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Report No. 10: Examination of a Failed 2-Inch Diameter Galvanized Steel Pipe: Valley Gas Company, Woonsocket, Rhode Island

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Metallurgy Division
Institute for Materials Research
National Bureau of Standards
Washington, D. C. 20234

February 23, 1973

Failure Analysis Report

Prepared for
Office of Pipeline Safety
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

Two sections of a fractured 2-inch diameter galvanized steel pipe used in a natural gas residential distribution service were examined to determine the mode of fracture and to analyze factors that could possibly have contributed to the failure.

Notched impact and tensile specimens taken from the failed section of pipe were tested in uncharged and hydrogen charged conditions at temperatures of from 35 to 212° F for the impact tests and of 35 and 70° F for the tensile tests. The uncharged tensile specimens failed in an entirely ductile manner by dimpled rupture with large elongations. The hydrogen charged tensile specimens failed in a comparatively brittle manner. The impact specimens failed in a similar brittle manner and with low-energy absorption, when tested at the lower temperatures whether charged or uncharged. Impact specimens tested at 190 and 212° F did not fracture.

Scanning-Electron-Microscope (SEM) examinations of the fracture surfaces of the failed pipe and the test specimens showed that the brittle fractures mentioned above were all similar, being fractures of a predominantly transgranular, quasi-cleavage mode with some dimpled rupture being observable at local sites.

Chemical analysis and metallographic examination indicated that the failed pipe was probably conventionally produced (welded and annealed, hot-dip galvanized) steel utility pipe. Surface examination of the corrosion present on the pipe indicated that the pipe had been in service for a significant period of time before the fracture.

The presence of a 10 degree bend in one section of the pipe about 35 inches from the fracture, coupled with a dent and surface scarring present at that point, indicates that the pipe could have been hooked by ditch digging equipment before the fracture occurred.

It was concluded that the fracture had been produced at the root of the pipe thread at its junction with a pipe coupling as the result of the application of an external load. The fracture occurred at that particular point as a combined result of stress concentration by thread and coupling geometry, reduced wall thickness at that thread root, and, possibly, a small previously existing, short crack partially through the wall of the pipe at that thread root. The fracture occurred in a brittle manner with little or no plastic flow, and the brittleness could have been caused by or worsened by the absorption of hydrogen discharged at the thread root, as a result of the galvanic current produced by the galvanized coating used for corrosion protection.

Report No. 10
Examination of a Failed 2-Inch Diameter Galvanized Steel Pipe: Valley Gas Company, Woonsocket, Rhode Island

1. INTRODUCTION

An examination of the fracture of a 2-inch diameter galvanized steel pipe used in natural gas distribution service in Woonsocket, Rhode Island, was requested on February 14, 1972 by Mr. Lance Heverly for the Office of Pipeline Safety, Department of Transportation. It was reported* that the pipe had failed in service on February 8, 1972 and that the failure was accompanied by an explosion which led to the deaths of 3 persons and to injuries to 6 others. It was suspected* that the pipe may have been damaged earlier during the ditch digging and back filling procedures used in a nearby sewer installation. In addition**, a 2-foot boulder was found on top of the pipe after the failure.

The fractured pipe was delivered on February 28, 1972 by Mr. Gerald Harvey, New York Testing Laboratories, Inc. At that time discussions were held between Mr. Harvey, Mr. Lance Heverly (OPS) and Dr. M.L. Picklesimer (NBS) on the examinations and tests to be conducted. In the course of these discussions, Mr. Harvey obtained by telephone the following additional information from a Mr. Bateman of the Valley Gas Company, Woonsocket, Rhode Island: (1) the soil around the filed pipe consisted primarily of loose gravel, and (2) gas service to the house which exploded had been disconnected on June 1, 1971 by cutting out a 3-foot length of pipe.***

1.1 Parts Submitted

The fractured pipe was delivered in two pieces, with each piece containing one of the fracture faces of the failed pipe section. One piece was short, about two feet in length, and the other was relatively long, about seven feet in length, with a coupling on one end. These are shown in Figures 1 and 2,respectively.

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* Conversations between Mr. Lance Heverly, Office of Pipeline Safety, and Dr. M. L. Picklesimer, National Bureau of Standards on February 14, 1972.

** Conversation between Mr. Donald Whitcolm, Rhode Island Public Utilities Commission and Dr. M. L. Picklesimer, National Bureau of Standards on February 24, 1972.

*** No information was obtained about the acidity, or electrical resistivity of the soil. The soil temperature was estimated to be just above freezing.

1.2 Objectives of the Examination

The principal objectives of the examination to be conducted on the failed pipe were (1) to characterize the fracture surface to attempt to determine the fracture mode, and (2) to attempt to determine the cause of the failure and/or obtain information pertinent to this objective.

2. EXPERIMENTAL PROCEDURES

2.1 Macroscopic and Microscopic Examinations

Each of the two pieces of failed pipe was examined macroscopically and photographed. The fracture faces of both pieces were also examined with a stereomicroscope at magnifications of from 7X to about 20X.

The shorter of the two pieces of pipe was sectioned for examination [in the Scanning Electron Microscope (SEM)] of the fracture surfaces at locations A, B, and C, as shown in Figure 1. The sample from location C was also used to determine the elements present in the surface coating on the pipe. Each sample contained a fracture section about 3/8-inch wide by the full remaining wall thickness by about 1/4-inch long. In addition, a metallographic specimen was taken as a longitudinal cross-section adjacent to the location of sample C.

2.2 Preparation of Specimens

Longitudinal impact and tensile specimens were machined from the lower portions of the shorter length of the failed pipe. Typical impact and notched tensile 1-inch gage length specimens are shown in Figure 3. All of the specimens retained the nominal 2-inch diameter curvature of the pipe in the gage sections.

The impact specimens were made as subsize Charpy V-notch* type, 3/8-inch wide by 2 3/8-inch long by full wall thickness, with the notch located at the midpoint along the length of the specimen.

The tensile specimens were of three modifications of the sheet-type geometry: (1) 1-inch gage length, notched, (2) 2-inch gage length, notched, and (3) 2-inch gage length, unnotched.

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* The curvature of the pipe was retained in these specimens and so they are non-standard subsize Charpy specimens.

The gage section of the tensile samples was approximately 3/8-inch wide by the full-wall thickness of about 1/8 inch. The grip ends of these specimens were 1 1/8-inch wide by 1 1/4-inch long by 1/8-inch thick. Prior to testing, the grip ends of the tensile specimens were flattened with a hammer to make them compatible with the available tensile-testing grips. This caused no deformation of the gage section. The unnotched specimens were tapered slightly along the cut edges of the gage section, so as to promote failure within the gage length. The notched-tensile specimens were notched at the center of the gage length.

The notches on both the impact and the notched-tensile specimens were located in the convex side of the specimen, corresponding to the outer surface of the pipe. For the notched tensile specimens, the notches were made with the sharp edge of a jeweler's file, while being observed at 7X under a stereomicroscope. The file produced a notch with a root radius of about 0.010 to 0.015-inch, and with a depth of about 0.018 inch as gaged with an 0.018-inch diameter copper wire. Filing was continued until the wire gage could be placed flush with the surface of the specimen. Before notching the impact specimens, corrosion products and some of the parent metal were cleaned from the surface over a band at the center of the specimen length. The notch was then located in the center of this band, as shown at location 2 in Figure 3. These notches were machined to provide a root radius of 0.010 inch at a notch depth of about 0.025 inch, in accordance with ASTM Standard E 23-66 for Subsize Charpy V-notch specimens.

2.3 Hydrogen Charging Procedures

For most of the tensile and impact tests conducted, specimens were prepared so that results for both hydrogen-charged and uncharged conditions could be obtained. Hydrogen charging for all of these tests, except for one tensile test, was accomplished by placing the specimen in a 5 percent H_2SO_4 (sulfuric acid) aqueous solution, with the specimen as the cathode and an annular stainless steelsheet as the anode in an electrolytic cell established with a 1.6V dry-cell battery. The specimen was surrounded by the anode and was separated from it by the electrolyte. Prior to charging with hydrogen, the unnotched tensile specimens and the impact specimens were coated with wax along their machined edges. The impact specimen tested at 190° F was also waxed on both the convex and concave surfaces except in the region of the notch.

The only exception to these charging practices was made for the test referred to later in this report as the "interrupted tensile test". For this test, the acid electrolyte was replaced with a 1M Na_2SO_4 electrolyte to avoid excessive corrosion from the long-time exposure to the acid charging solution. The sulfuric acid electrolyte was found to be too corrosive during the extended time tensile test of Specimen No. 12, which broke near one of the grip ends of the specimen after pronounced corrosive attack there.

2.4 Procedures for Impact and Tensile Testing

Impact specimens were tested at temperatures of 35, 70, 190, and 212° F. The test method used was in accordance with ASTM E 23-66 for notched-bar impact testing of metallic materials.

The tensile specimens were strained in tension at a cross-head rate such that a loading rate of 100 pounds per minute was obtained in the range of loads near 1000 pounds. This cross-head rate was established by successive approximations during continuous loading in an electro-mechanical tensile machine, and the testing machine was then allowed to run at that cross-head rate until the specimen fractured.

One of the notched tensile specimens was tested with a procedure referred to herein as the "interrupted tensile test". This test was conducted by loading the specimen in the manner given above until a load of 2000 pounds was reached. This load (2000 pounds) was near or only slightly less than the maximum load observed in a companion specimen tested under slightly different environmental conditions. After the initial load application to 2000 pounds, the machine was stopped so that the cross-head was fixed (i.e. "constant strain" in the specimen). After an initial load drop occurred (completed in less than one minute) observations were made over a period of several hours (1 to 17) to determine if the load continued to drop. If it had, the specimen should fracture eventually, indicating that fracture might have been produced by the initial strain application in service. If no additional drop in load occurred during the observational period, the load was reapplied in accordance with the schedule given in Appendix A, until failure occurred during the last application of load.

3. RESULTS

3.1 Macroscopic Examinations

The fractured pipe was received in two pieces, each containing one of the fracture faces of the failed pipe section and both containing a longitudinal seam weld visible on the interior. One piece was short, about two feet in length, with one end cut with a saw and the other end being one face of a fracture at the root of a pipe thread. The shorter length of pipe had apparently been threaded into a coupling on one end of the longer piece of pipe, where the face of a fracture was still in place. The fracture had occurred at the root of the thread just at the end of the coupling. The fractured end of the shorter length of pipe is shown in Figure 1, and several views of the longer length of pipe are shown in Figure 2. Careful comparison of surface irregularities on the fracture faces of both sections of pipe showed that the two faces mated, and the two had originally been one piece of pipe. The mating fracture faces are shown in Figures 1a and 2b.

The longer length of pipe was bent about 10 degrees at a point located approximately 35 inches from the end of the coupling containing the fracture. An opposite bend of approximately 6 degrees was present at a distance of about 63 inches from the same end of the coupling. The coupling was marked with a longitudinal stripe of "watery" orange paint of some sort in the plane of both bends in the pipe. If this stripe had been put on the top of the pipe while in place in the ground before removal, then the pipe had been pulled upward at the major bend. Both sections of pipe and the coupling appear to be galvanized, and all had a wide band of "rust" along the line of the paint stripe.

The point at which the pipe had received its major bend is shown in Figure 2 as point G. The surface of the pipe at point G was dented and scraped, as though it had been hooked by a strong, pointed device and pulled to make the bend, dent, and scrape. Point G is oriented about 180 degrees around the pipe from the orange paint stripe and a local site at which the fracture appeared to be ductile (progressing across a thread from one thread root to another). The apparent ductility at this site and the brittle fracture appearance of the balance of the fracture surface, indicated that this local site was the last to fail.

Each of the two fracture faces contained some rust at scattered locations, but the rusted areas matched clearly at only one position on the fracture, location C on one and location C' on the other. These are shown in Figures 1 and 2, respectively, and the features are compared directly in Figure 4. Since the rust was present on both faces in the same pattern, and the rusted areas of both fracture surfaces were depressed below the level of the "freshly fractured" part of each, it appears probable that the rust formed in a crack that existed before the final fracture occurred.

Looking directly along the longitudinal axis of the 7-foot long pipe from the end of the fracture, there is an angle of roughly 45 degrees between location C' and location G (which lies in the plane of bending) where the pipe appeared to have been externally loaded. It is probable that an external force applied at location G could have produced high tensile stresses at location C in a constrained piping system. In addition, rust observed on other parts of the outer surface of this pipe, as described below, was not generally present on the surface at location G.

Corrosion products in the form of a reddish oxide, presumed to be either iron oxide or oxides of a zinc-iron intermetallic phase, were abundant on the exterior surface of the shorter pipe. The coupling and much of the area of the longer pipe were less prominantly covered with this oxide. Other exterior parts of both pipes and the coupling were also grey or white in appearance in parts and these parts were presumed to be covered with zinc metal, zinc-iron intermetallics and oxides of zinc. The interiors of both pipes were grey and white in appearance and they were presumed to be covered with zinc metal and zinc oxide.

3.2 Metallographic Observations

The longitudinal and transverse sections taken from the shorter pipe showed nothing unusual in either the inclusion content or the microstructure of the steel. Longitudinal sections of the pipe in the unetched and the etched conditions are shown in Figure 5. The inclusion content of the steel is not high. It was roughly estimated to be below number 2 thin, for inclusions of Types A and B using the ASTM E 45 Method A rating.

The microstructure of the steel is a mixture of ferrite and pearlite, which are present in proportions that would correspond roughly to that of an SAE 1015 steel in the annealed or the hot-rolled conditions. the ferrite grains are irregular and elongated, and the pearlite colonies are small in size. On both the inner and the outer surfaces of the pipe, layers of intermetallic phases and zinc metal were observed, with the thickness of this layer being generally much greater on the inside of the pipe and lesser on the outside in the locations examined. Most of the exterior surfaces examined on the fractured pipe near the fracture face appeared to have very little or no zinc or iron-zinc intermetallics.

Examination of the microstructure of a longitudinal section taken at location C revealed that the microstructure just beneath the corroded region was essentially the same as that just beneath the fractured surface. In fact, these microstructures are indistinguishable from those at the other locations examined.

In concurrence with the findings from the macroscopic examinations of the fracture surfaces, the stereomicroscopic examinations of the fracture faces revealed that the fracture had occurred with little evidence of ductility, except at the local site that is about 180° from orientation G. This examination also confirmed two presumptions made after the macroscopic examination: (1) the corroded areas at location C and C' were depressions on the mating fracture surfaces, indicating that corrosion had occurred here on both faces, and (2) the uncorroded parts of these same locations, C and C', appeared to be mating fracture surfaces with the "hills" on one of the two faces matching in size and shape with the "valleys" on the mating fracture face.

3.3 Fractography of the Failed Pipe

In concurrence with the observations made with the light microscope, the fracture appearances were predominantly brittle at locations A, B, and C, as viewed in the Scanning Electron Microscope (SEM). This is shown by fractographs taken on specimens from locations A and C, respectively, in Figures 6 and 7 at magnifications of from 35X to 350X. The fracture mode is a brittle mode of predominantly transgranular quasi-cleavage, with local sites (indicated by arrows within the figures) where there is evidence of local ductility in

the form of dimpled rupture observable only at higher magnifications. These dimpled-rupture sites are believed to be the last sites to fail in the fracture process. It is believed that these local sites could have been athermally heated by the preceding fracture processes. This would have resulted in increased toughness and ability to flow plastically at the sites that failed last. The resulting fracture appearances would be a few local sites of ductile fracture (dimpled rupture) in a sea of quasi-cleavage fracture, as was actually observed on the samples examined.

There were occasional sites where intergranular cleavage (as contrasted to transgranular cleavage) was observed on both the pipe fracture and the fractures of the impact and tensile specimens (discussed later). This fact is not deemed important enough to justify further comment.

Two of the fractographs taken at location C, given in Figure 7, show a deposit on the fracture surface which is believed to be the corrosion product discussed previously. This deposit lies between the lines C-C and A-A in Figure 7a, and below line C-C in Figure 7b. Comparison of fractographs made before and after ultrasonic cleaning of this specimen shows that only a small amount of the rust deposit was removed by cleaning, as can be seen by comparing the same area in Figure 7a (after cleaning) with that in Figure 7b (before cleaning). The surface features in this area (marked U on the fractograph) were not as sharp or well-defined as those of nearby sites above the line C-C.

The principal elements present in the inner and outer surface layers at location C on the pipe were determined by x-ray emission analysis in the SEM. Both zinc and iron were strongly detected on these pipe surfaces. These qualitative analyses are consistent with the metallographic observations previously discussed.

3.4 Impact Test Results

The results of the V-notch impact tests of longitudinal specimens taken from the failed pipe are presented in Table 1. The data in Table 1 show that over the range of temperatures from 35° F to room temperature (about 70° F) and for both hydrogen-charged and uncharged specimens, the steel was not

very tough, absorbing less than 3 ft-lbs of energy per specimen. This indicates that, at service temperatures at and below normal room temperature, the pipe would have had very low resistance to fracturing by impact loads.

At temperatures of 190 and 212° F, the steel was much tougher, absorbing 12 and 18 ft-lbs per specimen, respectively. As shown in Figure 8, these specimens did not fail when tested. They simply bent enough to be pushed through the anvil by the striker of the test machine. In contrast with this behavior, the specimens tested at (and below) room temperature failed either completely or almost completely, as also shown in Figure 8. In the latter cases a small ridge of steel at the back of the specimen remained unfractured after the test. Their fracture faces have many tiny crystallographic facets which are highly reflective to light, indicating that the failure mode was relatively brittle.

3.5 Fractography of Impact Specimens

Fractographic examinations of the fractures of impact specimens (numbered 1, 2, 4, and 5) tested at temperatures at-and-below room temperature showed that all were similar in appearance in the region of the specimen that had been failed under the impact load. Hydrogen-charged specimens could not be distinguished from uncharged specimens. These appearances were not unlike those of the fracture of the failed pipe discussed earlier.

The stereoscopic fractograph of specimen number 5, shown as Figure 9, represents roughly the center 1/3 of the total-fracture surface. This stereo pair and the general appearances of the other fractures, represented by fractographs of specimen Nos. 5 and 1 given in Figure 10, are not unlike those shown earlier for the failed pipe given in Figures 6 and 7. The fracture mode is brittle, being predominantly transgranular quasi-cleavage, with local sites (indicated by arrows in Figure 10) of dimpled rupture observable at higher magnifications.

3.6 Tensile Test Results

The results of the tensile tests are given in Table 2. The data indicate that (1) the steel is notch strengthened, (2) hydrogen charging decreases the strength of notched specimens, (3) hydrogen charging markedly decreases the ductility of both the notched and the unnotched specimens, and (4) the data for 1-inch gage length specimens is similar to that for 2-inch gage length specimens.

The effect of notch strengthening is shown by comparing results of uncharged, 2-inch gage length specimens in the notched and unnotched conditions. The notched tensile strength is about 24 percent greater than the unnotched strength. The former is 68.0 ksi (average of 2 tests) and the latter is 53.7 ksi (one test).

The decrease in notched strength produced by charging with hydrogen is similar for the 1- and 2-inch gage length specimens. When averaged together, the notched strength data indicate that the average strength of uncharged specimens (numbered 3, 2, 8, and 5) is 67.1 ksi, and that of the charged specimens (numbered* 4, 1, 6, and 12) is 51.8 ksi, representing a decrease of about 23 percent in notch-tensile strength due to charging with hydrogen.

Thus, the decrease in notch-tensile strength due to hydrogen almost equals the increase in strength due to notch strengthening. Consequently, the notched hydrogen-charged specimens have about the same load carrying capacity per unit area (of remaining metal) as unnotched, uncharged specimens.

The effect of hydrogen charging on the ductility of the pipe is similar for the 1- and the 2-inch gage length specimens and it is observable in both unnotched and notched specimens. For the unnotched specimens, the reduction of area of the uncharged specimen is 52.3 percent, whereas that of the charged specimen is only 17.4 percent, representing a 67 percent decrease (2/3 of the original value) in the reduction of area, due to hydrogen. For notched specimens this value is a 70 percent decrease in reduction of area. The elongation values of notched specimens show an even greater effect, with a decrease of 85 percent of the original uncharged elongation being observable in hydrogen-charged specimens. The average elongation values for four specimens in each condition are 23.8 and 3.6 percent, respectively for the uncharged and charged specimens.

3.7 Interrupted Tensile Test Results

The interrupted tensile test (see section 2.5) specimens continued to sustain loads without noticeable slow-crack growth, even at load levels near the ultimate load for the specimen.

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* Data for Specimen No. 14 is not included here because it was tested differently.

This single test result indicates that slow-crack growth could not be obtained in one of the notched tensile specimens under the charging and loading conditions used. However, we note that charging with the 1M Na_2SO_4 solution, most likely, was not as severe as charging with the 5 percent H_2SO_4 solution used for the other test specimens. This conclusion is partly confirmed by the slightly greater ductility and much greater strength of the interrupted test specimen when compared with specimen Nos. 6 and 12, which were continuously strained to failure in the H_2SO_4 electrolyte.

3.8 Macroscopic Appearances of Fractured Tensile Specimens

The ductility losses of hydrogen-charged specimens are observable on the photographs of the fractured tensile-test specimens shown in Figures 11 and 12 for the notched specimens and in Figure 13 for the unnotched specimens. Each photograph shows two views of a test specimen; one view is along the length of the specimen in the region near the notch and the other view shows the fracture surface of the mating half of the same specimen.

All of the notched and unnotched specimens show necking (reduction of the cross-sectional area at the fracture) for the uncharged specimens (those at the tops of the figures) and little or no apparent necking for the charged specimens (those at the bottoms of the figures). Furthermore, the appearances of the fracture surfaces are markedly different for charged and uncharged specimens. The uncharged specimens show evidence of gross plastic flow in the form of large lips of shear fracture at the edges of the fracture face, whereas the charged specimens show virtually no shear lips. The charged specimens are thus quite flat in comparison. On these flat surfaces are seen numerous shiny facets which reflect light. These fracture appearances indicate that the fractures of the uncharged specimens are ductile while those of the charged specimens are comparatively brittle.

3.9 Fractography of Tensile Specimens

The fracture surfaces of specimens numbered 1, 2, 4 to 8, 11, and 14, were examined in the SEM. The results of the examinations are summarized in Figures 14 through 16. In general, the fractography of these samples indicated that all of the uncharged tensile samples examined (Nos. 2, 7, and 8) failed by a ductile mode (dimpled rupture), whereas all of the charged tensile samples examined (Nos. 1, 4, 11, and 14) failed by a comparatively brittle mode of predominantly

transgranular quasi-cleavage, with local sites of dimpled rupture observable only at higher magnifications. Furthermore, the fracture appearances of the charged tensile specimens were not unlike those of the impact samples (Nos. 1, 2, 3, and 4) discussed earlier and not unlike those of locations A, B, and C from the failed pipe.

Figure 14 shows a stereographic pair of fractographs of an uncharged notched tensile sample (No. 2) taken at 13X as well as a representative fractograph taken at 650X on this fracture surface. The dimpled rupture shown here is characteristic of the general appearance observed on the fracture surfaces on all of the other uncharged tensile samples.

Figure 15 shows a stereographic pair of fractographs taken at 19X on the fracture of a charged tensile specimen (No. 11). Fractographs taken at higher magnifications on charged specimens (Nos. 4 and 11) are shown in Figure 16. These fractographs show that charged specimens, whether notched or unnotched, failed with a fracture mode of predominantly transgranular quasi-cleavage, with only local sites of dimpled rupture.

4. DISCUSSION

The features observed on the fracture surfaces of the failed pipe indicate that the principal mode of fracture was brittle, being predominantly transgranular quasi-cleavage, with ductile dimpled rupture being observed at localized sites only at the higher magnifications. In addition, a rust pattern was observed at one location on both fracture faces which indicated that a crack had probably existed there at the root of the pipe thread for some time before the fracture was finally completed.

From the macroscopic examination of the pipe and the orientations of several features of the fracture surface (the previously existing crack, the "tearing" and ductility shown by the movement of the fracture from one pipe thread to a neighboring one, the orientation of the major bend and dent in the pipe, and the orientation of the scarred area in the major bend), it appears likely that the pipe could have been hooked by ditch digging equipment. The "freshness" of the scarred surface at the dent, in comparison to the corrosion pattern on the pipe in the neighborhood of the dent, indicates that the dent and scar were relatively new, and certainly had been made an appreciable time after the pipe was originally placed in service. The dented and scarred

area was a fulcrum of the bend in the pipe, indicating that the pipe was probably bent by the same force that made the dent. It is believed probable that the process of denting and bending the pipe produced high stresses in the threaded part of the pipe at the coupling and that the failure occurred because the metal at the root of the thread could not accommodate (by plastic flow) the strain required.

4.1 Possible Causes of the Brittle Fracture

The failure occurred in a brittle manner despite the fact that the low-carbon steels used for making galvanized pipe normally have a high capacity for plastic strain, i.e., good ductility, as was shown by the tests of the uncharged notched and unnotched tensile specimens. The lack of ductility shown by the fracture of this material in service warrants further discussion.

4.1.1 Geometry of the joint

The constraint of the coupling (a much more massive section) and the shape of the threads of the pipe tend to limit the maximum capacity of the pipe material for plastic strain there. The large reduction in wall thickness of the pipe at the root of the thread and the much greater wall thickness of the coupling would tend to concentrate the bending stress into the root of the thread. The shape of the threads would also strongly limit the "length" of the region over which plastic flow could occur. This length is essentially that at the root of the thread. The combined effects would then serve to concentrate both stress and strain at the root of the pipe thread located at the edge of the coupling.

Although believed to be improbable, it is possible that the constraint provided by the coupling and the thread would make the pipe fail at this point with little evidence of ductility when slowly strained in bending at the estimated temperature of the service failure. This concept could not be adequately tested in the laboratory with the available materials (the longer length of pipe was not the one that failed in service). While the notched tensile specimens were tested under conditions of stress and geometry that did not fully duplicate the constraint on the threaded pipe wall in service before failure, the tests do show that notched tensile specimens can be made to fracture very ductilely, with large amounts of plastic flow even at the root of the notch, in a manner very different from that observed on the fracture produced in service.

4.1.2 Local corrosion

There is some evidence that a crack, about one-third of the remaining wall thickness deep, had existed in part of the root of the thread at the junction with the coupling for some period of time before the final fracture occurred. If it had predated the actual failure it would have augmented the effects of the local stress concentration produced at the edge of the coupling, so that this region of the pipe wall could have failed at a stress lower than that required in neighboring regions on the same thread. Thus, this location may have been the origin of the final fracture.

4.1.3 Galvanic cell action

The steel pipe was shown to have been galvanized (by both x-ray emission analysis and microstructural examination) on both the interior and exterior surfaces. Also, iron-zinc intermetallic layers were observed on the crest of the second thread from the fracture face, as can be seen in the photomicrographs shown in Figure 17. Since galvanized surface layers produce their protective action against corrosion of the steel pipe wall by galvanic currents, making the exposed steel in the root of the threads cathodic, hydrogen could have been first discharged on the steel surfaces in the root of the threads and then absorbed by the steel. It is known [1,2][1] that absorbed hydrogen can severely limit the plastic strain occurring before fracture in low-carbon steels. Thus, it is believed probable that the "brittleness" of the fracture in service was significantly increased by charging with hydrogen discharged by cathodic currents produced by the interaction of zinc, iron and the environment.

4.1.4 Tensile and impact tests

Tests of subsize notched impact specimens and of hydrogen-charged tensile specimens (both notched and unnotched) taken from the failed pipe showed that the steel pipe could be made to fracture with little ductility at normal service temperatures. Also, the fracture mode could not be distinguished from that of the failed pipe by either light or electron fractography (SEM). These findings suggest that the steel at the failed pipe thread would have had little ability to accommodate strain in service if it had been stressed by impact loads, or if it had been stressed slowly in a hydrogen charging environment of sufficient severity.

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[1] Figures in brackets indicate the references at the end of this report.

However, the charging conditions used for the specimens used in the slowly stressed tensile tests may not have duplicated the conditions present in service at the time of the failure. Factors which would have promoted high charging fugacities (severe charging of hydrogen) in service, include soil which contains poisons (such as hydrogen sulfide), soils with high electrical conductivity and low pH, and large galvanic cell potentials between the steel and its galvanic protector. If all of these factors were unfavorable in service at the time of the failure, the charging conditions of the experiments were probably less severe than the service conditions. Much further work would be required to determine if galvanized pipe can be made to fail in a brittle manner under charging conditions that more accurately simulate the actual service conditions.

5. CONCLUSIONS

The following conclusions were drawn from the examinations and laboratory tests conducted:

(1) The pipe fractured in a brittle manner by a predominantely transgranular quasi-cleavage fracture mode, with local areas of dimpled rupture observable only at high magnification.

(2) The failure was probably caused by the application of an external load to the piping system and by the concentration of the bending stress produced in the root of a pipe thread where the pipe entered a coupling.

(3) The fracture faces observed on the two pieces of pipe mated, showing that the two pieces had originally been one.

(4) The microstructures and inclusion content of pipe samples indicated that the pipe material was not abnormal for welded and annealed, hot-dip galvanized steel utility pipe.

(5) X-ray emission analyses detected zinc and iron on both the inner and outer surfaces of the pipe indicating that the pipe had been galvanized.

(6) Factors that may have contributed to the failure of the pipe, by limiting the strain capacity of the pipe metal, include thread and coupling geometry, possible impact loading, hydrogen embrittlement, and corrosion at a thread root.

(7) A crack, about one-third of the remaining wall thickness deep, may have existed in part of the root of the fractured thread before the final fracture occurred. If so, this region could have started to fracture at a lower stress than others in the neighborhood required, and could have been the origin of the final fracture crack.

(8) The brittle fracture features of transgranular quasi-cleavage observed on fractures of notched impact specimens (both uncharged and hydrogen-charged) and on fractures of hydrogen-charged tensile specimens could not be distinguished from the features observed on samples of the fracture surface of the pipe that failed in service. On the other hand, uncharged tensile specimens failed in an entirely ductile mode, readily distinguished even by eye from that of either the failed pipe or the charged specimens.

ACKNOWLEDGEMENT

The authors wish to acknowledge Mr. Donald E. Harne for the extensive metallographic, photographic, and mechanical testing work that he did in conjunction with this examination.

REFERENCES

1. "On some remarkable Changes produced in Iron and Steel by the Action of Hydrogen and Acids" by W. H. Johnson, Proc. Royal Soc. (London) 23, p. 168 ff, Jan. 14, 1875.

2. Metals Handbook, 8th Ed., Vol. 1, 1961, p. 1165 American Society for Metals.

Table 1. Impact Test Results For Subsized Charpy V-Notch* Specimens

Specimen Number	Temperature of Test (F)	Observed Energy Absorption (ft-lb)	Charged or Uncharged	Environment
1	76	2.5	Uncharged	Air
2	35	2.5	Uncharged	Ice water
3	212	18.0	Uncharged	Boiling water
4	84	2.5	Charged, 5% H_2SO_4	Held in solution for one hour prior to breaking
5	35	1.5	Charged, 5% H_2SO_4	Held in cooled solution for one hour prior to breaking
6	190	12.0	Charged, 5% H_2SO_4	Held in boiling solution for one hour prior to breaking

* The curvature of the pipe was retained in these specimens and so they are non-standard subsized Charpy specimens.

Table 2. Tensile Test Results

Test Environment	Specimen Number	Fracture Strength (psi)	Elongation %	Reduction of Area, % Loc. 1 [a]	Loc. 2 [a]	Loc. 3 [a]	Ultimate Load (lb)	Cross-Section Area(in^2)
1" Gage Length - Notched Specimens								
Uncharged								
75 F, air	3	67,200	29.7	19.2	-	17.5	2760	(.0411)[e]
35 F, H_2O	2	65,200	28.9	15.2	-	13.7	2975	(.0456)[e]
Charged with 1.6 V Cathodic Potential								
75 F in 5% H_2SO_4	4	51,300	4.5	3.5	-	4.8	2330	(.0454)[e]
35 F in 5% H_2SO_4	1	49,300	4.8	5.7	-	5.4	2360	(.0479)[e]
2" Gage Length - Notched Specimens								
Uncharged								
75 F, air	8	69,600	16.9	8.9	-	12.3	2980	(.0428)[e]
35 F, H_2O	5	66,400	19.9	8.6	-	11.8	2960	(.0446)[e]
Charged with 1.6 V Cathodic Potential								
35 F in 5% H_2SO_4	6	53,900	3.0	3.3	-	4.2	2348	(.0436)[e]
75 F in 5% H_2SO_4	12[f]	52,200	2.2	2.0	-	2.0	2390	(.0458)[e]
75 F, 1M Na_2SO_4	14[b]	64,400	4.5	5.5	-	5.0	3020	(.0469)[e]
2" Gage Length - Unnotched Specimens								
Uncharged								
75 F, air	7	53,700	c	17.3	19.0	52.3[d]	2960	(.0551)
Charged with 1.6 V Cathodic Potential								
75 F in 5% H_2SO_4	11	57,500	9.7	10.2	17.4	9.5	2730	(.0475)

a See Figure 3 for locations.

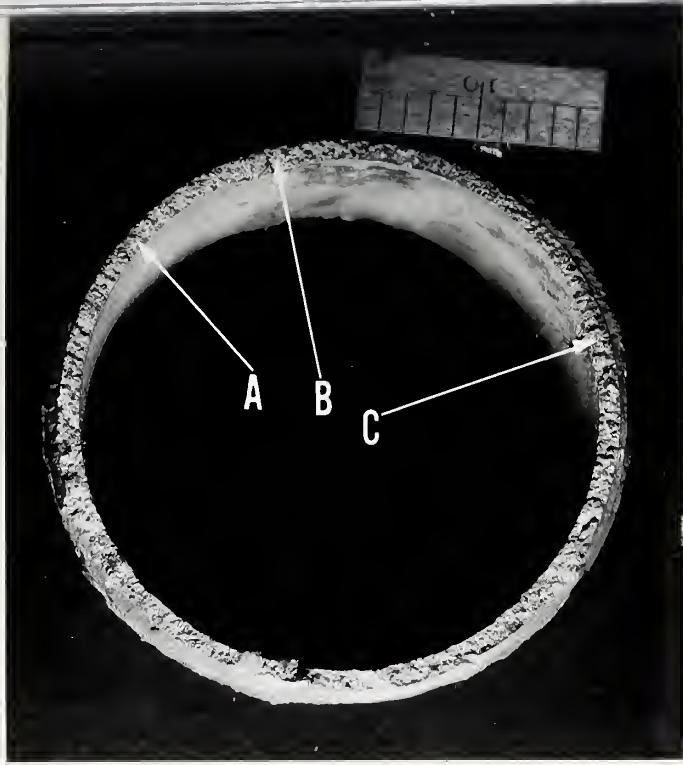
b Interrupted test - see Appendix A for loading schedule.

c Not taken due to sample breaking outside of gage marks.

d Fracture occurred at location 3.

e For metal beneath the notch.

f Specimen failed near grips after extensive corrosive attack.



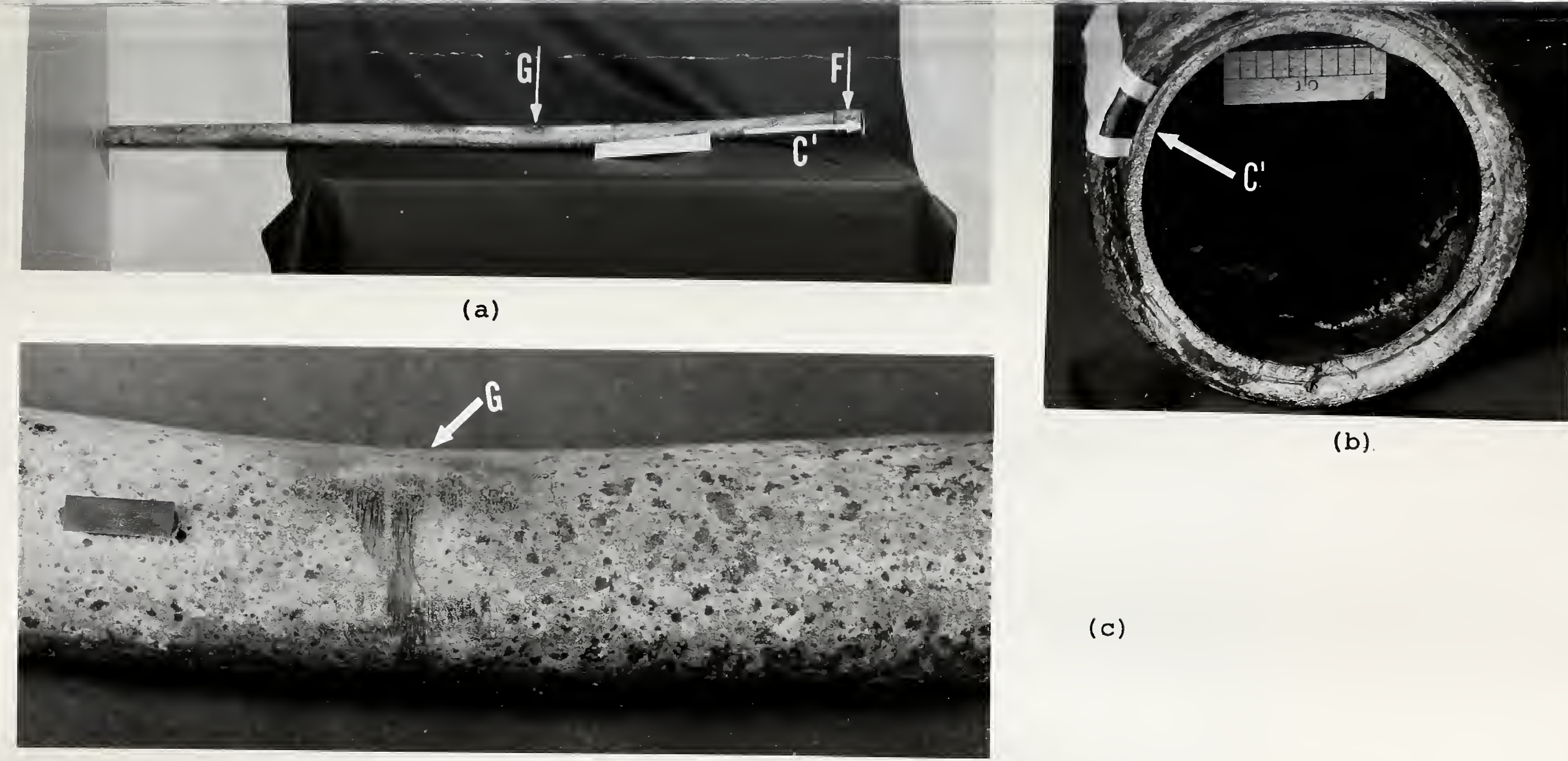
(a)

(b)

Figure 1. Photographs of the Fracture Surface of the Short Length of Pipe.

Location A, B, and C show where specimens were cut for Scanning Electron Microscope (SEM) studies, locations D show pipe threads below the fracture, and location E is a saw cut made at NBS to allow removal of specimen C.

(a) Before Sectioning. Scale div. = 0.1 inches. About 1.3X.
(b) After Sectioning. About 2X.



(a)

(b)

(c)

Figure 2. Photographs of the Longer Length of Pipe As-Received at NBS. Location F is the coupling containing the other half of the fracture of the failed pipe, location G is the site of a scarred region on the surface of the pipe and the fulcrum point of an approximately 10 degree bend in the pipe, and location C' corresponds to location C on the fracture surface shown in Figure 1.

(a) The pipe as-received, oriented to show bending at location G. Scale = 12 inches.
(b) The fractured end of pipe remaining in the coupling. About 1X.
(c) The scarred surface at the bend fulcrum point G. About 0.7X.

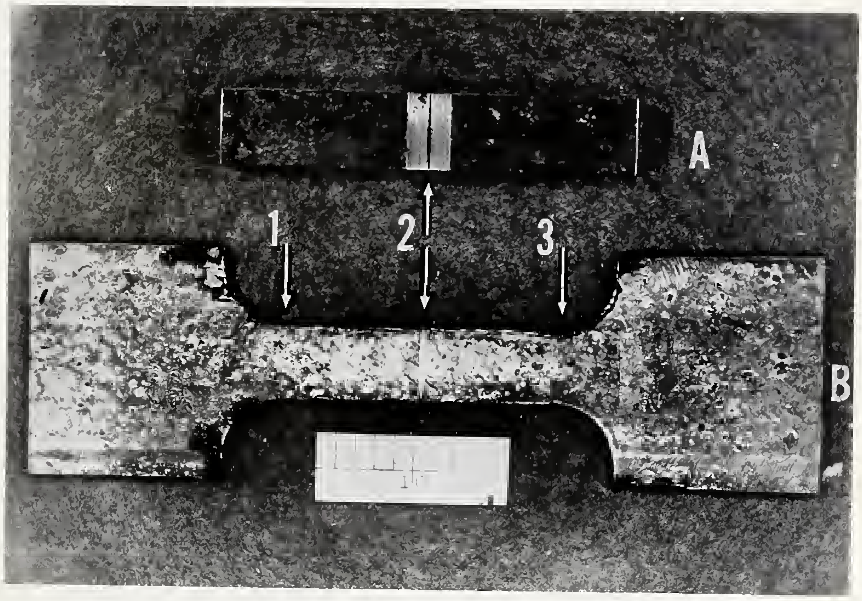


Figure 3. Photographs of Typical Subsize Impact (A) and Short Tensile (B) Specimens. Both specimens are notched at location 2. Measurements of reductions of area and elongation were made on the tensile specimens at locations 1, 2, and 3. About 1X.

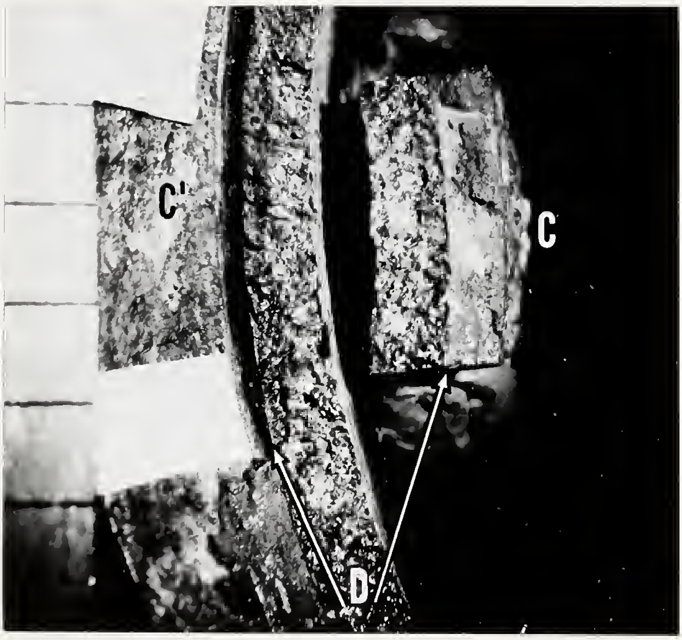
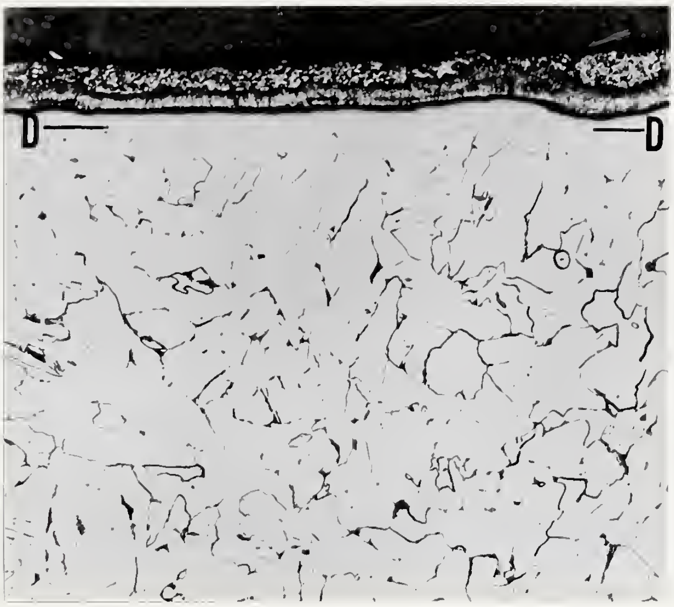
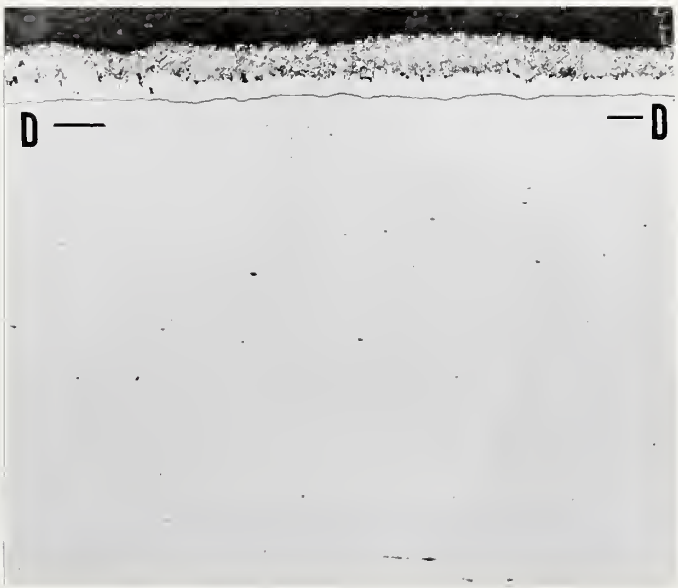


Figure 4. Matching Corroded Fracture Surfaces at Locations C and C'. Root of thread is indicated by the arrows D. The corroded region extends about 1/3 down the fracture surface from the root of the thread. About 5X.



(a)



(b)

Figure 5. Photomicrographs of Longitudinal Cross Section of Pipe. Two iron-zinc intermetallic layers on the outer surface of the pipe are shown just above line D-D on each photomicrograph. About 100X.

(a) General microstructure. Etched with 5% Nital.
(b) Inclusion content. Unetched.

(a)

(b)

Figure 6. SEM Fractographs at Location A of Figure 1.

(a) Fracture surface is above line A-A, side of thread below. 35X

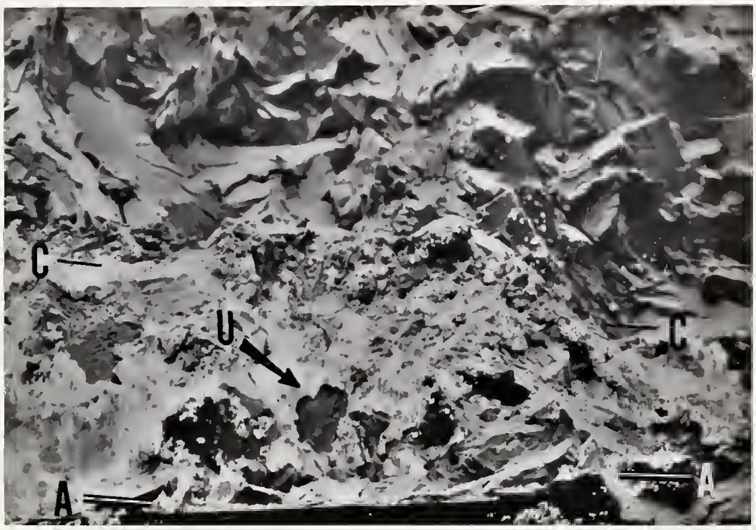
(b) Region of fracture surface at higher magnification. Fracture is predominantly by transgranular quasi-cleavage mode, but some small amounts of dimpled rupture are shown at arrows. 350X

Figure 7. SEM Fractographs at Location C of Figure 1.

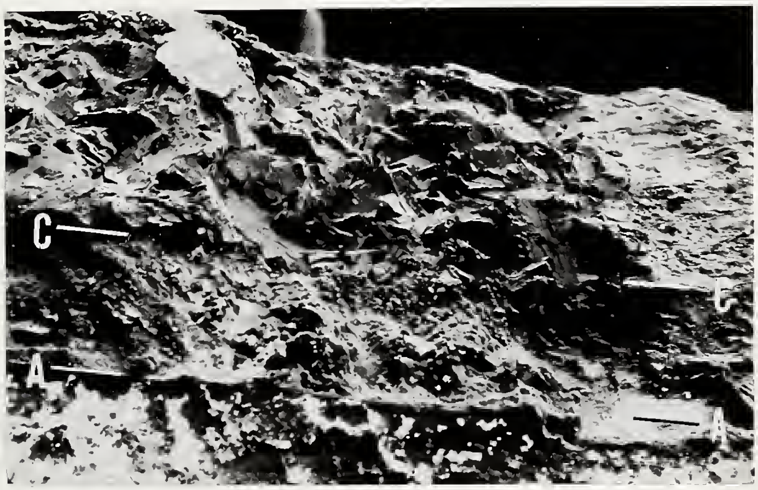
(a) Junction of corroded and "fresh" regions of fracture surface after ultrasonic cleaning. The face of the pipe thread is located below line A-A, a corroded region of fracture surface between lines A-A and C-C, and "fresh" fracture above line C-C. Arrow U shows where the ultrasonic cleaning removed some corrosion product. 60X

(b) Junction of corroded and "fresh" regions of fracture surface before ultrasonic cleaning. "White" deposit below line C-C is a corrosion product that does not conduct electricity readily and consequently is charged by the electron beam of the SEM. 33X

(c) Field near the center of the "fresh" fracture region at higher magnification, showing predominantly transgranular quasi-cleavage, with some evidence of dimpled rupture (between arrows). 130X



(a)



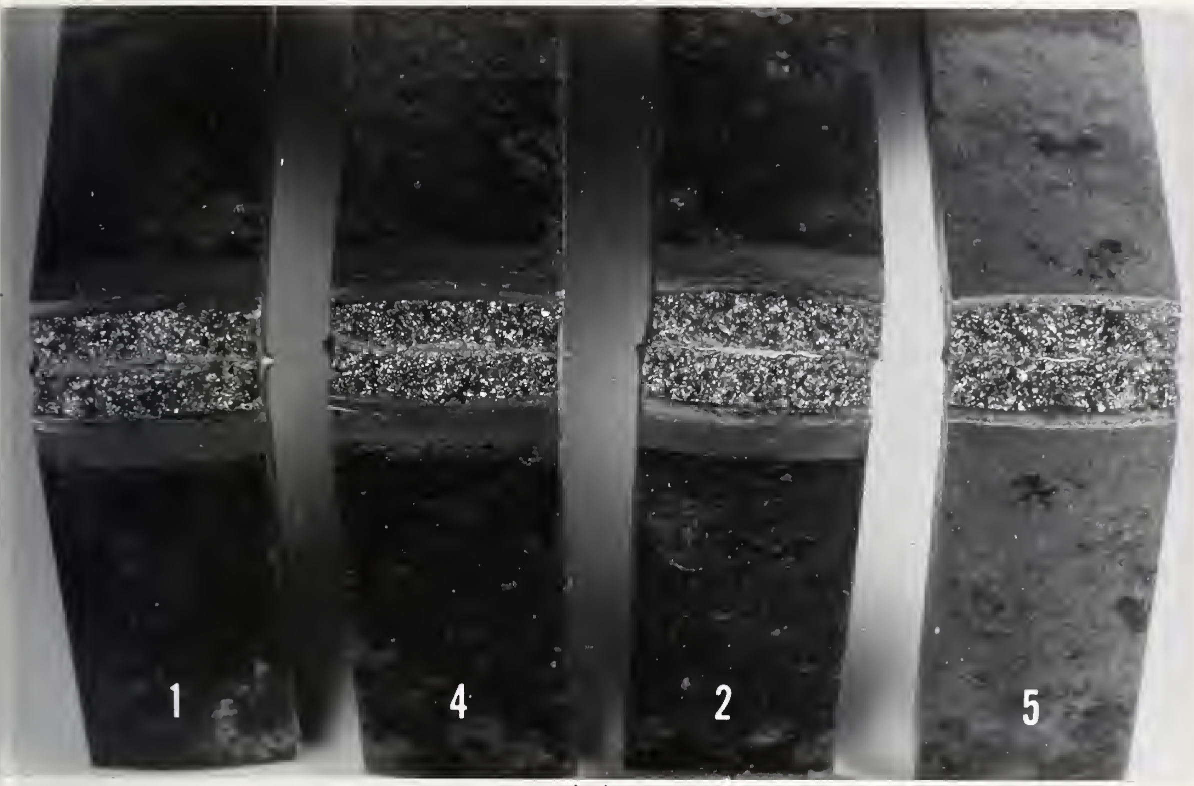
(b)

(c)

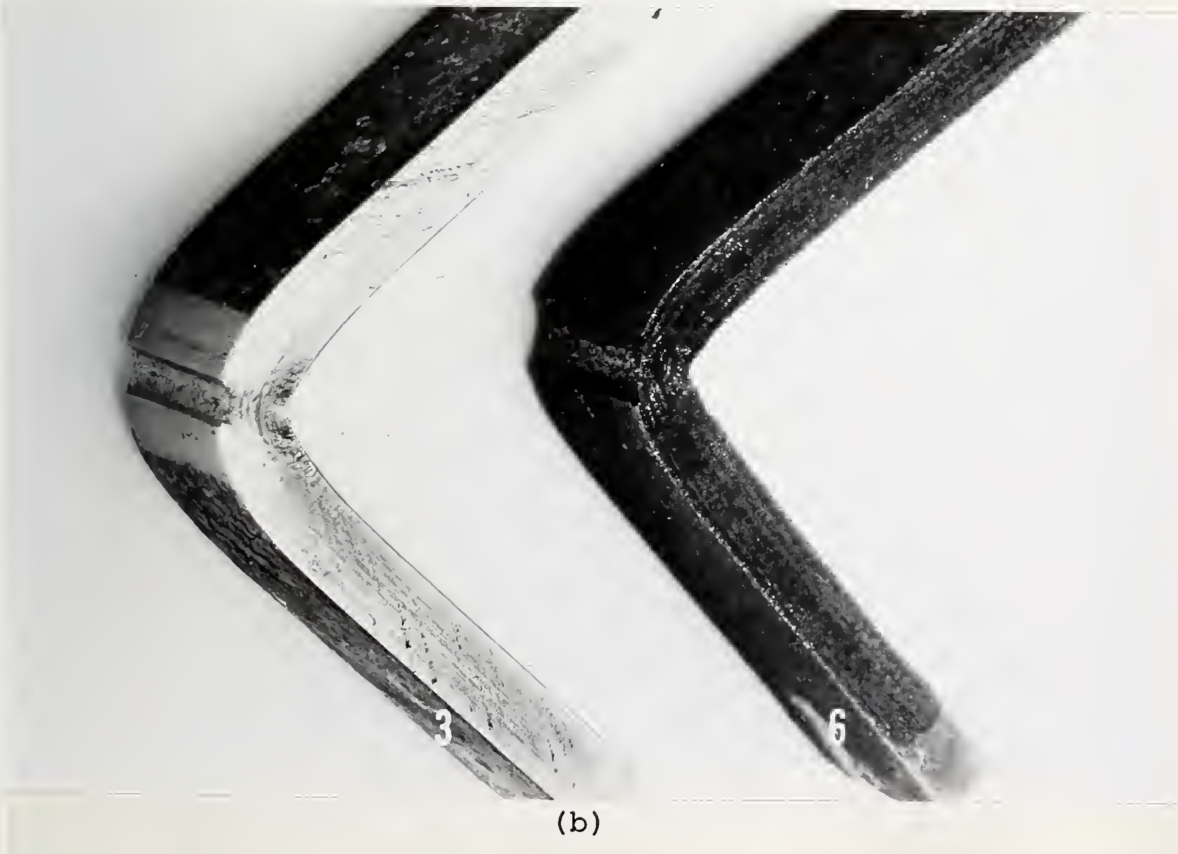
Figure 8. Macroscopic Appearance of Several Subsize Charpy V-Notch Impact Specimens After Testing. Magnification about 3X.

(a) Specimens 1, 4, 2, and 5 were tested at or below room temperature and show faceted fracture surfaces.

(b) Specimens 3 and 6 were tested at or above 190° F and did not fracture.



(a)



(b)

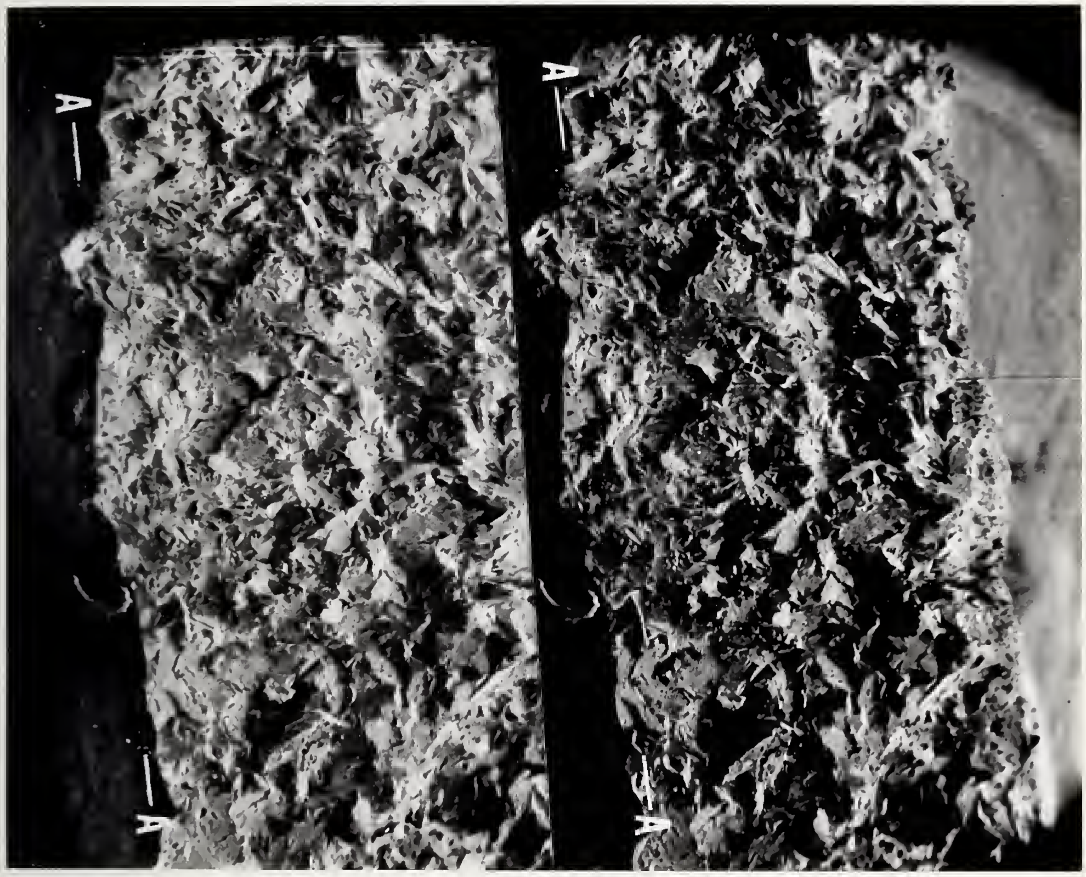


Figure 9. SEM Stereo-Pair Fractograph of Impact Specimen No. 5. Charged with hydrogen, tested at 35° F. Fracture appearance is representative of specimens 1, 2, and 4. Line A-A is the root of the notch. 21X

(a)

Specimen No. 5

(b)

Specimen No. 1

Figure 10. SEM Fractographs Taken of Charged and Uncharged Impact Specimens.

Both fractographs show the predominantely-transgranular quasi-cleavage fracture mode observed on all impact specimens tested at room temperature and below. Selected local sites (at arrows) show dimpled rupture. 100X

(a) Charged. Specimen No. 5.

(b) Uncharged. Specimen No. 1.

Figure 11. Fractures of Notched Tensile Specimens. One inch gage length. 4X

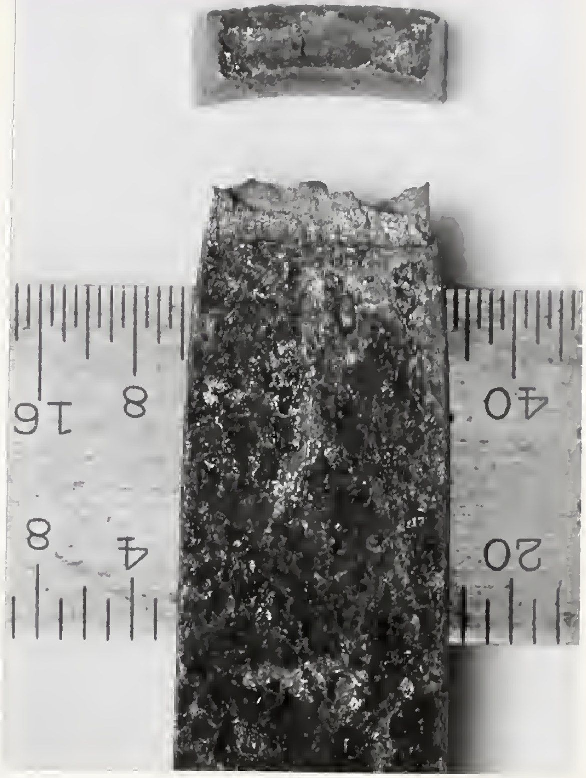
(a) Specimen No. 3. Uncharged. Tested at 75° F in air.

(b) Specimen No. 2. Uncharged. Tested at 35° F in water.

(c) Specimen No. 4. Charged. Tested at 75° F in 5% H_2SO_4 aqueous solution.

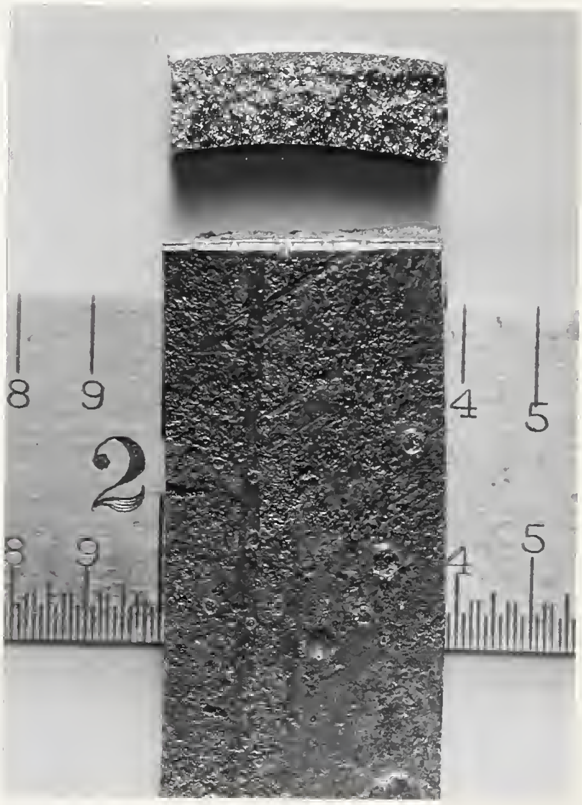
(d) Specimen No. 1. Charged. Tested at 35° F in aqueous 5% H_2HO_4.

(a)



(b)

(c)



(d)

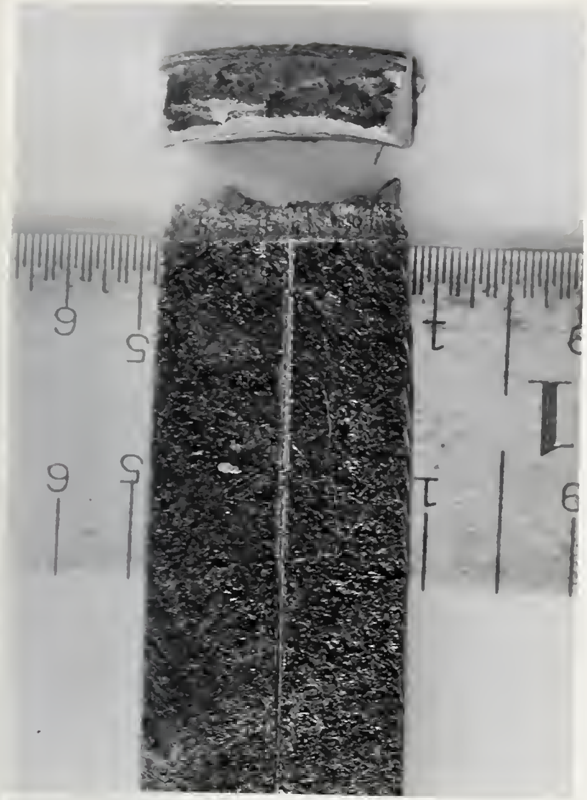
Figure 12. Fractures of Notched Tensile Specimens. Two inch gage length. 4X

(a) Specimen No. 8. Uncharged. Tested at 75° F in air.

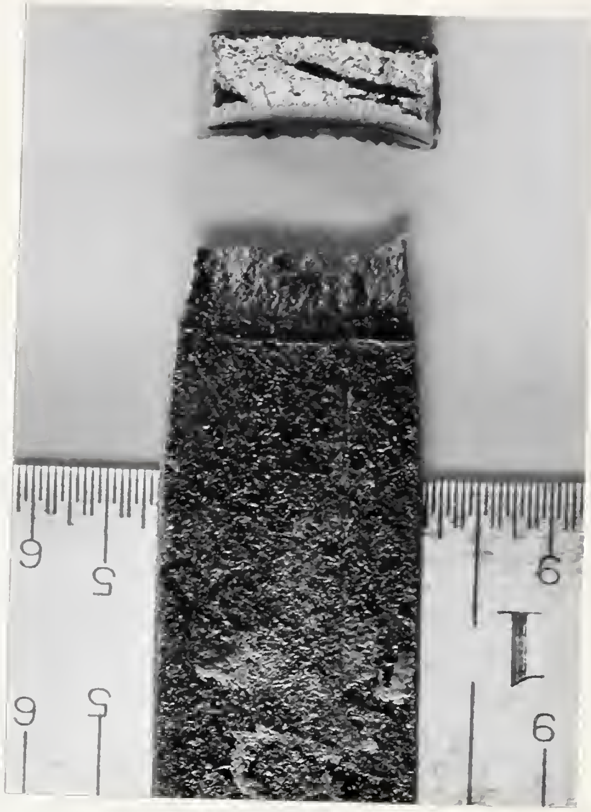
(b) Specimen No. 5. Uncharged. Tested at 35° F in water.

(c) Specimen No. 14. Charged. Tested at 75° F in 1M, Na_2SO_4.

(d) Specimen No. 6. Charged. Tested at 35° F in aqueous 5% H_2SO_4.

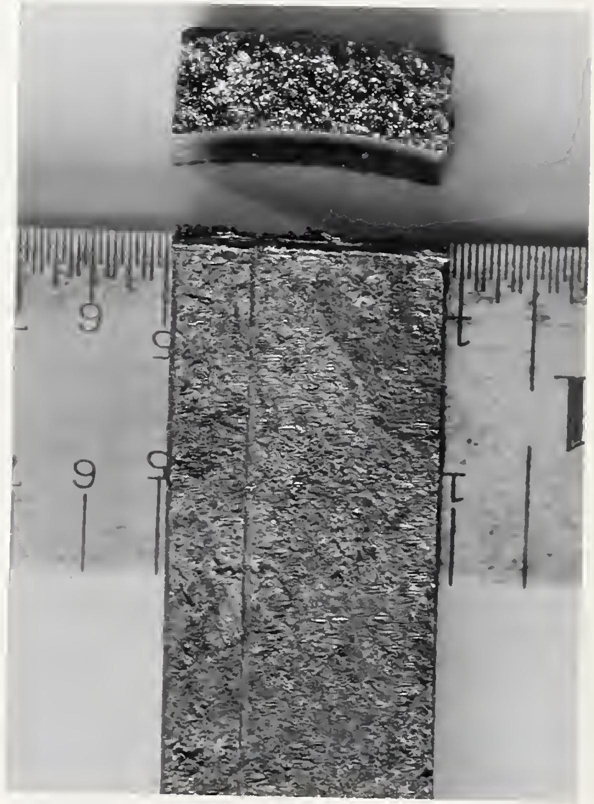


(a)

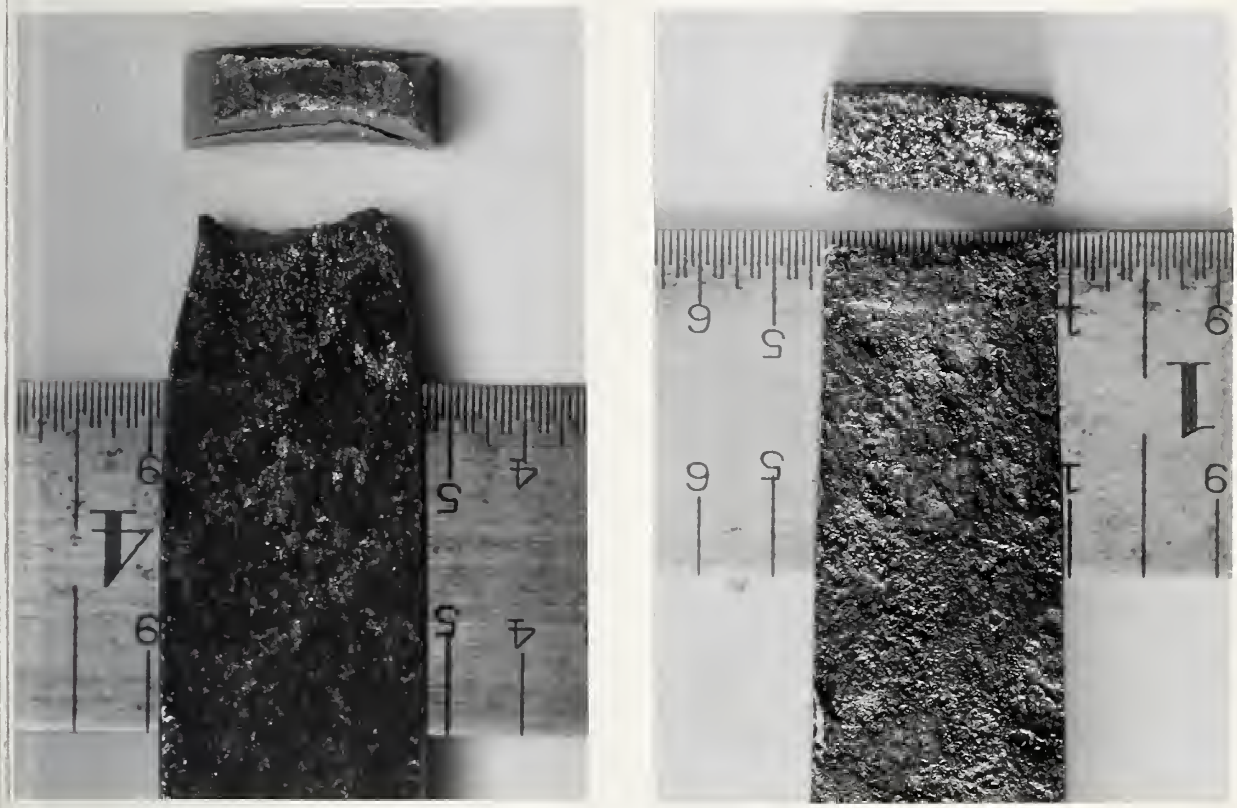


(b)

(c)



(d)



(a) (b)

Figure 13. Fractures of Unnotched Tensile Specimens. Two inch gage length. 4X

(a) Specimen No. 7. Uncharged. Tested at 75° F in air.

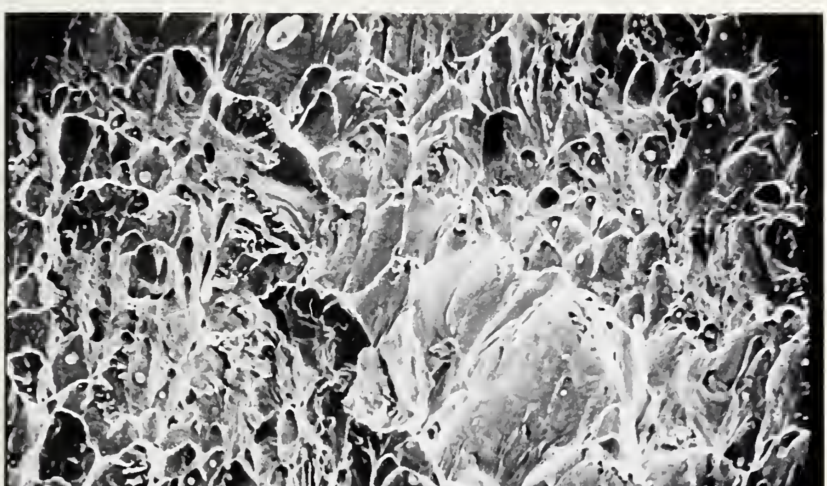
(b) Specimen No. 11. Charged. Tested at 75° F in aqueous 5% H_2SO_4.

Figure 14. SEM Fractographs of Uncharged Notched-Tensile Specimen No. 2. Features are typical of all uncharged tensile specimens examined in the SEM (Nos. 2, 7, and 8).

(a) Stereo pair showing the ductile fracture mode at low magnification. The region between the lines A-A and B-B is the notch deformed during testing. 13X

(b) The ductile fracture mode (dimpled rupture) shown at higher magnification in region near center of fracture surface. 650X

(a)


(b)

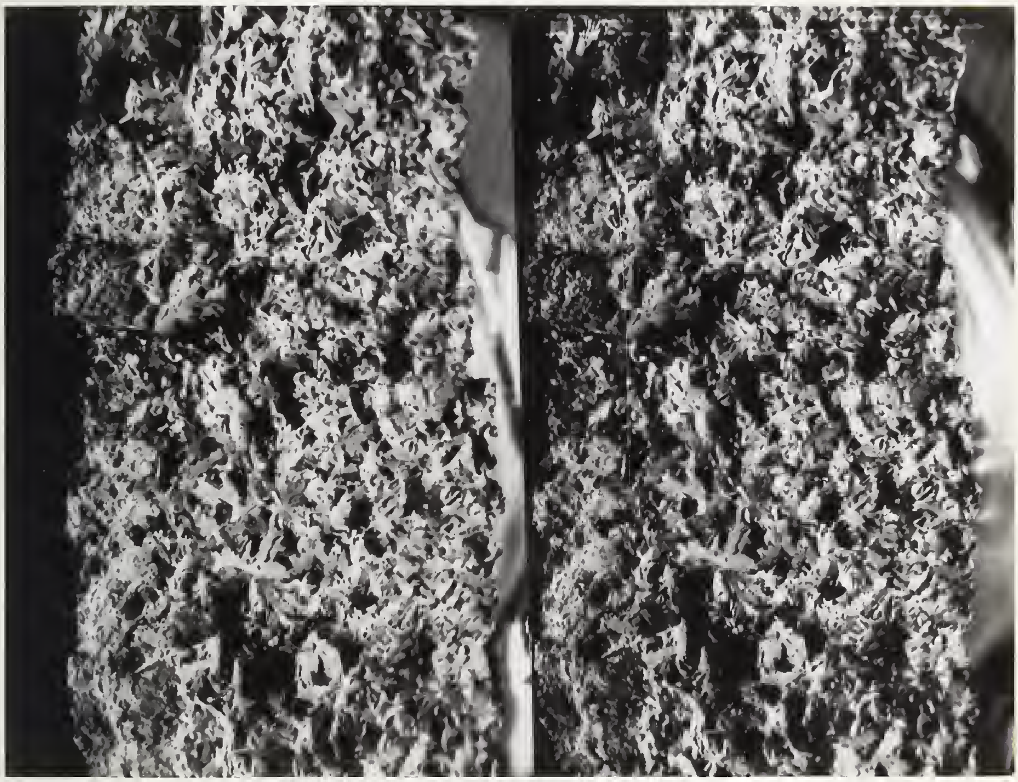


Figure 15. SEM Fractograph of Charged Unnotched Tensile Specimen No. 11. Stereo pair shows the comparatively brittle (transgranular quasi-cleavage) mode which was dominant in all of the charged tensile specimens examined in the SEM (Nos. 1, 4, 11, and 14). 19X

(a)

(b)

Figure 16. SEM Fractographs of Notched and Unnotched Tensile Specimen in the Charged Condition. The fracture surfaces and features of these specimens are quite similar, being predominantely transgranular quasi-cleavage. Dimpled rupture occurring only at local sites is shown by the arrows.

(a) Notched Specimen No. 4. 1100X

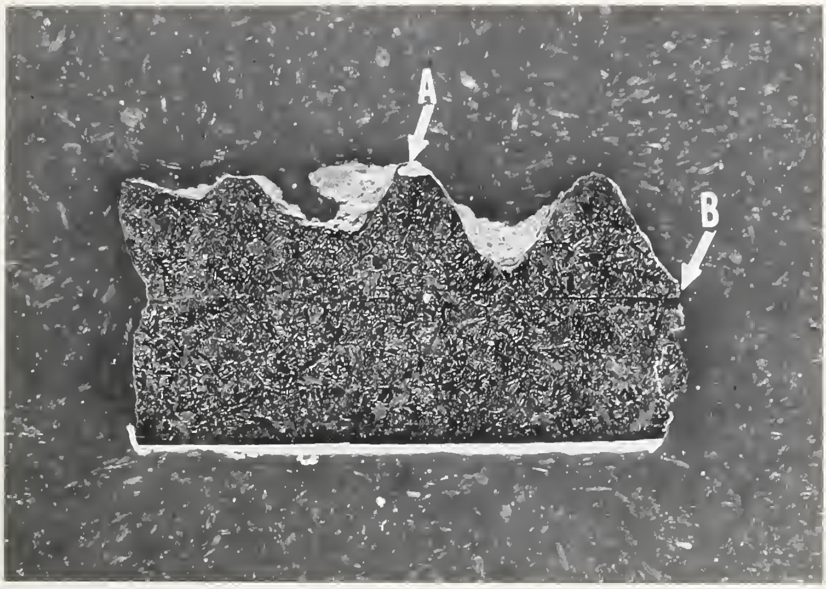
(b) Unnotched Specimen No. 11. 550X

Figure 17. Photomicrographs of Galvanized Coating Observed on Second Thread from the Fracture Surface. Specimen taken from near location C of Figure 1.

(a) Location of galvanized coating on tip of second thread from fracture face is shown by arrow A. The fracture face is shown by arrow B. 5% Nital etch. 10X

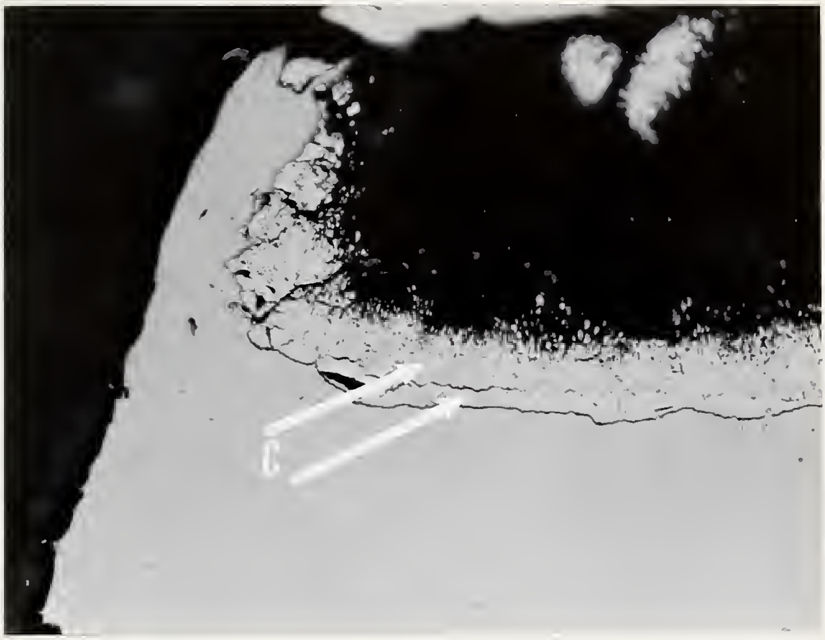
(b) Crest of second thread from fracture face (shown in a). Etched very lightly with picral etch. 160X

(c) Crest of second thread from fracture face at higher magnification. Two layers of iron-zinc intermetallic coating the outer surface of the section can be detected and are shown by arrows C. Etched very lightly with picral. 400X



(a)

(b)



(c)

Appendix A: Interrupted Tensile Test Results Using 1M Na_2SO_4 as the Electrolyte. Specimen No. 14.

Date	Time	Applied Load, When Test Interrupted	Observed Load Upon Relaxation of Applied Load
11/30/72	9:15 A.M.	2080	1900
	12:40 P.M.	N.C.	1900
	2:00 P.M.	N.C.	1900
	2:50 P.M.	N.C.	1900
	3:00 P.M.	2200	(a)
	4:35 P.M.	N.C.	2140
12/01/72	8:45 A.M.	N.C.	2090
	8:45 A.M.	2400	2090
	9:45 A.M.	2450 (b)	2330
	1:00 P.M.	N.C.	2320
	2:25 P.M.	N.C.	2305
	4:30 P.M.	N.C.	2305
12/04/72	8:50 A.M.	N.C.	2275
	12:20 P.M.	N.C.	2275
	1:55 P.M.	N.C.	2275
	4:00 P.M.	2330	2310
12/05/72	8:50 A.M.	N.C.	2310
	12:45 P.M.	N.C.	2310
	12:45 P.M.	2360	2360
	2:20 P.M.	N.C.	2360
	3:35 P.M.	2450	(a)
	4:35 P.M.	2500	(a)
12/06/72	8:40 A.M.	2550	2480
	10:00 A.M.	2600	2510
	12:45 P.M.	2650	2500
	3:30 P.M.	2700	2570
	4:30 P.M.	2750	2520
12/07/72	8:40 A.M.	2800	2640
	9:50 A.M.	2840	2700
	11:00 A.M.	2900	2750
	12:15 P.M.	2950	2830
	1:15 P.M.	3000	2830
	2:25 P.M.	3020	(Specimen Broke)

N.C. - i.e. test held at constant cross-head displacement

(a) Not observed

(b) Holding for week-end.

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15. SUPPLEMENTARY NOTES

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.)

Two sections of a fractured 2-inch diameter galvanized steel pipe used in natural gas residential distribution service in Woonsocket, Rhode Island were examined to determine the mode of fracture. Notched tensile and impact specimens made from the pipe were tested in the uncharged and hydrogen-charged conditions. The fractures in the uncharged tensile specimens were ductile, occurring by dimpled rupture. Those in the impact specimens, the hydrogen-charged tensile specimens, and the original pipe were "brittle", occurring with very little to no ductility by transgranular quasi-cleavage. Since the fracture features of the original pipe fracture were duplicated by the hydrogen-charged notched tensile specimens, it was concluded that the galvanized pipe failed in service due to (1) an external force, (2) stress concentration by the junction of the root of the pipe thread and the face of the 90 degree pipe elbow, and (3) a low ductility at the root of the pipe thread probably as a result of charging with hydrogen produced by the galvanic current from the corrosion protection of the galvanized coating.

17. KEY WORDS (Alphabetical order, separated by semicolons)
brittle fracture; galvanized steel pipe; hydrogen charging; natural gas service.

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