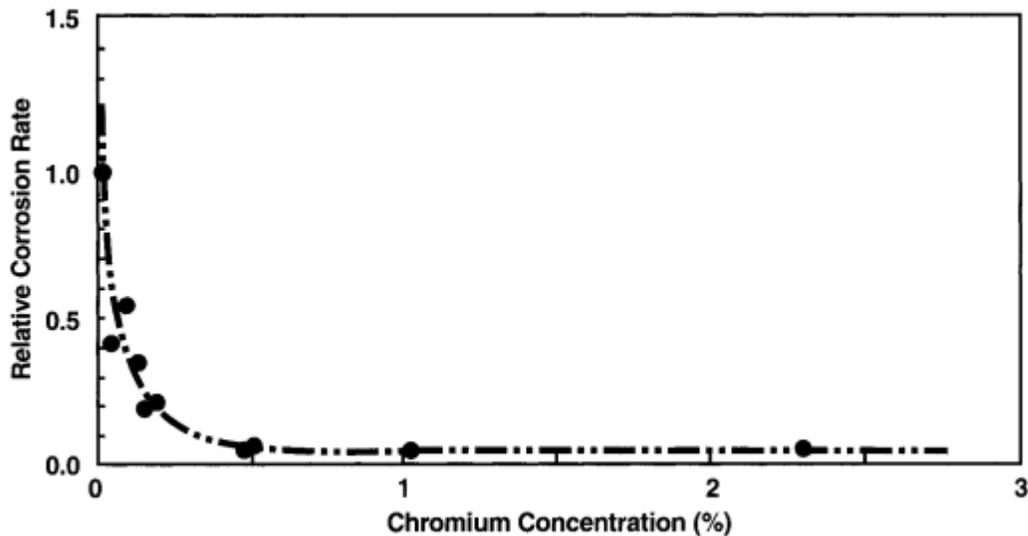


Figure 15 – Corrosion rate based on chromium concentration. Reproduced from Flow Accelerated Corrosion in Power Plants, pp - 3-32, EPRI, Palo Alto, CA: 1998. TR-106611- R1

<sup>2</sup> Corrosion rate based on chromium concentration. Reproduced from Flow Accelerated Corrosion in Power Plants, pp - 3-32, EPRI, Palo Alto, CA: 1998. TR-106611- R1

If ad hoc pipe and fitting replacement with higher chromium steel is to be considered as a fix the end user needs also to consider the downstream effects of the higher chromium material. For instance, if a carbon steel elbow fails due to two phase FAC and a new elbow is installed that contains 0.3 -1.5 % chromium content, industry experience shows the new elbow will mitigate the two phase FAC at this location. Experience has also shown that there is a very good chance that the two phase FAC can begin to affect the piping downstream of the elbow that was replaced. In many cases, FAC on the carbon steel will persist downstream of the elbow until the temperature of the condensate drops low enough to stop the two-phase FAC. It could be argued if you do not have a way to inspect the piping downstream of the elbow that failed due to two phase FAC, it would be better to replace the failed elbow with the same material and just setup a program to monitor and replace the elbow before it reaches a critical minimum wall.

#### 2.1.7.4 Other Factors

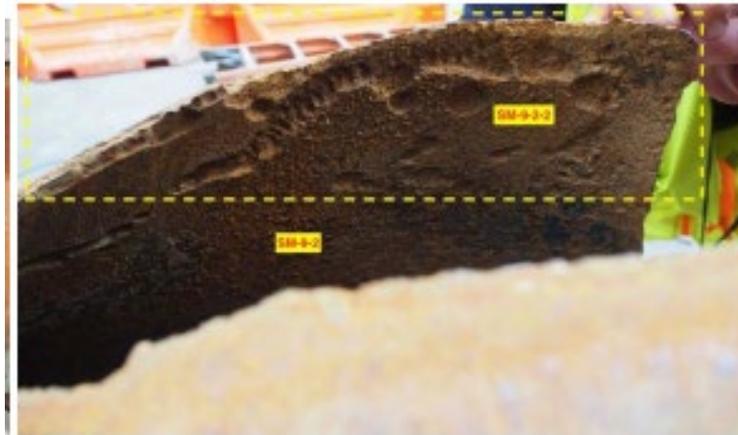
There are several other factors that can increase the risk of two-phase FAC, including the velocity of the system, steam quality, and system geometries. Unfortunately, some these factors need to be considered when the system was originally designed. The factors of pH, chromium content, and steam quality (if insulation is not kept up) are factors that the end user has some ability to control.

#### 2.1.7.5 CECONY Steam System Comments (FAC)

The CECONY steam system has experienced several two phase FAC events over its lifetime. Figures 12 thru 14 are various pictures from root cause failure reports on the CECONY system. These pictures show the two phase FAC mechanisms was present.



Figure 16 - West 58th Street Steam Pipe Failure



**Figure 17 - 20th Street and 5th Avenue**



**Figure 18 - 57th Street and 5th Avenue**

While age is a potential reason for two phase FAC failures, other factors could also be responsible for a faster corrosion rate. For example, in a December 30, 2005 report from Tetra Engineering Group to CECONY, An observation detailing the summary findings stated “Often, the failed sections were adjacent to sections previously replaced anywhere from ten to fifty years in the past.” This is a significant statement that indicates that something changed in the system downstream of the original repairs that could have setup the two phase FAC mechanism. Possibilities include pipe elevation creating a local low spot, a weld with a high profile changing the geometry of the flow, and insulation damage.

### **2.1.7.6 Mitigating Techniques for FAC**

Two phase FAC is nearly impossible to stop from occurring for existing systems. For new construction, using materials with the minimum recommended 1.5% chrome content, as discussed in Section 3.1.7.3, can significantly reduce susceptibility to two phase FAC. For existing systems, however, a complete replacement is not likely economically feasible.

Two phase FAC can be slowed down by increasing the pH of the system to over 9.6 which is not possible on the CECONY steam system for reasons discussed earlier. Two phase FAC can also be slowed down by ensuring carryover is not occurring at the steam plants which reduce the chlorides and sulfates that are also contributing to corrosion of the steam



system. As discussed CECONY has appropriate programs and processes in place to reduce the impact of drum carryover. In addition ensuring that traps are maintained and working to reduce the pooling of steam condensate, ensuring all pipe supports are free and working properly, and ensuring that insulation is maintained to keep steam quality from decreasing are other ways to reduce the risk of two phase FAC.

These practices may help reduce the susceptibility to corrosion and resulting leaks, but do not eliminate the susceptibility for leaks entirely. Because these types of leaks are significant safety threat to personnel and the general public typically the operator will develop a FAC inspection program to identify and inspect high likelihood areas. The results of the FAC inspection programs can lead to planned piping replacement as necessary to allow for management of two-phase FAC.

### **2.1.7.7 Other General Comments**

Although DNV found no evidence of crevice corrosion incidents in the records provided by CECONY, crevice corrosion failures around crevices like welds are possible because of steam system conditions. In addition, because of the chemical factors of CECONY steam condensate discussed in this report, steam end users may experience iron deposits and corrosion of their systems. CECONY has not, however, received complaints from customer that steam condensate is causing any corrosion issues. Most customers have drip pots and traps that are maintained. Crevice corrosion and customer corrosion, if they become issues, can be reduced in the same manner as general corrosion and pitting described above.

## **2.2 Leak Before Break Assessment**

Based on inspection data provided by CECONY, it is known that regions of local metal loss exist in the pipe system. While corrosion can be mitigated, it is unlikely to be halted. As such, it is important to determine the effects corrosion may have on the system. Of particular importance is the integrity of the piping system and the ultimate status of the pipe if the metal loss progressed through wall. Answering this question is what leak before break (LBB) studies seek to understand. LBB is a fracture mechanics-based assessment of a through wall crack-like anomaly. In this instance, the LBB assessment methodology is being used to assess through wall corrosion primarily due to these local thin areas. The through wall corrosion is being assessed as a crack-like anomaly using the fracture mechanics approach, which is a conservative method of assessment.

In the LBB assessment methodology, a through wall crack is studied to determine at what length the crack would need to grow before a pipe rupture is predicted. A very short flaw under a given load may be stable, and not be expected to grow, while a long flaw may be unstable and lead to a brittle fracture of the pipe under that same load. The maximum length a flaw can be before pipe rupture is predicted is called the critical flaw size. Understanding this critical flaw size provides better understanding of the susceptibility of the system to fracture. The energy and steam released during a large rupture may significantly increase the risk to people and surrounding structures compared to a smaller pinhole steam leak.

### **2.2.1 Methodology**

An LBB assessment consists of two parts: critical flaw size calculation and a calculation of the associated leak rate to detectable thresholds. The leak rate is a minimum figure assuming the only path the steam could travel would be through the crack face. Because the features most prevalent in CECONY's system are local metal loss features, it is possible the leakage rate may be larger than the minimums provided here. These values are provided to be referenced against a detection threshold. If the leak rate is lower than the detectable threshold, the crack may go undetected until an unstable length is achieved. If the crack is stable and detectable, the flaw can be identified and repaired prior to a larger rupture.

The LBB study was conducted per API 579/ASME FFS-1 2016<sup>3</sup> section 9.5.2. This assessment methodology uses a failure assessment diagram (FAD) which assesses a crack-like feature for both brittle fracture and plastic collapse. Brittle fracture occurs when there is a rapid progression of a crack with very little plastic deformation of the material. Plastic collapse results when loads in the material causes deformation which reduces the thickness through which the load is transferred, or necking. This continues to progress until failure occurs in the material. Each of these failure modes needs to be assessed as either may result in failure. The crack's stress intensity is compared to the materials fracture toughness, while the reference stress is compared to the materials yield stress to establish the toughness ratio ( $K_r$ ) and the load ratio ( $L_r$ ), respectively. These are plotted on the FAD. If a particular flaw falls in the acceptable region, the flaw is calculated to be stable, while if the flaw is outside the stable envelope, rupture may occur under the loading assessed.

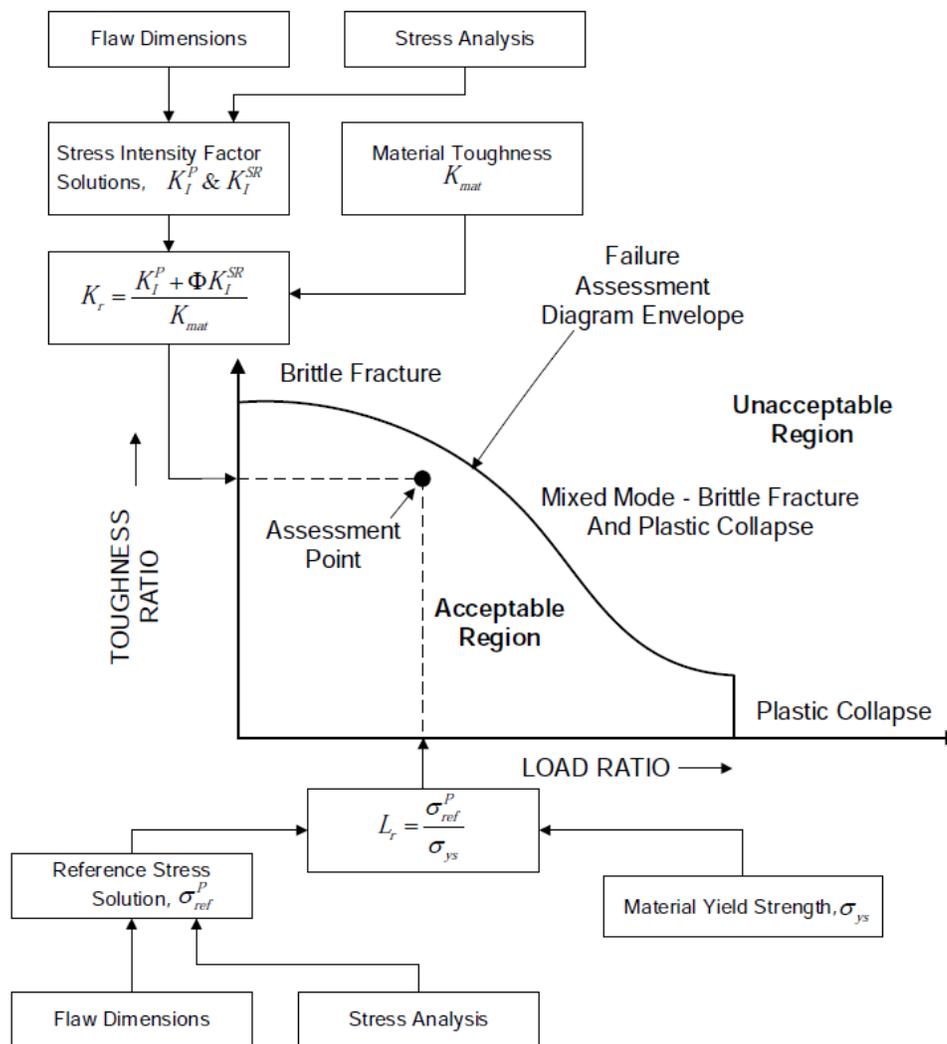


Figure 19 – Sample FAD (Reproduced from API 579 Figure 2.2)

<sup>3</sup> Anon., "Fitness-For-Service," API 579-1/ASME FFS-1, American Petroleum Institute, Washington, D.C., June 2016.

It is conservative to assess the through wall corrosion flaw as an axial crack. As the radius at the tip of the flaw increases, the stress intensity and reference stress at the crack tip is reduced. This results in an increased burst pressure and an increased critical flaw size. This is illustrated by Figure 20.

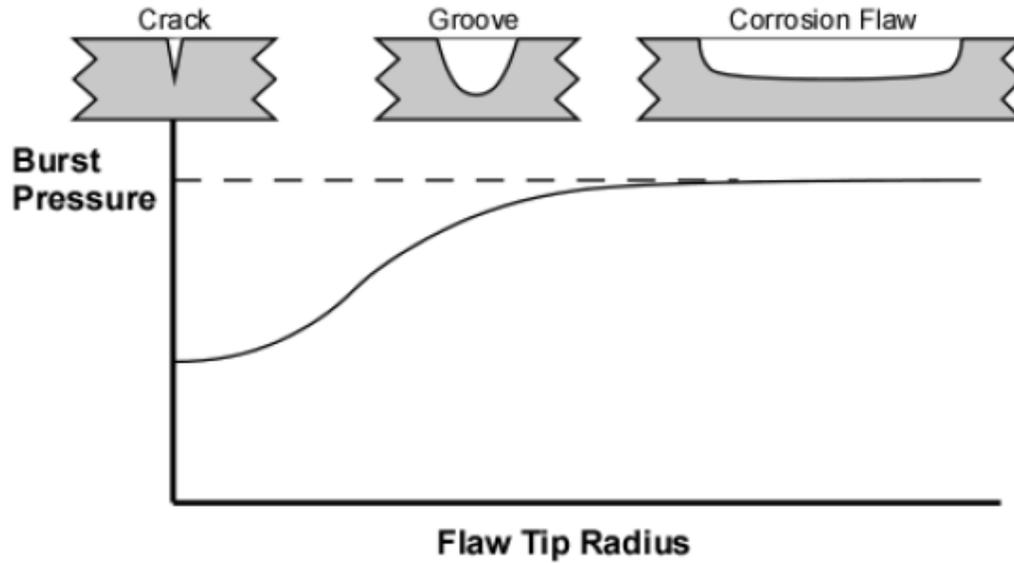


Figure 3.3 Effect of flaw tip radius on burst pressure for a fixed material toughness.

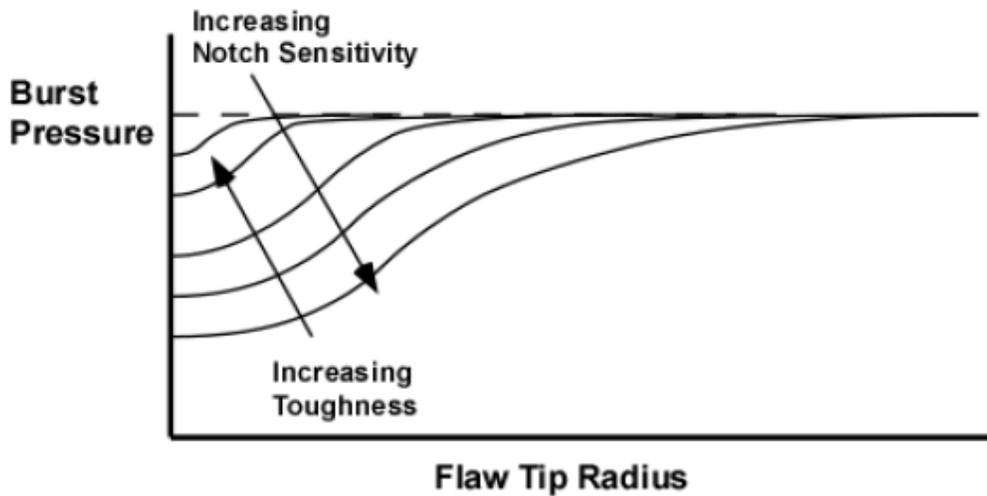


Figure 3.4 Combined effect of notch acuity and toughness on burst pressure.

Figure 20 – Effects of flaw tip radius and toughness on burst pressure. Reproduced from PRCI Report PR-460-134506 Figures 3.3 and 3.44.

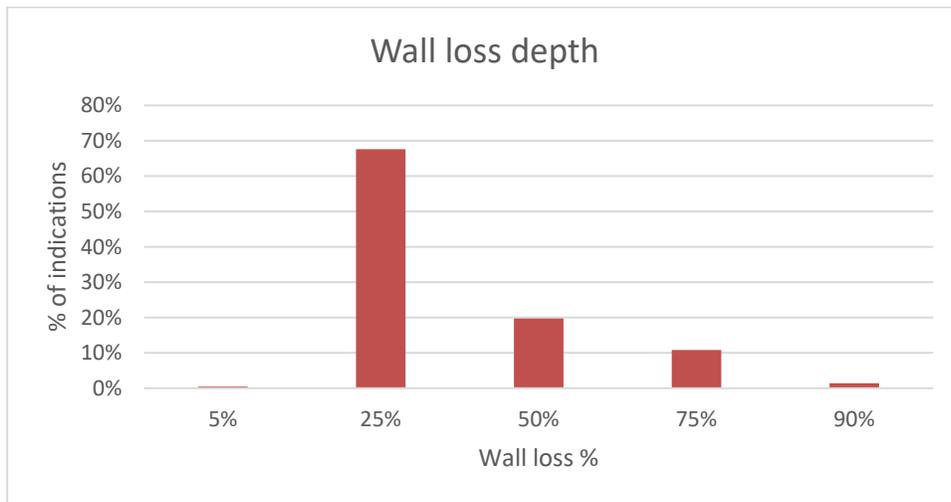
<sup>4</sup> PRCI, "Assessing Crack-Like Flaws in Longitudinal Seam Welds: A State-of-the-Art Review". Project Number PR-460-134506, March 31,2017

In the case of a through wall crack, the loads applied to the pipe and the now open crack face create a path for steam to exit the pipe. The amount of steam leaking outside the pipe is based on the area of this opening. Appendix 9E of API 579 is used to calculate a crack opening area from which an associated leak rate is calculated. This leak rate can be assessed to determine whether this would be identifiable. If this leak rate is not identifiable, the crack may continue to grow over time through a variety of mechanisms until the crack is identified, or a pipe rupture occurs.

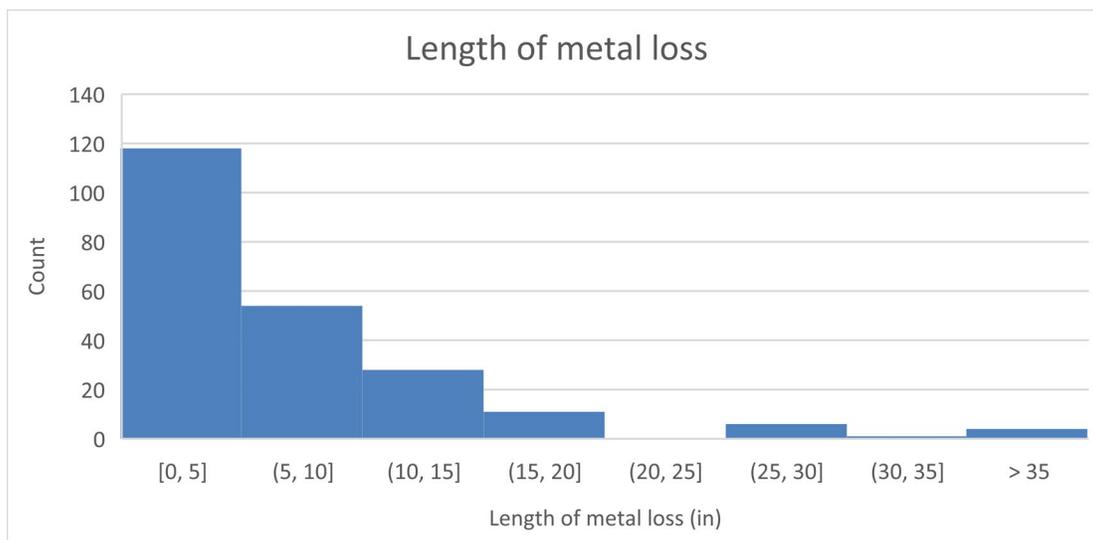
### 2.2.2 Inspection Data

Inspection data of CECONY’s system was provided and reviewed by DNV for 222 indications found between 2019 and 2021. The lengths, depths, and wall loss measurements were coarse due to the video inspection methods of obtaining the information. Length and depth measurements were provided in increments of approximately 3 inches, while wall loss was segmented to 5, 25, 30, 75, and 90% through wall.

Two thirds of inspected indications were reported as 25% wall loss per Figure 21. Similarly, three quarters of flaws had a length less than 10 inches per Figure 22.



**Figure 21 - Reported wall loss depth for indications**



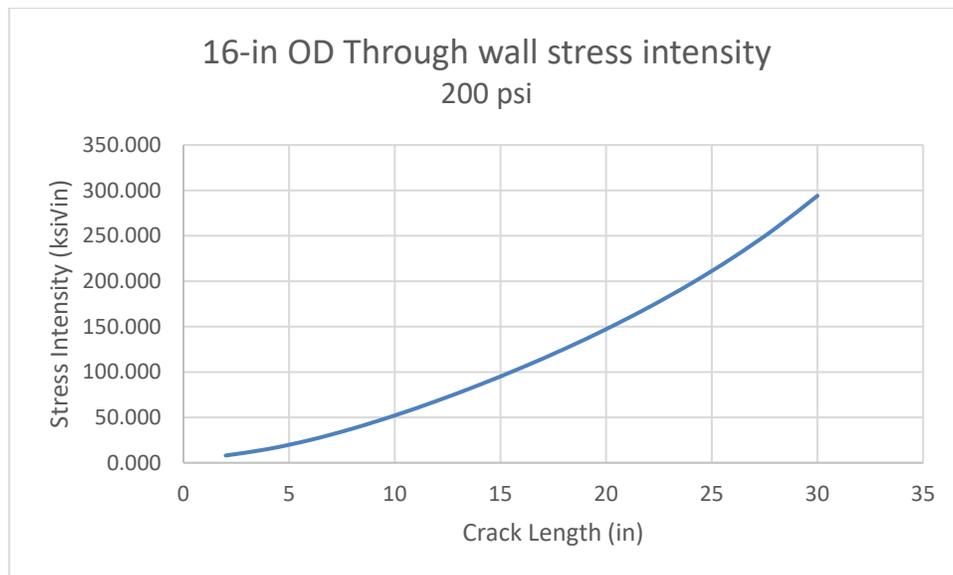
**Figure 22 – Length of reported metal loss features.**

This initial LBB assessment focuses on the larger diameter piping due to the larger hazard associated with a rupture event. The three largest diameter piping segments in the distribution system captured in the inspection information had an outer diameter (OD) of 16, 20 and 24 inches. Of these three, the 16-inch case was deemed the most pertinent to study initially. For 20 and 24 inch pipes, wall loss was limited to 50% or less. With the design pressure of 200 psi for the distribution system, nominal stresses are below yield. In the 16-inch OD piping, regions of metal loss up to 90% were identified. Depending on the orientation, and morphology of the metal loss, the stresses in this case are expected to exceed those in the 20 and 24 inch cases. CECONY has stipulated that outside the noted regions of corrosion, the wall thickness can be assumed to be nominal. This would mean that the wall loss is contained inside the footprint noted for each area. For the LBB study, it will be assumed that the region of metal loss has progressed through wall and the crack tip is reaching an area of nominal wall thickness.

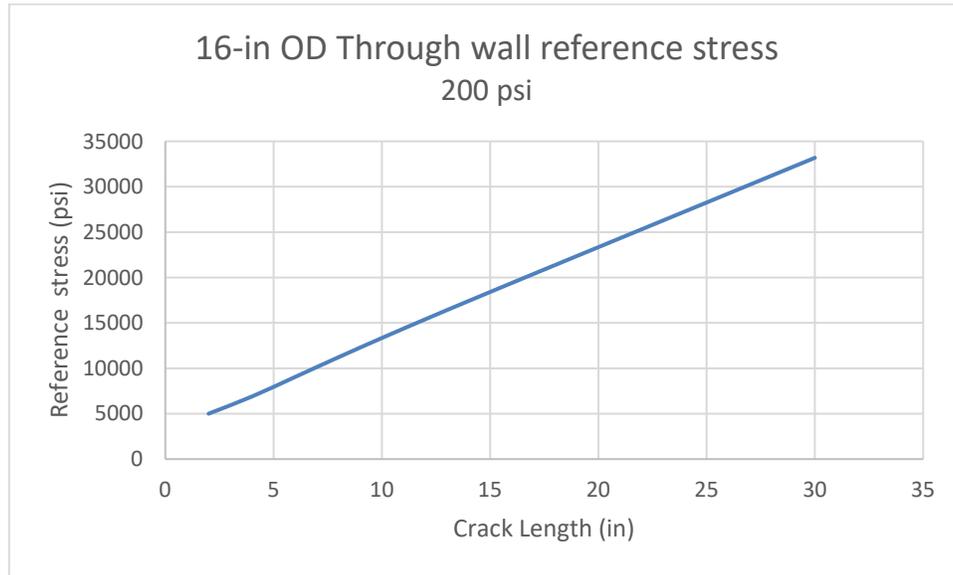
### 2.2.3 LBB Calculations

Stress intensity and primary stress calculations follow calculations in API 579 Part 9 for axial through-wall cracks in pipe. Axial flaws were chosen as the stress intensity and primary stress in this orientation is more severe than circumferential flaws when assessing loading from internal pressure. As such, under normal operating conditions, this is expected to be the limiting case. The wall thickness at the ends of the rupture is assumed to be the nominal thickness of the pipe. This would be analogous to a perforation in the pipe occurring through the extents of the region of local corrosion and reaching the nominal wall thickness at the extents of the local area of corrosion.

The stress intensity for the 16-inch OD case under 200 psi internal pressure loading for various crack lengths is presented in Figure 23. This stress intensity would be compared to the material's toughness to determine the  $K_I$  in the FAD diagram. The reference stress, which is used to generate the load ratio,  $L^P_R$ , under the same loading scenario is shown in Figure 24.



**Figure 23 – Stress intensity of a through-wall axial crack under 200 psi internal pressure at various crack lengths**



**Figure 24 – Reference stress for a through-wall axial crack under 200 psi internal pressure at various crack lengths**

Presented above is the stress intensity and stress the material of the pipe would be subjected to at various crack lengths and is based only on the pipe’s geometry and loading. The stability of the crack is dependent on the material properties of the pipe – specifically the pipes yield strength, ultimate tensile strength, and crack toughness.

## 2.2.4 Pipe Materials

CECONY’s system consists of a variety of pipe materials. Current specifications for pipe sized up to a diameter of 24-inch include ASTM A53 Grade B, ASTM A106 Grade B, and API 5L Grade B per CECONY’s S-9035-11 procedure. While this is all required to be seamless pipe now, steam piping specifications between 1954 and 2011 allowed for seamed ERW welds for this material. Prior to the 1950’s some wrought iron piping was used. CECONY’s estimate for the amount of wrought iron piping still in service is less than 5% of its system. Of particular importance for the leak before break assessment, are these material’s yield strength (YS), ultimate tensile strength (UTS), and fracture toughness. The YS and UTS affect the pipe’s ability to resist plastic collapse, while the fracture toughness affects the material’s ability to withstand brittle fracture. Each of these values are impacted by the temperature of the steel. Generally, materials will have reduced tensile properties (YS and UTS), but have higher toughness values at temperatures above room temperature. For instance, for a A53 Grade B seamless pipe, the yield strength at room temperature is 35,000 psi. This is reduced to 29,900 psi at 400°F per ASME BPVC Section II Part D, a boiler and pressure vessel code covering material properties. An ASTM A72 wrought iron, per B31.1, has an increasing yield strength in this temperature range. In each case, a lower bound material property will be utilized for calculations.

As temperature increases from room temperature, toughness generally improves, however reaches an upper-shelf limit beyond a certain material dependent temperature. For materials with an unknown chemistry, this upper shelf limit is assumed to be 100 ksi√in per API 579 9F.4.2.1.e and is reached at approximately 60°F. The upper shelf limit for a dynamic arrest toughness,  $K_{IR}$ , has the same upper shelf limit, but is reached at 125°F.

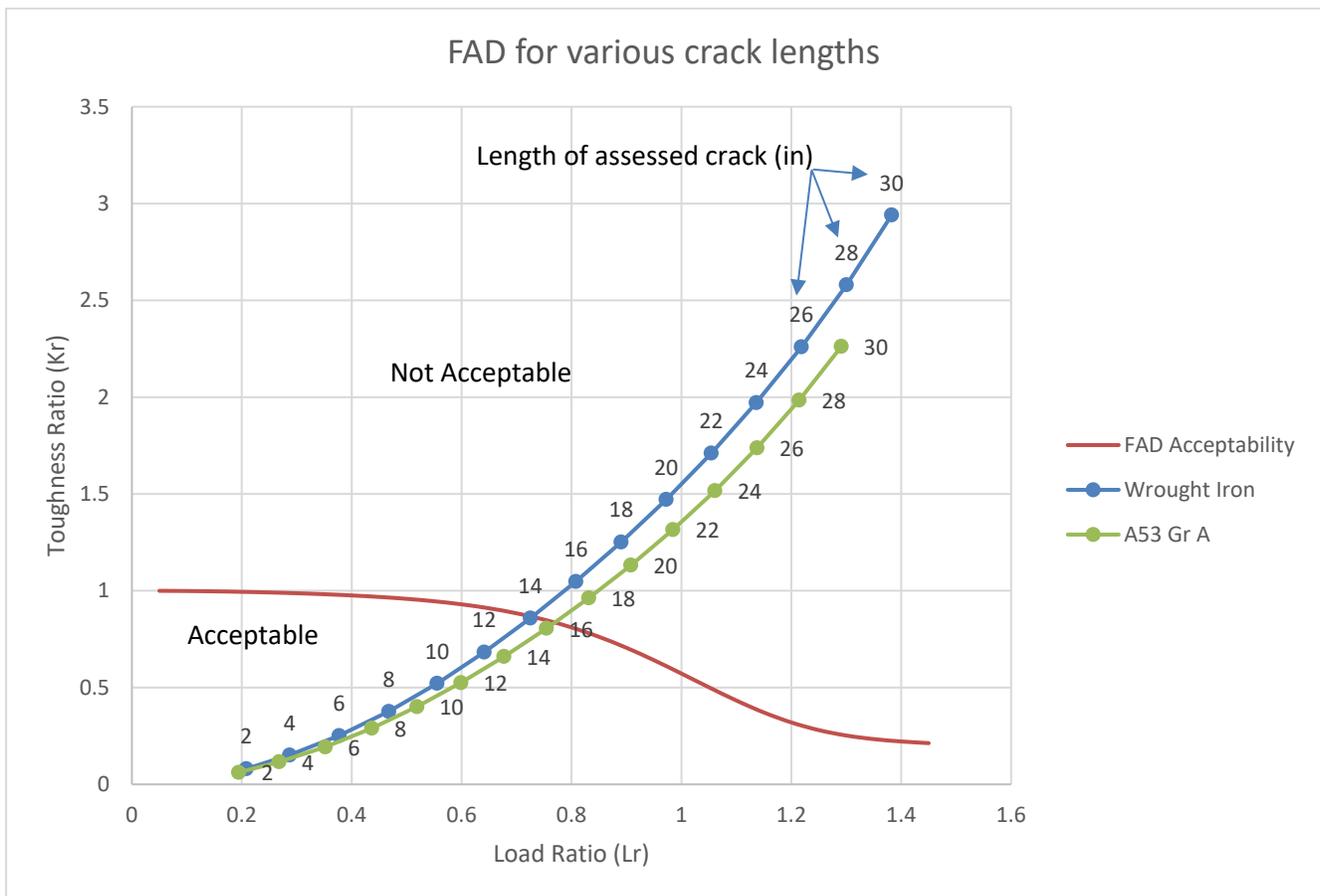
For the purpose of the LBB assessment, particular attention is given to materials which have been in service longer, as these are more likely to have higher amounts of corrosion. Two materials were assessed: a wrought iron pipe material, and a vintage A53 pipe. Material information for the vintage A53 utilized material tests on an ASTM A53 Grade A pipe installed in

1924 which had been previously assessed by Lucius Pitkin, Inc (LPI) at the direction of CECONY after a 2007 failure<sup>5</sup>. This work found the tensile properties of the 1924 vintage A53 steel were an average of 94% of the 2006 A53 specification. A lower-bound dynamic arrest toughness for this material 130 ksi√in was derived for the 1924 vintage pipe at operating temperatures. Additional material testing conducted in 2019 on a 1932-vintage and 1991-vintage A53 pipe showed material properties exceeding those of the 1924 vintage material<sup>6</sup>. For conservatism, the material properties from the 1924 pipe were used.

**Table 2 – Assessed pipe material parameters**

Material	Yield Strength (psi)	Ultimate Tensile Strength (psi)	Fracture Toughness (ksi√in)
ASTM A53	25,700	50,000	130
Wrought Iron	24,000	40,000	100

Incorporating this yield and toughness information with the results from section 3.2.3 yields the FAD shown in Figure 25. This figure shows a maximum acceptable crack length for the 16-inch OD wrought iron pipe of 14 inches, and 16 inches for the A52 Grade A pipe.

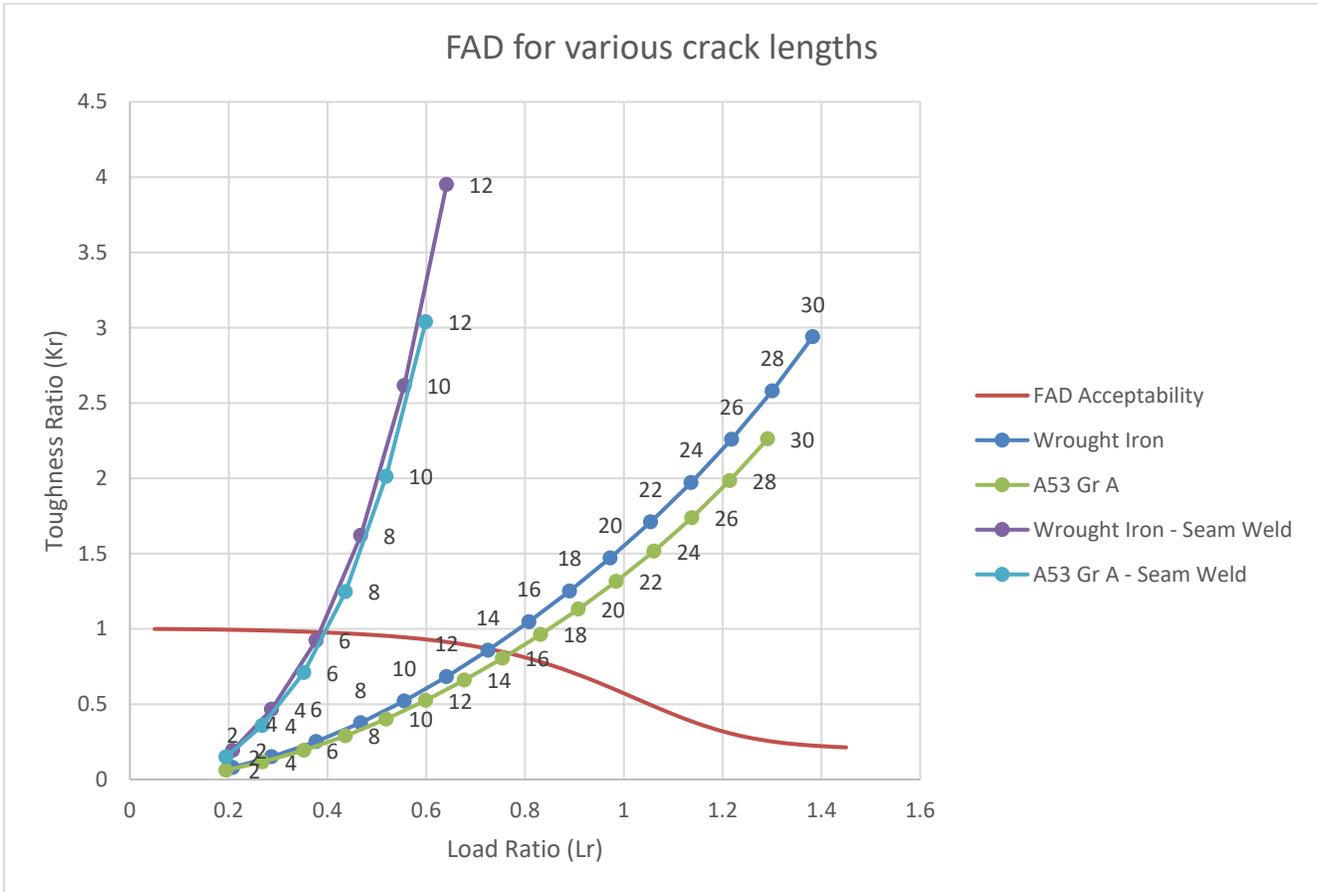


**Figure 25 – FAD for Wrought Iron and A53 Grade A steel. The region above the red line would be unacceptable, while the region below is acceptable. Lengths of each assessed crack is shown next to each data point. Crack lengths are shown in inches.**

<sup>5</sup> Lucius Pitkin, Inc, "Evaluation of July 18, 2007 Steam Incident – 41<sup>st</sup> Street & Lexington Avenue, New York, NY", Report number F07294, December 17, 2007

<sup>6</sup> Affiliated MRD, LLC, "Metallurgical Evaluation of Ruptured Steam Pipe", PO No 5159167, July 23, 2019

Seam welds introduce additional residual stress on top of the operational stresses the pipe is operating under. These residual stresses serve to increase the stress intensity along the crack tip, therefore reducing the size of a stable flaw. The results displayed above illustrate the stress intensity and reference stress of flaws in the base metal sufficiently far from the seam weld. Because only pipes newer than 2011 are required to be seamless, these residual stresses should be considered in the instance that a region of local metal loss grew through wall along a seam weld. Calculations for residual stresses in the seam weld were taken from API 579 Section 9D.6. The FAD for flaws both with and without the residual stress from the seam weld are displayed in Figure 26.



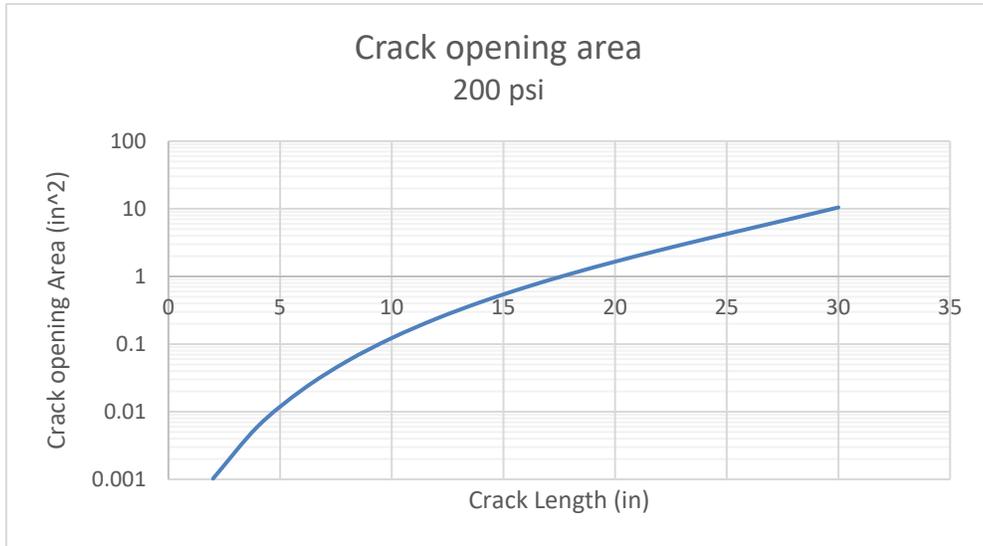
**Figure 26 – FAD for Wrought Iron and A53 Grade A steel both with and without the residual stress from the seam weld. Cases including the residual stresses from the seam weld are appended with “Seam Weld” in the legend. The region above the red line would be unacceptable, while the region below is acceptable. Lengths of each assessed crack is shown next to each data point. Crack lengths are shown in inches.**

### 2.2.5 Leak rate

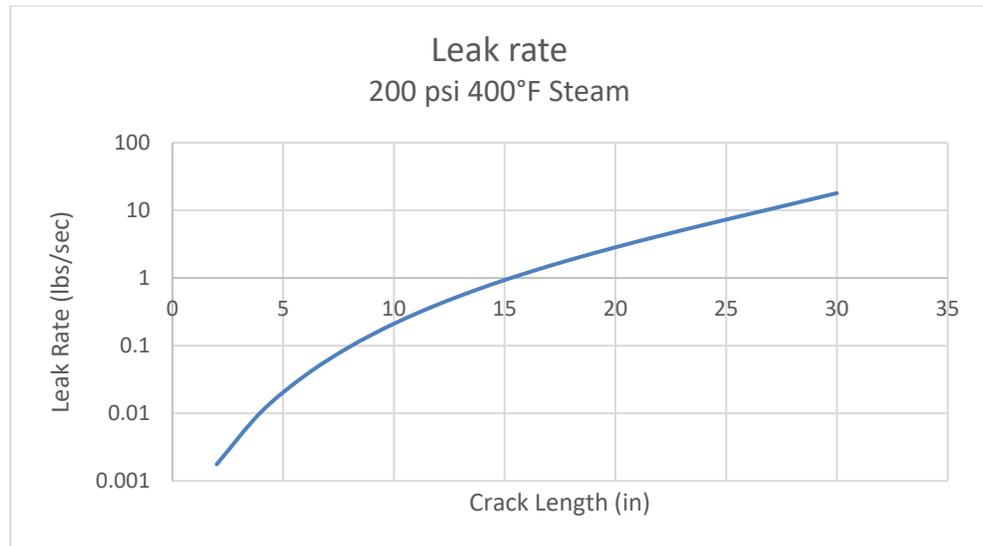
Once a through wall crack has formed, some amount of steam will begin to leak through the pipe wall. The amount of leakage is important to calculate as it allows for these through wall cracks to be detected. If not identified, the crack may slowly grow through various damage mechanisms such as corrosion or fatigue until the flaw’s critical length is reached. This calculation comes in two parts; first, the crack opening area for the part is calculated, then the associated leak rate is calculated. Because the crack face and pipe are exposed to the pressure inside the pipe, the pipe will separate slightly along the crack face allowing for steam to escape. The area created by this crack opening, is called the crack opening area and is calculated using equations in part 9E of API 579. Note that this crack opening area is based on the pipe wall being of a nominal thickness across the crack face. As such, if an area of metal loss from corrosion were to grow to be through wall,

the expected crack opening area and associated leak rate would be expected to be higher, and thus, more easily detected. The calculations presented below represent an axial crack through otherwise nominal wall thickness pipe.

Calculations for the flow rates associated with a given crack area show that for superheated steam at 200 psi and 400°F, a crack length of 14 inches (the maximum acceptable length for wrought iron pipe away from a seam weld), a leak rate of 0.72 lbs/second is predicted. The critical crack length for a flaw in a seam weld in a wrought iron pipe is 6 inches, which has a calculated leak rate of 0.036 lbs/sec.



**Figure 27 – Crack opening area for a through-wall axial crack under 200 psi internal pressure at various crack lengths**



**Figure 28 – Leak rate for through-wall axial crack under 200 psi, 400°F steam at various crack lengths**



## 2.2.6 Assumptions and Limitations

The above calculations are based on generally conservative assumptions. The calculations of acceptable crack lengths utilize reference stress and stress intensity calculations which account for a single linear crack-like feature. In the instance of a through wall leak of a local thin area, it is possible the stress pattern will serve to reduce the stress at the crack tip, leading toward a longer acceptable crack length. Toughness measurements are based on lower-bound, upper-shelf toughness measurements; meaning, the actual toughness of the material is likely higher than the assessed material toughness. A material toughness higher than the assessed toughness would result in a larger allowable flaw size. Additionally, the leak rate calculations were based on an axial crack through pipe of a nominal wall thickness. Cracks running through regions of metal loss would have an increased crack opening area, and therefore have an increased leak rate, leading to a higher likelihood of detection.

There are several limitations associated with the above assessment. The above assessment assumed, at CECONY's direction, the wall thickness at the edge of the local thin area reaches the nominal wall thickness. Extended regions of corrosion would reduce the pipe's ability to resist crack propagation. The above calculations also assumed an upper-bound design operating condition of 200 psi at 400°F. Pressures or temperatures above this value would alter the allowable flaw size. Temperatures well below this value may also reduce the toughness of the material as the toughness may no longer be at an upper shelf value. Water hammer events were also not assessed in this study.



### 3 SUMMARY OF FINDINGS AND CONCLUSIONS

DNV reviewed documents provided by CECONY to understand the common degradation and failure mechanisms present in the steam transmission and distribution piping. The documents contained information regarding the piping metallurgy, materials of construction, and steam chemistry. In general, the documents indicate that the CECONY steam system is being exposed to general corrosion, pitting, and flow accelerated corrosion.

With respect to general corrosion, a review of pH values recorded at each of CECONY's steam generating stations yielded an average range of 5.09 to 6.64 which corresponds to an approximate corrosion rate of 4 mpy to 3.8 mpy respectively, applied to any steam condensate. As it related to corrosion susceptibility, CECONY's steam distribution pipes are seeing three contributing sources to its overall corrosion threat profile, pH based general corrosion, steam condensate localized aggressive pitting, and flow accelerated corrosion (FAC). Further, DNV concludes that CECONY is limited, based on FDA restrictions placed on steam end users, in its ability to adjust steam condensate pH and must therefore rely on preventative inspection and maintenance of its traps, hangers, and insulation, limiting and effectively responding to drum carryover as well as limiting contaminants in its steam generation

DNV recommends that CECONY continue its practice of proactively reviewing its preventive mitigation and maintenance procedures and record keeping, with specific emphasis on continued adherence to written procedures and internal standards.

Corrosion of piping is an ongoing process that can never be completely mitigated. Considering the age of the CECONY steam system it would be expected at some point to start to see an increase in corrosion related leaks on the system without continued expansion and development of their corrosion control detection and mitigation methods. The fact that the reported corrosion related leak frequency remains relatively consistent considering the age of the system, reflects on the dedication by CECONY to control corrosion to the best of their abilities especially considering some of the obstacles that are faced daily in controlling corrosion.

A leak before break assessment was completed on a 16 inch outer diameter pipe with material properties conservatively representing vintage pipe materials present in CECONY's system. This assessment is conducted to assess whether the regions of local metal loss would result in a pipe rupture, or if they are more likely to result in a stable leak. These flaws were assessed as varying length through-wall cracks. Assessment of local metal loss features as crack-like flaws is conservative and results in conservative stable flaw lengths. Material properties in the case of the A53 material used in the assessment were based on material tests performed on CECONY's 1920's and 1930's pipe. CECONY has stated that less than 5% of the distribution system uses wrought iron piping. As such this material is also assessed. Both materials utilized lower-bound tensile and toughness information in determination of crack stability. Additionally, assessments were conducted for features effected by residual stresses in the seam weld as well as features unaffected by seam weld residual stresses.

Stable crack sizes of 6 inches in length for wrought iron material and 7 inches in length for A53 material were calculated in the seam weld under design pressure (200 psig) and temperature (400 °F). For cracks outside the seam weld, stable crack lengths of 14 and 16 inches were calculated for the wrought iron and A53 material, respectively. Flaws smaller than these lengths that grow through wall would not be expected to result in a larger pipe rupture. Instead, these would be expected to result in a stable leak. The leak rate for a 6 inch through wall crack-like flaw was calculated to be 0.036 lbs/second and 0.72 lbs/second for a crack of 14 inches in length. These resulting leak rates are expected by CECONY to be detectable, allowing for repair prior to a flaw's growth to a potentially critical length. This limits the risk associated with these flaws. Because the features in CECONY's system are local metal loss rather than crack-like features, it is expected for leak rates to be higher, resulting in leaks being easier to detect.



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