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Examination of Failed Six-Inch Diameter Cast-Iron Pipe Water Main, Philadelphia, Pennsylvania

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Washington, D.C. 20234

January 1980

Issued April 1980

Failure Analysis Report

Prepared for
National Transportation Safety Board
Washington, D.C. 20594

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U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, *Secretary*

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SUMMARY

At the request of the National Transportation Safety Board, the National Bureau of Standards performed an examination of a fractured six-inch diameter cast-iron pipe water main from Tacony and Margaret Streets in Philadelphia, Pennsylvania. An explosion and fire had occurred at this location on May 13, 1979. At that time, both the six-inch diameter water main pipe and the eight-inch diameter cast-iron natural gas main pipe at the site of the explosion and fire were found to be completely fractured transversely in three places. Failure of the water pipe appeared to be due to an externally applied bending load.

The nonuniform wall thickness indicated that the pipe was pit cast and therefore rather old. Today, such pipe is normally centrifugally cast which results in a uniform wall thickness.

Each of the three fracture faces submitted for examination was covered with a rather tightly adhering layer of corrosion product. The corrosion product was not easily removed, and the corrosion process had obliterated some of the fracture features indicating that the fractures were not fresh. Cleavage was the predominant fracture mode. There was significant graphitization close to the fractures.

The hardness of the material was typical for gray cast iron. The chemical composition was typical for this material, but the phosphorus content was higher than desirable according to today's practice. The microstructure appeared to be satisfactory with the possible exception of more steadite than desirable according to today's practice.

1. INTRODUCTION

1.1 Reference

National Transportation Safety Board, Washington, DC 20594. This investigation was conducted at the request of Mr. Jerry A. Houck, Metallurgist, National Transportation Safety Board. The requesting letter was dated June 25, 1979.

1.2 Background Information

The information in this section was furnished by the National Transportation Safety Board and by representatives of the Philadelphia Gas Works. On May 4, 1979, there was an explosion and fire at Tacony and Margaret Streets in Philadelphia, Pennsylvania. The explosion and fire were attributed to the ignition of an accumulation of natural gas at the site.

After the explosion and fire, both the eight-inch diameter cast-iron pipe natural gas main and the six-inch diameter cast-iron pipe water main at the site were found to be broken. The two pipelines were in close proximity and both lines had fractured completely in a circumferential manner in three places. (The results of an NBS examination of the failed gas pipe can be found in NBS Report NBSIR 80-1985, issued February, 1980).

When the pipelines in the region of the fractures were uncovered, the soil beneath the gas main was missing to a depth ranging from 3 inches to about 3 feet, 9 inches below the level where the pipeline had originally been installed. This missing soil created a cavity and left the gas pipeline unsupported. When the gas line fractured, it fell into this cavity.

1.3 Parts Submitted

Pieces of the water main pipe containing one fracture face from each of the three fractures were submitted to NBS for examination. The parts, designated W1, W2, and W3, are shown as received at NBS in figures 1, 2, and 3, respectively. The pieces shown in figures 1 and 2 were complete, intact transverse sections. The pieces shown in figure 3 (W3) were from a transverse section that included the end of the pipe length. It was reported that this section was fractured longitudinally into the three pieces shown while being removed from the adjoining pipe length. The fracture in W1 passed through the approximate center of a service tap hole in the pipe.

2. PURPOSE

The National Transportation Safety Board requested that NBS determine the mode of failure for the broken water pipe.

3. RESULTS OF EXAMINATIONS, TESTS, AND ANALYSES

3.1 Visual Examination of the Pipe Wall Surface

Each piece of the submitted pipe was covered with a rather adherent layer of soil and some corrosion product. The pieces were cleaned ultrasonically, first with a commercial detergent, and then with buffered hydrochloric acid. Essentially all of the soil was removed from the outside of the pipe by the cleaning procedures. Some corrosion of both the inside and outside walls of the pipe was evident.

There was a lack of uniformity in the pipe wall thickness indicating that the pipe was pit cast, and therefore rather old. As an example of the nonuniform thickness, the wall thickness at the fracture in W1 ranged from about 0.43 inch minimum to about 0.53 inch maximum.

3.2 Fractographic Examination

All three fracture surfaces were covered with corrosion product. The fracture surfaces were cleaned ultrasonically at the same time the pipe walls were cleaned. Some of the corrosion product adhered tightly to the fracture surfaces, and much of it remained on the surfaces after cleaning. The fact that the corrosion product was difficult to remove indicates that the pipe had probably been broken for some time. The cleaned surfaces of fractures W1, W2, and W3 are shown respectively in figures 4, 5, and 6.

Visually and macroscopically, all three fractures appeared similar. Therefore, a detailed fractographic examination was performed on only one of the fracture surfaces. After cleaning, part of the fracture surface from the piece of pipe designated W1 was examined with the scanning electron microscope (SEM). Many of the fracture features had been obliterated by the corrosion process, but the fracture mode appeared to be predominantly cleavage. Cleavage indicates a very low ductility or brittle fracture, which would be expected for an overload fracture in gray cast iron.

A low magnification SEM fractograph is shown in figure 7. Although some of the detail has been lost due to the corrosion process, and some is masked by the corrosion product that remained on the fracture surface, evidence of cleavage can still be seen. A much higher magnification SEM fractograph is shown in figure 8. Corrosion product remaining on the fracture surface is quite evident.

3.3 Examination for Graphitization

Transverse sections were taken close to each of the three fractures. These sections were polished metallographically to determine the extent of graphitization. The sections from W1, W2, and W3 are shown in figures 9, 10, and 11, respectively. Some graphitization adjacent to the inside wall surface is evident in each section, and in some regions, the depth of the graphitization is significant. In one region in the section from W1 (figure 9), graphitization starting at the inside had penetrated about 1/3 of the pipe wall thickness.

The transverse sections from W1 and W2 exhibited essentially no evidence of graphitization adjacent to the outside wall surface, but there was significant graphitization adjacent to the outside wall surface of W3 over most of the circumference of the section. This section is very close to the end of the pipe length.

3.4 Chemical Analysis

A sample from piece W2 was submitted to a commercial laboratory for chemical analysis. The results of that analysis are as follows:

<u>Element</u>	<u>Percent (by weight)</u>
Total carbon	3.21
Combined carbon	1.01
Manganese	0.42
Phosphorus	1.97
Sulfur	0.084
Silicon	1.86
Nickel	0.04
Chromium	0.01
Molybdenum	< 0.01
Copper	0.14

The carbon equivalent¹ (% total carbon + 1/3 (% silicon + % phosphorus)) for the material is greater than 4.3%, indicating that the material is hypereutectic and would therefore be expected to be relatively low in strength. Current ANSI Standard A21.6-1975 (American Water Works Association Standard C106-75) for cast iron pipe centrifugally cast in metal molds, for water or other liquids, and ANSI Standard 21.8-1975 (AWWA C108-75) for cast iron pipe centrifugally cast in sand-lined molds, for water or other liquids, specify a maximum phosphorus content of 0.50% and a maximum sulfur content of 0.12%. Since this pipe was pit cast, and therefore probably rather old, the standards quoted would not apply. They are cited for comparison only. Compared to today's practice, however, the phosphorus content is quite high. Excessive phosphorus leads to the formation of steadite (iron-iron phosphide eutectic). Steadite is hard and brittle, and if present in sufficient quantities, it may have adverse effects on the mechanical properties of the cast iron.

3.5 Hardness Measurements

Rockwell K (HRK) hardness measurements were taken on the transverse section from W2 that is shown in figure 10. Ten measurements were made around the circumference. The range in hardness was HRK 85 1/2 to 97 and the average value was 92.8. The approximate equivalent Brinell (HB) hardness values range from 136 to 176 and the approximate equivalent HB average is 159. The variation in hardness is rather large, but the average hardness is typical for ordinary gray cast iron¹.

3.6 Metallographic Examination

An etched longitudinal section through W1 showing the entire pipe wall thickness with the fracture profile horizontal at the top appears in figure 12. This section passes through a region of graphitization which can be seen adjacent to the inside wall surface at the left. An as-polished longitudinal section through W1 showing part of the fracture profile at higher magnification appears in figure 13. The thin, dark particles are graphite flakes with an essentially type A distribution². A longitudinal section showing the entire wall thickness of W3 slightly removed from the fracture appears in figure 14. This figure is at a lower magnification than figure 12. It should be noted that the region shown is very near the end of the pipe length where it connected to another pipe length while in service. There is significant graphitization adjacent to both the inside and outside wall surfaces.

An etched longitudinal section through W1 in a region which has not been subject to graphitization is shown in figure 15 at much higher magnification than in figure 13. The microstructure consists of graphite flakes (long, thin, dark particles), pearlite (fingerprint pattern), ferrite (light gray patches), and probably steadite (small, rounded particles within the ferrite patches). A region in a longitudinal section through W1 exhibiting almost total graphitization is shown in figure 16.

4. DISCUSSION

This six-inch diameter cast-iron pipe water main fractured completely in a circumferential manner in three places. There was corrosion product on the fracture surfaces. This corrosion product adhered rather well to the fractures, and some of the fracture features had been obliterated by corrosive attack. These two factors suggest that the pipeline had been fractured for some time. In contrast, the fracture examined from the failed cast-iron pipe natural gas main from the same location appeared to be relatively fresh (NBS report NBSIR 80-1985). The pipe failed in a brittle manner as expected for an overload fracture. Cleavage was the predominant fracture mode. The locations of the fracture origins were not established.

One of the fractures passed through the approximate center of a service tap hole in the pipe. This tap hole would have reduced the cross section of the pipe in the plane of the fracture which, in turn, would reduce the load carrying capacity of the pipe somewhat at this location. A significant amount of graphitization was found adjacent to the fractures.

In a region near the end of the pipe length, there was graphitization adjacent to both the inside and outside wall surfaces of the pipe. Away from the end of the pipe, graphitization was found only adjacent to the inside wall surface. The graphitization would have also reduced the effective cross section of the pipe somewhat.

It appears that the pipe failed due to the application of an external bending load.

The chemical composition of the pipe material appeared to be satisfactory with the possible exception of phosphorus. The phosphorus content was higher than desirable according to today's practice. A high phosphorus content may lead to the formation of excessive steadite, a hard, brittle constituent. It is unclear whether the high phosphorus content was a contributing factor to the failure.

The hardness of the material varied considerably, but the average hardness was acceptable for gray cast-iron. The microstructure of the pipe material appeared to be satisfactory although some steadite was present.

5. CONCLUSIONS

1. This failed gray cast iron pipe water main had fractured completely in three places in a transverse manner.
2. Failure appeared to be due to an external bending load applied to the pipe.
3. Much of the corrosion product adhered rather tightly to the fracture surfaces and the corrosion process had obliterated some of the fracture features. These two factors suggest that the fractures had occurred some time ago.
4. The fracture mode was predominantly cleavage indicating that the fractures were brittle, which is normal for gray cast-iron.
5. There was significant graphitization in localized regions near the fractures.
6. The fracture origins were not established.
7. The chemical composition of the pipe material appeared to be typical for gray cast-iron with the possible exception of a higher phosphorus content than is usual in today's grades of cast-iron.
8. The hardness of the material, although exhibiting considerable variation, was within the range typical for gray cast-iron.
9. The microstructure of the material appeared to be satisfactory, with the possible exception of more steadite than desirable.

5. ACKNOWLEDGEMENT

The metallography and hardness measurements were performed by Leonard C. Smith of the NBS Fracture and Deformation Division. The photographic work was performed by Leonard Smith and Joel C. Sauter, also of the NBS Fracture and Deformation Division.

REFERENCES

1. Gray and Ductile Iron Castings Handbook, Gray and Ductile Iron Founder's Society, Inc., 1971.
2. Metals Handbook, 8th Edition, Volume 7, American Society for Metals, 1972.



Figure 1. Piece of submitted pipe designated W1 as received at NBS showing the fracture surface. The fracture passed through a service tap hole. X 2/3



Figure 2. Piece of submitted pipe designated W2 as received at NBS showing the fracture surface. X 2/3





Figure 3. Pieces of submitted pipe designated W3 as received at NBS showing the fracture surface. These pieces had formed a continuous transverse section which was fractured longitudinally into three pieces in the field when it was removed from the adjoining pipe length. X 2/3

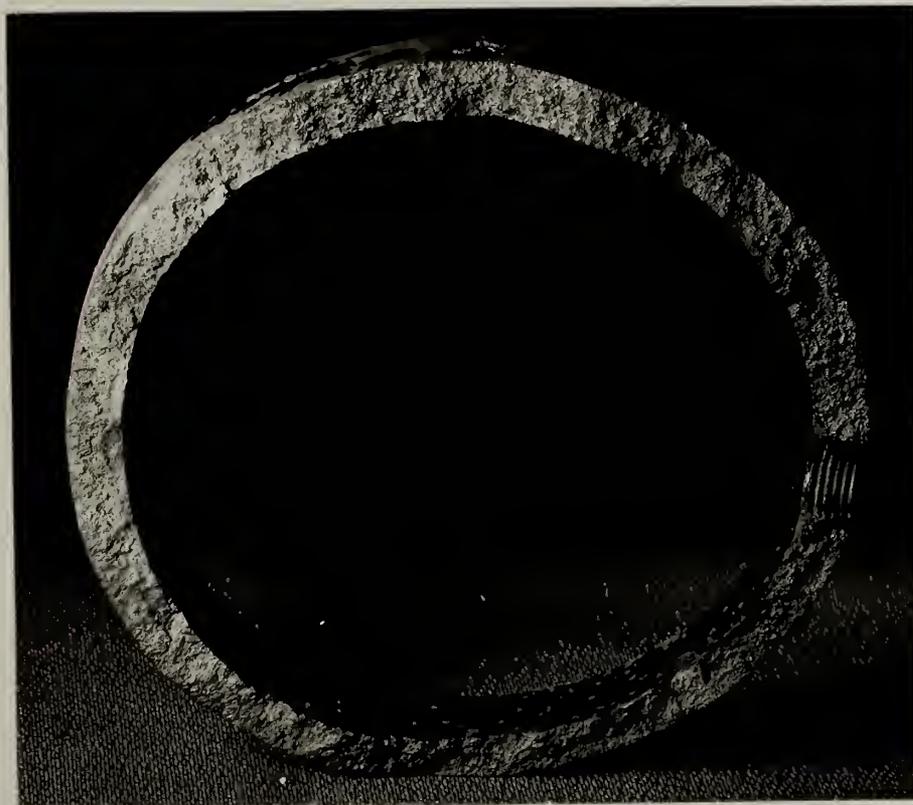


Figure 4. Fracture surface W1 after cleaning. X 2/3





Figure 5. Fracture surface W2 after cleaning. X 2/3



Figure 6. Fracture surface W3 after cleaning. X 2/3





Figure 7. SEM fractograph of W1. The fracture mode is predominantly cleavage. X 185

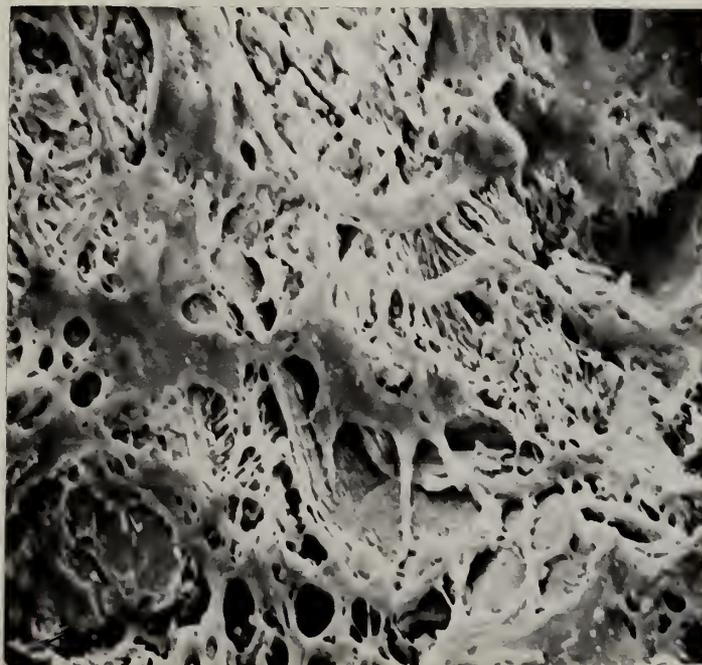


Figure 8. SEM fractograph of W1 at much higher magnification than figure 7. Corrosion product is evident. X 1000

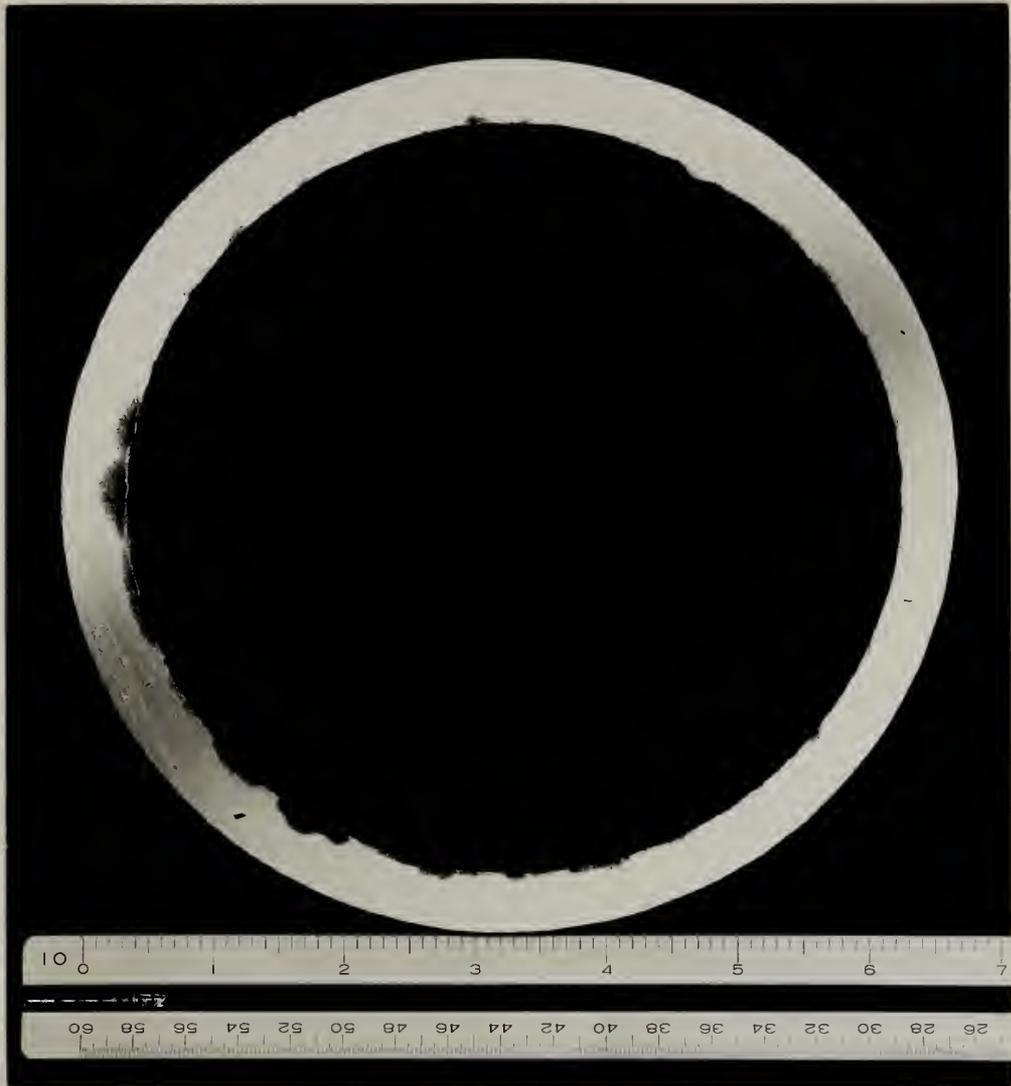
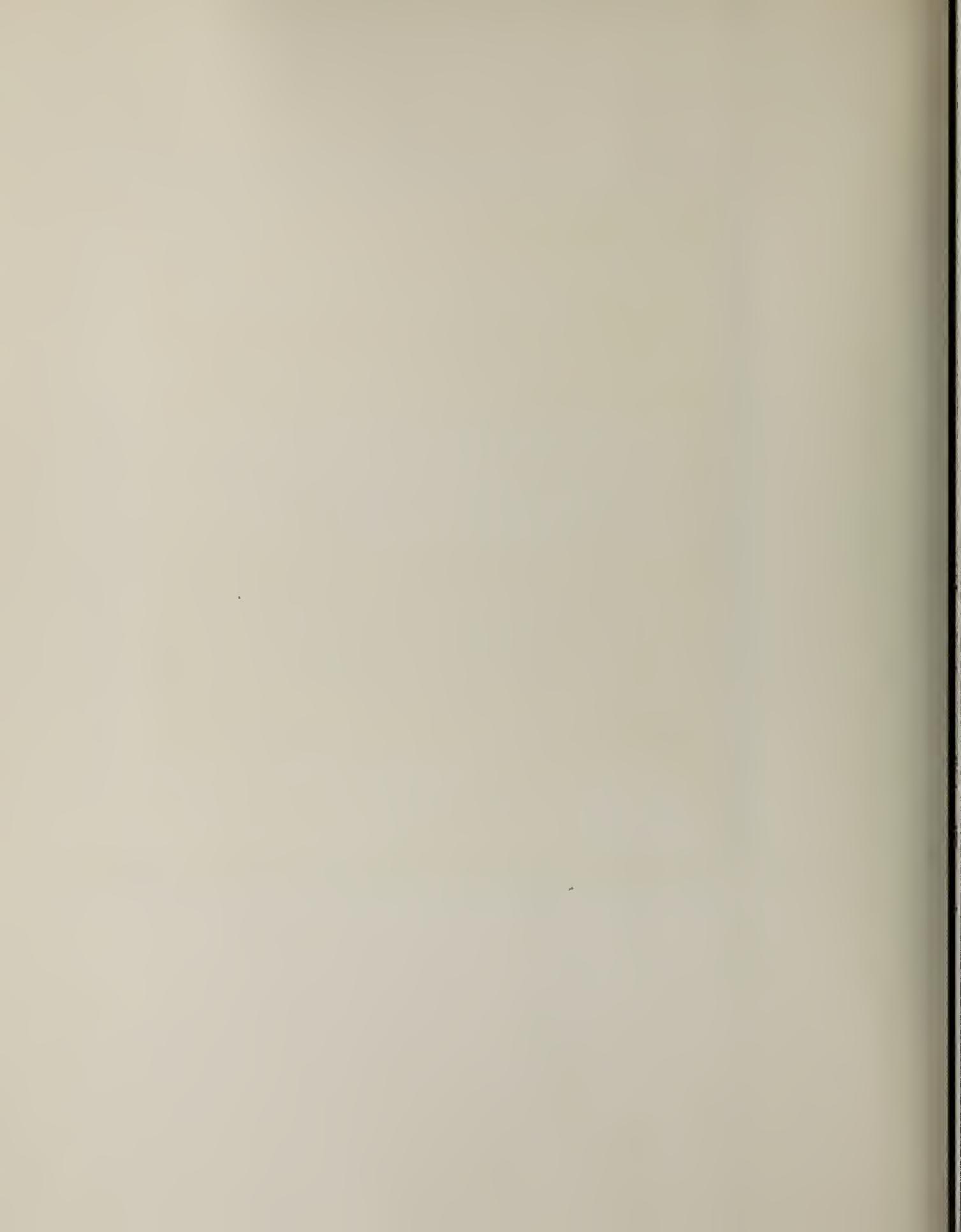


Figure 9. Transverse section through W1 about 3/4 inch from the fracture showing graphitization adjacent to the inside wall surface. X 2/3



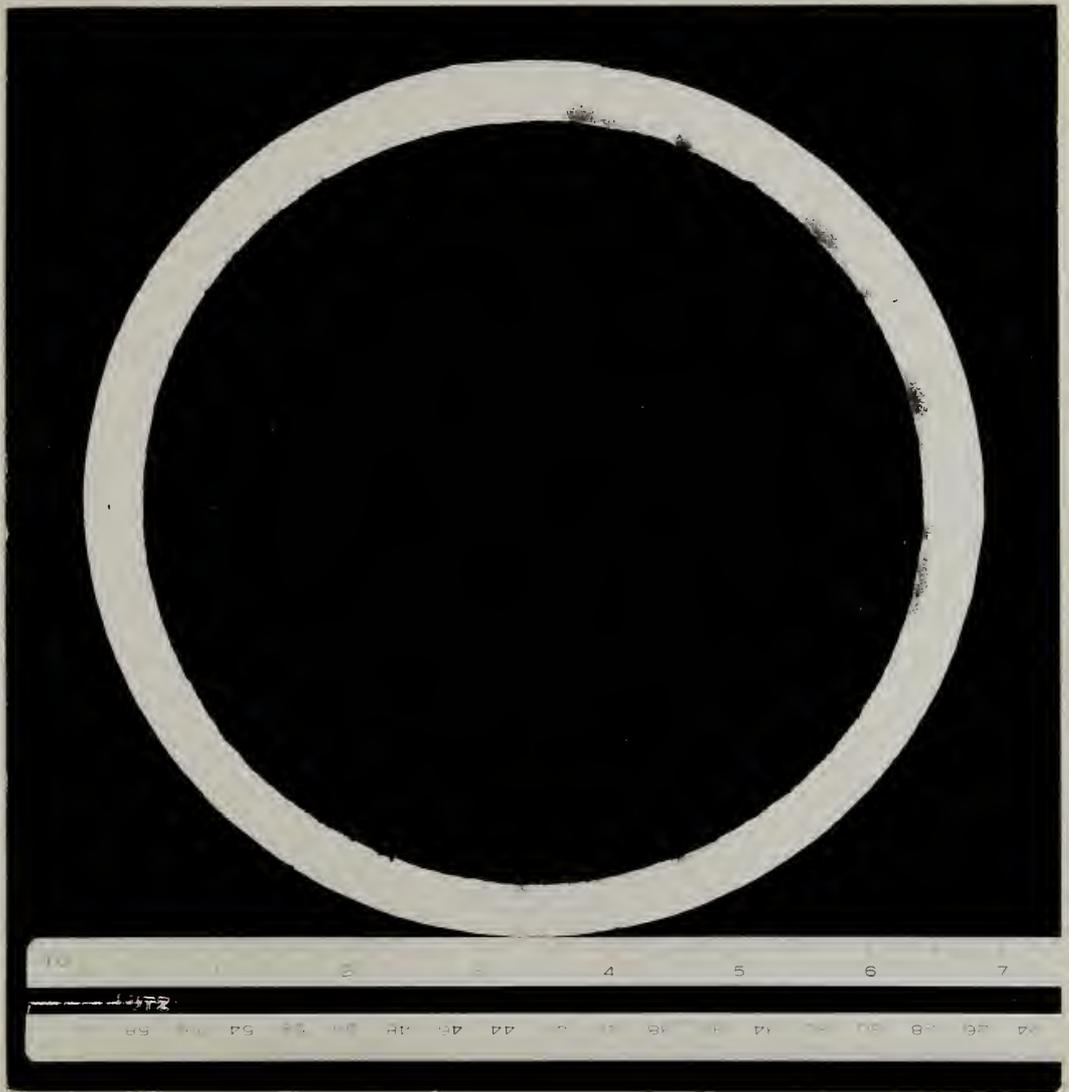
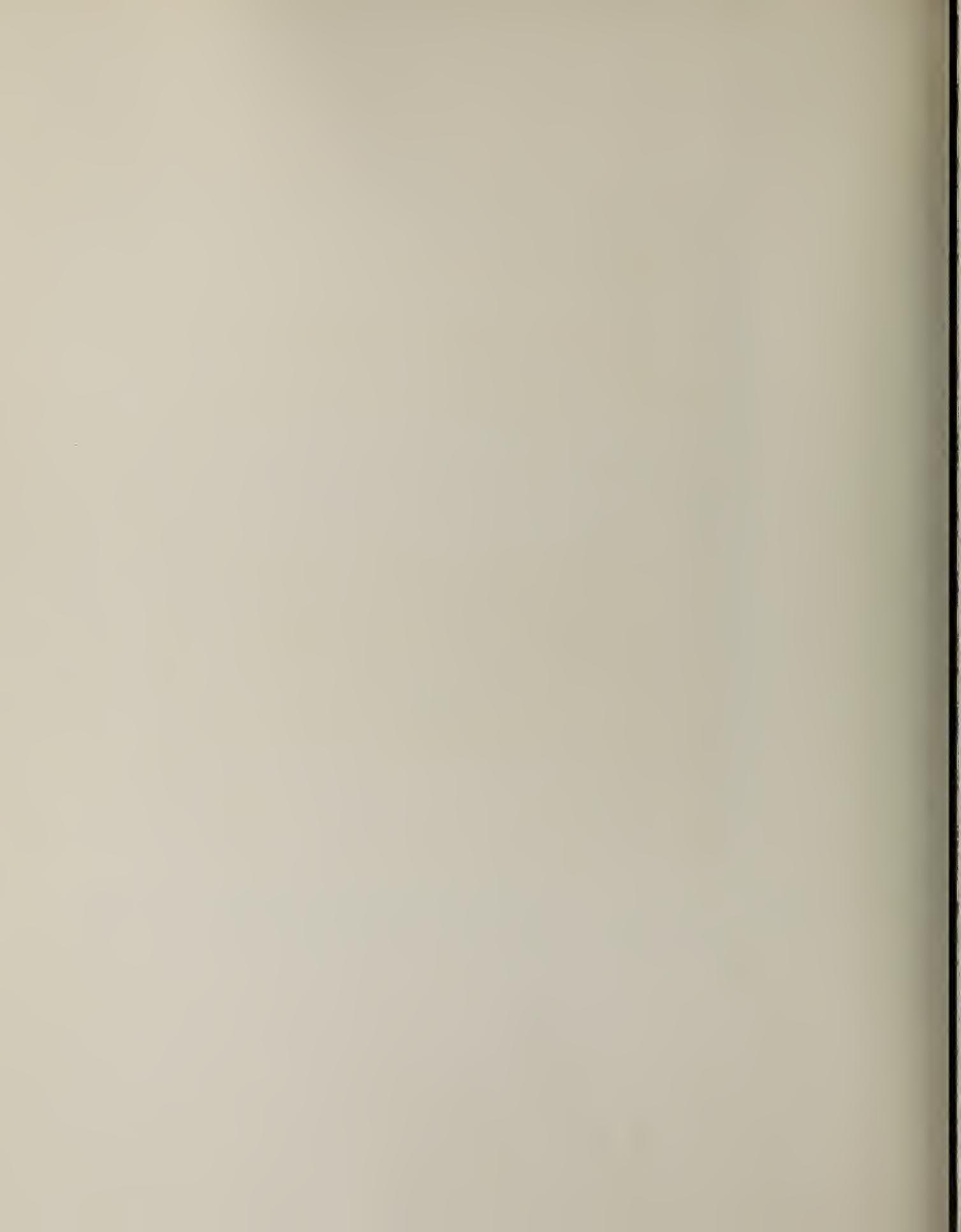


Figure 10. Transverse section through W2 about 3/4 inch from the fracture showing some graphitization adjacent to the inside wall surface.

X 2/3



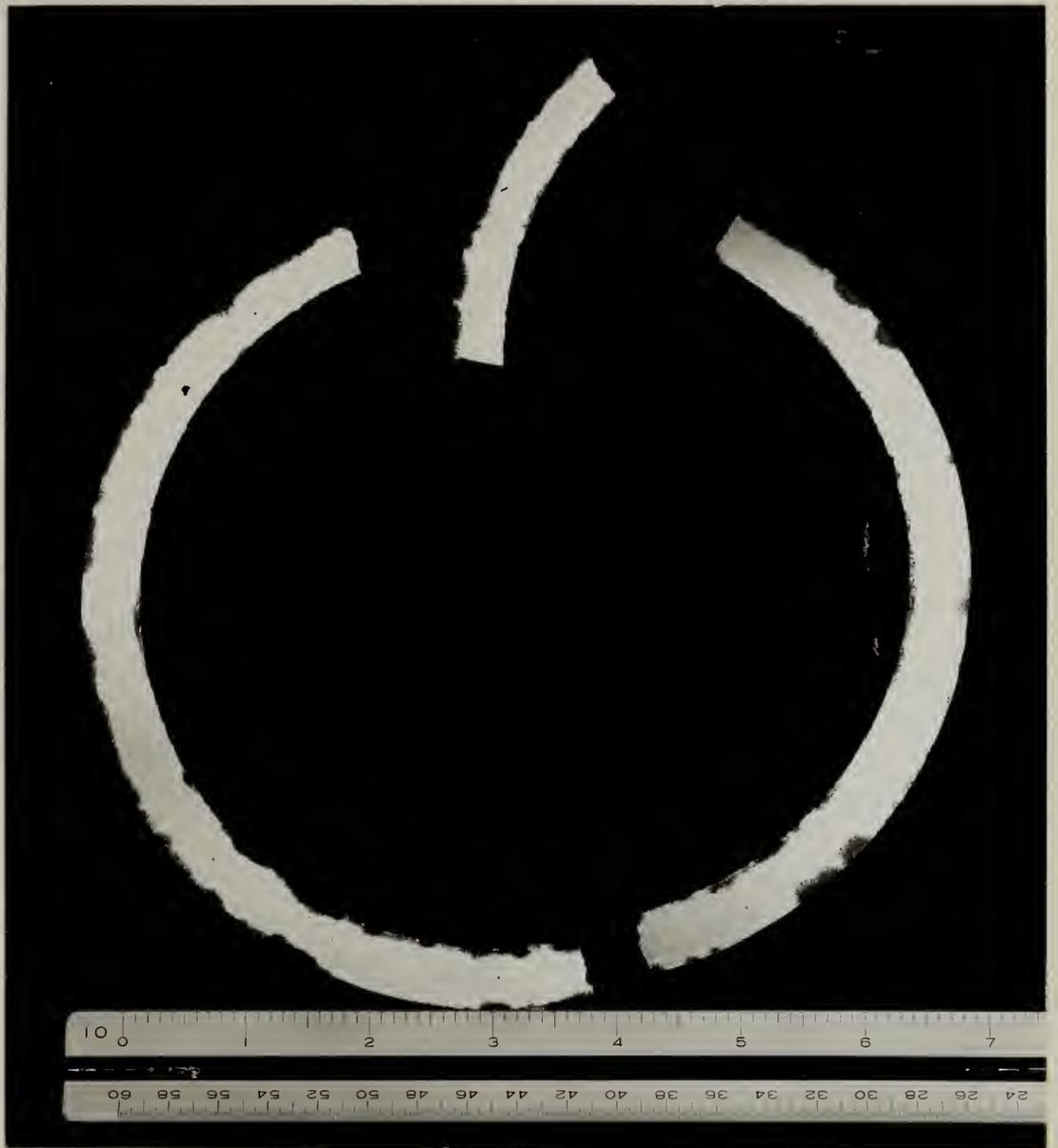


Figure 11. Transverse section through W3 ranging from about 1/2 to 2 inches from the fracture showing graphitization adjacent to both the inside and outside wall surfaces. X 2/3





Figure 12. Etched longitudinal section through W1 showing the fracture profile (horizontal at the top). The entire wall thickness of the pipe is shown. The inside wall surface is at the left and the outside wall surface is at the right. Significant graphitization can be seen adjacent to the inside wall surface. Etchant: 1% nital

X 11



Figure 13. Unetched longitudinal section through W1 showing the fracture profile (horizontal at the top). The thin, dark particles are graphite flakes. The small gray particles appear to be non-metallic inclusions. As polished

X 100



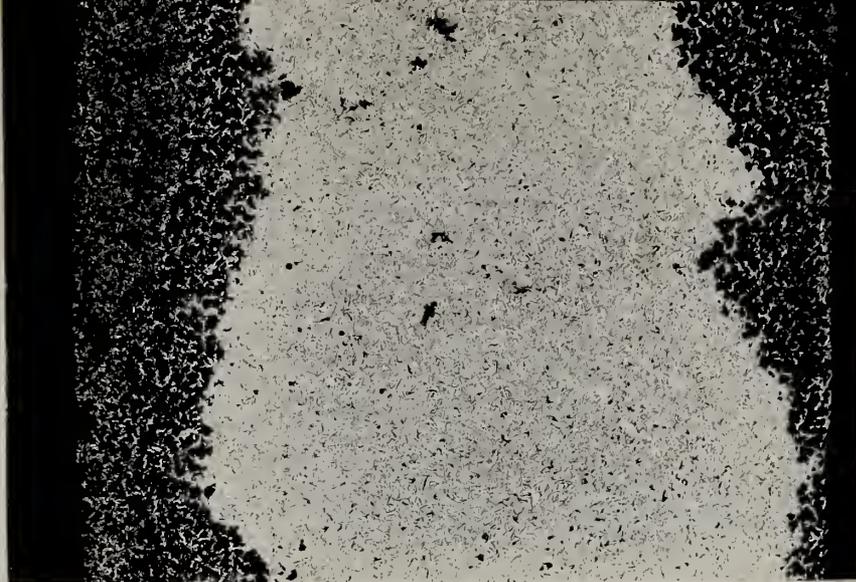


Figure 14. Etched longitudinal section showing the entire wall thickness of W3. Graphitization is evident both adjacent to the inside wall surface (left) and adjacent to the outside wall surface (right).
Etchant: 1% nital X 8

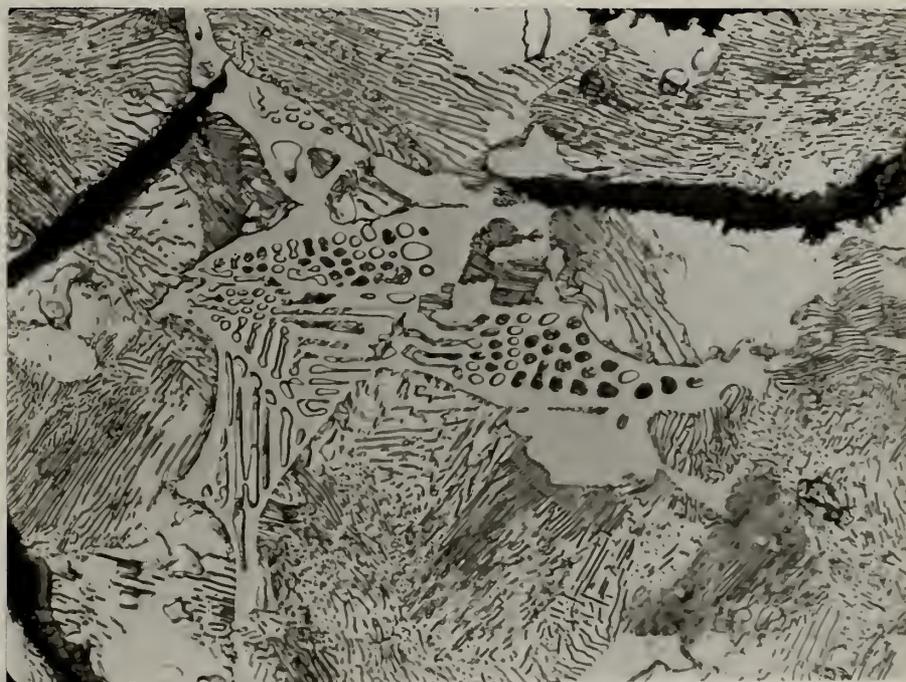


Figure 15. Etched longitudinal section through W1 in a region which has not been graphitized. The microstructure consists of graphite flakes (long, thin dark particles), pearlite (fingerprint pattern), ferrite (light gray patches), and probably steadite (small rounded particles within the ferrite patches).
Etchant: 1% nital X 1000





Figure 16. Etched longitudinal section through W1 in a region that has been essentially totally graphitized.
Etchant: 1% nital

X 1000



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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.) At the request of the National Transportation Safety Board, the National Bureau of Standards performed an examination of a fractured six-inch diameter cast-iron pipe water main from Tacony and Margaret Streets in Philadelphia, Pennsylvania. An explosion and fire had occurred at this location on May 13, 1979. At that time, both the six-inch diameter water main pipe and the eight-inch diameter cast-iron natural gas main pipe at the site of the explosion and fire were found to be completely fractured transversely in three places. Failure of the water pipe appeared to be due to an externally applied bending load. The non-uniform wall thickness indicated that the pipe was pit cast and therefore rather old. Today, such pipe is normally centrifugally cast which results in a uniform wall thickness. Each of the three fracture faces submitted for examination was covered with a rather tightly adhering layer of corrosion product. The corrosion product was not easily removed, and the corrosion process had obliterated some of the fracture features indicating that the fractures were not fresh. Cleavage was the predominant fracture mode. There was significant graphitization close to the fractures. The hardness of the material was typical for gray cast-iron. The chemical composition was typical for this material, but the phosphorus content was higher than desirable according to today's practice. The microstructure appeared to be satisfactory with the possible exception of more steadite than desirable according to today's practice.							
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; Cast-iron; Cast-iron pipe; Cast iron water pipe; Cleavage; Graphitization							
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