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# Silver Eagle Refinery Explosion Investigation: Metallurgical Analysis

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# Silver Eagle Refinery Explosion Investigation: Metallurgical Analysis

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# Contents

# List of Figures

# List of Tables

# Acronyms and Abbreviations

| | |
|---|---|
| CFEI | Certified Fire and Explosion Investigator |
| CSB | Chemical Safety Board |
| $H_2$ | Hydrogen |
| $H_2S$ | Hydrogen Sulfide |
| LEL | Lower Explosive Limit |
| MDDW | Mobil Distillate Dewaxing Unit |
| NFPA | National Fire Protection Association |
| P&ID | Process and Instrumentation Drawing |
| PE | Professional Engineer |
| UEL | Upper Explosive Limit |

# Limitations

At the request of the Chemical Safety Board (CSB), Exponent conducted an investigation of circumstances associated with the November 4, 2009 explosion at the Silver Eagle Refinery in Woods Cross, Utah. Exponent investigated specific issues relevant to this explosion as requested by the CSB. The scope of services performed during this investigation may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented herein is at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

The findings presented herein are made to a reasonable degree of engineering and scientific certainty. We have made every effort to accurately and completely investigate all areas of concern identified during our investigation. If new data becomes available or there are perceived omissions or misstatements in this report regarding any aspect of those conditions, we ask that they be brought to our attention as soon as possible so that we have the opportunity to fully address them.

# Investigation

## Background

On November 4, 2009, an explosion occurred in the Mobil Distillate Dewaxing Unit (MDDW) of the Silver Eagle refinery, located in Woods Cross, Utah. The unit was undergoing hot hydrogen regeneration of the catalyst at the time of the explosion. Regeneration of the catalyst is a periodically performed procedure, in which the normal liquid hydrocarbon feed is stopped and a hydrogen-rich gas mixture is fed through the catalyst bed. The process is also heated from a normal operating temperature of 700°F to approximately 800°F. This allows the hot hydrogen to desorb heavy ends from the dewaxing catalyst. A process and instrumentation drawing (P&ID) of the portion of the MDDW where the explosion occurred is shown in Figure 1. There are two catalyst bed reactors in the MDDW, the South Reactor (RTR30101) and the North Reactor (RTR30103). The pipe failure occurred as a sudden and complete rupture of the 10-inch diameter line at the exit of the South Reactor. The discharge line contracts to eight inches in diameter at a flange connection just downstream from the rupture site, with an eight-inch line feeding Heat Exchanger EXC-30115 (Figure 1).

Temperature and pressure measurements were made at the discharge of the South Reactor, labeled “F” and “C” in Figure 2, respectively. Inlet and exit temperatures for the South Reactor are shown in Figure 3. The catalyst regeneration procedure began at 9:00 p.m., as seen in the initial heating of the reactor. The reactor inlet temperature rose from 680°F at 9:00 p.m. to 806°F at 3:00 a.m., and remained essentially constant for the start of a planned 24-hour catalyst regeneration cycle. At 9:11 a.m., approximately six hours into the procedure, the inlet temperature suddenly dropped, and the exit temperature increased to over 1000°F (Figure 4). This resulted from the pipe rupture between 9:11 a.m. and 9:12 a.m., causing the inlet temperature to drop as the system depressurized, and the outlet temperature to rise since the outlet thermocouple was exposed to the resulting fire. Pressure in R30101 was increased from normal operating levels just below 600 psig to about 640 psi during the catalyst regeneration process (Figure 5). At the time of the accident, the pressure was at 642 psi (Figure 6).

Security video of the accident covered the MDDW (Figure 7). The location of the pipe rupture is marked with a red circle. A frame from this video reveals the initial release of gas from the ruptured pipe (Figure 8). This release rapidly expanded (Figure 9), and the hot gas mixture ignited shortly after rupture (Figure 10). A shock wave from the resulting explosion expanded through the adjacent neighborhood, causing varied degrees of blast damage to residential homes.

Exponent's explosion investigation and analysis was conducted by Gregory J. Haussmann, Ph.D., P.E. His report was issued to the CSB on June 30, 2012.

# Site Visits to Silver Eagle Refinery

Exponent performed an initial site visit and inspection on January 7 and 8, 2010. This included an inspection and documentation of the MDDW and an inspection and survey of the residential community adjacent to the Silver Eagle refinery.

## Ruptured Pipe in the MDDW

The origin of the explosion was a pipe failure at the bottom of South Reactor R30101. The 10-inch diameter discharge line ruptured in the skirt underneath the reactor. The discharge line runs from the bottom of R30101 up to Heat Exchanger EXC-30115. The resulting reaction force caused by rapidly escaping high pressure gas bent the piping around a reactor support beam (Figure 11). After rupture of the pipe, high pressure gas was escaping from both ends of the pipe failure. One end of the fractured pipe ended up wrapped around a reactor support beam (Figure 12), while the second end was attached to the bottom of the reactor (Figure 13).

There was explosion damage to light structural elements on the adjacent "hydro pad", where water blasting/cleaning activities took place (Figure 14). A view from the hydro pad includes the surrounding residential community (Figure 15).

Exponent retained Balling Engineering to perform site survey activities. This included measuring the as-found geometry of the R30101 discharge piping. An elevation view is shown in Figure 16. The fractured end of the pipe is labeled as Point #1025. Before the rupture, this pipe ran through an opening in the skirt around the base of R30101, labeled as Point #1029. The rupture occurred under the skirt around R30101. A plan (overhead) view of the pipe is shown in Figure 17.

The ruptured pipe ran from the bottom discharge of South Reactor R30101 to Heat Exchanger EXC-30115. A 10-inch diameter pipe exits Reactor R30101 and reduces to eight inches in diameter at a flange connection just downstream of the fracture location outside the reactor skirt. Pipe supports underneath the pipe are illustrated in Figure 17, with the longest unsupported run of pipe measuring just less than twelve feet. A photograph of one of the pipe supports is shown in Figure 18. A sliding support was observed, with reaction forces from the pipe rupture having shifted the pipe off the support plate. Inadequate pipe support is not considered a contributing factor to this accident.

## Sectioning and Removal of Ruptured Pipe Components

A second site visit and inspection was conducted on March 29 and 30, 2010. The incident ruptured discharge line pipe in the MDDW Unit was examined, and components were sectioned and removed from the site for further metallurgical analysis, under the direction of Mr. Darko Babic.

The upstream end of the fractured segment still attached to the bottom of the reactor was labeled “SER 34” and sectioned for removal from the site, as shown in Figure 19 and Figure 20. The downstream end of the fractured segment that had wrapped around a reactor support beam was labeled “SER 35” and also sectioned for removal from the site, as shown in Figure 21 with the sectioning location through the eight-inch-diameter pipe indicated. Prior to sectioning, fluid remaining in the piping was drained through the valve designated “SER 36” and stored in a glass bottle (Figure 22).

Two additional items were found near the fractured sections SER 34 and SER 35 that appeared to be pieces of the ruptured piping segment. Outside of the reactor skirt, a piece of steel approximately 20 inches in length was found (Figure 23). This item was labeled “SER 27” and retained for further examination and analysis (Figure 24). Inside of the reactor skirt, a piece of steel approximately 32 inches in length was found (Figure 25). This item was labeled “SER 28” and also retained for further examination and analysis. Additional debris items found inside the reactor skirt were also collected and retained.

# Engineering Analysis

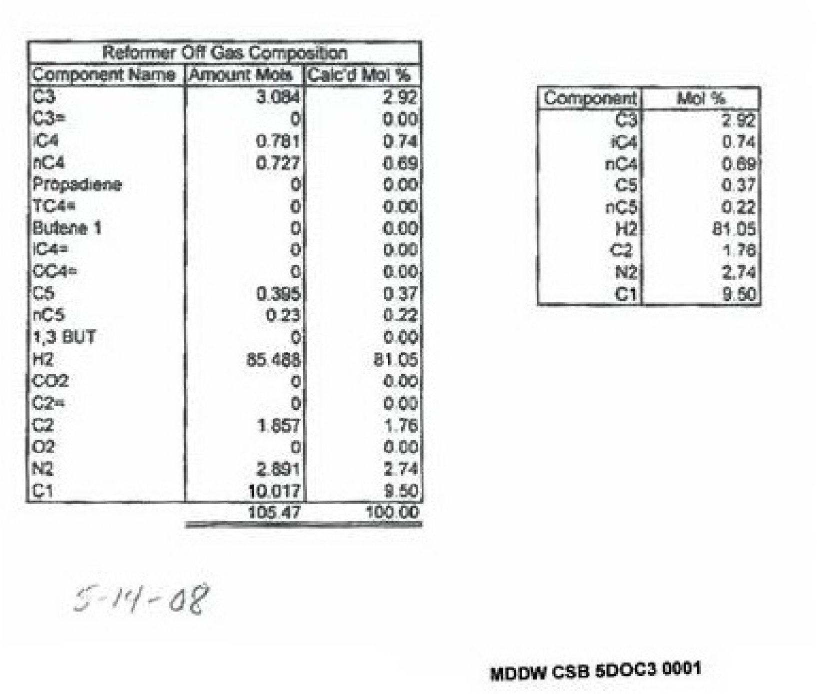
## Release and Explosion

Following the sudden rupture of the R30101 exit pipe, high pressure gas was released from both ends of the ruptured pipe. These were a 10-inch diameter pipe connected to the bottom of R30101 (Figure 13) and a longer length of 10-inch diameter pipe connected by a flange to an eight-inch diameter stainless steel pipe that fed heat exchanger EXC 30115 (highlighted in Figure 1).

The composition of the gases is listed in Table 1 below. The primary species was hydrogen (81% by volume), followed by C1 or methane (9.5%), and small amounts of other light hydrocarbons and nitrogen. Temperature (Figure 4) and pressure measurements in the MDDW unit (Figure 6) show conditions at the discharge of R30101 were 642 psig and 785°F.

Choked flow calculations were conducted for the gas mixture described in Table 1, as pressures were high enough to produce sonic flow at the pipe discharge. Under these conditions, the release rate of each gas species was calculated. Analysis of the security video revealed that the time between pipe rupture (Figure 8) and the initial explosion (Figure 10) was approximately 0.66 seconds. This time was used to calculate the amount of each gas species released at the time of the explosion, as listed in Table 2.

**Table 1. Composition of gas in R30101 during catalyst regeneration.**



| Reformer Off Gas Composition | | |
|---|---|---|
| Component Name | Amount Mols | Calc'd Mol % |
| C3 | 3.084 | 2.92 |
| C3= | 0 | 0.00 |
| iC4 | 0.781 | 0.74 |
| nC4 | 0.727 | 0.69 |
| Propadiene | 0 | 0.00 |
| TC4= | 0 | 0.00 |
| Butene 1 | 0 | 0.00 |
| IC4= | 0 | 0.00 |
| CC4= | 0 | 0.00 |
| C5 | 0.395 | 0.37 |
| nC5 | 0.23 | 0.22 |
| 1,3 BUT | 0 | 0.00 |
| H2 | 85.488 | 81.05 |
| CO2 | 0 | 0.00 |
| C2= | 0 | 0.00 |
| C2 | 1.857 | 1.76 |
| O2 | 0 | 0.00 |
| N2 | 2.891 | 2.74 |
| C1 | 10.017 | 9.50 |
| | 105.47 | 100.00 |

| Component | Mol % |
|---|---|
| C3 | 2.92 |
| iC4 | 0.74 |
| nC4 | 0.69 |
| C5 | 0.37 |
| nC5 | 0.22 |
| H2 | 81.05 |
| C2 | 1.76 |
| N2 | 2.74 |
| C1 | 9.50 |

5-14-08

MDDW CSB 5DOC3 0001

**Table 2. Amount of gas released at the time of ignition.**

| Gas Species | Quantity |
|---|---|
| Hydrogen | 43.0 kg |
| Nitrogen | 20.3 kg |
| Methane | 40.3 kg |
| C2 Hydrocarbons | 14.0 kg |
| C3 Hydrocarbons | 57.7 kg |
| Total | 175.3 kg |

## Metallurgical Analysis

Examination and analysis of the items removed from the Silver Eagle Refinery in March 2010 was conducted at Exponent's laboratory in Phoenix, Arizona under the direction of Mr. Darko Babic on August 10 and 11, 2010.

Ultrasonic thickness (UT) testing on the fractured end of the SER 35 segment was conducted at locations along the length and around the circumference of the ruptured pipe. Thickness measurements ranged from 0.120 to 0.244 inches (Figure 26). The fractured end was then sectioned from the remaining segment approximately 12 inches upstream of the flange shoulder with a handheld reciprocating saw (Figure 27).

UT measurements were also conducted on the SER 34 segment, ranging from 0.522 to 0.570 inches along the elbow intrados (inner curve), and 0.372 to 0.448 inches along the elbow extrados (outer curve), with the wall thickness measurements generally decreasing with distance downstream. Wall thickness measurements near the fracture surface were taken around the circumference of the pipe, and ranged from 0.032 to 0.112 inches. At the upstream field-cut end of SER 34, thickness measurements were between 0.526 and 0.585 inches. The fractured end was then sectioned from the remaining segment approximately six inches upstream of the fracture with a band saw (Figure 28).

Samples for quantitative chemical analysis were sectioned from the upstream field-cut end of the SER 34 segment, the lab-cut end of the SER 35 segment, the SER 35 segment flange, and the downstream eight-inch-diameter field-cut end of the SER 35 segment. All four samples were removed using a handheld reciprocating saw (Figure 29).

Examination of the SER 34 fracture area revealed that the fracture occurred just downstream of the circumferential weld between the elbow and the straight segment. Cross-sectional specimens containing the weld and the fracture surface were then cut for metallographic and quantitative chemical analysis (Figure 30). The chemical analysis samples were sectioned from the 6 o'clock location and labeled "6-1" (the upstream elbow segment), "6-2" (the circumferential weld), and “6-3” (the downstream straight segment containing the fracture surface).

Quantitative chemical analysis of the seven specimens was conducted. The Form U-1 Manufacturers’ Data Report from the original construction of the pressure vessel in 1966 had specified the ASTM alloys for the pressure vessel shell and heads, and for nozzles.[1] The results are given in Table 3 and Table 4, with the applicable 1966 ASTM alloy specifications in Table 5. The compositions of the specimens from the 10-inch straight segment (“SER 35” and “6-3”) were consistent with the specifications current in 1966 for ASTM A213, Grade T12 alloy steel. The compositions of the specimens from the elbow segment (“SER 34” and “6-1”) were consistent with Grade T11. The 8-inch specimen was consistent with 304 stainless steel.

**Table 3. Summary of quantitative chemical analysis results from the pipe segment specimens.**

| Element | SER 34 Composition, wt.% | SER 35 Composition, wt.% | Flange Composition, wt.% | 8-inch Pipe Composition, wt.% |
|---|---|---|---|---|
| Fe | balance | Balance | balance | balance |
| C | 0.09 | 0.15 | 0.17 | 0.05 |
| Si | 0.66 | 0.23 | 0.68 | 0.46 |
| Cr | 1.19 | 0.91 | 1.10 | 18.16 |
| Mo | 0.60 | 0.54 | 0.50 | 0.38 |
| Mn | 0.50 | 0.34 | 0.59 | 1.72 |
| S | 0.006 | 0.017 | 0.016 | 0.018 |
| P | 0.009 | 0.007 | 0.022 | 0.030 |
| Cu | 0.03 | 0.06 | 0.17 | 0.30 |
| Ni | 0.08 | 0.11 | 0.19 | 8.17 |
| Al | 0.02 | <0.01 | 0.08 | <0.01 |
| Nb | <0.01 | <0.01 | 0.01 | 0.02 |
| Ti | <0.01 | <0.01 | <0.01 | <0.01 |
| V | 0.01 | 0.01 | 0.02 | 0.06 |
| Co | <0.01 | 0.01 | 0.03 | 0.16 |
| Sn | 0.02 | 0.02 | 0.02 | <0.01 |
| W | <0.01 | <0.01 | 0.04 | 0.03 |

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[1] “Form U-1A, Manufacturers’ Data Report for Unfired Pressure Vessels”, completed by Sun Shipbuilding and Dry Dock Company, Chester, PA, dated September 1966. Doc. no. MDDW CSB 1DOC1 0065.

**Table 4. Summary of quantitative chemical analysis results from the SER 34 fracture cross-section specimens.**

| Element | 6-1 (Elbow) Composition, wt.% | 6-2 (Weld) Composition, wt.% | 6-3 (Straight Segment) Composition, wt.% |
|---|---|---|---|
| Fe | balance | Balance | balance |
| C | 0.10 | 0.07 | 0.15 |
| Si | 0.67 | 0.48 | 0.23 |
| Cr | 1.19 | 1.25 | 0.91 |
| Mo | 0.62 | 0.62 | 0.56 |
| Mn | 0.50 | 0.54 | 0.33 |
| S | 0.006 | 0.023 | 0.022 |
| P | 0.009 | 0.017 | 0.007 |
| Cu | 0.03 | 0.06 | 0.06 |
| Ni | 0.08 | 0.08 | 0.11 |
| Al | 0.04 | <0.01 | <0.01 |
| Nb | <0.01 | 0.01 | <0.01 |
| Ti | <0.01 | 0.02 | <0.01 |
| V | 0.01 | 0.05 | 0.01 |
| Co | <0.01 | 0.01 | 0.01 |
| Sn | 0.02 | 0.02 | 0.02 |
| W | <0.01 | <0.01 | <0.01 |

**Table 5. Alloy composition specifications from the American Society for Testing and Materials in 1966, when the pressure vessel and piping were reportedly manufactured.**

| Element | ASTM A213-66 specification (Grade T11), wt.%[2] | ASTM A213-66 specification (Grade T12), wt.%[2] | ASTM A182-65 specification (Grade F11), wt.%[3] |
|---|---|---|---|
| Fe | balance | balance | balance |
| C | 0.15 max | 0.15 max | 0.10-0.20 |
| Si | 0.50-1.00 | 0.50 max | 0.50-1.00 |
| Cr | 1.00-1.50 | 0.80-1.25 | 1.00-1.50 |
| Mo | 0.44-0.65 | 0.44-0.65 | 0.44-0.65 |
| Mn | 0.30-0.60 | 0.30-0.61 | 0.30-0.80 |
| S | 0.030 max | 0.045 max | 0.040 max |
| P | 0.030 max | 0.045 max | 0.040 max |

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[2] ASTM A213-66, “Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat Exchanger Tubes”, American Society for Testing and Materials, 1966.

[3] ASTM A182-65, “Standard Specifications for Forged or Rolled Alloy-Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service”, American Society for Testing and Materials, 1965.

Examination of the metallographic longitudinal cross-sections that included the weld and the fracture surface clearly indicated that wall thinning had occurred through the weld metal and the base metal of the 10-inch straight segment from the inside diameter (ID), as shown in Figure 31 and Figure 32. The rupture was in the straight segment base metal.

Thickness measurements were made near the edges of the fracture surfaces on the SER 27 and SER 28 pieces. On SER 27, measurements ranged between 0.065 and 0.171 inches (Figure 33). On SER 28, measurements ranged between 0.039 and 0.170 inches (Figure 34). Subsequently, SER 27 and SER 28 were aligned with the fracture surface from SER 34, with fracture surface features confirming their original in-service locations as part of the 10-inch straight segment (Figure 35).

# Discussion and Conclusions

According to information provided to Exponent during the course of our investigation, the incident piping was installed and put into service in the MDDW at the Silver Eagle Refinery with the South Reactor (RTR30101) in 1993.[4] The reactor pressure vessel was originally constructed in 1966. The unit typically operated in the temperature range of 500°F to 800°F, and was rated to 1000 psi at 800°F at the time of the incident.[5] The nominal system pressure was reported to be 625 psi at 735°F. It has not been determined if the 10-inch elbow and straight segment were new at the time of the 1993 installation in the MDDW, or if they had been used in prior service with the reactor pressure vessel during its previous application as a lube stock hydrotreater. Regardless, to date no documentation has been produced indicating that the wall thickness of the straight segment was ever measured from build date to the time of the incident.

In 1993, UT readings on the 10-inch elbow ranged from 0.671 to 0.805 inches. The October 2007 Inspection Sheet stated an “original thickness” noted by the inspector as “0.719" AS PER DWG”.[4] To date, no documentation or design drawings have been produced to show or verify where the inspector determined this original thickness value. In October 2007, the UT thickness measurement for this elbow at Wall Thickness Measurement Location 43 was 0.483 inches, indicating wall thickness loss had occurred in the prior 14 years of service.

A “Diesel Hydrotreater Startup Report” issued by Albemarle Catalysts following a turnaround in April 2006 indicated that sulfiding was conducted to activate the catalyst.[6] The report mentioned that the “straight run diesel from the crude unit had a sulfur content of 1.0 wt%.” It also stated that hydrogen sulfide ($H_2S$) concentration in the recycle gas “exceeded 0.5 vol%” during the sulfiding.

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[4] Silver Eagle MDDW Pressure Vessel Inspection Sheet, October 15, 2007, Doc. No. MDDW UOSH20 0025.

[5] Silver Eagle PV-SER-1 Pressure Vessel External Inspection Report, October 18, 2007, Doc. No. MDDW UOSH20 0021.

[6] Albemarle Catalysts Diesel Hydrotreater Startup Report, April 18, 2006, Doc. No. MDDW UOSH20 0035-0042.

Sulfidation corrosion is a known issue in oil refinery process streams operating between 450°F and 1000°F where sulfur or $H_2S$ is present.[7] Low-alloy carbon steel with low levels of silicon, chromium, and molybdenum are particularly vulnerable. Reaction of the pipe metal surface with sulfur compounds in the process stream results in the formation of a sulfide scale. On susceptible components, this scale may be non-adherent and, particularly under turbulent flow conditions, leads to significant wall thinning.

Naphthenic acid corrosion can also lead to damage in petrochemical process piping. The term “naphthenic acid” refers to all of the organic acids present in crude oil. There can be competition between the sulfidation corrosion and naphthenic acid corrosion reactions, and in some cases sulfidation corrosion can be accelerated by the presence of naphthenic acids.[8] The naphthenic acid corrosion product is soluble in oil, which results in wall thinning without residual corrosion products or films remaining on the affected material. High velocities and turbulent flow can accelerate naphthenic acid corrosion, but the corrosion rates diminish above 700°F, and naphthenic acid corrosion will not occur when the organic acids have been transformed into the vapor phase.[9] Naphthenic acid corrosion is typically characterized as having more localized attack than sulfidation corrosion, particularly at areas of high flow velocity.[10] Service experience has reportedly shown that 304 stainless steel suffers localized corrosion in naphthenic acid service above 425°F, with the molybdenum-containing alloys such as 316 providing better corrosion resistance.[8]

While additional analysis, such as characterization of the surface scale still present on the incident piping components, may further confirm the presence of sulfide scale, the evidence is currently consistent with sulfidation corrosion as the primary cause of the wall thinning in the 10-inch piping that resulted in the rupture. Turbulent flow at the elbow likely caused the most

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[7] API Recommended Practice 939-C, “Guidelines for Avoiding Sulfidation (Sulfidic) Corrosion Failures in Oil Refineries”, First Edition, American Petroleum Institute, May 2009.

[8] H.J. de Bruyn, “Naphthenic Acid Corrosion in Synthetic Fuels Production”, Proceedings of Corrosion 98, NACE International, 1998, Paper No. 576.

[9] G.M. Bota et al., “Naphthenic Acid Corrosion of Mild Steel in the Presence of Sulfide Scales Formed in Crude Oil Fractions at High Temperature”, Proceedings of Corrosion 2010 Conference & Expo, NACE International, 2010, Paper No. 10353.

[10] R.D. Kane and M.S. Cayard, “A Comprehensive Study on Naphthenic Acid Corrosion”, Proceedings of Corrosion 2002, NACE International, 2002, Paper No. 02555.

significant wall thinning at the rupture location just downstream of the elbow. The low silicon, chromium, and molybdenum contents of the straight segment, and the service temperatures and process stream chemistry, are all consistent with sulfidation corrosion. It appears that corrosion monitoring of the straight segment was not conducted between 1993 and the time of the rupture. The remainder of the line downstream, composed of 8-inch-diameter 300-Series stainless steel, is less susceptible to sulfidation corrosion. In addition, because service temperatures were reportedly above 700°F, naphthenic acid corrosion is less likely to have been the primary cause of the wall thinning on the ruptured segment.

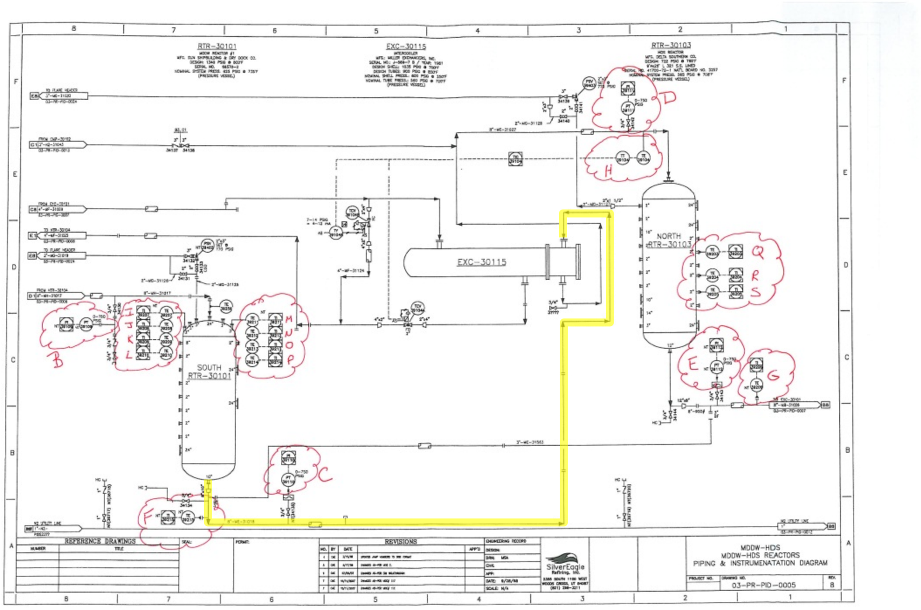


Figure 1. Process and instrumentation diagram (P&ID) of the MDDW reactors.

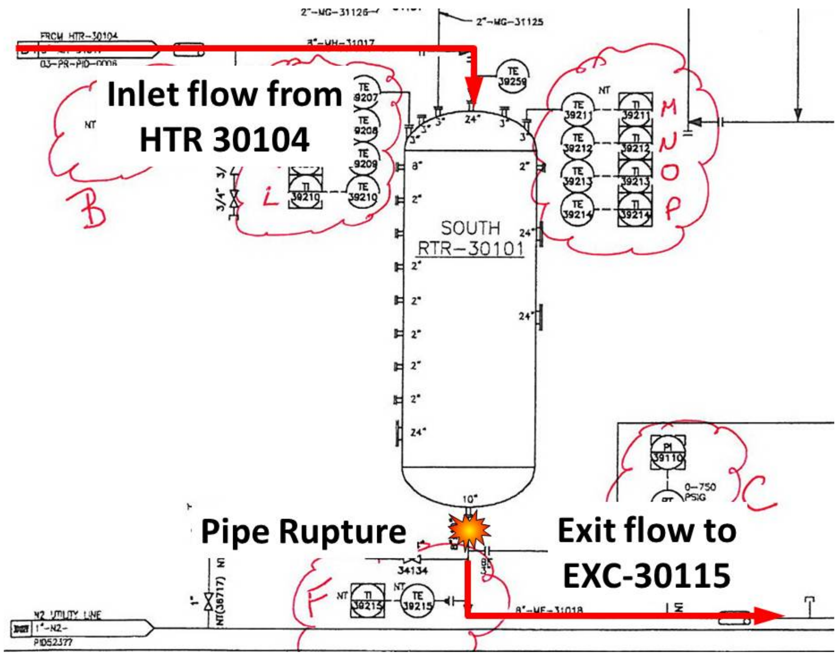


Figure 2. Annotated P&ID of the rupture site.

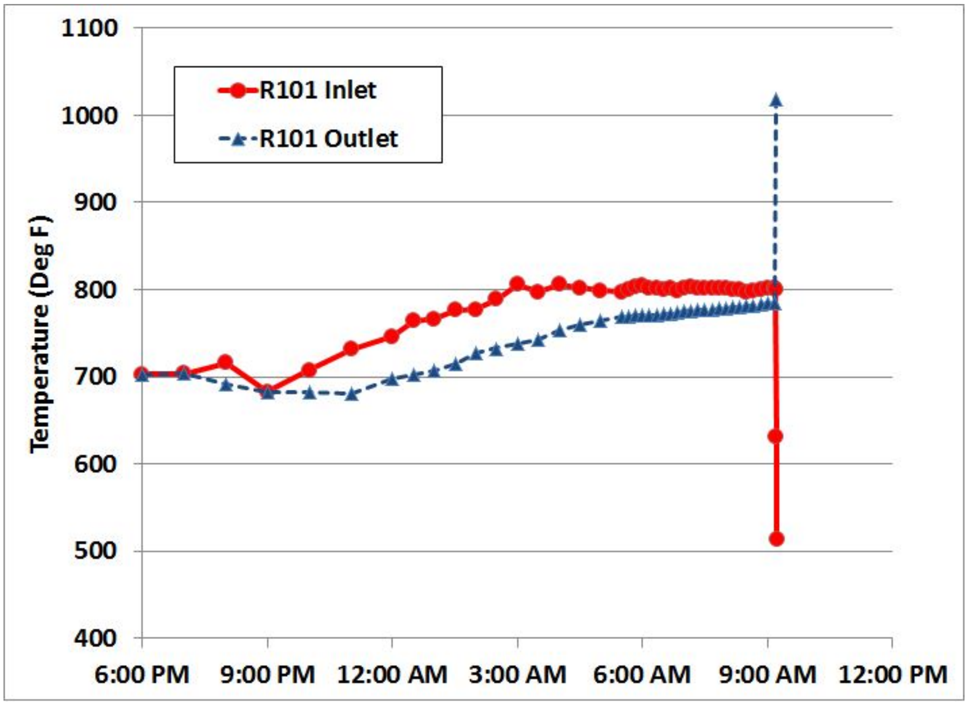


Figure 3. R30101 inlet and exit temperatures.

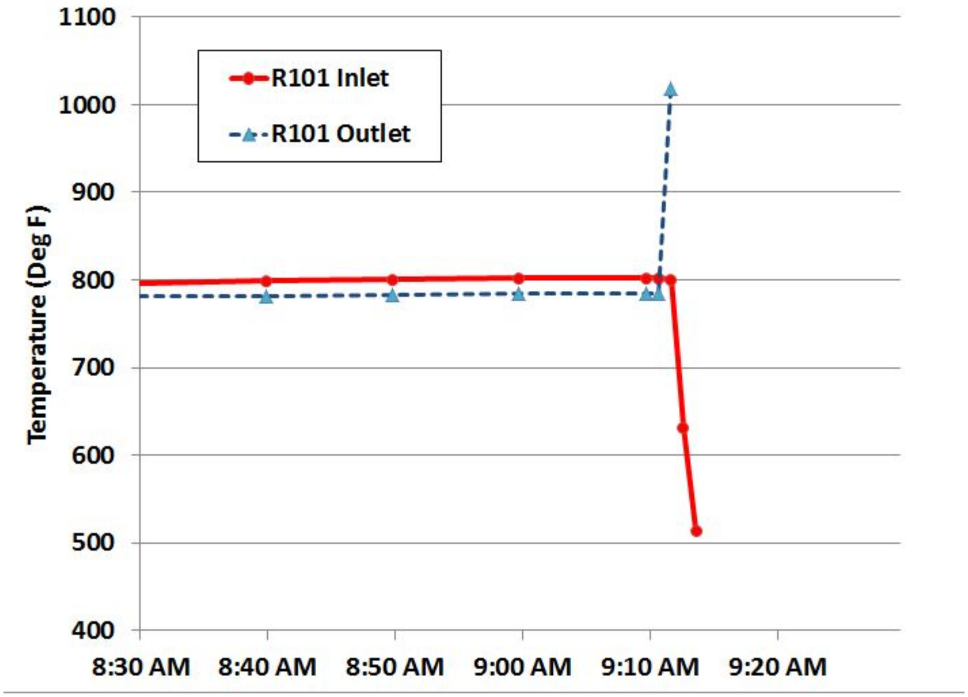
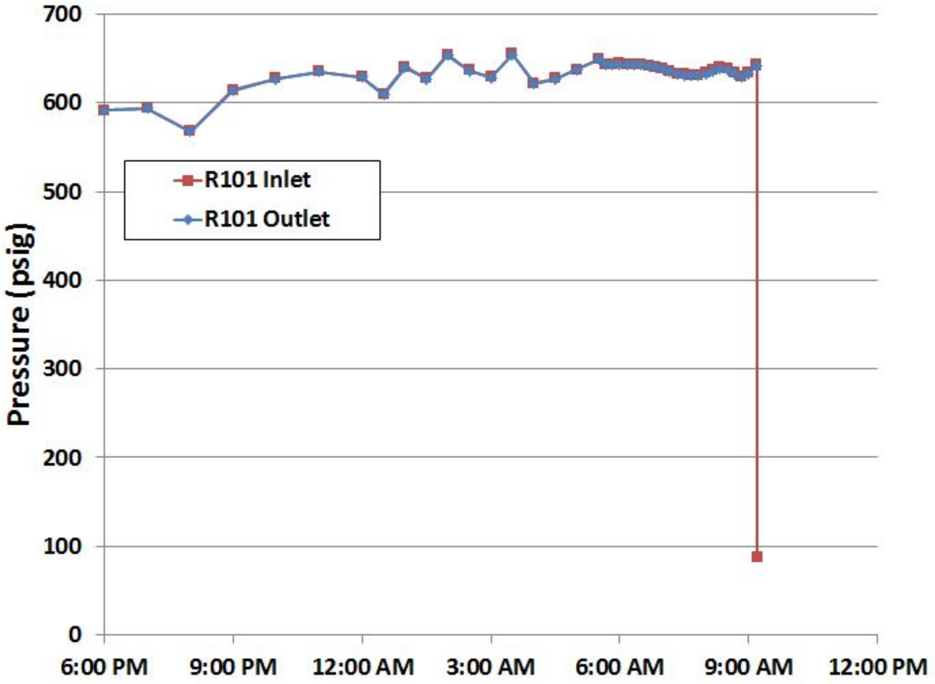


Figure 4. R30101 inlet and exit temperatures (detail).



graphics

Figure 5. R30101 pressure during catalyst regeneration.

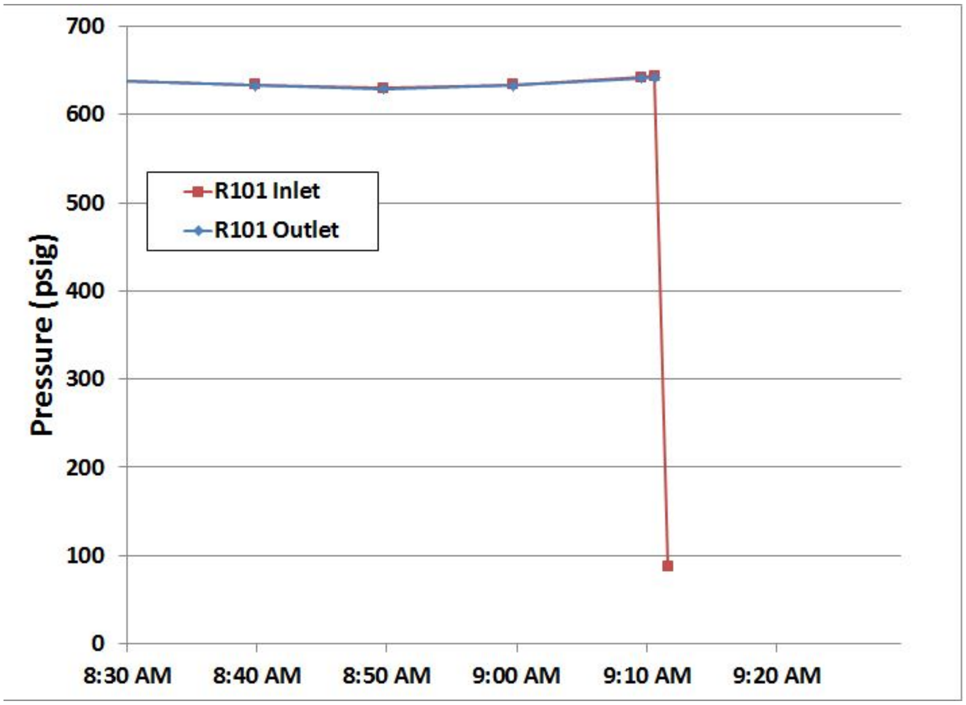


Figure 6. R30101 pressure at time of failure.

Figure 7. Security video before rupture.

Figure 8. Initial gas release on security video.

Figure 9. Security video showing gas release rapidly expanding.

Figure 10. Ignition of released gas.

Figure 11. R30101 discharge pipe bent around reactor support beam.

Figure 12. Ruptured end of pipe wrapped around support beam.

Figure 13. Ruptured end of pipe still attached to R30101.

Figure 14. Explosion damage to light structural elements, hydro pad.

Figure 15. View from hydro pad towards adjacent residential community.

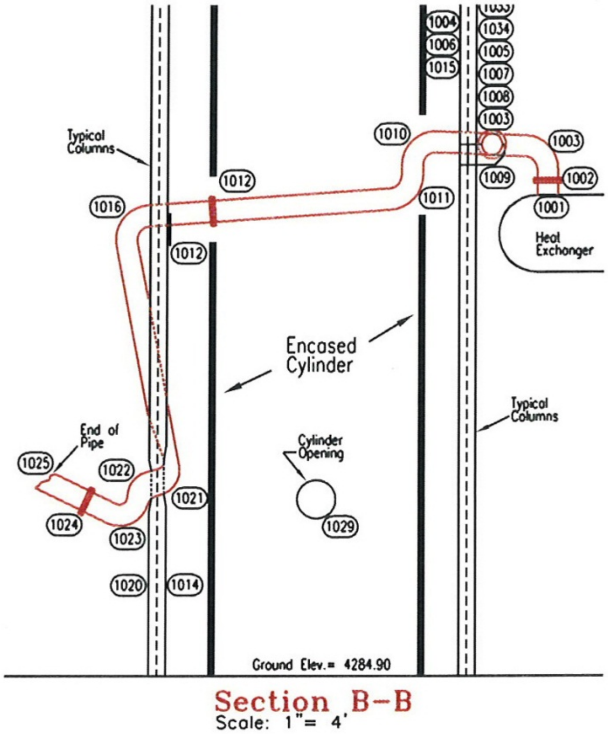


Figure 16. Elevation view of surveyed pipe.

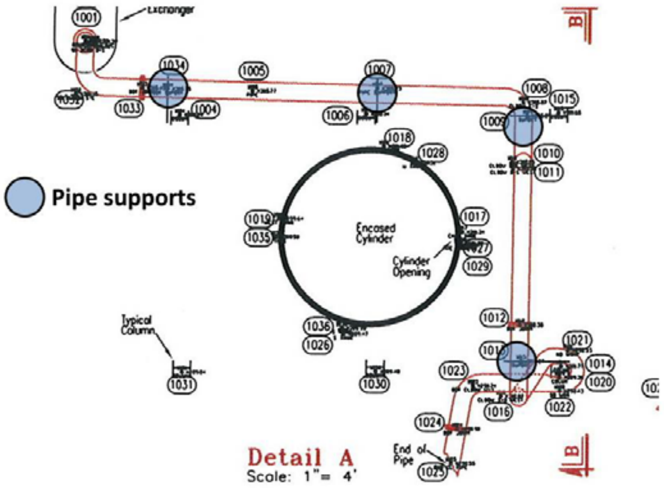


Figure 17. Plan view of surveyed pipe.

Figure 18. Pipe support location.

Figure 19. Images of the upstream end of the fractured pipe prior to its removal in March 2010.

Figure 20. Images of the "SER 34" ruptured segment after sectioning and removal in March 2010.

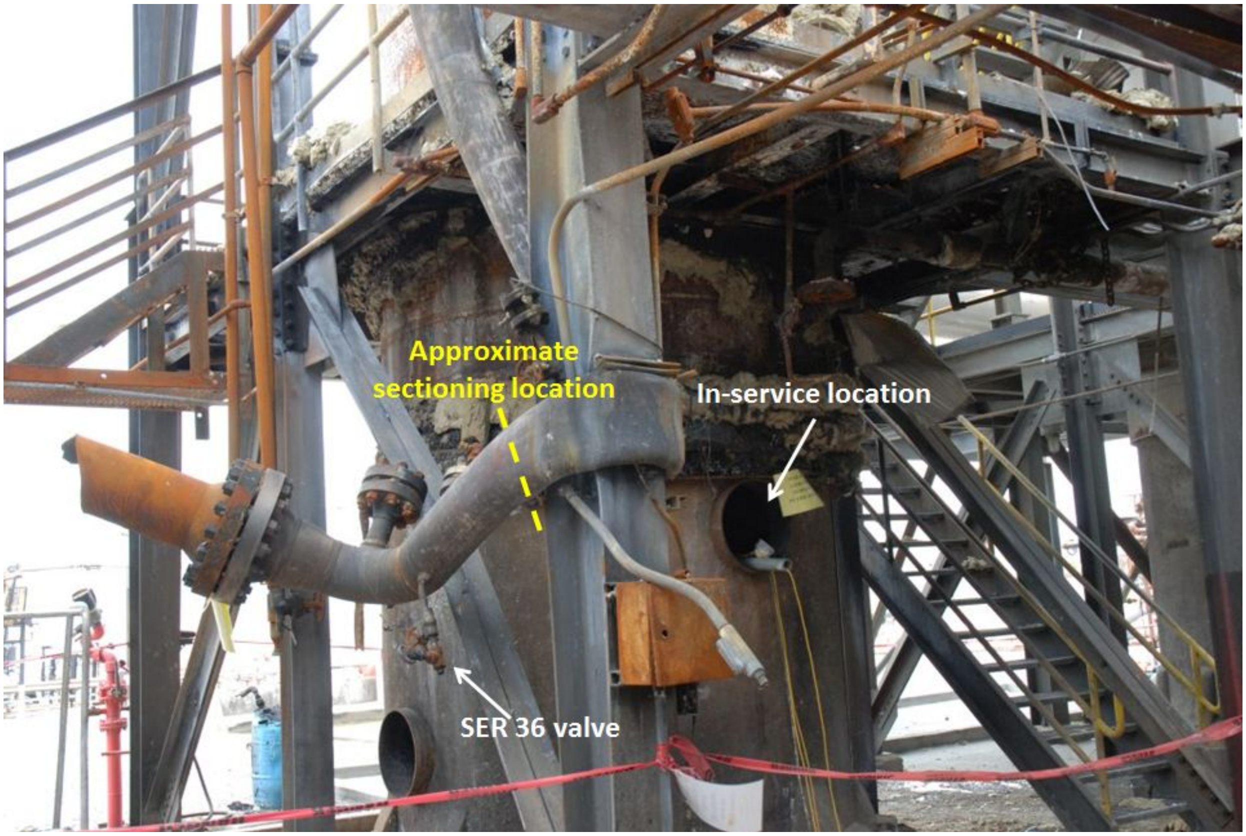


Figure 21. Image of the downstream fractured section "SER 35" prior to sectioning for removal from the site in March 2010.

Figure 22. Image of SER employees draining fluid from the "SER 36" valve in March 2010.

Figure 23. Images of the "SER 27" item as-observed outside of the reactor skirt in March 2010.

Figure 24. Image of the "SER 27" item, found outside the reactor skirt, as labeled in March 2010.

Figure 25. Image of the "SER 28" item as-observed inside the reactor skirt in March 2010.

Figure 26. Images showing UT measurements taken on the SER 35 segment in August 2010.

Figure 27. The fractured end of SER 35 during sectioning in August 2010.

Figure 28. The fractured end of SER 34, before and after sectioning in August 2010.

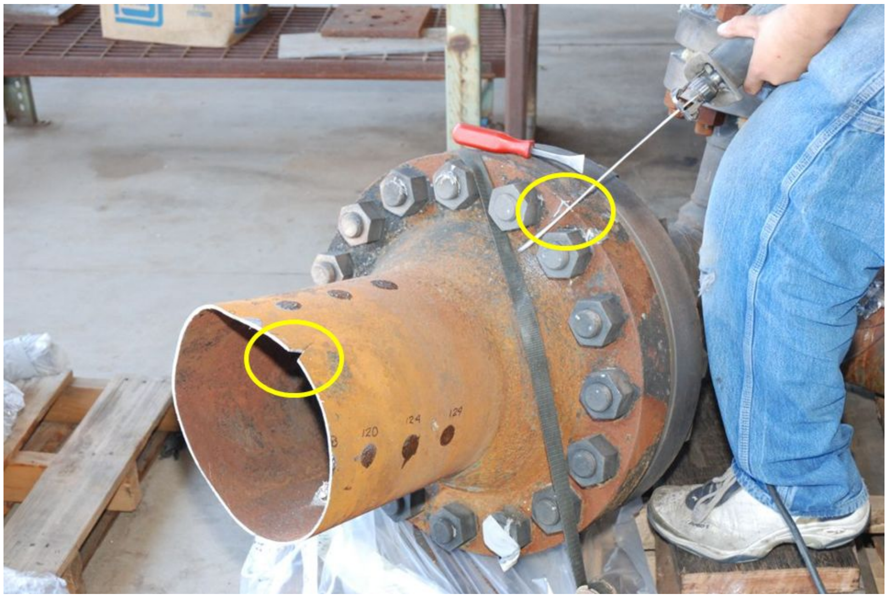


Figure 29. Image showing quantitative chemical analysis samples being sectioned from the 10-inch pipe and flange on SER 35 (circled) in August 2010.

Figure 30. Images showing sectioning of the SER 34 fracture surface for metallographic and quantitative chemical analyses in August 2010.

Figure 31. Image of the metallographic longitudinal cross-section specimen from the 6-o'clock location on SER 34, showing wall thickness loss at the ID surface through the weld metal and base metal of the straight segment.

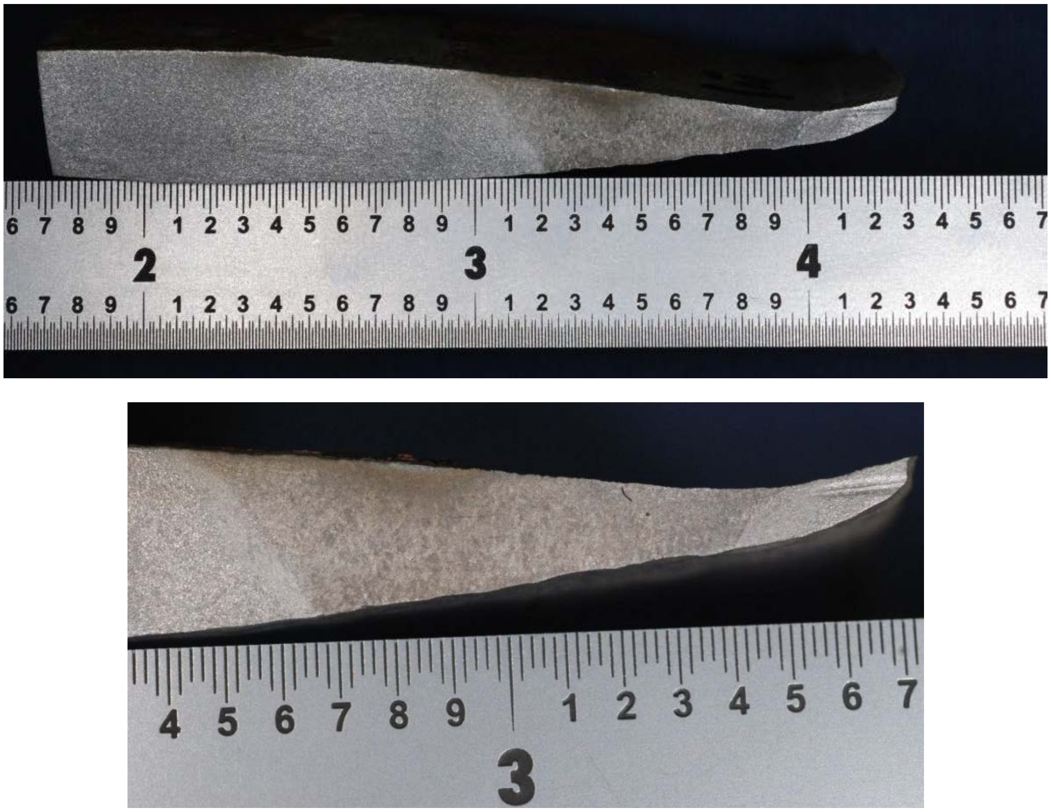


Figure 32. Images of the metallographic longitudinal cross-section specimen from the 12-o'clock location on SER 34, showing wall thickness loss at the ID surface through the weld metal and base metal of the straight segment.

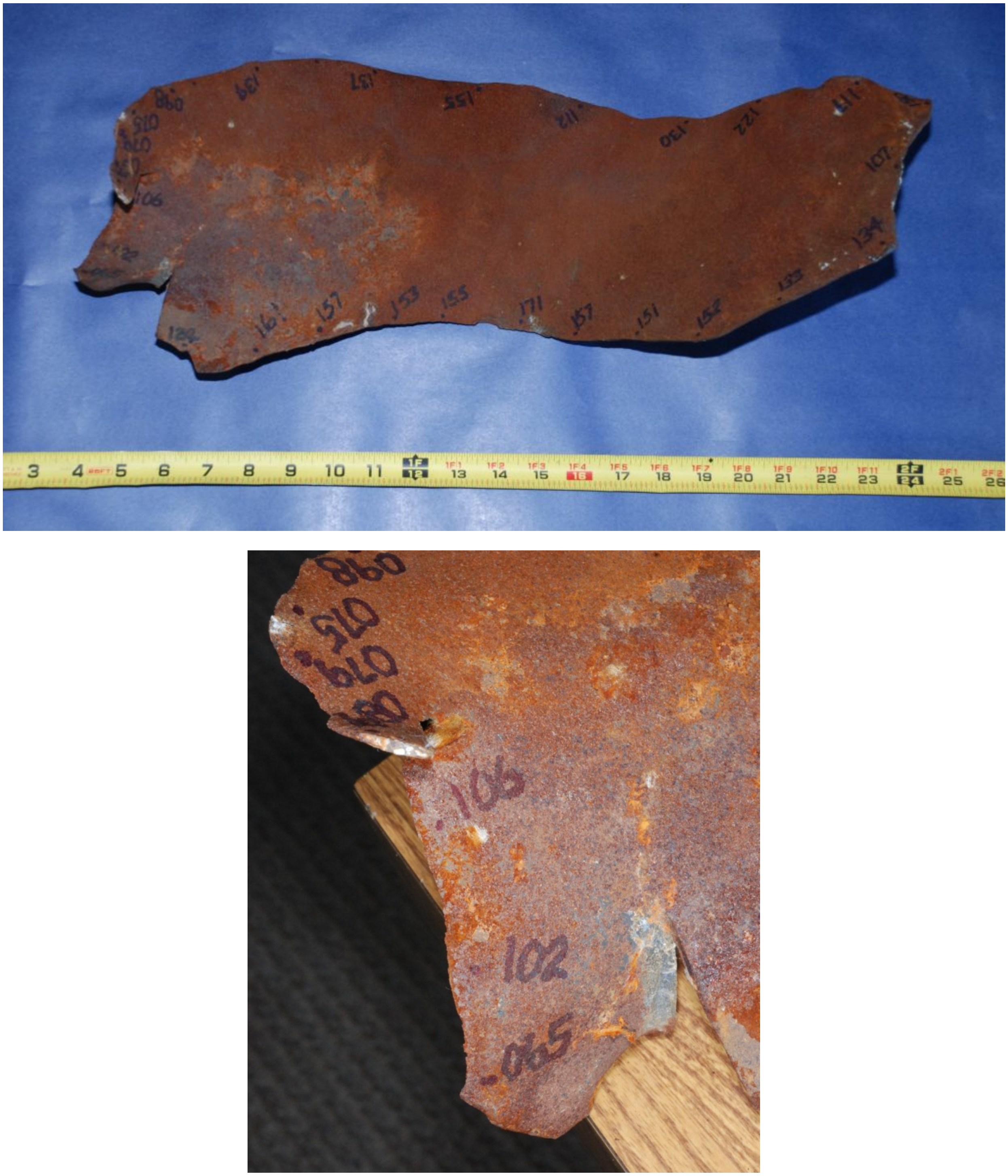


Figure 33. Images of SER 27 showing the results of wall thickness measurements.

Figure 34. Images of SER 28 showing the results of wall thickness measurements.

Figure 35. Images showing the in-service locations of SER 34, SER 28, and SER 27 based on alignment of fracture surface features.