NBSIR 74-625

Examination of Failed Two Inch Steel Pipe Natural Gas Main, Columbia Gas Company, Spring Garden Township, York County, Pennsylvania

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Metallurgy Division
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Washington, D. C. 20234

January 1975

Failure Analysis Report

Prepared for

Office of Pipeline Safety
Department of Transportation
Washington, D. C. 20590

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Department of Transportation
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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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SUMMARY

The Mechanical Properties Section of the National Bureau of Standards examined a length of a cracked two inch diameter plain carbon, welded steel natural gas main pipe at the request of the Office of Pipeline Safety. The pipe had a transverse crack extending about 85% of the circumference. The pipeline had suffered considerable mechanical damage in the vicinity of the failure, and the crack, which propagated in an essentially brittle manner, appeared to have initiated in a gouged area near the bottom of the pipe. There was a considerable amount of corrosion product on the surface of the pipe in the gouged area. The amount and distribution of corrosion product on the fracture surface indicated that the crack had formed in at least two stages, and that a crack was present prior to the time of failure. During the first stage, the crack may have penetrated the entire wall thickness of the pipe in one region opposite the crack origin near the bottom of the pipe. The likely mechanism of fracture for the first stage of the crack appears to be stress corrosion cracking. For the second stage of the crack, either stress corrosion cracking or impact appears to be the likely mechanism of failure.

The pipeline was installed in 1949. In 1971, a sanitary sewer system was installed in the same street with the sewer laterals passing under the gas main. Failure in the gas main occurred at the location of one of these laterals about three years after the installation of the sewer system.

There was a considerable amount of pitting on the pipe surface, some of the pits penetrating more than half the wall thickness of the pipe. Analysis of soil samples taken from three sites along the pipeline indicated that the soils were of low corrosivity. Pit depths of the magnitude found are consistent with the expected corrosive attack for exposure of plain carbon steel in soils of low corrosivity.

A length of the gas main pipe, still in service and located about 51 feet from the site of the failure, showed no evidence of significant mechanical damage. This length contained fewer pits than the submitted length, and the pits were less severe.

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1. INTRODUCTION

1.1 Reference

Office of Pipeline Safety, Department of Transportation, Washington, D. C. 20590. This investigation was conducted at the request of Mr. Lance F. Heverly of the Office of Pipeline Safety (OPS) under order number DOT-AS-10041. The request was made on January 16, 1974.

1.2 Background Information

The information in this section was furnished by Mr. Lance F. Heverly of OPS and Mr. William E. Smeigh, Jr., of the Pennsylvania Public Utility Commission.

On January 8, 1974, there was an explosion which essentially destroyed a house located at 1324 South Ogontz Street in Spring Garden Township in York County, Pennsylvania. The house was on the southwest side of the street. The explosion was attributed to an accumulation of natural gas which had leaked from a crack in a two inch steel gas main pipe under South Ogontz Street in front of the house in which the accident occurred.

The gas main had been installed in 1949 and was reported to have been about 42 inches below the paved street at the location of the failure. At the time of failure, gas pressure was estimated to be about 35 psig and the soil temperature was estimated to be 45°F. The pipeline was constructed of schedule 40, two inch diameter welded steel pipe. Cathodic protection was provided for the pipeline. The installation dates and the locations of the three closest anodes are given below:

Location	Installation Date
135 feet south of fracture	8/13/71
195 feet south of fracture	5/8/73
216 feet north of fracture	11/30/71

A sanitary sewer system had been installed in South Ogontz Street in 1971 with the lateral service lines to houses on the southwest side of the street passing under the gas main. At the time of the explosion, the residence at 1324 South Ogontz

Street was connected to a septic system in front of the house (between the house and the street). The sewer lateral, which passed about 1 1/2 feet under the gas main, had never been connected to the residence and was capped at the approximate location of the property line.

The crack in the gas main pipe occurred at the approximate location where the sewer lateral passed under the pipe.

1.3 Parts Submitted

A length of the two inch gas main pipe about six feet long was delivered to T. R. Shives of the NBS Mechanical Properties Section on January 15, 1974 by Trooper Thomas R. Minnich, Fire Marshall, Pennsylvania State Police. The length of pipe is shown as received in figure 1. Before delivery to NBS the region containing the crack had been covered with a rubber gasket and a metal clamp which can be seen in the photograph (figure 1).

2. PURPOSE

The Office of Pipeline Safety requested that the NBS Mechanical Properties Section determine the mechanism of fracture and, inasfar as possible, the cause of failure.

3. PLAN OF EXAMINATION

3.1 General Plan

At a series of three meetings at the National Bureau of Standards among representatives of the Office of Pipeline Safety, the Pennsylvania Public Utility Commission, the Columbia Gas Company, and the Mechanical Properties and Corrosion and Electrodeposition Sections of NBS, the general plan of the examination was discussed. These meetings were held on January 16, May 7, and June 7, 1974. It was agreed that any cleaning or cutting of the fracture surface would be confined to the south side of the fracture. As set forth at the first meeting, the analysis of the failure was to include documentation of the deformation and other mechanical damage to the surface of the pipe, fractographic examination of the south fracture surface, metallographic examination, and other tests or analyses that were deemed advisable as the examination progressed. At the second meeting a program to determine the corrosivity of the soil in the vicinity of the pipe failure was presented by Mr. Edward Escalante of the NBS Corrosion and Electrodeposition Section. This program was agreed to at the third meeting.

It was also decided that when the soil samples were being taken, a small length of the pipeline away from the failure would be exposed for visual examination. Because of the brittle and fresh appearance of the second stage of the fracture, a series of impact tests were run on some of the pipeline material in order to characterize its fracture behavior at high strain rates.

Most of the tests, examinations, and analyses employed in this investigation are routine methods which do not require further explanation here. Exceptions to this generalization are the soil corrosivity characterization program and the impact tests.

3.2 Soil Corrosivity Characterization

3.2.1 Background

The soil corrosivity characterization program was devised by and, with the exception of the chemical analyses, was carried out by Mr. Edward Escalante of the NBS Corrosion and Electrodeposition Section. The following is taken from his report of the results of the soil characterization:

> The corrosivity of a soil might be defined as the ease with which a soil can destroy a given metal. The degree of corrosivity is largely determined by a number of measurable parameters which are inherent in the makeup of the soil. Experience has shown that these parameters are soil resistivity, redox potential, and pH(1). Further insight about the corrosivity of a soil can be gained from a chemical analysis of the soil and from measurement of the corrosion potential of the metal in the ground(2).

3.2.2 Procedure

Three sites along the gas main pipeline under South Ogontz Street were selected for the soil corrosivity characterization measurements. They are as follows:

Site 1: In undisturbed soil adjacent to and just east of the location of the failure.

Site 2: Directly over the gas main 51 feet north of site 1.

Site 3: Adjacent to and just east of the gas main pipe 27 feet north of site 2.

The failure (adjacent to site 1) had occurred where a capped sanitary sewer lateral at 1324 South Ogontz Street passed under the gas main pipe. Site 2 was selected to be at the location of another capped sewer lateral at 1320 South Ogontz Street where again the lateral passed under the gas pipe. The residences at 1320 and 1324 South Ogontz Street were both utilizing septic systems.

Site 3 was essentially half-way between the sewer laterals to 1320 and 1316 South Ogontz Street. All three sites were selected to be away from all anodes that had been installed to provide cathodic protection for the pipeline, except for two anodes that were installed near the site of the failure when the length of failed pipe was replaced. These latter two anodes had been installed for such a short time before our examination that they would not be expected to have any effects on results of the examination except for the pipeline potential.

At each site, a six inch square hole was cut through the blacktop by Columbia Gas Company personnel. A small hole was bored with a two inch diameter soil auger to a depth that eventually reached about 38 inches at sites 1 and 3. At site 2, the initial hole was enlarged to three feet by four feet and was dug to a depth sufficient to expose about a two foot length of the pipeline for examination. At this location, the top of the gas pipe was about 34 1/2 inches below the top of the blacktop. At all three sites the soil contained a considerable amount of shale. At site 2, there was a special fill material to a depth of about one foot below the pavement. This material is not thought to have a significant effect on the corrosivity of the soil at the level of the pipe.

The following is paraphrased from Mr. Escalante's report:

> Redox potential and pH measurements were made at the site at the approximate depth of the pipeline. Resistivity measurements were made on soil samples removed from the excavations adjacent to the pipeline using a standard soil cup and an AC wheatstone bridge circuit. The potential of the pipeline was measured versus a Cu-$CuSO_4$ electrode. All potential measurements were made using a high impedance (10^{14} ohm) voltmeter. Samples for chemical analysis in the laboratory were transported in 500 cm^3 glass jars with plastic lids. The soil samples were analyzed for water soluble carbonates, nitrates, sulfates, and sulfides. A total acid determination was also made on two samples.

3.3 Impact Tests

The pipe material is a plain, low carbon, relatively low strength steel which would be expected to exhibit good ductility. Indeed, a longitudinal piece cut from the pipe about 24 inches south of the fracture could be bent double at room temperature with only slight cracking, as shown in figure 2, indicating that the material did possess good ductility, at least at relatively low strain rates.

In order to determine the fracture behavior of this pipe steel at the relatively high strain rates characteristic of a Charpy impact test, several longitudinal specimens were cut from a length of the submitted pipe material between 7 and 10 inches south of the fracture. Geometric restrictions imposed by the shape of the pipe and the wall thickness of the pipe resulted in specimens much smaller than the standard ASTM Charpy specimen. The impact specimen dimensions were 3 inches long, slightly less than 1/4 inch wide, and about 1/10 inch thick (the thickness direction being a radius eminating from the longitudinal axis of the pipe). The scale was removed from both the inside and outside wall surfaces by surface grinding. The specimens were "notched" transversly in the center on the side corresponding to the outside wall surface of the pipe with a jeweler's saw. The saw-cut notch was approximately 0.02 inch deep. Then the specimens were cyclically stressed in reversed bending to initiate a fatigue crack at the base of the saw-cut notch. Specimens so "notched" were then broken in a Charpy impact machine.

4. RESULTS OF EXAMINATIONS, TESTS, AND ANALYSES

4.1 Visual and Macroscopic Examination

4.1.1 Submitted length of pipe

The submitted length of pipe was bowed down and to the west as it lay in the soil. The center of the bow was just south of the fracture. The bow can be seen in figures 1, 3a, and 3b which show the top, east side, and bottom of the pipe, respectively. Before being submitted to NBS, the pipe length had been marked with the letters "S" (south) and "N" (north) on the top to indicate orientation. The "S" can be seen at the left end of the pipe length in figure 1.

When the clamp was removed from the pipe, a transverse crack was exposed in the approximate center of the submitted length. The crack had traversed about 85% of the circumference of the pipe, extending clockwise from about the one o'clock position to the eleven o'clock position, assuming the letters "S" and "N" marked on the pipe when it was received to be in the twelve o'clock position. The two ends of the crack can be seen in figure 4a which shows the top of the pipe after the clamp had been removed.

Looking from the south toward the north, the right side, bottom, and left side of the pipe in the area of the crack are shown in figures 4b, 4c, and 4d, respectively. As can be seen in figure 4c (arrow A), the pipe had been dented near the bottom in the vicinity of the crack. Other mechanical damage was evident, especially on the bottom of the pipe and again in the vicinity of the crack. Some of this damage can be seen in figures 4c and 4d. This damage appears to have been caused by something scraping or gouging the pipe in the transverse direction. The crack passed through one of these gouged areas. There was a heavy deposit of corrosion product on the pipe surface where the damage had occurred. Mechanical damage was found on other areas of the pipe length, but it did not appear to be as severe as that near the crack.

There was a considerable amount of pitting on the outside surface of the entire length of pipe submitted for examination. Examples of pitting in the vicinity of the crack are quite evident in figures 4a and 4b. Cross sections two and five inches south of the crack and a longitudinal section taken between 22 and 24 inches south of the crack are shown in figures 5a, 5b, and 5c, respectively. Each of these sections was cut through what appeared to be one of the deeper pits. As can be seen in figure 5, some of the pits had penetrated more than half the wall thickness of the pipe, or approximately 0.08 inch. Some macroscopic deformation is evident in figure 5c, indicating probable mechanical damage in this area.

The inside wall surface of the pipe length was covered with a light scale, but this scale was considered to have an insignificant effect on the integrity of the pipe.

4.1.2 Pipeline in the Field

At site 2 (described in Section 3.3.2), about a two foot length of the pipeline was excavated and cleaned of loosely adhering soil with a small, stiff bristle bursh. Part of the exposed pipe is shown after cleaning in figure 6. The pipe length was examined in place visually and with a hand magnifier on the top, both sides, and (with the aid of mirrors) on the bottom for general condition. The pipe was covered with a black, sooty substance that could be easily rubbed off on the hands.

There was no mechanical damage evident such as that detected in the submitted pipe length. There were some pits, particularly near the south end of the excavated length, but these pits did not appear to be nearly as severe as those on the pipe length that was submitted for examination.

4.2 Fractographic Examination

4.2.1 Visual and Macroscopic

Taking precautions to prevent further propagation of the crack during handling, the pipe length was cut transversly about two inches on either side of the crack. The remaining four inch length of pipe containing the crack was then cut longitudinally on a three o'clock-nine o'clock diameter from the south saw-cut face in to the crack. This dissection exposed the crack over about 180° of the pipe circumference. The wall thickness of the pipe at the crack at the bottom of the pipe in the gouged area had been reduced by more than 70% at one point, apparently by a combination of mechanical damage and corrosion. This can be seen in figure 7 where part of the south side of the fracture surface is shown. The crack apparently initiated at this gouged area.

Both the north and south opposing fracture surfaces were covered with corrosion product in an essentially similar pattern. There appeared to be a distinct change part way across the fracture surface (as viewed radially) in the degree of corrosive attack. Corrosion product was heavier on the outside circumferential part of the fracture surface than on the inside circumferential part. This indicates that the part of the fracture intersecting the outside wall surface of the pipe had probably formed at an earlier time than the more recent appearing part adjacent to the inside wall surface. The distinction between the severity of the corrosive attack was evident over the entire 180° portion of the fracture exposed, with the possible exception of a small region adjacent to the gouge at the bottom of the pipe where the older part of the crack may have penetrated the entire wall thickness. The older and recent parts of the fracture can be seen in figure 7.

4.2.2 Scanning Electron Microscope Examination

The primary feature exhibited by the entire exposed portion of the more recent appearing part of the fracture was quasi-cleavage (indicating brittle fracture). There was a small amount of dimpled rupture (indicating ductile fracture), most of which was found adjacent to the inner wall surface.

Thus, the recent part of the fracture was principally brittle; i.e., very low ductility. Two areas exhibiting features typical of the recent fracture away from the inner wall are shown in figures 8 and 9. One area adjacent to the inner surface of the pipe exhibiting a mixture of quasi-cleavage and dimpled rupture is shown in figure 10.

Regions of the older appearing part of the fracture were covered with a rather heavy film of corrosion product which obscured the fracture features. An area exhibiting this film is shown in figure 11. After cleaning the fracture surface in an ultrasonic cleaner, enough of the corrosion film had been removed so that many of the fracture features could be seen. Quasi-cleavage was the primary feature exhibited (figures 12 and 13), but there was some dimpled rupture near the apparent fracture origin (figure 14).

4.3 Metallographic Examination

An area of an as-polished longitudinal section through the pipe adjacent to the south fracture surface exhibiting a typical inclusion content for the pipe material in the areas examined is shown in figure 15. The average inclusion content in this typical area does not appear to be abnormally high.

An etched longitudinal section intersecting the fracture near the apparent fracture origin near the bottom of the pipe is shown in figure 16. The outside surface of the pipe is horizontal at the top of the figure, and the fracture profile is at the right in the region designated "D". Macroscopic deformation near the fracture is evidenced by the upward curvature. This deformation apparently was caused mechanically by an external source. Deformation on a finer scale can be seen in a gouged area adjacent to the outside surface of the pipe in the region designated "A" in figure 16. Areas designated "B", "C", and "D" in figure 16 are shown at higher magnification in figures 17a, 17b, and 17c, respectively. Area B (figure 17a), at the periphery of the gouge through which the crack passed, had suffered mechanical damage and subsequent corrosive attack. The area adjacent to the fracture shown in figure 17b (area C, figure 16) is in the gouged region through which the crack passed. There is a relatively heavy deposit of corrosion product at area C.

Although corrosion product is evident on the outside wall surface in both figures 17a and 17b, none could be seen on the profile of the fracture shown in figure 17c. The fracture had been ultrasonically cleaned before the section shown in figures 16 and 17 was prepared. This cleaning operation may have removed enough of the corrosion product so that it could not be seen in profile or, indeed, the corrosion product may have been too thin even before cleaning to be detected in profile. As indicated in figure 17c, the fracture appears to be primarily intergranular in nature in this region, which is in contrast to the results of the fractographic examination. The areas of the fracture examined with the scanning electron microscope exhibited primarily transgranular quasi-cleavage. Apparently both intergranular and transgranular fracture modes are exhibited by different areas of the fracture.

The wall thickness of the pipe adjacent to the fracture had been reduced by about 70% in the section shown in figure 16. This was apparently due to a combination of mechanical damage (gouging) and subsequent corrosion, which may have been accelerated by the material in the deformed region being in a relatively high stress condition. There appears to be some evidence of microscopic deformation adjacent to the gouged area, which would be expected from the mechanical damage. The material that had probably suffered the most severe deformation may have been corroded away. There appears to be a secondary crack perpendicular to and away from the fracture (arrow E, figure 16). The corrosion product was unusually heavy in this region.

The microstructure of the material consists primarily of ferrite (light phase) with some pearlite (dark phase).

4.4 Chemical Analysis

A chemical analysis was performed by a competent commercial laboratory on a sample of the pipe material. The results of that analysis are given in Table 1. The pipe was fabricated from a plain, low carbon steel. It meets the chemical composition requirements of ASTM Standard A53-73 for type F welded pipe, and it meets all the requirements for type E except for a high phosphorus content(3). The standard specifies a maximum phosphorus content of 0.050% for type E pipe.

4.5 Hardness and Dimensional Measurements

Rockwell B hardness measurements were made on three transverse sections through the pipe length located 2, 5, and 24 inches south of the fracture. A minimum of ten measurements was made on each section. The results are given in Table 2 along with approximate equivalent ultimate tensile strength (UTS) values(4). In each cross section, the lowest hardness values were obtained at the location of the longitudinal weld in the pipe. The approximate ultimate tensile strength based on hardness is above the minimum required for type F and grade

A, type E welded pipe as specified in ASTM Standard A53-73(3).

ASTM Standard A53-73 specifies that the outside diameter of the pipe should be 2.375 inches within mill tolerances. The outside diameter of the submitted pipe was 2.38 inches for an average of four measurements made at 45° intervals on a transverse plane. The average wall thickness in a region away from the fracture measured 0.150 inch, which is well above the minimum 0.135 inch required by ASTM 53-73.

4.6 Soil Corrosivity Characterization

Data from measurements made at the site of the pipeline are given in Table 3. The results indicate that the soil is slightly alkaline. The redox potential is above +500 mv and, therefore, considered noncorrosive from the standpoint of anaerobic bacterial attack(5). The resistivities at sites 1 and 3 were well over 10,000 ohm-cm which would indicate non-aggressive soil. The soil at site 2 with a resistivity of just under 5000 ohm-cm is judged to be moderately aggressive. The potential of the pipeline indicated that it is under very weak cathodic protection in the area of site 1 where, according to the Columbia Gas Company, magnesium anodes were installed at the time the failed length of pipe was replaced. This protection was reduced at site 2 and further reduced at site 3.

The results of the chemical analysis of the soil samples are given in Table 4. The carbonate content is high, but not abnormal for an alkaline soil, as indicated by the pH. The nitrate, sulfate, and sulfide contents are low for all of the samples. The sulfate content at site 2 is two or three times higher than at sites 1 and 3, but nevertheless, low compared to National Bureau of Standards soils(6). The low values of these acid forming anions is reflected in the low total acid determinations.

4.7 Impact Tests

Impact tests were run on three of the pre-cracked specimens described in Section 3.3. One each was tested on a Charpy impact machine at 25, 45, and 65°F. The 25° temperature approximated the temperature of the air in York on the day of the explosion, and the 45° temperature approximated the estimated temperature of the soil at the site of the failure. The fracture surfaces produced at the three temperatures are shown in figure 18. For about the first 90% of the impact fracture in each case, the dominant feature was quasi-cleavage indicating low-ductility or brittle fracture. Scanning electron fractographs showing examples of this part of the fracture surfaces are shown in figures 19a, b, and c for the specimens tested at 25, 45, and 65°F, respectively. For each specimen, however, there was an abrupt change in the fracture mode with the fracture going from brittle to ductile. There was a band of dimpled rupture at the last part of the fracture to form. This part of the fracture was farthest from the notched surface and may be related to specimen configuration. The width of the band of ductile fracture (dimpled rupture) was about 11, 8, and 9% of the total fracture produced in impact at 25, 45, and 65°F, respectively. A scanning electron fractograph representative of the ductile regions of the specimen fractures is shown in figure 20. A fractograph showing the transition from quasi-cleavage to dimpled rupture in the specimen tested at 45°F is shown in figure 21.

5. DISCUSSION

This two inch steel gas main pipe failed in a brittle manner at a location of the pipeline where the pipe had suffered rather severe mechanical damage. This damage consisted of bowing, denting, and gouging of the pipe. The crack causing failure passed through, and probably initiated at, a gouge that was adjacent to a dent near the bottom of the pipe. The wall thickness of the pipe had been reduced by about 70% near the apparent origin of the crack, and there was a significant amount of corrosion product on the outside of the pipe in the gouged region.

The crack leading to final failure appears to have formed in at least two stages at different times, as evidenced by the amount and distribution of corrosion product on the fracture surfaces. Thus, apparently there was a crack present prior to the time of final failure of the pipe. Both the older and recent parts of the crack were essentially brittle in nature, but the older part of the crack, which had penetrated about half of the wall thickness of the pipe over most of the approximately 180° portion of the fracture surface examined, and perhaps penetrated the entire wall thickness of the pipe near the crack origin, exhibited somewhat more ductility than the part of the crack that formed later. This was shown by comparison of fractographs which indicated somewhat more dimpled rupture in the older part of the crack than in the more recent part.

Since this normally ductile steel failed in a brittle manner, the apparent mechanism of fracture for the older part of the crack was likely stress corrosion cracking. Failure occurred in a relatively highly stressed area of the pipe, the stressed condition having been created by mechanically deforming the material (the mechanical damage mentioned above). There was more corrosion product in the gouged area of the pipe through which the crack passed than in other areas of the submitted length, which is probably due to a combination of the stress condition of the pipe at the gouged area and the absence of any surface protection for the pipe. Even though this pipe is classed as a "bare" pipe, there was a light protective coating consisting of a black, tarry appearing substance on the outside surface of the pipe. This coating was missing in the gouged area.

The mechanism for the more recent part of the crack was probably either stress corrosion cracking or impact. The impact tests conducted in the laboratory resulted in primarily cleavage fractures at temperatures similar to those to which the pipe was subjected at the time of the failure. There was some dimpled rupture exhibited by the more recent part of the field fracture adjacent to the inner wall surface of the pipe. This part of the fracture was likely the last to form. This region of dimpled rupture in the field fracture was much smaller than that observed in the laboratory-produced fractures. The fact, however, that the laboratory fractures were primarily cleavage indicates that impact may be a possible fracture mechanism for the more recent part of the field fracture.

Compared with data gathered by the National Bureau of Standards on soils throughout the United States, the results of the soil analyses indicate that the soil in the areas of the pipeline examined is of low corrosivity. This fact would not necessarily eliminate the possibility of failure due to stress corrosion cracking.

The submitted pipe length had a number of corrosion pits on the outside surface, some of which were about 0.080 inch deep. This represents more than half of the wall thickness of the pipe. National Bureau of Standards soil data(6) reveal that maximum pit depths of from 0.060 to 0.400 inch over a period of thirty years exposure might be expected in this soil. This is consistent with the maximum pit depths found in the cross sections of the submitted pipe length examined. Although the examination was essentially superficial, there appeared to be fewer pits in the length of pipeline that was still in service (at site 2) than in the submitted length, and those pits observed appeared to be less deep. Both this length of pipe and the submitted length were located where capped sewer laterals leading to 1320 and 1324 South Ogontz Street, respectively, crossed under the gas main. There were septic systems in the front yards of both 1320 and 1324 South Ogontz Street. The pipe at site 2

(1320 South Ogontz) had not suffered the mechanical damage that the pipe in the vicinity of the failure had sustained.

At the outset of this investigation, it was thought that possible seepage from the septic system or the capped sewer lateral at 1324 South Ogontz Street may have provided a medium to accelerate the corrosion process or to promote stress corrosion cracking. This suspicion was not borne out by the results of the soil analysis.

The inclusion content and the microstructure of the pipe material appeared to be satisfactory. The chemical composition meets the requirements of ASTM Standard A53-73 for type F welded steel pipe and the ultimate tensile strength (based on hardness measurements) meets the requirements of the same ASTM Standard for type F and grade A, type E welded steel pipe. The pipe diameter and wall thickness satisfy the requirements of this Standard for schedule 40 pipe.

6. CONCLUSIONS

1. There was a transverse crack in the approximate center of the submitted length of pipe. This crack traversed about 85% of the pipe circumference, extending in a clockwise direction from one o'clock to eleven o'clock.

2. There was a considerable amount of mechanical damage to the pipe consisting of a bow, dents, and gouges on the outside surface in the vicinity of the failure. The mechanical damage produced a region in the vicinity of the crack that was more highly stressed than was most of the material away from the crack.

3. The crack appeared to initiate at a gouge near the bottom of the pipe. At the apparent origin, the wall thickness of the pipe had been reduced by about 70%, likely by a combination of mechanical damage and corrosion.

4. As evidenced by the corrosion product on the fracture surface, the crack had formed in at least two stages. Both parts of the crack were essentially brittle in nature, but the older part exhibited slightly more ductility than the more recent part. This indicates that part of the crack had been in existence prior to the time of failure. The older part of the crack may have penetrated the entire wall thickness of the pipe.

5. The likely fracture mechanism of the older part of the fracture was stress corrosion cracking. The likely fracture mechanism of the more recent part of the fracture was either stress corrosion cracking or impact.

6. There were numerous pits in the outside wall surface of the submitted length of pipe. Some of these pits penetrated more than half the wall thickness of the pipe, but the pit depths appear to be consistent with NBS data for exposure in nonaggressive soils.

7. Pitting appeared to be much less severe and there was no evidence of significant mechanical damage on the pipe length examined which was located about 51 feet from the site of the failure.

8. The soils examined in areas along the pipeline are considered to be of low corrosivity.

9. There was no evidence from the soil analysis of any leakage from the septic system or the sewer lateral that may have contributed to the failure.

10. Laboratory impact tests on non-standard pre-cracked impact specimens machined from the pipe material resulted in fractures which were about 90% quasi-cleavage and 10% dimpled rupture. The dimpled rupture was essentially all in a band at the last part of the fracture to form and may be related to specimen configuration. These fractures were somewhat similar to the more recent part of the field fracture, although the field fracture exhibited less dimpled rupture than the laboratory impact specimens.

11. The chemical composition of the pipe material meets the requirements of ASTM Standard A53-73 for type F welded steel pipe.

12. The ultimate tensile strength (based on hardness data) meets the requirements of ASTM Standard A53-73 for type F and grade A, type E welded steel pipe.

13. The outside diameter and the wall thickness of the pipe meet ASTM Standard A53-73 for schedule 40 pipe.

14. Nothing abnormal was noted concerning the microstructure or inclusion content of the pipe material.

7. ACKNOWLEDGEMENT

The soil corrosivity characterization program and the analysis of the data from that program were carried out by Mr. Edward Escalante of the NBS Corrosion and Electrodeposition Section. Mr. L. C. Smith of the NBS Mechanical Properties Section performed the photographic and metallographic work and assisted in other areas of the investigation.

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Table 1. Results of Chemical Analysis of the Pipe Material

Element	Percent (weight)
Carbon	0.09
Manganese	0.45
Phosphorus	0.071
Sulfur	0.022
Silicon	< 0.05
Nickel	< 0.05
Chromium	< 0.05
Molybdenum	< 0.05
Copper	< 0.05

Table 2. Results of Hardness Measurements

Cross Section Location	Hardness, R_B Average	Range	Approx. Equiv. UTS, ksi
2" south of fracture	74	62-79	56-73
5" south of fracture	71	62-77	56-72
24" south of fracture	70	63-72	56-70

Table 3. Results of the Measurements Made at the Site of the Pipeline

Location	Soil Resistivity, ohm-cm	Redox Potential vs Saturated Calomel Electrode, volts	Soil pH	Pipeline Potential vs Cu-$CuSO_4$, volts
Site 1	22,330	+0.530	7.4	-0.7610
Site 2	3,930	+0.530	7.9	-0.6425
Site 3	12,320	+0.520	7.6	-0.6100

Table 4. Results of the Chemical Analysis of Soil Samples

Location	Water Soluble Carbonates mg CO_3^{-2}/100 gm	Water Soluble Nitrates mg/100 gm	Water Soluble Sulfates mg/100 gm	Water Soluble Sulfides mg/100 gm	Total Acidity mg $CaCO_3$/100 gm
Site 1, near surface	24	0.52	5.1	< 0.5	---
Site 1, 38" below surface	6	0.40	6.3	< 0.5	1.5
Site 2, 24" below surface	24	0.20	11.7	< 0.5	---
Site 2, 40" below surface	18	0.28	19.8	< 0.5	---
Site 3, near surface	18	0.28	6.3	< 0.5	---
Site 3, 38" below surface	6	0.23	6.7	< 0.5	1.5

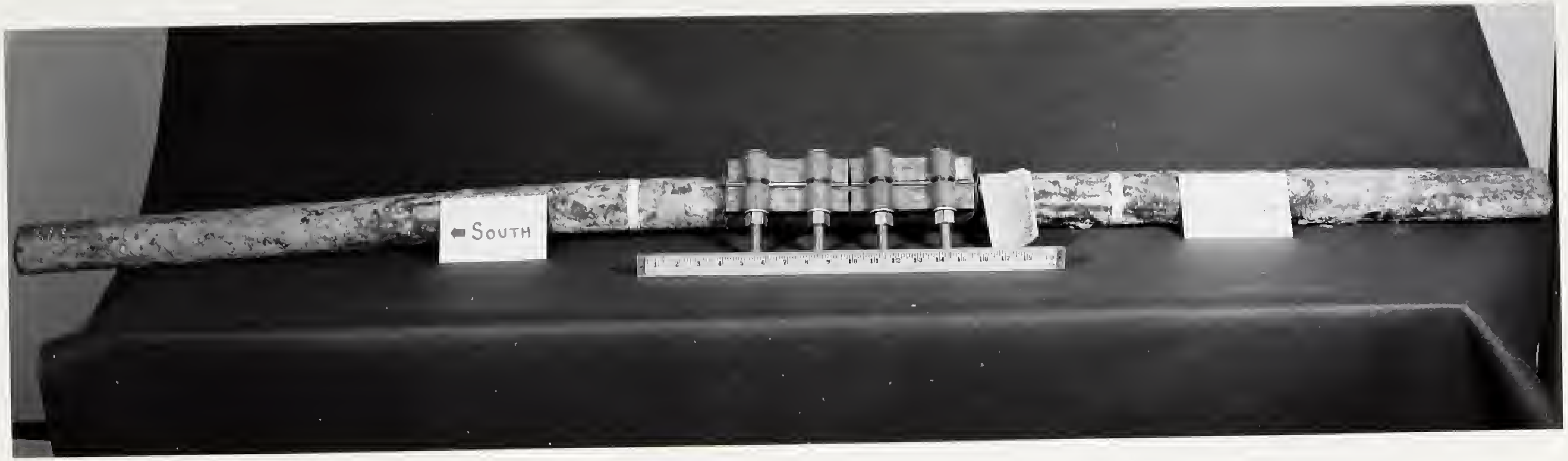


Figure 1. Pipe Length as received at NBS with the clamp in place. With the pipe positioned as it was in service, the clamp was reported to be attached so that the longitudinal axes of the bolts were horizontal at the top of the pipe. A bow in the pipe just south (left) of the clamp can be seen. X 1/8

Figure 2. Longitudinal piece cut from the pipe length about 24 inches south of the fracture. This piece exhibited good ductility since it was bent through a sharp angle and exhibited only slight cracking. X 4

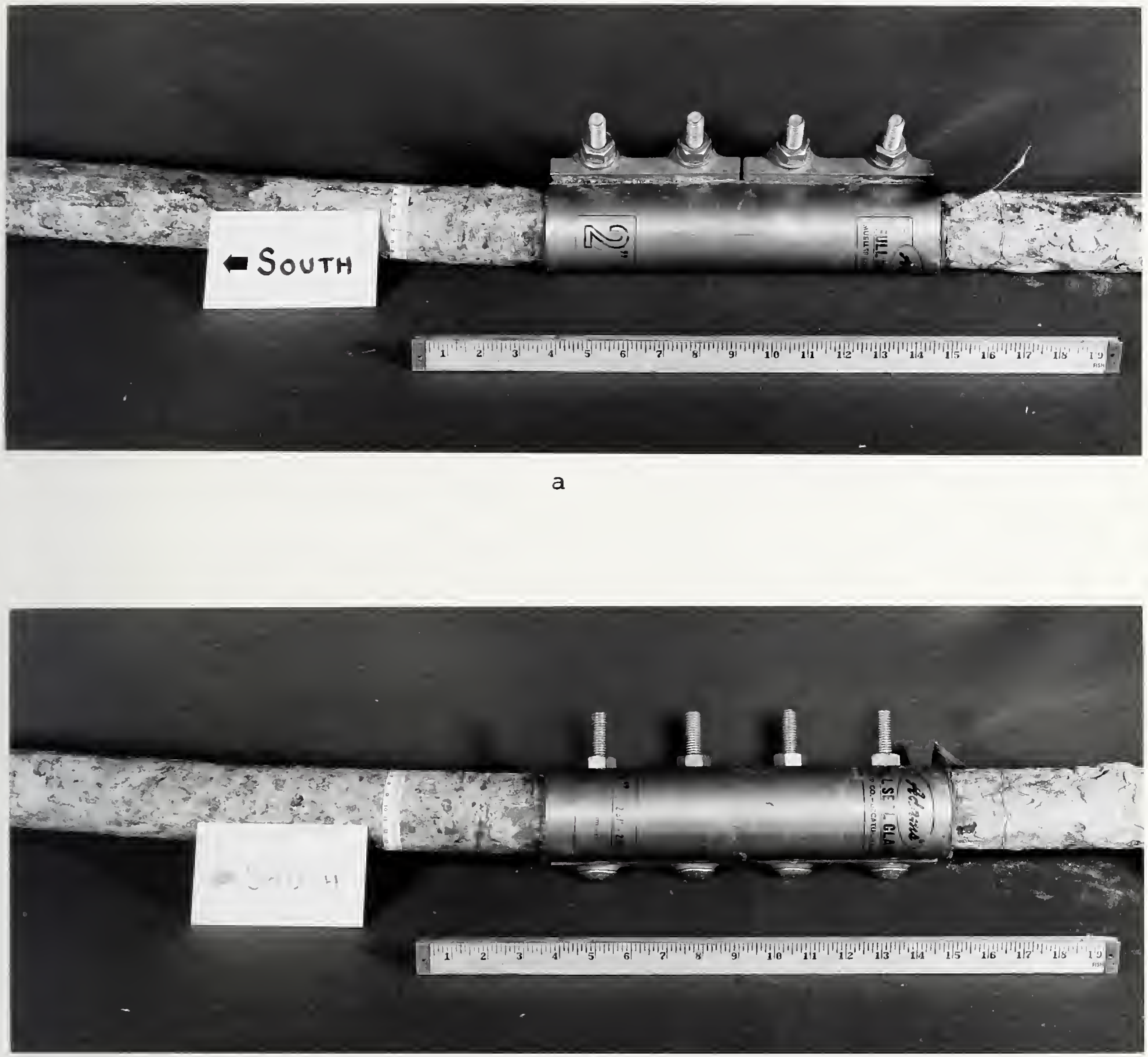


Figure 3. Part of pipe length as received showing bow south of the clamp. X 1/5

a. East side of pipe
b. Bottom of pipe

Figure 4. Four views of the pipe in the area of the crack after removal of the clamp. X 1

Arrow A indicates dent near the bottom of the pipe
Arrows B indicate gouge near bottom of the pipe through which the crack passed
Arrows C indicate examples of pitting on the surface of the pipe

a. Top of pipe
b. East side of pipe
c. Bottom of pipe
d. West side of pipe

Figure 4.

Figure 4 continued.

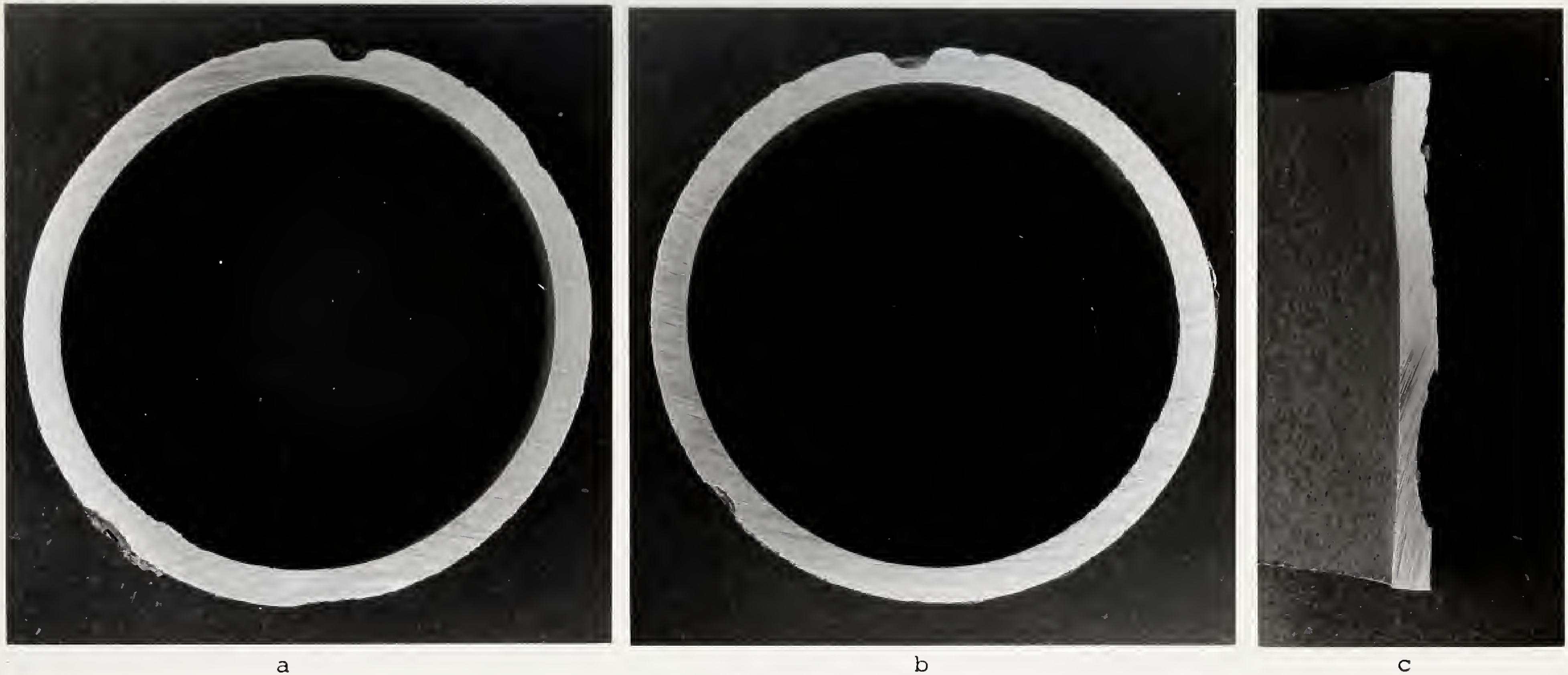


Figure 5. Sections through the pipe length in locations where pits appeared to be among the deepest. Top of pipe is at top in a and b. X 1 1/2

a. Transverse section two inches south of the crack.
b. Transverse section five inches south of the crack.
c. Longitudinal section 22 to 24 inches south of the crack.

Figure 6. Top view of part of the pipeline excavated at site 2. X ∿ 1/2

Figure 7. Bottom half (as the pipe was positioned in service) of the south side of the fracture. Thin area at about 7 o'clock is where the crack passed through a gouge. Note lighter color of the fracture near the inside wall surface of the pipe. This region is the recent part of the fracture. X 1 1/2

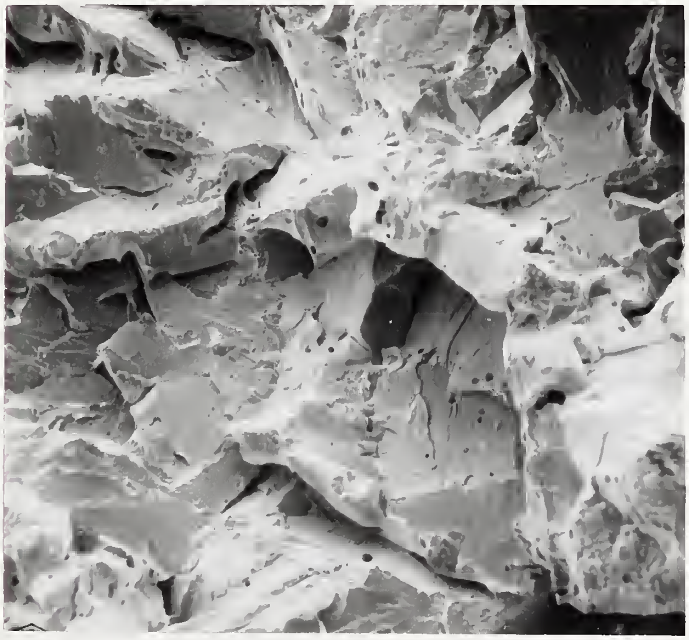


Figure 8. Scanning electron fractograph taken in region of "fresh" fracture showing essentially all quasi-cleavage. X 260

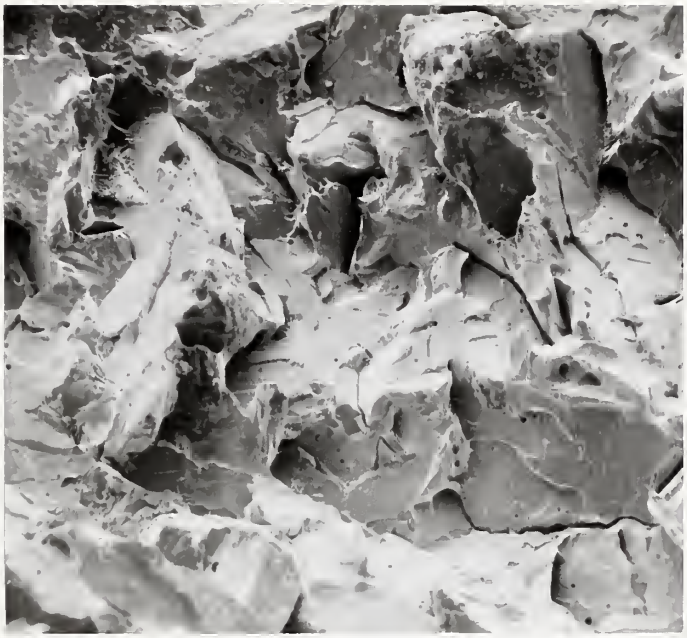


Figure 9. Scanning electron fractograph taken in region of "fresh" fracture showing essentially all quasi-cleavage. X 260

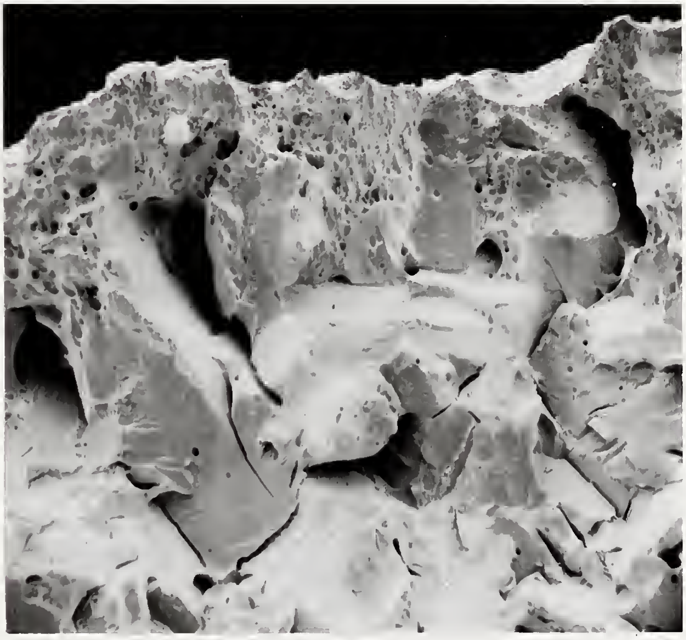


Figure 10. Scanning electron fractograph taken in region of "fresh" fracture adjacent to the inner wall surface. The primary fracture feature is quasi-cleavage. Some dimpled rupture is evident. X 260

Figure 11. Scanning electron fractograph taken in the older appearing part of the fracture before ultrasonic cleaning. The film of corrosion product is evident. X 690

Figure 12. Scanning electron fractograph taken in the older part of the fracture after ultrasonic cleaning. Quasi-cleavage is the primary fracture feature. X 95

Figure 13. Scanning electron fractograph taken in the older appearing part of the fracture. The primary feature exhibited is quasi-cleavage. X 137

Figure 14. Scanning electron fractograph taken in the older appearing part of the fracture near the apparent fracture origin. There is a small amount of dimpled rupture. X 670

Figure 15. Longitudinal section through the pipe near the south fracture surface showing an average inclusion content for the areas examined. As polished. X 100

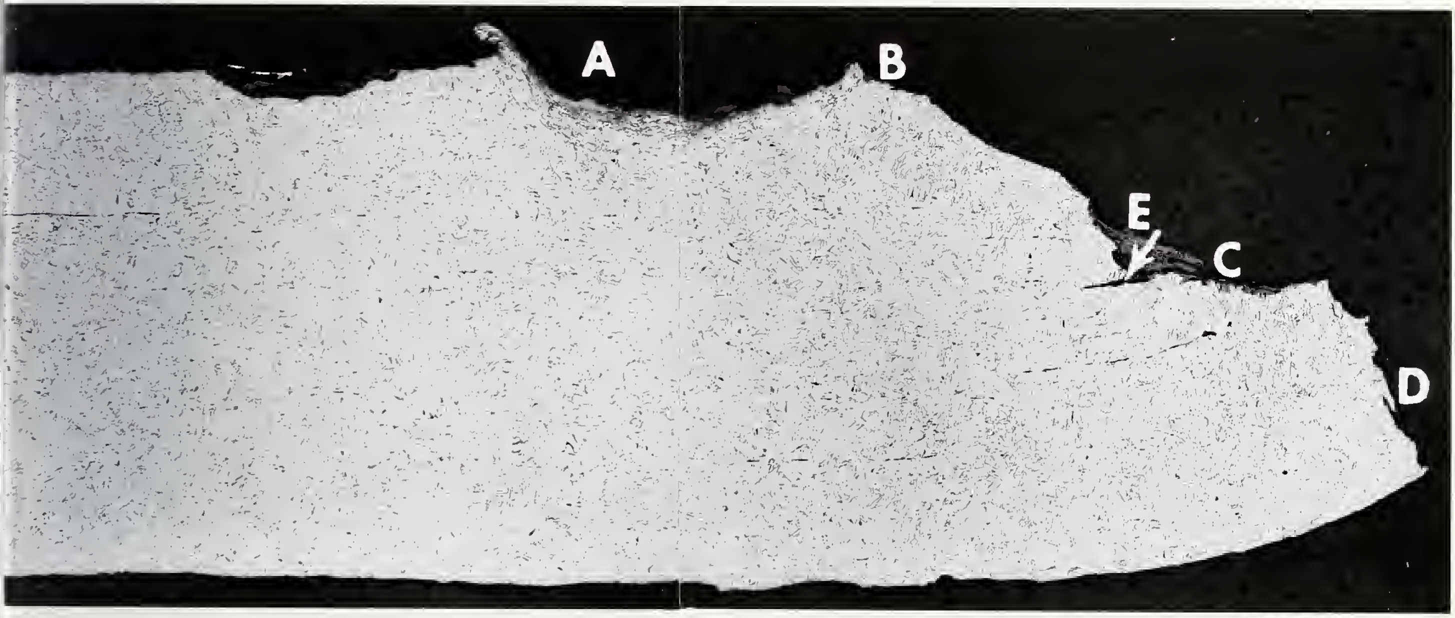
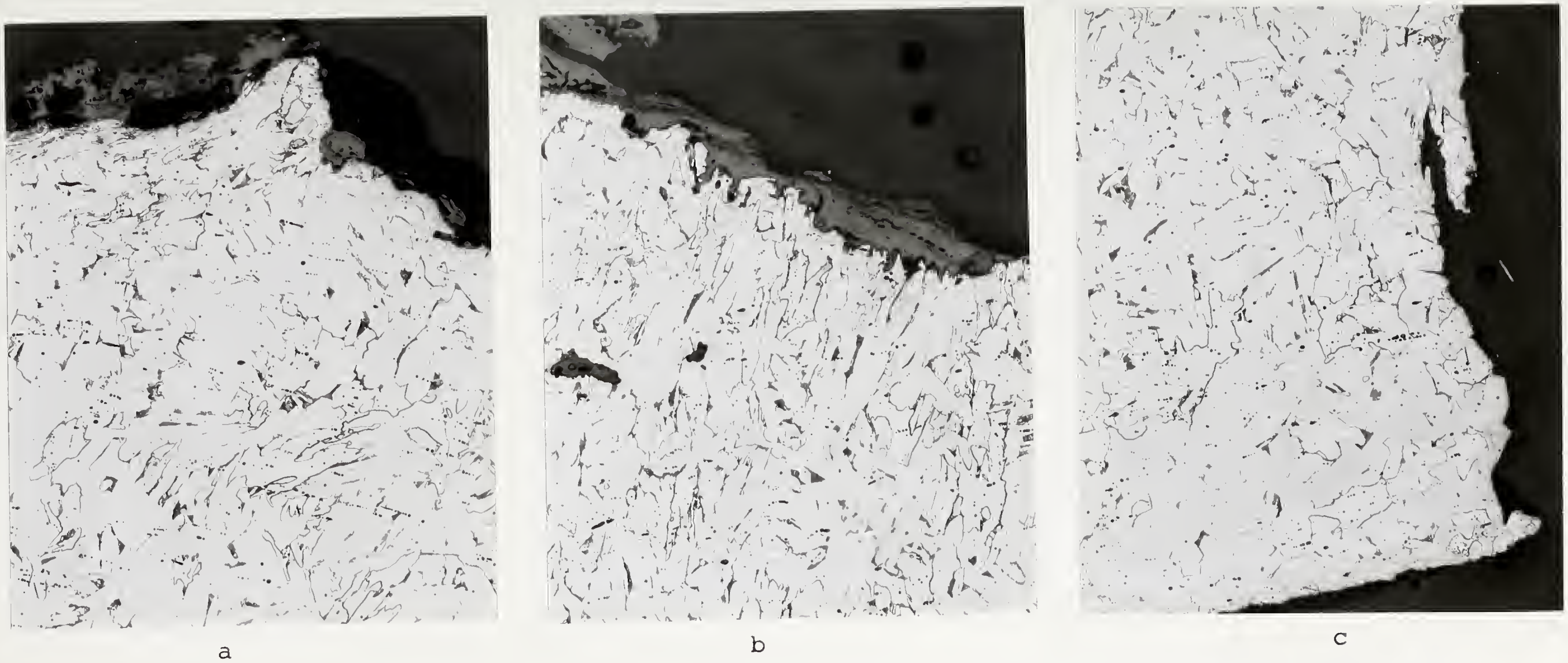


Figure 16. Longitudinal section intersecting the south fracture surface near the apparent crack origin. The outside wall surface of the pipe is at the top. The fracture profile is at the right (D). Macroscopic deformation is evident near the fracture. Deformation on a finer scale can be seen at A. E indicates a secondary crack. Areas B, C, and D are shown at higher magnification in figure 17.
Etchant: 1% nital X16



a

b

c

Figure 17. Areas B, C, and D in figure 16 are shown above in a, b, and c, respectively. X 100
Etchant: 1% nital

a. Outside wall surface of the pipe is at the top. There is evidence of mechanical damage and subsequent corrosive attack.
b. Gouged region showing evidence of corrosive attack and corrosion product.
c. Fracture profile (vertically at the right). Fracture appears to be primarily intergranular.

a b c

Figure 18. Fracture surfaces of laboratory impact specimens. The direction of crack propagation is from left to right. A indicates saw-cut notch on outside wall surface, B indicates fatigue crack, C indicates region of quasi-cleavage, D indicates region of dimpled rupture. X 30

a. Testing temperature 25°F.
b. Testing temperature 45°F.
c. Testing temperature 65°F.

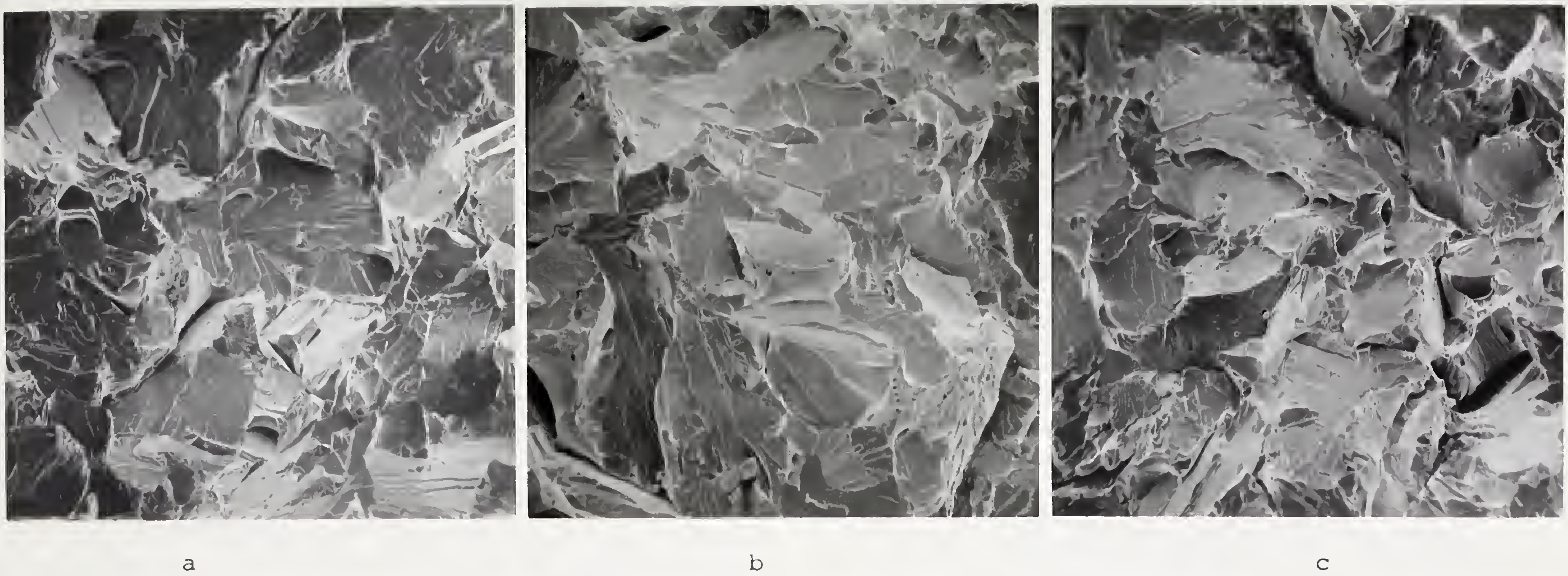


Figure 19. Scanning electron fractographs of the brittle region of the laboratory impact specimen fracture surfaces. The dominant feature is quasi-cleavage. A small amount of dimpled rupture can be seen. X 235

a. Testing temperature 25°F.
b. Testing temperature 45°F.
c. Testing temperature 65°F.

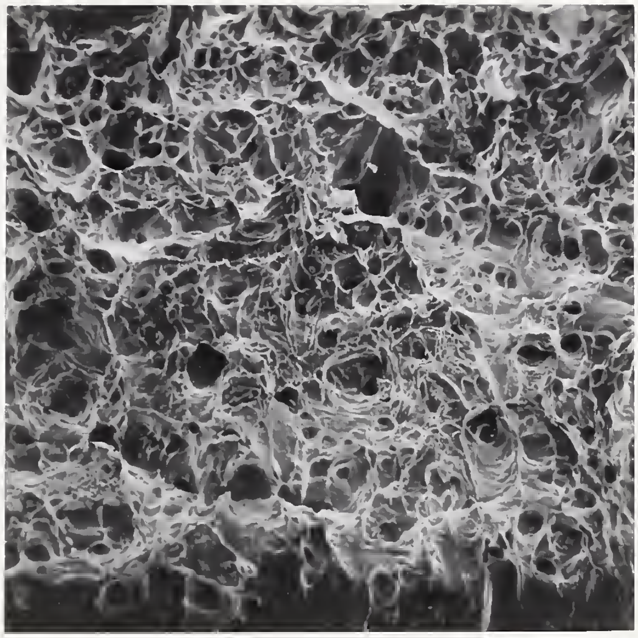


Figure 20. Scanning electron fractograph from the specimen tested in impact at 45°F. This area is in the ductile part of the fracture. The primary feature exhibited is dimpled rupture. X 425

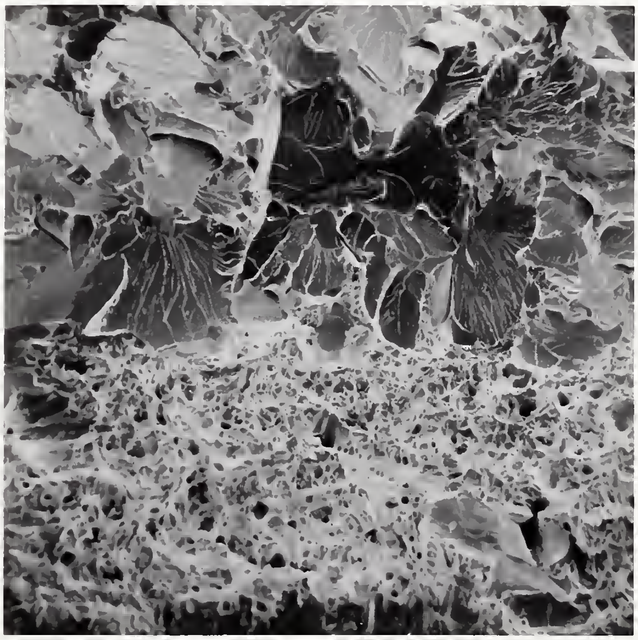


Figure 21. Scanning electron fractograph showing the transition from essentially brittle fracture (top) to ductile fracture (bottom). There is a small area of quasi-cleavage in the predominantly ductile region. X 165

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The Mechanical Properties Section of the National Bureau of Standards examined a length of a cracked two inch diameter plain carbon, welded steel natural gas main pipe at the request of the Office of Pipeline Safety. The pipe had a transverse crack extending about 85% of the circumference. The pipeline had suffered considerable mechanical damage in the vicinity of the failure, and the crack, which propagated in an essentially brittle manner, appeared to have initiated in a gouged area near the bottom of the pipe. There was a considerable amount of corrosion product on the surface of the pipe in the gouged area. The amount and distribution of corrosion product on the fracture surface indicated that the crack had formed in at least two stages, and that a crack was present prior to the time of failure. During the first stage, the crack may have penetrated the entire wall thickness of the pipe in one region opposite the crack origin near the bottom of the pipe. The likely mechanism of fracture for the first stage of the crack appears to be stress corrosion cracking. For the second stage of the crack, either stress corrosion cracking or impact appears to be the likely mechanism of failure.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Brittle fracture; gas main pipe; impact; low carbon steel; stress corrosion cracking

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