NBSIR 78-1572

Examination of Failed One Inch Diameter Bare Steel Pipe Natural Gas Service Line, Waynesboro, Virginia, Columbia Gas Company of Virginia, Inc.

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Center for Materials Science
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Failure Analysis Report

Prepared for
[Of]fice of Pipeline Safety Operations
[De]partment of Transportation
[Wa]shington, D.C. 20590

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FIGURES (continued)

SUMMARY

The submitted one inch diameter bare steel gas pipe service line failed due to the initiation and propagation of a transverse crack at the root of a thread where the pipe was attached to a 90^{o} elbow. The primary fracture mode for most of the fracture was cleavage indicating a brittle fracture. The probable fracture mechanism is stress corrosion cracking. The pipe had suffered rather severe pitting corrosion and the threads adjacent to the fracture on one side of the pipe were badly corroded.

The chemical composition, microstructure and hardness of the pipe material appeared to be satisfactory.

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1. INTRODUCTION

1.1 Reference

Office of Pipeline Safety Operations, Department of Transportation, Washington, DC 20590. This investigation was conducted at the request of Mr. Frank E. Fulton, Office of Pipeline Safety Operations, under contract number DOT-AS-70037 dated March 10, 1978.

1.2 Parts Submitted

A piece of nominally one inch diameter bare steel pipe about 3 1/2 feet long with a 90° elbow attached to either end was submitted to NBS for examination. A short length of one inch diameter bare steel pipe was attached to the other end of each elbow. The 3 1/2 foot length of pipe contained a crack at the threads where it was attached to one of the elbows. The pipe was delivered to NBS by the State Corporation Commission of the Commonwealth of Virginia on January 5, 1978. The pipe is shown as received at NBS in figure 1.

1.3 Background Information

The information in this section was provided by the Office of Pipeline Safety Operations.

On December 23, 1977, there was an explosion and fire at a residence located at 777 Locust Avenue in Waynesboro, Virginia. The explosion was believed to have resulted from natural gas leaking from the gas service line into the residence.

A crack was found in a vertical section of the bare steel pipe gas service line adjacent to a 90° elbow. The crack in the pipe was in close proximity to the wall of the house. The part of the line containing the crack was removed from the line on December 29, 1977, six days after the explosion and fire. After the section had been removed, the remaining line was pressure tested and two leaks due to pitting corrosion were found several feet from where the crack had been located. The section of pipe containing these two leaks was not submitted to NBS.

At the crack location, the pipe was under about 6 1/2 feet of loose fill cover, on top of which was a six inch thick concrete slab. There were two inches of flagstone on top of the concrete slab. The fill was fairly free of rocks, etc. The top of the vertical length of pipe (the end opposite that containing the crack) was under about 33 inches of loose fill with the concrete and the flagstone on top.

The gas line had been installed in January, 1950. Operating pressure in the main was 15 psig. The regulator outlet pressure into the service line was 7 inches of water column.

Before the pipe was submitted to NBS, the surface of the pipe adjacent to the crack had been wire brushed by Columbia Gas Company of Virginia, Inc., personnel to remove dirt and scale so that a closer examination of the pipe could be made.

2. PURPOSE

The Office of Pipeline Safety Operations (OPSO) requested NBS to examine the submitted cracked pipe sample and to perform a fractographic examination, a metallographic examination, a chemical analysis, and thread measurements. After the fracture mode had been determined, the OPSO, through Mr. Frank E. Fulton, agreed to further testing in order to attempt to determine the fracture mechanism.

3. RESULTS OF ANALYSES, EXAMINATIONS AND TESTS

3.1 Visual Examination

An approximately one inch length of the long piece of pipe adjacent to the crack, and the two short lengths of pipe attached to the elbows, were relatively free of soil and surface scale when the pipe sample was received at NBS. In the vicinity of the crack, the pipe had been wire brushed by gas company personnel in order to facilitate a closer examination of the pipe. The rest of the pipe was covered with a fairly tightly adhering coating of soil and corrosion product. Some of the material adhering to the pipe surface can be seen in figure 1.

The crack in the pipe was transverse and was located at the root of a thread adjacent to one of the 90° elbows. The crack had opened up somewhat resulting in about a 95° angle (figure 2) instead of a 90° angle at the elbow. The crack was propagated to complete fracture by bending in the NBS laboratory. The fracture thus exposed for examination is shown in figure 3. The field portion of the crack had propagated through the entire wall thickness for about one half the circumference of the pipe. There was a considerable amount of corrosion product on the fracture surface suggesting that the crack may not have been fresh. Parts of both the field fracture and the portion of the fracture produced at NBS are shown at higher magnification in figure 4.

Part of the outside surface of the piece of pipe containing the crack was cleaned of soil and scale. Extensive pitting corrosion was revealed. Pitting in a region about two inches from the crack can be seen in figure 5. The threads at the end of the pipe where the crack occurred were badly corroded on one side of the pipe. Two views

of the threaded portion of the pipe, one in a severely corroded region and the other in a less corroded region are shown in figures 6a and 6b. The small piece of pipe connected to the elbow at the bottom of the vertical piece of pipe was also rather badly corroded. The piece of pipe connected to the elbow at the top of the vertical piece of pipe appeared to be only slightly corroded.

3.2 Thread Measurements

Some of the thread parameters were determined where the threads were only slightly corroded. The four threads closest to the fracture were considered. The results of these determinations are given below. Specified values for these parameters from the American Standard Taper Pipe Threads Standard, 1968, are listed for comparison.

	Measured	Specified
Threads per inch	11.4	11.5
Angle of taper	1° 46'	1° 47'
Angle of threads	60°	60°

The threads on the piece of pipe adjacent to the fracture that remained in the elbow were not measured since that piece of pipe was not removed from the elbow.

In addition to the above thread measurements, the effective wall thickness of the pipe (the distance between the thread root and the inside wall surface of the pipe) was measured at several places around the circumference of the pipe at the fracture. The effective wall thickness at the fracture in the region of the field crack ranged from about 0.061 inch in a badly corroded region to 0.069 inch in a region which was very slightly corroded.

A longitudinal section intersecting the fracture was taken through the pipe approximately along a diameter. Both sides of the section pass through the field fracture. This section is shown in figure 7. The section was taken so that one side passed through a region where the threads were judged to have been the most severely corroded (left side in figure 7). The other side passed through one of the least corroded regions (right side in figure 7). On the right side, the threads appear to be in good condition with corrosion being minimal. On the left side, however, the bodies of several of the threads had been corroded away. Although the roots of the threads were somewhat corroded, most of the corrosion took place in the thread bodies. In the plane of the section shown in figure 7, the effective wall thickness appears to be slightly less at the arrow than at the fracture.

3.3 Fractographic Examination

One of the two mating fracture surfaces was cleaned in ammonium citrate in order to remove the corrosion product to facilitate a closer examination of the fracture. After soaking in the ammonium citrate for seven minutes, most of the corrosion product that could be seen with the eye or with a low power microscope had been removed. Some product remained in one region adjacent to the outside of the pipe near the center of the field fracture (as measured circumferentially).

After cleaning, parts of both the field fracture and the fracture produced at NBS by propagating the field crack were examined with the scanning electron microscope (SEM). Corrosion had apparently blunted some of the features of the field fracture. Some corrosion product could still be seen on the fracture surface. Cleavage was the predominant fracture mode exhibited by the field fracture. SEM fractographs from the field fracture showing cleavage are shown in figures 8 and 9. Cleavage indicates a very low ductility or a brittle fracture. What appear to be etch pits (geometric depressions) can be seen in figure 9. Part of figure 9 is shown at higher magnification in figure 10 where the apparent etch pits can be more easily seen.

The predominant fracture mode exhibited by the part of the fracture produced at NBS was dimpled rupture which indicates a ductile fracture. An SEM fractograph from the NBS produced part of the fracture is shown in figure 11.

3.4 Chemical Analysis

A sample of the pipe material was submitted to a commercial laboratory for chemical analysis. The results of that analysis are given in the table that follows. The chemical composition requirements for grade A25, class II electric or butt welded steel pipe as set forth in American Petroleum Institute Standard 5L 1971, are included for comparison.

Element	Composition by analysis	API 5L specified composition
Carbon	0.10%	0.21% max
Manganese	.35	.30 min, 1.60 max
Phosphorus	.064	.045 min, .080 max
Sulfur	.027	.06 max
Silicon	.02	----
Nickel	.02	----
Chromium	.02	----
Molybdenum	<.01	----
Copper	.03	----
Vanadium	.01	----
Aluminum	<.005	----

The chemical composition of the pipe falls within the specified limits of API Standard 5L.

3.5 Metallographic Examination

Both sides of the longitudinal section through the field crack that are shown in figure 7 were examined metallographically. Parts of both sections adjacent to the fracture are shown in figures 12 and 13. In figure 12, the fracture passes through a severely corroded region of the threaded portion of the pipe, whereas in figure 13, the fracture passes through a region that had corroded very little.

The microstructure of the pipe material consists primarily of ferrite (light color in the photomicrographs) and pearlite (dark in the photomicrographs). The microstructure appears to be satisfactory for normalized low carbon steel.

Essentially no deformation was exhibited adjacent to the cleavage portion of the fracture in either side of the section. There was some deformation adjacent to the fracture near the inside of the pipe where the fracture mode was ductile. The fracture path was transgranular both where the fracture mode was cleavage and where it was ductile. A transgranular crack path is consistent with both cleavage and dimpled rupture. There was some secondary cracking at the fracture. Some examples of the secondary cracking can be seen in figure 14.

In several places near the cleavage portion of the fracture, there is evidence of mechanical twinning. Mechanical twinning is usually produced by a shear loading[1]. Examples of the twinning are indicated by the arrows in both figures 12 and 13. The example indicated in figure 13 is shown at higher magnification in figure 14. No evidence of twinning was found away from the fracture.

A photomicrograph showing the effects of corrosive attack of one of the threads appears in figure 15. In this region, the corrosion appears to be general in nature and it does not follow grain boundaries.

3.6 Hardness Measurements

Rockwell B (HRB) hardness measurements were made on a transverse section through the pipe about two inches from the fracture. The average of seven measurements was HRB 70, and the range was HRB 68-73.

3.7 Impact Tests

Since the field fracture of this normally ductile material exhibited a brittle fracture mode, it was decided, with the concurrence of the

OPSO, to conduct tests to determine the fracture characteristics of the material under different loading conditions such as impact and tensile loading.

Because of the restrictions of the wall thickness and the curvature of the pipe, neither ASTM standard full size nor standard subsize Charpy impact specimens could be machined from the pipe material. Therefore, specimens with the following dimensions were used for impact tests: thickness, 0.193 inch; width, 0.100 inch; length, 2.165 inch. The notch was 0.05 inch deep with a radius of 0.010 inch at the bottom. One specimen was tested at 23°C (room temperature) and one was tested at 0°C. These two temperatures were assumed to bracket the temperature at the crack when failure occurred.

The results of the two tests were very similar. The energy absorbed on impact was 5 ft-lb for the specimen tested at 0°C and 5.5 ft-lb for the one tested at room temperature. The relative amounts of dimpled rupture and cleavage differed somewhat between the two specimens, with the specimen tested at the higher temperature having a greater percentage of dimpled rupture than the one tested at 0°C. The relative amounts of dimpled rupture and cleavage for the two specimens were estimated as follows:

Testing temperature	% dimpled rupture	% cleavage
23°C	65	35
0°C	60	40

Photomacrographs of the fracture surfaces of the two impact specimens are shown in figure 16. The fracture mode in the region adjacent to the notch is dimpled rupture, whereas the fracture mode in the region away from the notch is cleavage. It can be seen in the figure that there was a considerable amount of lateral expansion in the impact specimens. It would appear that the cleavage mode of fracture is inconsistent with the lateral expansion. A possible explanation may be that the deformation resulting in the lateral expansion preceded the passing of the crack front during testing.

3.8 Tensile Tests

Two approximately eight inch long pieces were cut from the piece of pipe containing the field fracture. The pieces were threaded on both ends to simulate the piece of pipe involved in the field fracture. The pipe pieces were tested in tension. One specimen was tested at a relatively low cross head speed of 0.02 inch per minute and the other was tested at the maximum cross head speed of the testing machine which was 16 inches per minute. The tests were conducted to determine what effect testing speed might have on the fracture mode for an axial tensile test.

There was a large difference in the force required to fracture the two specimens. The maximum load for the high speed test was 16,500 pounds, whereas the maximum load for the low speed test was 5000 pounds.

The fractures produced by the tensile tests were examined with the scanning electron microscope. The fracture from the high speed test exhibited dimpled rupture as the fracture mode in all the regions examined. The fracture from the slow speed test exhibited dimpled rupture as the fracture mode in all the regions examined except for one small region that exhibited cleavage. This region is shown in figure 17. The region of cleavage was not associated with the welded seam in the pipe. A metallographic examination was made of a transverse section through the region of cleavage. Nothing abnormal in the microstructure that might account for the cleavage was detected.

4. DISCUSSION

The submitted portion of this one inch diameter bare steel gas pipe service line failed due to the propagation of a transverse crack that had initiated at the root of a thread where the pipe was attached to a 90° elbow. The crack had propagated through the entire wall thickness of the pipe for slightly more than one half the pipe circumference. The fracture was essentially brittle except for a small region adjacent to the inside wall surface of the pipe which appeared to be ductile overload.

The pipe material would be expected to behave in a ductile manner in either a tensile or bending overload failure, as evidenced by the results of the tests performed in the NBS laboratory. Since the field fracture exhibited very little ductility, the two most likely candidates for a fracture mechanism would appear to be stress corrosion cracking and impact.

A reasonable hypothesis is that the crack initiated via stress corrosion cracking. The rather severe corrosion of the threads on one side of the pipe as well as the extensive pitting of the outside of the pipe in all regions examined provides evidence that the pipe was subjected to a corrosive medium. The part of the fracture exhibiting some ductility was probably the last to fail and appears to have failed due to overload from an externally applied force.

The evidence in favor of stress corrosion cracking is as follows: 1) After soaking for seven minutes in ammonium citrate, some of the corrosion product remained on the fracture surface indicating that at least some of the corrosion product was not superficial. Where the corrosion product was not superficial, the field crack was probably not fresh. 2) The apparent etch pits on the fracture surface also indicate

that the fracture may have been present for some time. 3) The impact specimens exhibited considerably more ductility than the pipe field fracture. 4) There is some secondary cracking which is common in stress corrosion cracking.

The presence of twinning adjacent to the fracture suggests that a mechanical force may have acted on the pipe. The combination of the twinning and the brittle fracture suggests the possibility of impact loading. It is conceivable that the twinning was caused by the torsional forces applied to the pipe when it was attached to the elbow when the pipeline was installed.

The fact that the field crack had opened up enough to form a 95° angle at the normally 90° joint between the pipe and the elbow might also lend support to the idea that a mechanical force may have acted on the pipe. But the crack could very well have opened up during handling of the pipe after the explosion. Therefore, little significance can be attached to the opening of the crack.

The microstructure, chemical composition, and hardness of the pipe material appear to be satisfactory. Those thread parameters measured agree well with those specified by the American Standard on taper threads.

5. CONCLUSIONS

1. The submitted portion of this one inch diameter bare steel gas pipe service line failed due to the initiation and propagation of a transverse crack at the root of a thread at a point where the pipe was attached to a 90° elbow.

2. Except for a small region adjacent to the inside of the pipe, the fracture was essentially brittle in nature, with cleavage being the primary fracture mode.

3. Stress corrosion cracking is the most likely fracture mechanism for the initiation of the crack.

4. The part of the crack adjacent to the inside of the pipe was probably the last to form and is likely due to ductile overload.

5. The pipe threads were severely corroded on one side of the pipe adjacent to the fracture.

6. The outside of the pipe was rather severely pitted.

7. The chemical composition of the pipe material meets the requirements of American Petroleum Institute Standard 5L, 1971, for grade A25, class II electric or butt welded steel pipe.

8. The microstructure and hardness of the pipe material appear to be satisfactory.

6. REFERENCE

1. Morton C. Smith, Principles of Physical Metallurgy, Harper and Brothers, New York, 1956.

7. ACKNOWLEDGEMENT

Mr. Leonard C. Smith of the NBS Fracture and Deformation Division assisted in this investigation. He performed the metallographic specimen preparation and the hardness measurements. Mr. Smith and Miss Marcia Cline, also of the Fracture and Deformation Division, did the photographic work.

Figure 1. Pipe sample as received at NBS. Arrow indicates location of crack. Long length of pipe was vertical in service. End of pipe with crack was at the bottom as the pipe was oriented in service. Accumulation of soil and corrosion product can be seen on long length of pipe. X 1/6

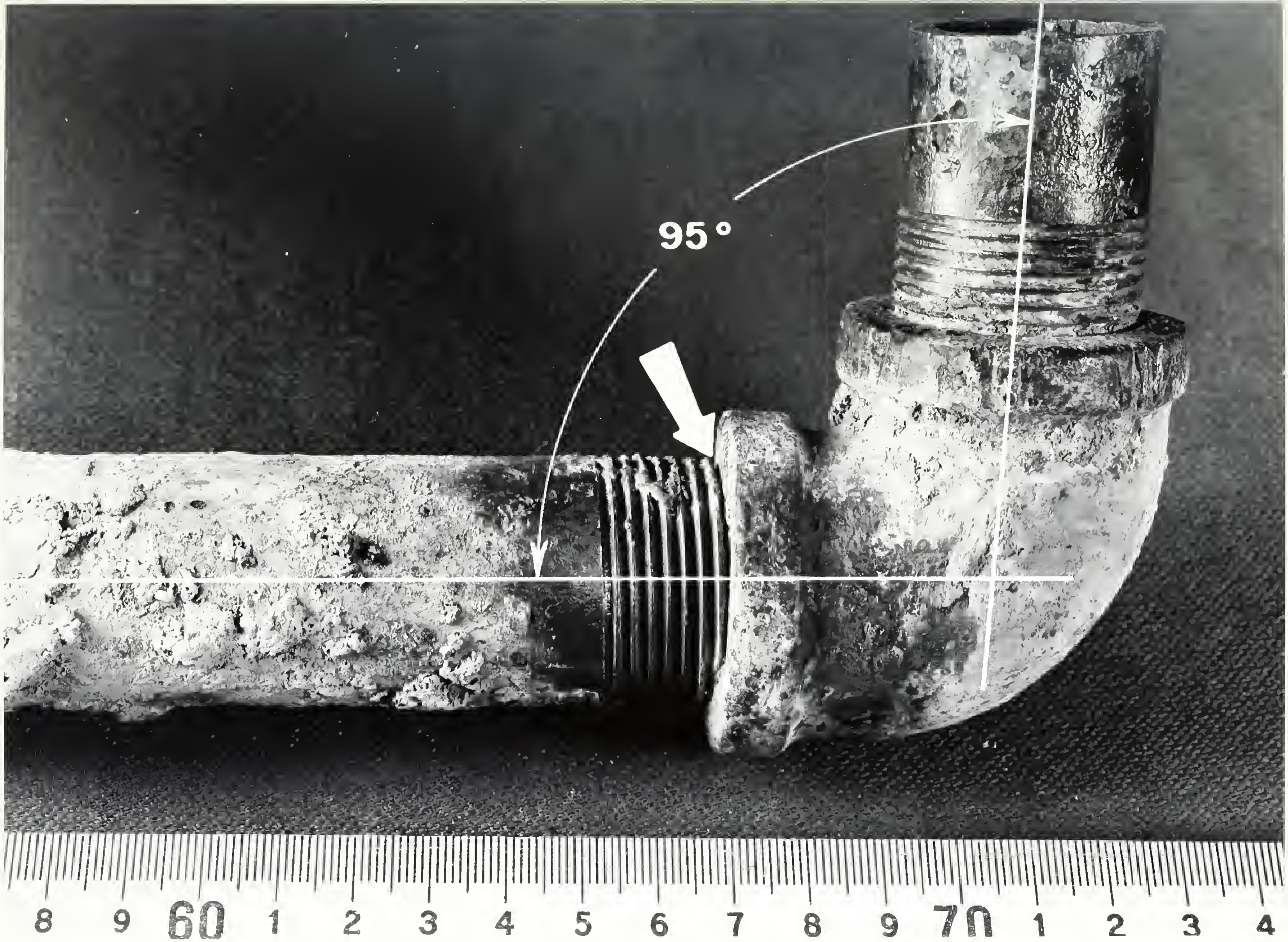


Figure 2. Part of the submitted pipe including the crack (arrow). When received at NBS, the crack faces had separated somewhat and the angle at the nominal 90^{o} bend was about 95^{o}. The region of the pipe near the crack that had been cleaned by the gas company can be seen. X 1.3

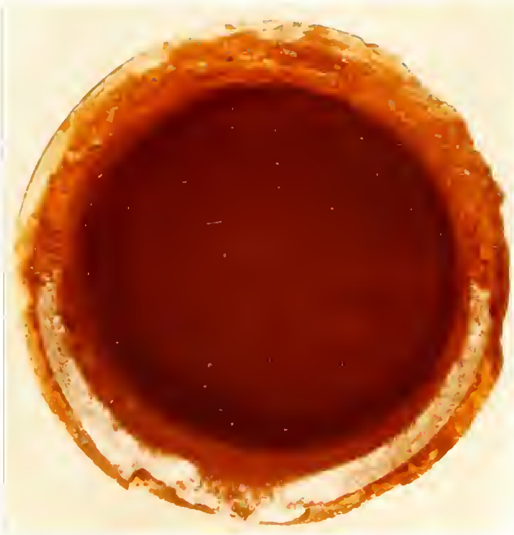
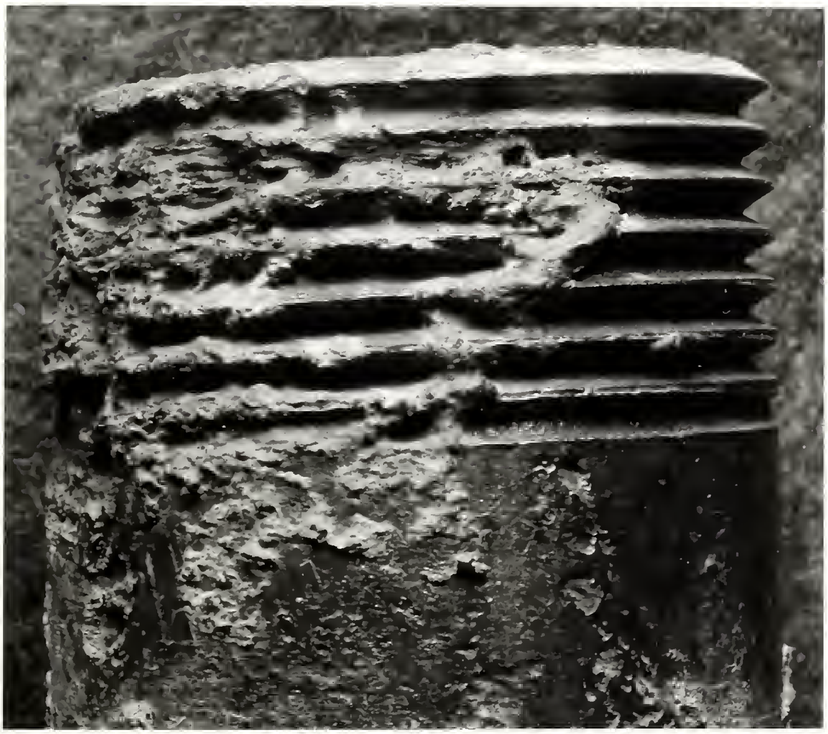


Figure 3. Fracture surface after fracture was completed at NBS and before it was cleaned. The corroded part of the fracture (approximately the top half in the figure) is the field fracture. The bottom half is that part of the fracture completed in the laboratory. X 2

Figure 4. Parts of the field fracture (top) after cleaning and the NBS completed fracture (bottom). Magnification is higher than in figure 3. X 7

Figure 5. Part of the piece of pipe containing the crack about 2 inches from the crack. The pipe surface has been cleaned of soil and scale in this region revealing extensive pitting corrosion. X 7

a.



b.

Figure 6. Parts of the threaded portion of the pipe adjacent to the crack. X 3

a. Severely corroded region.
b. Less corroded region.

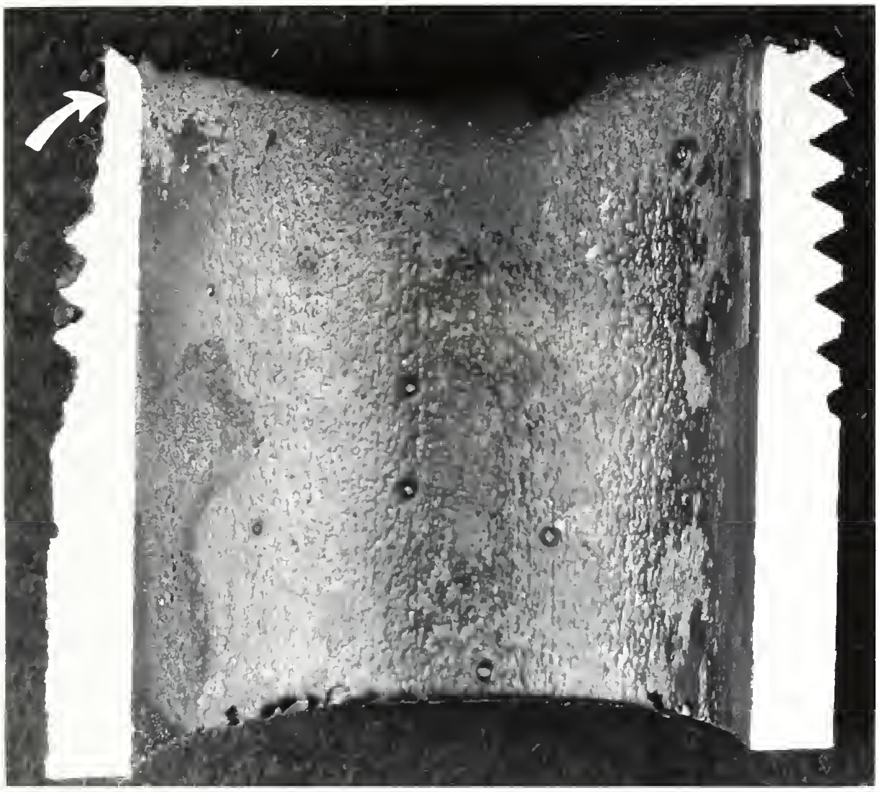


Figure 7. Longitudinal section through the pipe intersecting the fracture (horizontal at top). The threads are severely corroded on the left. The arrow indicates the region of severest corrosion in the section. On the right, corrosion is minimal. X 3

Figure 8. SEM fractograph of the field fracture. Cleavage is the predominant fracture mode. X 255

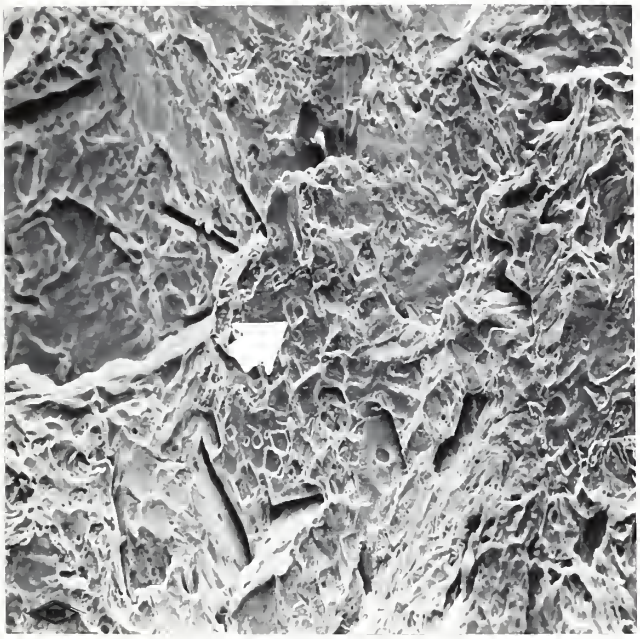


Figure 9. SEM fractograph of the field fracture in a different area from that shown in figure 8. Cleavage is the predominant fracture mode. The geometric depressions appear to be etch pits. One of these depressions is indicated by the arrow. X 240

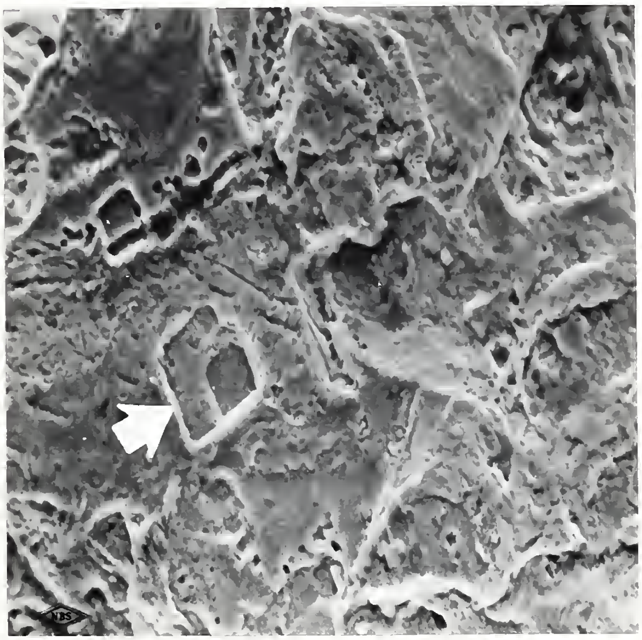


Figure 10. Part of the field shown in figure 9, but at higher magnification. The arrow indicates an apparent etch pit. X 1200

Figure 11. SEM fractograph of the part of the fracture completed at NBS. Dimpled rupture is the predominant fracture mode. X 450

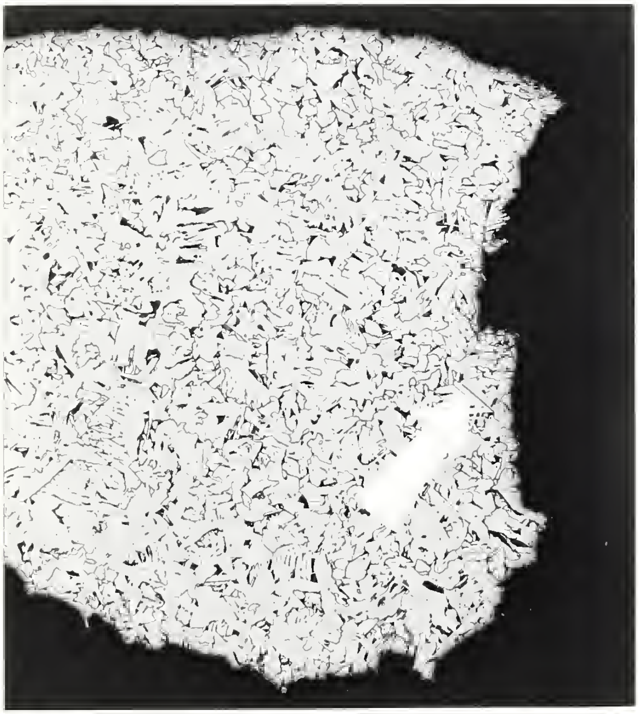


Figure 12. Longitudinal section intersecting the field fracture adjacent to a region where the pipe threads were severely corroded. The fracture profile is vertical at the right. The inside wall surface is horizontal at the top and the corroded threads are horizontal at the bottom. There is some apparent deformation at the fracture adjacent to the inside of the pipe. The crack path is transgranular. The arrow indicates a region of mechanical twinning.
Etchant: 1% nital X 50

Figure 13. Longitudinal section through the pipe showing the field fracture profile (vertical at the right) adjacent to a region where the pipe threads were corroded very little. The inside wall surface of the pipe is horizontal at the bottom and the thread roots are just beyond the top of the figure. There is some deformation at the fracture adjacent to the inside wall surface. The arrow indicates a region of mechanical twinning.
Etchant: 1% nital X 50

Figure 14. Part of the field shown in figure 13 at higher magnification. The arrow indicates the same region of mechanical twinning as indicated in figure 13. Some secondary cracking can be seen.
Etchant: 1% nital X 200

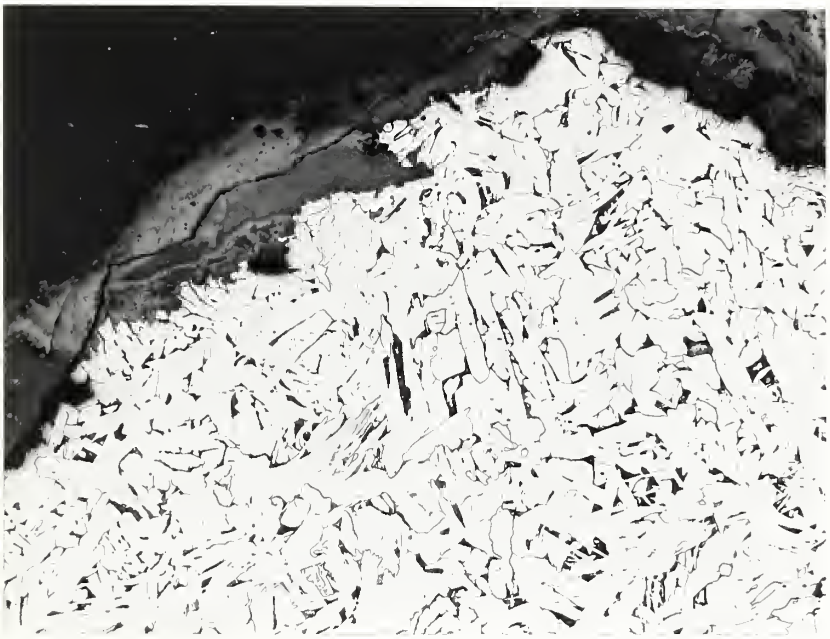


Figure 15. Etched longitudinal section showing part of one of the corroded threads. The grey material along the thread surface is corrosion product.
Etchant: 1% nital X 100

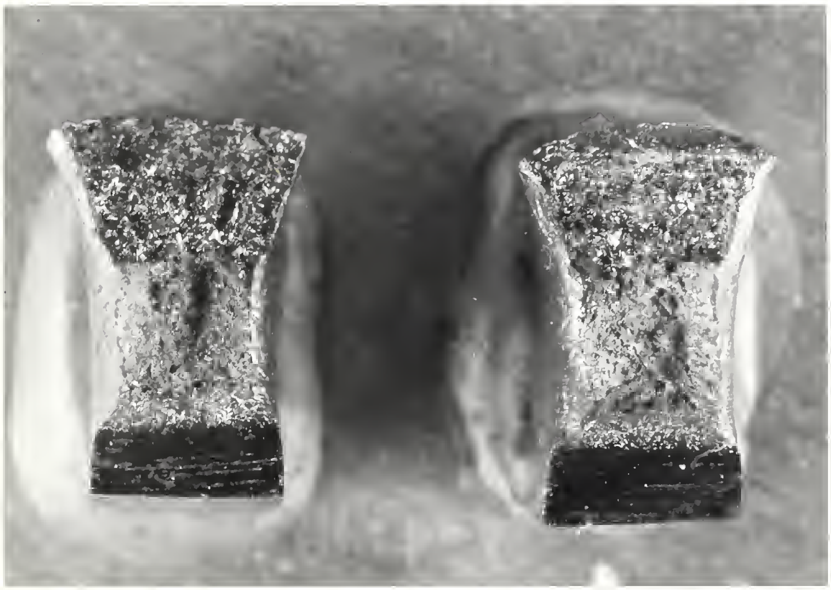


Figure 16. Fracture surfaces of impact specimens tested at NBS. The specimen tested at 0°C is at the left, the one tested at room temperature is at the right. In each case, the notch is at the bottom, dimpled rupture is exhibited in the center region, and cleavage is exhibited in the upper region. A large amount of lateral expansion can be seen in the upper region. X 10

Figure 17. SEM fractograph from the pipe sample tested in tension at 0.02 inch per minute. There is a region of cleavage in the center of the figure. The rest of the fracture exhibited dimpled rupture. X 95

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO.	2. Gov't. Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

EXAMINATION OF FAILED ONE INCH DIAMETER BARE STEEL PIPE NATURAL GAS SERVICE LINE, WAYNESBORO, VIRGINIA, COLUMBIA GAS COMPANY OF VIRGINIA, INC.

5. Publication Date

6. Performing Organization Code

7. AUTHOR(S)

T. R. Shives

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

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

13. Type of Report & Period Covered

Failure Analysis

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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 submitted one inch diameter bare steel gas pipe service line failed due to the initiation and propagation of a transverse crack at the root of a thread where the pipe was attached to a 90° elbow. The primary fracture mode for most of the fracture was cleavage indicating a brittle fracture. The probable fracture mechanism is stress corrosion cracking. The pipe had suffered rather severe pitting corrosion and the threads adjacent to the fracture on one side of the pipe was badly corroded.

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; corrosion; natural gas pipe; pitting corrosion; steel pipe; stress corrosion cracking.

18. AVAILABILITY ☐ Unlimited

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☐ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

19. SECURITY CLASS (THIS REPORT)	21. NO. OF PRINTED PAGES
UNCLASSIFIED	
20. SECURITY CLASS (THIS PAGE)	**22. Price**
UNCLASSIFIED	

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