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Approved by: /\ Professor Roger Olleman

An evaluation was made of factors contributing to the service failure of a 12 inch diameter cast iron water pipe in Pendleton, Oregon. The quality of the pipe was found to be acceptable when compared to the acceptance limits established by the American National Standards Institute, Inc. However it exhibited numerous casting defects such as blowholes, gas porosity, lapping zone discontinuities and poor casting surface indicating a poorly cast product. Metallurgical study also revealed a discontinuous solidification pattern which produced a thin separated metal layer at the pipe's outer wall. The cause of the failure, however, was not attributed to any of these defects. Between 71 and 88 inches on the fracture surface, an unusual black surface appearance was observed. Microscopic examination and electron microprobe analysis of the corrosion deposit in this area revealed a very thick adherent layer of corrosion products, found nowhere else on the fracture surface, and a penetrating type corrosive attack. This corrosive attack was determined to be characteristic of graphitic corrosion that occurred over a long period of time.

Based on the results of this evaluation, it was concluded that the failure was not caused by any metallurgical defect, by corrosion
alone, or by service stresses. It appeared to be caused by the presence of a longitudinal hairline crack on the inner pipe wall that was formed as a result of impact received before or during installation. Over the four and one-half years of service that the pipe was in service, corrosion and service stresses increased the depth and length of the crack until the pipe was so weakened that a seven feet four inch longitudinal crack opened all the way through the pipe wall over a short period of time.
EVALUATION OF FACTORS CONTRIBUTING TO THE
FAILURE OF CAST IRON WATER MAINS

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EVALUATION OF FACTORS CONTRIBUTING TO THE FAILURE OF CAST IRON WATER MAINS

1.0 INTRODUCTION

Cast iron water mains have been used since King Louis XIV of France, in 1664, had them installed to supply water from a pumping station at Marly-on-Seine to Versailles, 15 miles away. These mains, or pipes, must be designed, tested, handled, installed and used properly to ensure years of dependable service. However, in spite of all precautions, failures do occur. The fraction of pipes that fail in use is quite small. On the other hand, the results of a single failure may create a great inconvenience to the parties involved, and can cause large costs for property damage, and repairs. This in turn, is apt to lead to considerable litigation.

1.1 PURPOSE OF STUDY

On December 11, 1968 the City of Pendleton, Oregon suffered a major break in a cast iron water main and the piece of fractured pipe was submitted to Prof. Roger D. Olleman for investigation. It was a 12 inch diameter cast iron water main, which had failed with a longitudinal crack after approximately four and one-half years of service. Of the original 18 foot length of pipe, 14 feet was shipped to Prof. Olleman. The piece of as-received pipe is shown in Figure 1, with the fracture circled with a chalk line. Realizing the importance of prevention of similar failures in the future, an extended
Figure 1. Cast Iron Water Main as received from the City of Pendleton, Oregon. Longitudinal crack is circled with chalk.
evaluation was undertaken of the factors which could have contributed to this failure.

1.2 INFORMATION ON BROKEN PIPE

This particular pipe was one of 194 pieces ordered from the Pacific State Cast Iron Pipe Company on November 12, 1963 under Federal Specification Number WW-P-421a, similar to WW-P-421c, used here for reference purposes. It was a 12 inch diameter Class 150 "Tyton" joint Super DeLavaud cast iron water pipe weighing approximately 1140 pounds and ordered with a thin cement lining on the interior of the pipe. According to a report by Mr. Ray Struthers, Water Superintendent for the City of Pendleton, this pipe was part of a pumping transmission line from a low level reservoir at an elevation of 1290 feet to a high reservoir at an elevation of 1473.5 feet. Failure occurred at an elevation of approximately 1365 feet. The installation of the pipe was done in the spring of 1964 in accordance with the American Water Works Association specifications. Pendleton's installation consisted of rock excavation, top soil bedding, and soil backfill.

This fracture started approximately three to four feet from the bell end of the pipe and measured seven feet four inches longitudinally down the length of the pipe. There were only two pipeline connections to this particular line, both approximately two city blocks away from the failure, and an air relief valve approximately 15 feet away from the fracture. Mr. Struthers reported that internal water pressure, recorded over a 24 hour period after replacement of the broken pipe, was a maximum of approximately 40 psi. No other information was
given as to the conditions found upon excavation of the broken pipe, and no reason for its failure could be determined at the site.
2.0 REVIEW OF POSSIBLE CAUSES OF CAST IRON WATER MAIN FAILURES

Failures of cast iron water mains can be attributed to many causes. In the following sections, a discussion is given on those causes considered of prime importance.

2.1 PIPE DEFECTS CREATED DURING MANUFACTURE

Standard procedures are followed at foundries to cast and produce high quality cast iron water pipes. In this case the casting process is the Super DeLavaud process. This is a centrifugal casting process which is designed to produce chill-free pipe (59, 60, 70). In this process molten cast iron is supplied by a long trough inserted into a horizontal mold that is rotating about its longitudinal axis. Casting begins at the far end of the mold, which is the bell end of the pipe. A thin film of pulverulent, powdery, material, such as ferro-silicon, is sprayed down just ahead of the molten iron on a stream of air. This film retards the extraction of heat to the water cooled mold jacket (2, 52). The molten iron leaves the pouring trough in the direction of the mold rotation. The rate of mold rotation is adjusted to suppress metal-mold slippage and to hold the molten iron against the rotating mold surface by centrifugal force. Simultaneously, the rotating mold is moved along its axis at a controlled rate so that an even helix of molten iron is laid down with sufficient overlap between successive coils in the helix to ensure fusion and proper bonding between coils. After pouring, the casting is allowed to
cool to approximately 1500 F in the rotating mold. It is then extracted and sent to the annealing furnace where it is heated to a maximum temperature of 1750 F and allowed to cool to 1200 F in about one hour.

Under properly controlled conditions, the product of this centrifugal casting method should have a close grained structure with a minimum of gas holes and a uniform wall thickness throughout the pipe. The centrifugal force should remove all gas pockets and should force lighter impurity constituents towards the inside of the pipe. (34, 69)

According to the American National Standards Institute Specification A21.6 For Cast Iron Pipe, Centrifugally Cast in Metal Molds, for Water or Other Liquids, specific physical tests, internal hydrostatic pressure tests, and close inspection of each finished pipe are required of the manufacturer to insure a superior product for the purchaser. However, in spite of these tests, it is still possible for a defective pipe to leave the manufacturer and be put in service by the purchaser. Pipe defects may be in the form of inclusions from sources such as the ladle or trough, or may be gas holes caused by too rapid solidification in the mold. Other possible defects are: laps arising from poor fusion between successive layers of the helix, cracks, irregularities in pipe thickness, and residual stresses. All of these cause weakness, when compared with defect free pipe under the same installation and environment conditions. (34, 69, 71)
2.2 DAMAGE TO PIPE DURING HANDLING AND TRANSPORTING

Careless handling of cast iron pipes at the foundry, as well as in transit to their destination, is a possible cause of pipe damage. This damage usually appears in the form of external pipe bruises and hairline cracks. Impact between one or more pipes, or the dropping of a pipe on a hard object such as a rock during loading or unloading, is sufficient cause to suspect that a defect has been induced in the pipe. After any such event the pipe should be subjected to careful examination before considering it for installation. Of the possible defects induced in the pipe, hairline cracks have been found to be the hardest to locate in field inspections. Hairline cracks are caused by external impact with hard objects, and start on the inside of a pipe and propagate from the inside to the outside of the pipe wall. (60, 61). The major factor here is the severity of impact. If the impact is quite severe, visible cracks will be produced on the outside surface. With less severe impacts, cracks may be produced but may not be visible in an external inspection. The result of hairline cracks in the pipe is quite apparent. The pipe may pass all the preliminary tests after installation and remain in service for some time before the crack propagates to a serious failure under the pipe's environmental and stress conditions in service. (6, 18, 38)

2.3 DAMAGE CAUSED BY INSTALLATION METHODS

2.3.1 Static Overload Conditions

Faulty installation of cast iron water mains has been found to cause failures by subjecting the pipe to beam loading. Compared to
a structural I-beam, a pipe is very poorly designed when it comes to carrying stresses induced by bending. It must be noted here that tests have found that pipes having six inch diameters or less will fail as beams with transverse or semi-transverse fractures. (73) On the other hand, pipes greater than six inches in diameter, are weaker as a circle or a ring rather than as a beam. This causes it to deform into an elliptical shape when excessive loads are applied. Failure will then occur longitudinally along the length of the pipe. The failure starts in the region of maximum tensile stresses. For a ring under an excessive external load this will occur along the bottom or top of the ring. (53, 62) Therefore, ditch or trench preparation and backfilling become important factors in installation procedures.

According to the American Water Works Association, AWWA, Standard C600-64, a properly prepared trench bottom with tamped backfill will carry the full length of the pipe and not induce beam stress conditions. On the other hand, poor trench preparation creates irregular or wavy surface conditions which leaves certain sections of pipe unsupported, and thus concentrates bending loads in those areas. This surface condition can also be caused by a heavy rain, water leakage, or ground water movement which washes away the tamped backfill. Also, if the backfill contains two types of soil with different expansion properties in aqueous or thermal environments, the settling of the pipe, or of adjacent pipes and trench fill, will cause an inverse beam loading condition with the same failure results. (4, 6, 74)
Pipe laid on a hard, rocky surface or unyielding structure, such as another pipe, is also susceptible to failure. The peaks of the rocky surface or underground structure act as stress raisers on the pipe. With the natural settlement of adjacent pipe sections, stresses of sufficient magnitude to cause failure may result. (6)

2.3.2 External Impact by Trench Filling

The chance also exists of a crack being initiated by trench filling practices. Even after proper trench preparation, including tamped backfill, covering the pipe by bulldozing or pushing a cover which contains large rocks that strike the pipe after falling from the height of the ditch, can initiate a crack. This has been shown by an impact test made by Stuart (60) on a six inch Super DeLavaud pipe under an internal water pressure of 65 pounds. A hammer weighing 50 pounds, falling from approximately two feet, caused a crack to form. Falling from approximately four feet, failure resulted.

Impact tests by Talbot (62,63) also involved an internal water pressure of 65 psi and subjecting the pipe to blows by a 50 pound hammer from increasing heights until a crack in the pipe became apparent. Talbot stated that in every case the crack ran longitudinally along the top of the pipe. The flattening of the cross section at the point of impact and the bending of the wall inward formed a crack on the underside of the top wall of the pipe. The crack did not become apparent until it propagated completely through the wall. Impact test results by Wiggin, Enger, and Schlick (73) under similar testing conditions added further verification that the internal cracks
were formed on the inner pipe wall and propagated in the longitudinal direction of the pipe.

The formation of internal cracks in the pipe wall by impact was detected in Stuart's tests by allowing molten tar to seep into the cracks before breaking the specimens for inspection. The shape of the black surface deposit on the crack surface in the Pendleton pipe is essentially the outline recorded by the tar coating in Stuart's tests. It was also noted by Talbot (63) in another test that when a pipe failed under low internal pressure, due to an initial crack or other weakness, the crack propagated on a single longitudinal line. When the pipe required its full strength to resist internal pressure, a number of cracks branched away from the initial line of crack propagation. From service experience, pipe failures characterized by breaks running longitudinally from the spigot end of the bell end have in most cases been related to the formation of hairline cracks. (18, 38)

The pipe in Pendleton was laid in a trench where rock had to be excavated. The formation of a hairline crack in the Pendleton pipe due to improper trench filling practices is a reasonable possibility.

2.4 DAMAGE IN SERVICE OPERATION

2.4.1 Corrosion

Corrosion should always be considered as a possible cause of failure initiation. According to the AWWA standards, it is standard practice to order cast iron pipe with a thin cement lining on the
inside, to prevent the possible corrosive effects of the transported water, and with a bituminous coating of either coal tar or asphalt base on the outside.

Internal corrosion, better known as tuberculation, occurs either where poor bonding exists between the cement lining and metal, or where a break in the cement lining reveals base metal to the aggressiveness of the water. This would allow an electrochemical reaction to take place with resultant pitting or crevice type corrosion in the cast iron pipe. Tubercles or mounds of corrosive products build up and cover anodic areas where pits are developing. (21, 30, 50, 66) Externally, there are many factors which could cause corrosion if an opening occurs in the bituminous coating. The greatest concern here is the effects of soil and water environments, bacteria, and stray D-C electric currents.

Extremely acidic soils, extremely basic soils, and moist environments are known to be good electrolytes for the conduction of electricity. In the presence of two electrically connected dissimilar metals, such as a cast iron water pipeline in contact with a neighboring gas pipeline, or the presence of dissimilar surface conditions on the cast iron pipe, such as a chipped area on the pipe, galvanic corrosion can take place. (21, 22, 25, 38) Galvanic corrosion depends on a potential difference formed between an anodic material or area and a cathodic material or area. It also requires the presence of an electrolyte, and a low resistance electrical connection must exist between these two materials or areas.
Materials used in backfilling containing two chemically different soils can also cause corrosion. According to Charles W. Tipps, corrosion engineer for the City Public Service Board, San Antonio, Texas, the more active soil will generate an electric current through an electrochemical process and corrode the pipe in that area while cathodically protecting the rest of the pipe in the less reactive soil. (65)

The growth of anaerobic bacteria, introduced into the fairly oxygen free atmosphere of the pipe backfill from the surface, is another possibility for corrosion. Reacting with soluble salts, they cause a chemical change in the soil which increases the corrosive conditions around the pipe. (21, 38, 65, 66) Bacterial reactions can also cause a differential in oxygen concentration, in which case the oxygen deficient areas become anodic relative to the rest of the pipe and are attacked. This usually happens at the bottom of the pipe.

Another important form of corrosive attack involves direct electrolysis, or "stray D-C currents" which occur in the ground from electrical systems such as cathodic protection systems or other D-C current producing systems. Cast iron, being a ferrous material, is $10^8$ times more conductive of electricity than soil, and hence offers a preferred path for current flow. One amp is said to remove 20 pounds of metal in a year. (22) Therefore, the electric current would use the pipeline as its means of travel until it reaches a suitable point of departure to complete its circuit. The area where the stray current is picked up by the pipe becomes the cathode and
the area where the stray current leaves the pipe to complete its circuit becomes the anode. In this anodic area, there is a loss of the metal by ionization which creates a localized type of corrosion suitable for a failure site.

Stress corrosion can also be important. In this process sustained tensile stresses, due to residual stresses or service stresses, act on a crack in the presence of an electrolyte, and can create a situation whereby a rapid penetrating corrosive attack can take place.

It is unlikely that corrosion itself will cause failure. Its most likely effect is to weaken an area of the pipe by pitting or create a reduction in thickness. This weakening does, however, promote failures from other causes such as surge pressures in the pipe or other excessive stress conditions.

2.4.2 Water Hammer

Hammer effects can take place in any elastic body. This phenomenon describes the ability of a material to create internal stresses within itself when it is in motion. This motion can be either an acceleration or a deceleration. The magnitude of such stresses within the material depends upon the rate of velocity change taking place. In this case, the material creating the stresses is water. Water, being confined in the pipe, transmits its internal stresses to the walls of the pipe. When these stresses are of a substantial magnitude, an increase in pressure over the specified working pressure of the pipe can take place. Such an
experience has been recorded for a rapid shut down of a centrifugal pump in a water supply system. The sudden closure caused the pressure within a discharge main to fluctuate from a low of 80 psi to a high of over 300 psi within a short period of time. (24) Even if immediate failure did not occur, a repeated or cyclic water hammer effect could cause a fatigue failure or the creation of a weak area for failure initiation.

2.4.3 Combined Stresses

This discussion on possible causes of failure would be incomplete if consideration were not given to the effects of the working stresses. A pipe under only hydrostatic pressure has circumferential stresses equal to twice its longitudinal stresses. (43) This indicates that a longitudinal fracture produced by circumferential stresses would be more likely than a circumferential failure under the same internal pressure conditions. Circumferential stresses are also created by residual stresses produced during manufacture. Beam stresses created by static overload and installation conditions were discussed previously. In this stressed situation, a longitudinal failure is also predicted. Hence, by combining the stresses caused by: hydrostatic pressure, water hammer, residual stresses and beam stresses, a situation could result by which even a defect free pipe could fail under working conditions that would not appear at first to be severe.

Other stress sources, such as natural phenomena, construction vibrations, temperature effects, cyclic water hammer effects from
positive displacement pumps, etc., could also contribute significantly to the stresses in a pipe. But investigation of these possibilities is beyond the scope of this investigation.
3.0 INVESTIGATION

No detailed information was available concerning installation conditions, trench conditions on excavation, the peripheral position of the crack, etc. Furthermore, it was impossible to conduct on-site tests relative to the stresses caused by hydraulic conditions during service. This investigation was, therefore, restricted to examination of the pipe and to analytical explorations of the stresses that would be produced in the pipe under various conditions. While the missing information could be quite important, it was felt that most of the failure causes discussed in the preceding section could be investigated by examination of the pipe and by analytical methods.

The following is a list of areas covered in this investigation:

- Visual Inspection
- Radiography
- Quality Determination
- Metallography
- Electron Microprobe Analysis
- Stress Analysis

3.1 VISUAL INSPECTION

Valuable information concerning the cause of a failure may often be found by visual observation of the fractured surface and the surrounding area. In particular, visible defects such as corrosion pits, cracks, inclusion concentrations, or external defects, are potential weak points which could cause premature failure, and as such should be given concentrated investigations. The entire fracture surface
was studied repeatedly using the unaided eye and a stereomicroscope with magnifications up to 30X.

3.1.1 Observations

Figures 2, 3, and 4 show the 12 inch diameter cast iron pipe with the bell end and part of the spigot, or straight end, cut off and the fractured area opened for inspection. The ends were removed by deeply notching a ring around the pipe and then breaking it apart. The crack opened to approximately 1/4 inch after the ends were removed. This established the presence of residual hoop stresses in the pipe. In Figure 1, the as-received pipe already possessed a fracture opening of approximately 1/16 of an inch. The fractured area was exposed by grinding a longitudinal notch in the outside of the pipe wall opposite to the fractured surface and slowly forcing the pipe open with a hydraulic jack until it broke along the notch.

The first objective of the fracture examination was to establish the failure mode and the history of propagation as interpreted from the fractured surface. The two most common modes of failure are shear, or ductile, failure and cleavage, or brittle, failure. A combination of shear and cleavage is also possible.

A ductile, or shear failure usually has a dull gray "fibrous" surface appearance and indicates a slipping off or plastic flow type of deformation. Shear failure occurs as a result of shearing stresses acting parallel with crystal slip planes. These are planes with high atomic density. For iron these planes include the \{110\}, \{112\} and
Figure 2. View of cast iron water main with the fracture surface exposed for inspection in the center. Bell end is at the top.
Figure 3. Side view of sectioned water main with fracture surface showing mode of crack propagation.
Figure 4. Sectioned water main and fracture mode observed from a different angle.
On the other hand, a brittle or cleavage failure usually shows a crystalline, reflective surface and indicates a nearly instantaneous failure with a minimum of plastic deformation. Failure in this mode is caused by tensile stresses acting along different sets of crystallographic planes known as cleavage planes, which in iron are the \{100\} planes. (64)

Figure 5 shows the two matching surfaces of the entire fractured surface as it appeared upon examination. Measured distances along the fracture, as shown, starting from the spigot end and proceeding towards the bell end. Area designations will be made throughout this paper by reference to the tape numbers shown in this Figure. The fractured surface was covered with rust. Unprotected cast iron, wet by the water moving out through the fracture, possibly went through a chemical reaction as follows:

Anodic: \[ \text{Fe} \rightarrow \text{Fe}^{+2} + 2e \]

Cathodic: \[ \text{O}_2 + 2\text{H}_2\text{O} + 4e \rightarrow 4\text{OH}^- \]

Total Reaction: \[ 2\text{Fe} + 2\text{H}_2\text{O} + \text{O}_2 \rightarrow 2\text{Fe}^{+2} + 4\text{OH}^- + 2\text{Fe} (\text{OH})_2 \]

Ferrous hydroxide, being unstable in the presence of oxygen, is oxidized further to ferric hydroxide by the following reaction.

Final Reaction: \[ 2\text{Fe(OH)}_2 + \text{H}_2\text{O} + \frac{1}{2}\text{O}_2 \rightarrow 2\text{Fe(OH)}_3 \]

Ferric hydroxide or hydrated ferric oxide is insoluble and precipitates out of the water. (23) It is orange to red brown in color and is the major constituent in common rust. Rust consists of at least three types of iron oxide in different conditions of oxidation. (67)
Figure 5. Appearance of the entire mating fracture surface under examination. Measurement starts at the spigot end of the fracture and increases towards the bell end.
The presence of rust on the surface obscured much of the detail which could have led to positive identification of the area where fracture initiated. Considerable caution had to be exercised, therefore, in interpreting visual observations.

The fracture was brittle, as shown by the relatively flat fracture surface, with no signs of plastic deformation. Limited deformation and a flat fracture surface would be expected in cast iron that failed in tension, since cast iron seldom displays much ductility on fracture.

Brittle failures often contain distinctive surface irregularities forming a chevron or herringbone pattern. This indicates a fast propagation rate, which is very common in steel fracturing in a brittle manner. These patterns are formed by the movement of the crack front as it branches and moves on different levels through the grains. The points of the chevrons point back to the fracture initiation site, which could be a corrosion pit, a crack, an inclusion, etc. (64)

Between zero inches, the end of the fracture nearest to the spigot or straight end of the pipe, and 35 inches, a faint herringbone pattern was found. However, the pattern vanished at about 35 inches. Some ripples also occurred intermittently along the surface towards the bell end, such as the area between 45 to 49 inches.

Many spots or inclusion were also present on the fracture surface between 20 and 68 inches. Their white appearance suggests that they were once part of the cement lining, before failure occurred, rather than a part of the metallurgical structure of the pipe.
In Figure 6, colored photographs of the area between 68 and 92 inches are presented. The surface appearance in this area showed a different color from the rest of the fractured surface. Variations in surface color also occurred in the region between zero and nine inches. From the orange color of rust, the fracture surface changed to black or dark gray color with a distinct black layer near the inside surface starting at approximately 70 inches and extending to the outside surface at approximately 81 inches. At this point, a smaller dark band continues to approximately 88 inches. The black area at 71 to 72 inches, on only one of the mating surfaces, is spilled oil and not part of the original surface structure.

Scaling of an external layer on the outside of the pipe were found quite regularly throughout the examination. Examples of this scaling or chipping layer can be seen in Figure 6 on the upper mating surface at 86 inches and at 87 1/2 inches. This scaling material measured approximately 1/32 of an inch to 1/16 of an inch in thickness. In Figure 7, a multiple scaling effect at zero inches is observed with at least two, and perhaps three layers. The two definite outside layers both measured approximately 1/32 of an inch in thickness. The appearance and thickness of these layers indicates that they could not be part of the bituminous coating. However, it must be noted here that this extensive surface layer separation shown in Figure 7 was not found along the fracture surface.

Gas holes or porosity cavities were frequently found approximately 1/32 of an inch or less away from the outside surface as shown in Figure 8. In this picture, two sections exhibiting this condition
Figure 6. Color photographs showing the difference in fracture surface appearance between 68 inches and 92 inches.
Figure 7. Multiple separation of thin metal layers on outer pipe wall at zero inches. Both layers measured approximately 1/32 of an inch in thickness.
Figure 8. Gas holes or porosity in hemispheric shape found approximately 1/32 of an inch away from the outside pipe surface.
were placed back to back and photographed at a magnification of approximately 5X. The hemispheric formation gives a good indication that gas was trapped on a layer which had already solidified. This was the previously mentioned external surface layer which was susceptible to chipping. Small cavities were also seen to occur in the lap or fusion zone between overlapping metal spirals.

At approximately 82 1/2 inches, a transverse crack was found which was about 2 inches in length. It was found on only one side of the longitudinal fracture. After radiographic examination, which will be covered in the next section, the transverse crack was sectioned to reveal its fracture surface. Initially, the area between 82 inches and 83 inches which contained the transverse crack was sectioned from the pipe to a depth of two inches below the longitudinal fracture surface, as shown in Figure 9. A second cut was then made 1/2 inch below, and parallel with the longitudinal fracture surface. The purpose of this cut was to reveal the surface condition of the transverse crack at its intersection with the longitudinal fracture surface. The fracture surface was found to be rusted over with a dull reddish brown color similar to that observed on the longitudinal fracture surface in this area. But, the distinct thin dark band observed during examination on the longitudinal fracture surface was not present, as shown in Figure 10. The specimen labeled 1 in Figure 10 has the longitudinal fracture at the top, and the transverse fracture surface faces in the direction of the bell end of the pipe.
Figure 9. Transverse crack located at 82 1/2 inches sectioned from the pipe at a depth of two inches below the longitudinal fracture surface. Cut made at 1/2 inch below the longitudinal surface revealed the surface condition of the transverse crack.
Figure 10. Color photograph of the intersection between the longitudinal fracture surface and the transverse fracture surface. Distinct thin band of material observed on the longitudinal fracture surface did not exist on the transverse fracture surface. The transverse surface in specimen number 1 faces in the direction of the bell end of the pipe.
A third cut was then made parallel to and 1/2 inch below the second cut to determine more completely the extent of rust formation. This is shown in Figure 11. The specimens obtained from this cut are labelled 3 and 4. Figure 12 shows the fracture surfaces on specimens 3 and 4. These surfaces show the formation of rust extending approximately one inch below the longitudinal fracture surface. The rust formation took on the shape of an arc which started at the outer pipe wall 1/2 inch below the longitudinal fracture surface and ended at the inner pipe wall one inch below the longitudinal fracture surface. The fracture surfaces in specimens 3 and 4 near the outer wall were not covered with rust. They were gray in appearance, typical of a fresh fracture surface. A slight tap with a hammer was required to separate these two specimens. This indicates that the crack which was observed on the outer surface to be two inches long, did not propagate completely through the pipe wall but propagated along the outer pipe surface. In all probability, crack propagation occurred primarily within the thin layer of metal found on the outer pipe surface.

This transverse crack could have been caused during excavation, handling, or transportation. Examination of the fracture surfaces showed no signs of a bituminous coating penetration from the outside to indicate the presence of a crack produced during the manufacture of the pipe. Signs of impact damage on the outer pipe surface along the path of crack propagation or at the intersection between the transverse crack and the longitudinal crack were not observed.
Figure 11. Transverse crack at 82 1/2 inches sectioned at a depth of 1/2 inch and one inch below and parallel with the longitudinal fracture surface to reveal the extent of rust formation.
Figure 12. Color photograph showing the arc shape rust formation on the transverse fracture surface starting at the outer pipe wall and ending at the inner pipe wall. Fresh fracture surface revealed during specimen preparation is shown on outer wall of specimens 3 and 4. Note thin metal layer separation on outer pipe wall.
Evidence in the form of a pit or a massive build up of corrosion products to indicate crack initiation from a corrosive attack by an external source were not found on the outer wall. The nature or mechanism by which the transverse crack initiated or could have resulted in the longitudinal crack was not detected during examination of the outer pipe wall. As noted earlier, the rust formation on the transverse fracture surface shown in Figure 12 indicates that the crack started from the inner pipe surface. Examination of the inner surface coated with the cement lining gave no visual indication of internal corrosion activity caused by the water due to poor bonding between the cement and pipe. According to the American National Standards Institute Specification A21-6-1970 Section 6-9, the pipe's internal cement lining is applied after the required 10 second 500 psi hydrostatic test at the foundry. The bituminous outer coating is applied before the test while it is still hot and clean. Since the transverse fracture surface showed no signs of surface penetration by either coatings it is a good possibility that this crack was initiated after manufacturing operations had been completed, possibly during handling, transportation, or in service. It is, however, almost certain that this crack existed at the time the pipe was excavated due to the rusted surface in the crack.

A check of the inside cement lining along the longitudinal fracture showed no evidence of corrosion deposits that would indicate tuberculation effects. This would tend to exclude internal corrosion as a source of failure. The outside surface of the pipe showed no
signs of bruises or damage of any sort. However, lapping zones were quite noticeable. Small cavities were found within a few of these zones, as mentioned before, and a metal "tear" starting at one of these zones occurred in the area of 88 3/4 inches and is shown in Figure 13. The external surface also showed a rough and pitted appearance which, together with the pronounced surface irregularities at laps, indicates possible manufacturing irregularities.

3.1.2 Analysis

Rust on the fracture surface prevented fine surface details from being observed. A faint herringbone structure was found, however, in the area between zero inches and 35 inches which indicated that the fracture could have started somewhere in the direction of the bell end. The peculiar change in surface appearance between 68 and 92 inches suggests that possibly this is the area in which the fracture had its beginning.

The change in appearance of the fracture surface in this region is probably related to a type of rust formation. Rust, as mentioned before, exists in three different states of oxidation, i.e., ferrous hydroxide or hydrous ferrous oxide (FeO·nH₂O), hydrous ferrous ferrite (Fe₃O₄·nH₂O), and ferric hydroxide of hydrous ferric oxide (Fe₂O₃·nH₂O). (67) Hydrous ferrous oxide is white when pure but normally green to greenish black when initially exposed to air. Hydrous ferrous ferrite forms a black intermediate layer between FeO·nH₂O and Fe₂O₃·nH₂O. Hydrous ferric oxide comprises most of
Figure 13. Metal "tear" starting at a metal lap zone at 88 3/4 inches.
ordinary rust and exhibits the orange to red brown color commonly seen. This surface coloration at the bell end of the fracture could be a combination of iron oxide in different states of oxidation. Another possibility is related to a form of disintegration peculiar to gray cast iron called graphitization when exposed to certain types of corrosive environments. According to Uhlig, gray cast iron is subject to graphitic corrosion when immersed in salt water, very dilute acids or buried underground in some soils, particularly those containing sulfates. (66) The graphitization process occurs over a period of time and involves an electrochemical action between two constituents in cast iron, i.e., ferrite and graphite. The anode being ferrite and the cathode graphite. Ferrite is the most reactive constituent in cast iron and graphite the most noble with pearlite, pearlite-phosphide eutectic, and cementite arranged in order of nobility between the two. (58) The removal of ferrite or iron from the matrix normally occurs around graphite centers leaving behind a black soft porous structure. (15, 58, 72) The black residual structure consists of graphite, cementite particles if present, and corrosion products such as iron oxides. (11, 72) The metal shows very little evidence of attack and the graphitized area is said to retain its original dimensions and shape. (11, 58, 72) The strength properties in the area of attack is considerably reduced but surprisingly the graphitized area of the cast iron pipe has enough strength to carry water under low pressure. (11, 56, 58) Gas cavities were found to be situated near the outside surface of the pipe and in lapping zones. These gas holes or cavities
were probably the result of the formation of gas upon solidification of the liquid metal on the mold surface. The centrifugal casting process described in section two should provide enough centrifugal force to force gas and non-metallic inclusions toward the inside of the pipe. Trapping of gas porosity at the outer surface may well have been caused by a fast rate of solidification of the casting, which would prevent the movement of such defects to the interior.

The areas of porosity seem to occur almost exclusively at the inner surface of the thin outer surface layer and in the lapping zones. The most likely conclusion is that the external layer, measuring approximately 1/32 of an inch to 1/16 of an inch in thickness, solidified before the rest of the molten metal. This situation could have been created by a quenching effect if the metal were poured into a "cold" mold. The well-defined lapping appearance on the external pipe surface suggest areas of incomplete fusion between molten metal spirals. This adds support to the previous assumption, and raises the question concerning how far does the quenching effect extend and promote lapping effects? This will be covered during metallographic analysis.

The only secondary crack found was at 82 1/2 inches. As yet, there is no indication that it existed prior to, or was caused by the same factors that caused the main pipe failure. However, based on past experience of structural failure investigators, when a secondary crack runs perpendicular to the main crack and terminates, it can safely be said that the secondary crack formed during or immediately after the propagation of the main crack to failure.
At no area on the fracture surface were the effects of fatigue or of a penetrating type of corrosion visible. However, the presence of the rust could possibly obscure such evidence.

The white particles on the fracture surface are believed to be cement particles that were forced into the crack by the hydrostatic force of the flowing water. They were then smashed between the mating surfaces, possibly on the closing of the fracture due to the elastic reaction of the pipe when pumping pressure was removed. Note that corresponding particle images are seen on each side of the fractured pipe surface.

From visual inspection, several areas were believed to be potential starting points for the fracture, such as the transverse crack, non-uniform fusion between laps, internally situated porosity, etc., but nothing definite was observed to single out any one area as "the place".

3.2 RADIOGRAPHY

Radiography was used to search for defects in the vicinity of the fracture, and to make a preliminary evaluation of the nature and severity of these defects. Radiography is a non-destructive test that uses x-ray radiation as a means of recording a material's internal defect features on film. (13) Defects such as gas holes, shrinkage cavities, inclusions, segregation areas, cracks, incomplete fusion etc., can be detected and partially evaluated as to their severity.
3.2.1 Radiographic Apparatus and Procedure

The radiographic equipment used was a 110 volt, 15 amp, Baltograph 200B made by the Balteau Electric Corporation of Stamford Connecticut. This equipment was capable of x-ray generating potentials up to 200,000 volts. The radiographic set-up is shown in Figure 14.

The control unit is located to the left of the picture and the x-ray source is located in the lead protected room to the right. The x-rays are projected downward and are passed through the material and recorded on the x-ray film beneath it. The negative is a recording of the amount of radiation transmitted through different areas of the material. The degree of darkening of the film is referred to as density. The darker or denser areas, when observing the negative against light, show the areas of the material which offered the least resistance to radiation penetration, as compared to the lighter areas on the negative which show a higher resistance to penetration. Thus, defects such as gas holes or shrinkage cavities, offering a lower resistance to x-ray penetration than a defect free area, are recorded on film.

A penetrameter is used to prove the acceptability or quality of a radiograph. Penetrameters are small, thin strips of metal, of the same type of base material as the material being radiographed. They contain three holes with diameters of approximately one, two, and four times the thickness of the penetrameter. Penetrameter thickness is approximately two percent of the thickness of the radiographed material. Before radiographing, the penetrameter is
Figure 14. Baltograph 200B radiographic equipment and radiographic set-up.
placed on the material. After testing, acceptable radiographic quality is established by the visibility of the penetrarmeter and its holes on the negative. (13, 20)

The film used was Type M industrial x-ray film produced by Kodak. This is an extra fine grain, high contrast film which has a high sensitivity to x-rays. This film is packaged in an envelope between lead screens. Lead screens reduce the effects of scattered radiation produced by the material, off the walls and floor, film holder, etc., when hit by direct radiation. Lead also intensifies the exposure by emitting electrons which cause better emulsion activation than the high energy x-rays. Hence, a better quality negative is produced. (13, 20)

Before use of this radiographic equipment, a pre-heat or preliminary warm-up is required to prevent damage to the x-ray tube. This is done by having the equipment on for five minutes, which is the maximum exposure time, and off five minutes for each ten kilovolts increment starting with 100 kilovolts and continuing up to whatever voltage is desired for use. These warm-up runs are made with the milliamp control at its minimum setting.

The first trial exposure time was determined from an exposure time versus material thickness chart for steel. This chart can be seen above the control unit in Figure 14. Experimentation showed that the best exposures were obtained with a combination of 150 kilovolts, five milliamps, and ten minutes exposure time.
A strip approximately four inches wide was cut from one side of the entire seven feet four inch fractured surface. This strip was cut in 11 pieces ranging from six inches to 9\(\frac{1}{2}\) inches in length. Each piece was radiographed. Areas at 83\(\frac{1}{2}\) inches to 84\(\frac{1}{2}\) inches and at 90\(\frac{1}{2}\) inches to 92 inches, in Figure 5, were already cut and mounted for metallography and were therefore excluded from radiographing. Figure 15 shows the pieces of the fractured surface after being cut. Piece number one, representing the fracture surface nearest the straight end of the pipe, is located at the bottom of the picture. In each of the 11 pieces shown, tape measurements are made right to left, proceeding from zero inches in piece number one, at the lower right hand corner, to 92 inches in piece number 11, at the upper left hand corner.

The cement inner lining was not removed because it was quite adherent to the pipe and difficult to remove. It did not confuse the interpretation of radiographic results.

3.2.2 Analysis of Radiographs

Figure 16a to 16k are contact prints of the radiographs of the sections of the pipe wall for the entire length of the fracture. The detail in these prints is not as good as in the original radiographs. Comparison of the blurred transverse lines in all of the radiographs with the external surface appearance of each of the specimens showed that these lines corresponded to areas where molten metal, on centrifugal casting, overlapped.
Figure 15. Longitudinal fracture surface after sectioning into 11 pieces for radiography. The section from zero inches to eight inches located on the bottom measuring from right to left.
Figure 16a. Radiographic print of the section of pipe wall between zero inches on the left and eight inches.
Figure 16b. Radiographic print of the section of pipe wall between eight inches on the left and 16 inches.
Figure 16c. Radiographic print of the section of pipe wall between 16 inches on the left and 24 inches.
Figure 16d. Radiographic print of the section of pipe wall between 24 inches on the left and 32 inches.
Figure 16e. Radiographic print of the section of pipe wall between 32 inches on the left and 40 inches.
Figure 16f. Radiographic print of the section of pipe wall between 40 inches on the left and 49 inches.
Figure 16g. Radiographic print of the section of pipe wall between 49 inches on the left and 58 inches.
Figure 16h. Radiographic print of the section of pipe wall between 58 inches on the left and 67 1/2 inches.
Figure 16i. Radiographic print of the section of pipe wall between 67 1/2 inches on the left and 75 1/2 inches.
Figure 16j. Radiographic print of the section of pipe wall between 75 1/2 inches on the left and 83 inches.
Figure 16k. Radiographic print of the section of pipe wall between 84 inches on the left and 90 inches.
Of the same density and blurred appearance are spots scattered throughout the radiographs. These were initially assumed to represent pits and craters on the external surface. However, further investigation showed this assumption to be unreliable. On cross-sectioning portions of the specimens, cavities were unexpectedly found to exist approximately 1/32 of an inch below the outside surface. Correspondence with the radiographs showed the assumed surface irregularities to be in actuality internal cavities. To add further confusion on interpretation, the external surface was covered with small pits and craters in the general vicinity. Lapping zones were clearly visible in the radiographs and other external surface irregularities of sufficient depth were also recorded.

Fairly large random gas holes or shrinkage cavities, and groupings of smaller gas holes, were found to exist occasionally throughout the radiographed specimens. Of interest here is their radiographic density. The deepest holes showed the greatest density, and are seen in figure prints as the brightest spots. The groupings of small gas holes produced images that were not as dense and were located mainly in the metal laps.

Figure 16a is the radiograph of the section of pipe wall between zero inches, starting from the left, and eight inches. The penetrmeter is the rectangular shadow near the center of the figure at the fracture surface. At approximately three inches from the left hand corner and 1/2 to 3/4 inches down from the fractured surface, two very distinct pits or cavities appear. The cross sectional radiographic view in Figure 17b shows wall thickness penetration of
Figure 17a. Radiographic print of the pipe wall thickness cross section at 67 1/2 inches revealing small clusters of gas holes beneath the outer wall and located in the area of the metal lapping zone. Fracture surface is on the right.

Figure 17b. Cross sectional radiographic view of the pipe wall thickness revealing two penetrating cavities with depths of 7/64 inch and 5/32 inch beneath the outer pipe surface. Fracture surface is on the right.
approximately 7/64 inch for the right cavity and approximately 5/32 inch for the left cavity. In this radiograph, the fracture surface is at the right. The measured thickness of the pipe in this area is approximately 15/32 inch. Thickness reductions of at least 1/4 and 1/3 are represented by these cavities, respectively. This is quite a substantial decrease in thickness, and its importance is increased by the fact that it occurs below a 1/32 inch layer of material which is of questionable quality.

Figure 17a shows a cross sectional radiographic view of a metal lap containing small clusters of gas holes within the area of fusion. The fracture surface is on the right hand side in this figure. This specimen was taken from the lap shown on the left edge of Figure 16i. Figure 16i shows the fracture region starting at 67 1/2 inch on the left and extending to 75 1/2 inch. The radiographic density of these gas holes, near the upper surface in Figure 17b, is very light requiring close visual observation. The holes in the vicinity of the lap appear from the radiograph to start approximately 1/64 inch below the surface.

Figure 16e shows the area between 32 inches and 40 inches measuring left to right. Cavities are apparent 4 3/4 inch from the left which appear to extend from the fracture surface to 3/32 inch below the fracture surface. A cross sectional radiograph of this area is shown in Figure 18a, in which these cavities appear on the extreme right. The largest cavity actually lies approximately 4/32 inch from the fractured surface located on the right. Maximum penetration into the pipe's thickness is approximately 2/32 inch. This cavity is also
Figure 18a. Cross sectional radiographic view of the cavities observed on the fracture surface at 36 3/4 inches. Fracture surface is on the right.

Figure 18b. Cross sectional radiographic view of the pipe wall thickness at 56 inches. The cavity is not observed on the fracture surface next to outer wall. Details along the edge of the fracture surface on the right are obscured by edge effects.

Figure 18c. Cross sectional radiographic view of the multiple surface layer separation found on the fracture surface, at the right, at zero inches. As shown, a degree of bonding between the surface layers and the rest of the wall thickness does exist.
formed against the thin surface layer at a depth of approximately 1/32 inch below the outside surface.

Figure 16g shows the radiograph of the specimen extending from 49 inches, on the left, to 58 inches. Examination of the fracture surface revealed a hole just below the outer surface layer and approximately 1/32 inch in diameter. This was at a point in the fracture surface two inches from the 58 inch end of the specimen, on the right in Figure 16g. Unfortunately, edge effects obscure some of the detail along the edges of the specimens in the radiographs, and the hole does not show up in Figure 16g. This does show, however, that the hole seen in the visual examination was not a small opening into a large cavity. A 1/2 inch wide strip was later cut from the specimen at this point with its long axis perpendicular to the fracture surface. This strip was then radiographed to show a cross section through the pipe wall as shown in Figure 18b. Again, edge effects obscure detail at the right end of this specimen and the hole in the fracture surface cannot be seen. This does confirm the conclusion reached from the radiograph of Figure 16g. The hole seen in the fracture surface was not an opening into a large cavity.

Figure 7 indicates that in at least some cases the outer surface layer was not bonded at all to the inner portion of the pipe wall. The gap shown in Figure 7 also shows clearly at the right end of the radiograph of Figure 18c. A 1/2 inch thick specimen was cut from the left end of the specimen of Figure 16a, that is, from the zero inch end of the crack, to make this radiograph. A small crack is also visible in the radiograph of Figure 18c at the left end of the specimen.
This crack could be seen by careful visual examination of the outer surface of the specimen. It was a separation between the surface layer and the rest of the wall material, with the surface layer being approximately 1/32 inch thick. However, cracks of these kinds were not visible in other cross section radiographs, i.e., Figure 17 and 18, so it must be concluded that in most cases there was some degree of bonding between the surface layer and the rest of the material.

A radiographic examination was also made in the vicinity of the transverse crack found during visual inspection. The radiograph of the transverse crack is shown in Figure 16j. In this radiograph it appears to be 1 1/4 inch long. Direct observation of the crack, however, showed it to be nearer to two inches in length. As can be seen, there were no visible defects in its general vicinity that could have caused it. To be certain, this area containing the transverse crack was sectioned and radiographed once again. Figure 19 shows this radiograph. No defect can be seen near the intersection of the transverse crack with the longitudinal fracture surface at the top of the half inch pieces. Careful examination of the area along the transverse crack also showed no signs of any defect, which reinforces the conclusion drawn from Figure 16j.

3.2.3 **Summary of Radiographic Study**

Although no specific fracture initiation site was found during radiography, considerable information was obtained concerning the metallurgical condition of the pipe.
Figure 19. Radiographic print of the transverse crack showing no signs of defects in the vicinity of the crack.
The external surface layer of metal was a defect condition which seemed to be associated with the formation of all other internal defects. In the radiographs a separation between this layer and the rest of the pipe wall was found to be the exception rather than the rule. This does not mean, however, that the interface between these layers was not generally weakly bonded. As described later, metallographic examination was also used to study this external surface layer.

Gas holes and penetrating cavities were found to be located on the inner surface of this layer. These were also examined microscopically and will be described and discussed in greater detail in a later section. As seen in Figure 17b, the penetrating type of cavity caused a major reduction in the thickness of the pipe. In this case, the reduction was as much as 30%!

Examination of the material in the pipe wall along the length of the fractured surface showed likely areas in which fracture could have initiated. There was a general reduction in the thickness of the pipe wall of approximately 1/32 inch due to the surface layer on the outer pipe wall. In addition, the pipe wall would be further weakened in some places by the presence of gas porosity below the surface layer. Evidence of gas porosity was found in many areas, such as in the region shown in Figure 18a. It may have been present along the fracture surface, but its presence could have been obscured from visual examination by rust.
Limited information on the metal lapping zones was obtained from the radiographs. Gas porosity was found in some of the lapping zones. Some of these were subjected to further study by metallography as will be described later.

No metallurgical defect was found in the immediate vicinity of the small transverse crack by either visual inspection or radiography. This suggests that this crack was not caused by a metallurgical defect.

Figures 16i, 16j, and 16k covered the area between 67 1/2 inches and 92 inches, which is the region in which the fracture surface showed a pronounced difference in coloration. The transverse crack and most of the laps showing gas porosity concentration were located in this region. There are no apparent defects along the fractured surface in this area to indicate points where the fracture might have originated, with the exception, of course, of the transverse crack.

3.3 QUALITY DETERMINATION

A pipe can be rejected at the Foundry for either of two reasons. The first reason is an unsatisfactory chemical analysis. That will be discussed in this section. The second, which will be covered in the next section, deals with its physical properties.

3.3.1 Chemical Analysis

Cast irons are primarily alloys of iron, carbon, and silicon. However, other elements like sulfur, phosphorus, and manganese are also present in appreciable amounts and can have significant effects on the final characteristics of the metal. The following paragraphs summarize the effects of each element. (1, 3, 12)
Carbon is the most important element in cast iron. Its controlling effects on mechanical properties can not be denied. The carbon contents of most cast irons lie between 2% and 4%. The bulk of this carbon appears in the structure of cast irons either combined with iron as the intermetallic compound cementite (Fe$_3$C), or as graphite. The mechanical properties of cast irons are primarily determined by the relative amounts and the distributions of these two phases.

Silicon is the second most influential element. It may appear in amounts up to 3% by weight. Silicon decreases the solubility of iron for carbon, which then alters the equilibrium diagram and promotes graphitization. In solid solution in the iron matrix, silicon increases brittleness, but also increases hardness and strength. However, above 3%, the matrix becomes very brittle.

The percent of manganese found in cast iron is usually less than 1%. Its major influence is to tie up sulfur by forming a manganese sulfide compound. Approximately three times the sulfur content is needed for this purpose. In excess quantities, it acts as a stabilizer for austenite and pearlite. When dissolved in the ferrite matrix, it adds strength and hardness.

Sulfur, below .15%, is said to have a negligible effect on properties. With manganese present in sufficient quantity, it should show no effect at all. However, uncombined sulfur is a carbide stabilizer and prevents graphitization if in excess quantity.

The phosphorous content in cast irons ranges from .05% to 1%. Little effect is shown on graphitization, although phosphorous does
lower the carbon necessary to undergo eutectic transformation. On the other hand, it acts as a carbide stabilizer and promotes the formation of a chill cast structure. Phosphorus tends to form a low melting point binary eutectic at approximately 1050°C. This eutectic, called steadite, is hard and brittle. Being a low melting point structure it is the last structure to solidify. This occurs in the so-called cell boundaries of cast iron which is similar to grain boundaries in other metals. Hence, the possibility of it forming a network is immense. One percent of phosphorus by weight is said to form nearly ten percent by volume of steadite. (3) Porosity, internal shrinkage, and reductions in machineability are attributed to phosphorus and the formation of steadite.

Two samples for chemical analysis were obtained from the cast iron pipe by drilling, and were sent to the U.S. Bureau of Mines Albany Metallurgy Research Center, Albany, Oregon. Sample number one was taken at eight inches and sample number two at 75 1/2 inches. The results obtained can be found in Table 1.

TABLE I. CHEMICAL ANALYSIS OF CAST IRON PIPE

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>Mn</th>
<th>Si</th>
<th>C</th>
<th>S</th>
</tr>
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<tr>
<td>Sample Number 1:</td>
<td>.59</td>
<td>.25</td>
<td>1.83</td>
<td>3.18</td>
<td>.06</td>
</tr>
<tr>
<td>Sample Number 2:</td>
<td>.57</td>
<td>.26</td>
<td>1.82</td>
<td>3.03</td>
<td>.07</td>
</tr>
</tbody>
</table>

According to the American National Standards Institute (ANSI) Specification A21.6-1970, Section 6-14 on chemical analysis, the phosphorus content should not exceed .9% and sulfur should not exceed
.12%. Failure to meet these requirements results in the rejection of the pipe. As can be seen, the phosphorus and sulfur content taken from the samples are well within this specification. As for the variation in carbon content, this can be attributed to the friable graphite flakes which are easily lost during drilling and handling. But this percentage is within the required carbon range of 3.0% to 3.75%. (12) The composition of the pipe is, therefore, well within the requirements of the standards. From the above results, it can be concluded that improper composition did not contribute to the failure of the pipe.

3.3.2 Physical Acceptance Tests

Two types of physical acceptance tests are used with cast iron pipe. The first type is the Talbot Strip Test and the second is hardness tests.

3.3.2.1 Talbot Strip Test

The Talbot Strip Test is one method of determining the quality of the material in a cast iron pipe. This test is restricted to pipes ranging from three inches to 24 inches in diameter. It is described in the appendix of section 6-A1 of ANSI Specification A21-1970. According to this description, 10 1/2 inch long strip specimens are tested. The only material available for these tests was, however, the pieces cut along the length of the fracture for radiography. As it turned out, 9 1/2 inch long specimens, taken from the piece between 58 and 67 1/2 inches, were the longest specimens that could
be obtained. It was felt that this change in dimension would have little effect on measured properties. This change in specimen did require modification in the Modulus of Rupture formula. See Appendix I for detail. The required depth of the specimens was 1/2 inch and the thickness of the pipe became the specimen's width. For these hand prepared specimens, the depth was approximately .53 inches and the thickness of the pipe was measured at approximately .46 inches. The specimens were tested as beams with nine inches between supports, instead of the specified ten inches, and with two loading points situated three inches apart. The failure load and maximum deflection were recorded for each test and were used to calculate the modulus of rupture and the secant modulus.

A Baldwin Testing machine with autographic load-deflection recording was used for these tests, as seen in Figure 20. The deflection magnification of the microformer deflection gage used in the tests was checked by comparing its recorded deflection readings with the simultaneous readings from a dial indicator. The stem of the dial indicator was placed in direct contact with the operating arm of the deflection gage so that movement of the arm caused both pen movement of the recorder and a changed reading of the dial indicator. A pen movement of 20 inches on the recorder corresponded to a one inch reading on the dial indicator. During testing, the deflection gage was mounted to indicate maximum beam deflection. Figures 21 and 22 are front and side views, respectively, of the testing setup. The deflection gage's operating arm is situated under
Figure 20. Baldwin testing machine with autographic load-deflection recording capability.
Figure 21. Angle view of test set-up with the microformer deflection gage used to measure beam deflection on the right.
Figure 22. Side view of test set-up with the microformer deflection gage's operating arm situated under the center of the beam. Located on the top of the beam is the fixture used to apply the two point loading.
the center of the beam. Deflection is then plotted as displacement on the recorder. The two point loading, often referred to as "third point loading", is applied by the fixtures shown. Tests were run to failure.

Three specimens, taken from the same area, were tested. Specimen number one was tested with the outside surface in compression and the inside surface in tension. Specimen number two was tested in the reverse manner with the outside surface in tension. And the last specimen, specimen number three, was broken according to Talbot Strip Test requirements. In this case, the outer and inner wall surfaces were on the vertical sides of the specimens as it was tested.

According to the ANSI Specification A21.6-1970 Section 6-12.1, the acceptance values are in terms of the Modulus of Rupture and the Secant Modulus of Elasticity. The Modulus of Rupture is the maximum stress in the outer fibers of the beam prior to failure, calculated on the basis of assumed elastic behavior. In other words, this is a measure of the strength of the pipe material. The Secant Modulus is a measure of the material's resistance to deflection under load. Equations used to calculate the Modulus of Rupture and the Secant Modulus of Elasticity are shown below.

\[
\text{Modulus of Rupture, } R = \frac{9W}{td^2}
\]

\[
\text{Secant Modulus of Elasticity, } E_s = \frac{21.3R}{ty}
\]

\[
W = \text{Failure load, lb}
\]

\[
t = \text{width of beam, inch}
\]
According to ANSI specifications, the minimum acceptance value for the Modulus of Rupture is 40,000 psi and the value for the Secant Modulus of Elasticity should not exceed 300 times the actual value of the Modulus of Rupture or a maximum of 12,000,000 psi for the above stated Modulus of Rupture. Results of the tests conducted on the three test specimens are listed in Table II.

**TABLE II. TALBOT STRIP TEST RESULTS**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>d-in</th>
<th>W-lb</th>
<th>y-in</th>
<th>R-psi</th>
<th>$E_s$-psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.52</td>
<td>560</td>
<td>.21</td>
<td>45,800</td>
<td>$10.1 \times 10^6$</td>
</tr>
<tr>
<td>2</td>
<td>.53</td>
<td>665</td>
<td>.18</td>
<td>53,200</td>
<td>$13.8 \times 10^6$</td>
</tr>
<tr>
<td>3</td>
<td>.46</td>
<td>685</td>
<td>.16</td>
<td>47,400</td>
<td>$11.9 \times 10^6$</td>
</tr>
</tbody>
</table>

Specimen number one, tested with the inside surface of the pipe in tension, had a Modulus of Rupture of 45,800 psi, and a Secant Modulus of 10,100,000 psi. Specimen number two, with the outside surface in tension had a Modulus of Rupture of 53,200 psi and a Secant Modulus of 13,800,000 psi! From this information, it can be concluded that the outside surface consists of a more deformation resistant material as compared with the more ductile inner surface. Also, the outside surface has a higher strength value to resist failure by bending than the inside surface.

Specimen number three was tested in the specimen orientation specified for Talbot Strip Tests, which takes into account the entire
thickness of the pipe. In this way, neither the inside nor the outside fibers determine the final modulus values as was the case in the first two tests. In the third test, the Modulus of Rupture was 47,400 psi and the Secant Modulus was 11,900,000 psi. Both values were within the acceptance limits.

Of the three load-deflection curves, only specimens numbered one and two, assuming the variations in measurements were approximately equal, could be compared with any degree of assurance. This can be traced to the manner in which each specimen was tested. Specimens one and two were tested with inner and outer wall surfaces, respectively, in tension, while specimen three had a section through the pipe wall in tension. Recall that the specimen's cross section was not a half inch square. The thickness of the pipe wall was approximately .46 inches and the other dimension of the specimens was approximately .53 inches. Specimen number three was the only specimen to be tested with a cross section through the pipe wall in tension. Tested as such, it had less width to withstand bending stresses but a deeper beam requiring a greater load, approximately 685 pounds, to cause failure. For the other two specimens, greater width was carrying the bending stresses but a shallower beam offered less resistance to deflection. The inside surface required approximately 560 pounds to initiate failure as compared to the approximate load of 665 pounds needed for the outside surface.

Comparison of the load-deflection curves of specimens one and two showed that the inside pipe surface had greater toughness than
the outside pipe surface. Toughness, or ability to absorb energy without failure, can be determined by the area under a load-deflection curve.

3.3.2.2 Hardness Test

According to section 6-12.2 on Hardness Tests in the ANSI Specification, two types of tests are required. The first requires that a hardness test be conducted on the outside pipe surface, after the annealing process, to determine whether or not a re-heat is necessary. Secondly, hardness tests are required to be conducted on Talbot strips. The hardness values obtained from the strips are kept on file by the manufacturer for a year before discarding. For both tests, the maximum acceptable average hardness value is a Rockwell B-95 and no single hardness test shall exceed B-98.

Hardness tests were run on the three Talbot strips taken from the area between 58 inches to 67 1/2 inches, and a representative sample from the area between zero inches to eight inches. In Section 6-A1 on Talbot Strip Tests, three locations were recommended. These were the outside surface, the inside surface, and the approximate middle of the pipe thickness. A hardness reading is required at each of the above specified surfaces at three evenly spaced locations along the Talbot strip.

Rockwell B hardness readings were obtained using a bench mounted Rockwell Hardness Tester, with a 100 kilogram load applied to a 1/16 inch ball indenter. Instead of the one required set of readings at
each Talbot strip location two sets were taken at each end of the strip and two near the failure site. Hardness readings for each tested specimen therefore consisted of 18 readings, six on the outside surface, six at the middle of the pipe wall, and six at the inside surface. The hardness readings are listed in Appendix II. Results show that a couple of hardness readings of B-94 were recorded for specimen three but no recorded readings went above B-98. The average hardness readings shown in Table III for each surface in the region between zero inches and eight inches and between 58 inches and 67 1/2 inches, were also within the hardness acceptability criteria of B-95.

<table>
<thead>
<tr>
<th></th>
<th>0 - 8 inches</th>
<th>58 - 67 1/2 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside pipe surface</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>Center of pipe thickness</td>
<td>79</td>
<td>76</td>
</tr>
<tr>
<td>Inside pipe surface</td>
<td>76</td>
<td>79</td>
</tr>
</tbody>
</table>

The results show a slight gradient in hardness from the outside to the inside surface. This was expected because of the hardening produced at the outside surface by the faster rate of cooling of the metal next to the water cooled mold. No pronounced difference in the hardness gradients in the two regions were recorded to indicate casting irregularities.
3.3.3 Summary of Quality Determination Tests

The quality determination tests indicate no positive basis on which this pipe could have been rejected. The chemical analysis complied with the ANSI Standards, although the carbon content was just above the minimum requirement of 3%. The hardness readings also indicate that the metallurgical condition of the cast iron pipe was acceptable. Talbot Strip Tests could also be considered favorable. Specimen three, tested according to Talbot strip test requirements fell within the established acceptance criteria. Although these tests were made under slightly non-standard conditions, the physical quality of the pipe appears to be acceptable.

3.4 METALLOGRAPHY

Control over a material's metallurgical structure is just as important as control over its chemical composition because structure often has a dominant effect on properties. Metallography is an important tool in studying the internal structure of materials, especially those in which failures have occurred. Defects observed visually can be analyzed as to their nature and extent in the material's metallurgical structure. The quality of a material can be evaluated from the microconstituents and their arrangement. (39) It is also possible to determine the conditions under which the material was manufactured.

The investigation thus far revealed unusual and undesirable material characteristics. The surface layer showed a tendency to
scale, gas holes, penetrating cavities, and lapping zone defects. These findings were strong evidence for the need of a careful study of the pipe's metallurgical structure.

3.4.1 Specimen Preparation

One half inch square specimens were taken from random locations along the length of the fracture surface. These specimens were identified by numbers corresponding to their locations as shown on the tape in Figure 5. By sectioning in different areas, an overall picture of the pipe's structure was obtained. Various other samples were also prepared to study in more detail specific defects that were observed previously. After the specimens were cut, they were mounted in Transoptic mounting powder and molded in a press. A temperature of 140 C and a pressure of approximately 3700 psi were used. Upon heating to 140 C, the heating apparatus was removed. Heat was then dissipated by a brass cylinder. After cooling to 70 C, both the pressure and the brass cylinder were removed and the mounted specimen was ejected.

A series of grinding steps was then required to remove the disturbed metal created during sectioning. The first procedure was to grind the mounted sample on a water cooled, motor driven 120X grit grinding belt, preferably in only one direction. Successive grinds on a 300X grit and then a 400X grit abrasive paper followed. At each new step of grinding the specimens were rotated 90 degrees to the previous grind. In this way, it was easier to determine when the
disturbed metal from the previous grind was removed. J. R. Vilella (68) recommends the use of a light pressure for grinding cast iron containing graphite flakes, to prevent the formation of deep scratches. This is especially critical during the last step before polishing. Vilella also recommends that the surface of the final sand paper be glazed with a soapstone or graphite bar to remove the coarseness of the paper. This results in all scratches being very fine, and they are easily removed during polishing. Following these recommendations, a light pressure grind on a worn 600X grit sandpaper was used as the last step in grinding.

Polishing of the specimen to a mirror-like surface was the next step. The most difficult task here was the retention of graphite in its true form. Graphite is a very fragile material and is easily removed or torn out during regular polishing techniques. Vilella recommends the use of "the dull side of a heavy, pure, silk satin" on a motor driven polishing wheel as giving the best graphite retention and polishing results. Also, the powder used in polishing should be worked into the wet mat by hand and all coarse particles removed before polishing. The procedure recommended by H. Morrogh (40) is similar to Vilella's with slight variations in techniques. However, Morrogh stresses the use of an alternate polishing and etching method. This method increases the removal of disturbed metal and reduces polishing time. The combined techniques of both authors were incorporated into the final modified version used in polishing.
Polishing was done in three stages. The first stage consisted of polishing the specimen by grinding on a paste-like mat made up of .3 micron alpha alumina micropolish. A soap solution was used as the damping media. Polishing was done 90 degrees to the previous grind which was on a worn 600X grit paper. During this procedure, alternate polishing and etching was used extensively. A 2% Alcoholic Nitric Acid solution was used as the etchant. After the removal of all of the grinding scratches microscopic observation of the sample would show comet tails or the directional orientation of polishing. The second stage in polishing was designed to eliminate this feature. Re-surfacing the cloth on the wheel, a circular polish was used to remove the flowed appearance. The third and last polishing procedure also consisted of a circular polish. This time, the mat was surfaced with a .05 micron gamma alumina micropolish paste. The specimen was then ready to be analyzed under the microscope. Specimens were taken from 0, 8, 24, 30, 40, 58, 75 1/2 and 82 inches as well as the spigot end of the pipe.

3.4.2 Solidification of Gray Cast Iron

Basically, solification of gray cast iron under equilibrium conditions starts with the formation of primary austenite dendrites which occurs over a range of temperatures as the melt is cooled from the liquid state. With the formation of austenite dendrites the remaining liquid is enriched with the dissolved carbon. Upon cooling to the eutectic temperature the melt now of eutectic composition starts to solidify as eutectic cells which are aggregates of austenite
and graphite solidifying with a spheroidal front. The graphite flakes grow more or less radially within the cells. As the flakes grow with one end in contact with the melt, it forms a layer of austenite around itself. On completion of eutectic solidification, the primary austenite dendrites gives an appearance of continuity with the secondary austenite. (16, 19, 27, 36, 37)

In centrifugal castings the melt most likely solidifies according to wall growth characteristics. (19) Phase transformation occurring within the melt in response to falling temperature will take place in "waves". All positions in the casting will undergo the same changes as the temperature decreases through the temperature range of liquid to solid. The time for each change to take place at any given position is determined by the rate of temperature drop which is dependent on heat transfer conditions. Rate of heat transfer, and hence temperature drop, are faster at surfaces than in central regions of the casting. Phase transformation and elimination of superheat will therefore occur first at the surface, i.e., at the mold walls.

Two bands or waves of freezing are said to traverse the casting during solidification. (19) The first wave results in the growth of austenite dendrites which sweeps from the mold wall towards the inner surface in a wavelike pattern. The material ahead of the dendrites will remain liquid until the advancing dendrite wave arrives. Dendritic growth will also result in thickening of the dendrites, a decrease in the amount of interdendritic liquid, and the enrichment of this liquid with carbon until it reaches eutectic composition. The second
wave, which involves the eutectic reaction, liquid $\rightarrow$ austenite + graphite, will not be able to proceed until the first wave is completed. This is because heat released by the liquid to austenite transformation will prevent the eutectic reaction from taking place. As the temperature is lowered to the eutectic temperature and the remaining liquid achieves eutectic composition, a eutectic hold or transformation delay, occurs in inner portions of the casting since the temperature of the inner thickness is not able to fall until the eutectic reaction wave starting at the mold wall reaches its location. Final transformation of the melt to a solid by the eutectic reaction causes an expansion due to the formation of low density graphite and internal pressure. The expansion resulting from early stages of the eutectic reaction forces the liquid phase between austenite dendrites to shrinkage void regions which may have been formed during the first wave. In addition, the ability of the liquid to be displaced partially relieves stresses associated with expansion in the casting. At the end of the eutectic reaction the expansion cycle ends and overall contraction begins.

As the casting is cooled down to room temperature, a temperature is reached where the austenite becomes unstable and undergoes a solid state phase transformation. The reaction that takes place at this temperature is called the eutectoid reaction. The eutectoid reaction is similar to the eutectic reaction except instead of a liquid forming two solid phases, a solid transforms into two solid phases. In this case, austenite transforms into a lamellar structure by the eutectoid reaction austenite $\rightarrow$ ferrite + cementite. This structure consisting
of alternating layers of ferrite and cementite is better known as pearlite. The microstructure of the casting now consisting of graphite flakes in a pearlitic matrix is essentially the resultant structure at room temperature. If subjected to an annealing heat treatment, this structure is altered by the breaking down of iron carbide, whether it be as free cementite or pearlite, into ferrite and graphite. (10, 26)

3.4.3 Microscopic Observation

Cast iron is considered to be a mixture of graphite in a steel matrix. (33) Depending on the rate of cooling, casting temperature, alloy additions, and heat treatment, a variety of graphite forms, i.e., flakes, rosettes, dendritic, lacy, etc., and matrix structures can occur. (41, 54) The first part of the microscopic examination consisted of examining the graphite shapes, sizes, amount, and distribution. (7, 8, 28, 31, 54) The second part was to evaluate the microstructure of the matrix. (8, 35, 42, 44)

3.4.3.1 Graphite Examination

Each specimen was analyzed at a magnification of 100X in the unetched condition. Microscopic investigation was performed initially on the material near each specimen's outer surface. A distinct graphite line was found in all samples except in the specimen taken at 58 inches. This line formation seemed to be composed of interconnected dendritic graphite flakes which segregates a thin layer of the pipe wall thickness at the outside surface. An example
of this line is shown in Figure 23. The specimen taken at 58 inches did not exhibit a graphitic line structure, as shown in Figure 24. In the specimen taken from 24 inches this line appeared wavy and non-continuous in areas. Semi-spherical gas cavities were occasionally found along this line.

According to the AFA and ASTM graphite flake type chart, graphite flake structures can be categorized into five general groupings ranging from A to E. The graphite structures found will be correlated to this standard unless verbal interpretation is more descriptive.

Within the thin layer of metal, near the outside surface, three types of graphite structures were found. Most common was the dendritic graphite cells consisting of very fine mesh type graphite, ASTM flake size No. 8, as seen in Figure 23. This dendritic graphite structure had the same form and texture as the Type D graphite found within the center thickness. In the specimens taken at 40 inches and 58 inches, a mixture of the dendritic graphite cells occurred with very fine graphite aggregates, ASTM flake size No. 7. This can be seen in Figure 24. The third type of graphite structure was found near the spigot end. This structure, shown in Figure 25, consists of what appears to be temper carbon mixed with the dendritic graphite cell structure.

Beyond the graphitic line, in the direction of the pipe's inner surface, the fine flake graphite and interdendritic graphite structures, ASTM standard Type D and E graphite flakes, had formed. Reference is now made to Figure 26 which represents the general
Figure 23. The graphitic line formation composed of interconnected dendritic graphite flakes is shown segregating a thin metal layer at the outer surface. Note the presence of the dendritic graphite cells consisting of very fine mesh type graphite in the thin metal layer.
Figure 24. Micrograph of the outer surface of the specimen taken at 58 inches shows the absence of the graphite line formation. The graphite formation at the outer surface is a mixture of dendritic graphite cells with very fine graphite aggregates.
Figure 25. Microstructure observed at the outer surface of the specimen taken near the spigot end of the pipe shows a mixture of temper carbon aggregates and dendritic graphite flakes. Note the formation of two graphitic lines.
Figure 26. Micrograph showing the graphite formations and general matrix structure over the entire pipe wall thickness starting from the outer surface on the right and proceeding to the inner surface.
matrix and graphite microstructure observed across the entire pipe wall thickness at a magnification of 100X. The graphite formations increased in density from the sparsely populated areas adjacent to the line formation to the densely populated interdendritic graphite network near the center. An outline of the prior austenite dendrites by fine graphite networks can be observed along the traverse. An indication of a directional orientation, perpendicular to the outside surface related to chilling effects can be seen within this interdendritic graphite region. This directional mode of solidification, or chilling tendency, as shown by the prior austenite dendrites and graphite formation, was in most cases, more non-directional than directional. However, the exception occurs in the samples selected at zero inches and at the spigot end in which directional chilling effects were exhibited. This will be covered later. As the traverse continued across the center, the interdendritic graphite formation, primarily Type D graphite, blends into an area of Type B graphite. This formation, better described as rosette groupings, is randomly scattered. The rosette structure is subsequently replaced by the Type A graphite flake structure, ASTM flake size No. 4, which continues to the inside surface.

The chill structure observed in the specimen taken at zero inches and at the spigot end of the pipe is shown in Figure 27 at a magnification of 50X. The photomicrographs were taken from the spigot end specimen. The graphite formations were very much smaller and of a finer nature. This chilled structure is characterized by
Figure 27. Chill structure observed in the specimen at the spigot end of the pipe showing a finer, more directional graphite structure oriented perpendicular to the outer wall. Dendritic graphite cells mixed with temper carbon aggregates are shown at the outer surface on the right.
the presence of the directional graphite and carbide needles oriented perpendicularly to the mold wall. Temper carbon aggregates and dendritic graphite clusters were found on the outer surface.

3.4.3.2 Matrix Analysis

Etching or chemically attacking the surface of the specimens revealed the microconstituents in the matrix. The magnification used for this examination varied from 100X to 600X. Near the outside surface, small irregular shaped cavities attributed to trapped gas were found in a thin layer of pearlite. Small groupings of ferrite and spheroidized and irregular shaped phosphide particles were found within this pearlitic layer. A layer of pearlite was also found on the pipe's inner surface. This area, about double the thickness of the outside surface, contained small cavities, inclusive materials, possibly cement impurities, along with Type A graphite flakes. A dirty appearance was found near both surfaces. The overall matrix structure was ferritic as shown in Figure 28. Ferrite existed mostly in the form of small equiaxed grains. Grain boundaries were not readily visualized at this magnification but were quite noticeable at the higher magnification of 600X. Very fine pearlite colonies were also found intermixed within the matrix. These colonies, shown in Figure 29, were most abundant in the center region where Type D and Type B graphite flakes were found. An area of pearlite colony concentration seemed to be in the eutectic crystallization or cell boundaries outlining the iron-iron phosphide eutectic struc-
Figure 28. Typical ferritic matrix structure found in pipe microstructure.
Figure 29. Very fine pearlite colonies surrounding iron-iron phosphide eutectic structures. Colonies were most abundant in the center of the pipe cross section along with Type D and Type B graphite flakes.
ture (steadite), which is the last of the liquid phase to solidify, and shrinkage cavities which were noticeably found in the center region.

3.4.4 Centrifugal Cast Microstructure

The manufacturer was contacted for microstructural data to determine if the microstructure observed was representative of that produced in a cast iron pipe by the Super DeLavaud method. However, such information was not available for release. Instead, two references which related the type of microstructure produced in centrifugally cast pipe by the DeLavaud method were used for comparative purposes.

In Stuart's report in 1935 (59, 60) of the Super DeLavaud method of producing cast iron water pipe, he stated that metallographic analysis of a thickness cross section for an eight inch diameter pipe contained only two graphite structures. The first consisted of a non-directional dendrite interlacing structure on the outer wall and the second consisted of "an extremely fine graphitic structure" found at the middle and continuing to the inner wall. From the micrographs shown in his papers, the microstructure at the outer surface appears to be Type D graphite outlining prior austenite dendrites while the fine graphite structure between the middle and inner wall appeared to be Type A graphite flakes. The matrix was ferritic. This Super DeLavaud metallurgical structure was said to be an improvement over that produced by the standard DeLavaud method.
Three separate and distinct graphitic structures were stated to exist in the standard DeLavaud microstructure. On the outer wall, the structure consisted of balls of temper carbon in a ferrite matrix. This was formed by tempering of the initial chill structure. In the middle, a directional dendritic graphite structure was present with dendrite orientation normal to the outside surface. The graphite structure found on the inside wall was Type A graphite flakes. The matrix in the middle and on the inside was ferritic.

In the Super DeLavaud method the addition of the pulverulent coating to the rotating mold to retard heat abstraction from the outer surface of the cast pipe moved the directional structure found in the center of the standard cast structure to the outer surface where it became non-directional.

In a later reference, a compilation of micrographs in a book edited by Lambert (29), micrographs are shown in the structures at the outer wall, middle, and inner wall of a centrifugally cast, eight inch diameter cast iron pipe. The photomicrograph of the outer wall shows fine graphite aggregates in a ferrite matrix with small amounts of pearlite and spheroidized phosphide. The microstructure of the middle showed interdendritic Type D graphite and fine flake graphite in rosette formations. The matrix was also ferritic with small amounts of pearlite outlining the phosphide eutectic or steadite. The inner wall structure was Type A graphite flakes also in a ferrite matrix with small amounts of pearlite colonies. These structures are somewhat different from those
shown by Stuart, but are probably more characteristic of the structures produced by later Super DeLavaud centrifugal casting techniques.

3.4.5 Microstructure and Defect Analysis

Comparison of the Pendleton pipe's microstructures with Lambert's microstructures shows a good correlation. The graphite structure at the outer wall of the Pendleton pipe, in the absence of the graphite separation layer, did consist of fine flake graphite aggregates in a ferrite matrix. The microstructure at the middle and inner wall were representative of the micrographs presented by Lambert.

Super and Standard DeLavaud pipes are cast in the same manner except for the pulverulent coating. Both are annealed by heating to 1750°F and then slowly cooling to 1200°F in approximately one hour. Observation of the surface of either casting would show it to be gray iron with no chill structure.

During the annealing process cementite produced as a chill product is normally decomposed into the stable structures of ferrite and graphite. (10, 26, 57) The decomposition of cementite is said to form compact temper carbon or quasi-flake graphite. (45) If graphite flakes are in existence they will act as centers for the deposition of free carbon. (10, 57)

The microstructure shown in Figure 27 was taken at the spigot end of the pipe. On comparison with Stuart's description of a Standard cast pipe's microstructure similarities can be seen. Temper carbon was found on the outer wall with a directional dendritic
graphite structure oriented perpendicular to the outer wall. By contrast, the fine graphite aggregates observed in Lambert's micrographs taken at the outer wall appear to be quasi-flake graphite.

Two points can be made from this discussion. The first is that the cast iron microstructure of the pipe under investigation is representative of that presented by Lambert. Secondly, it appears that a gradual transition from a Super DeLavaud cast structure to a Standard cast structure had taken place towards the spigot end of the pipe.

Many casting defects were found on the outer wall of this pipe. The major defects were the graphite separation layer, the formation of blowholes at the separation line interface, and lapping zone defects.

In order to analyze the metallurgical structure of the Pendleton pipe in more detail, a specimen extending from 68 inches to 71 1/2 inches and 1 1/4 inches down from the fractured surface, was prepared for analysis. The length of this specimen encompassed two lapping zones, one at 69 1/2 inches and the other at 71 inches, and a surface flow line on the exterior wall at 70 inches, which can be seen in Radiograph Figure 16i.

Figure 30 shows the lapping zone at 71 inches and reveals the presence of very fine dendritic Type D graphite cells. They are widely spaced in a matrix of ferrite and pearlite along with some tiny shrinkage cavities near the outer lip of the lap. In some areas the graphite appears to have nucleated around very small
Figure 30. Foldout of lapping zone discontinuity micrographed at 71 inches. Note the formation of gas bubbles between the layers of deposited metal indicating a lack of homogeneous solidification at the pipe's outer wall.
prior austenite dendrites. Note that the lap is open to the surface. Gas bubbles in spherical shapes had formed along this lap near the surface. The graphite formed on the lap is similar to the graphite formation found elsewhere along the graphitic separation layer. However, this line curves towards the inner thickness and disappears. This discontinuity was not continuous with the graphite separation layer. However, observation up to 71 1/2 inches revealed that the dendritic graphite cells continued past the end of the lap discontinuity along the outside surface and built up into the characteristic graphite separation layer pattern. It continued in a straight line to 71 1/2 inches. Adjacent to the graphite separation layer, very fine graphite flakes and interdendritic graphite colonies were present. A normal solidification trend was observed to proceed from the lap line across the remaining thickness cross section to the inner surface. The microstructure to the right of the lap zone also showed the fine graphite flakes mixed with small interdendritic graphite colonies. This area comprised the overlapping deposit of molten metal in the progressing helix. The graphite separation layer was not observed in the region.

The lap at 69 1/2 inches exhibited the same structure as the lap discontinuity at 71 inches but also revealed a thin, soft metal deposit at the outer surface of the lap. A layer of pearlite formed in this thin deposit. At this point the description of this lap structure is the same as discussed previously for the lap at 71 inches. Progressing to the left of the lap zone, the dendritic graphite cells gradually disappear and are replaced with fine
graphite flakes. At 69 3/4 inches, the fine flakes were replaced with dendritic graphite cells and the graphite separation layer soon appeared. This layer continued to a surface flow line at 70 inches. In the vicinity of the surface flow line the graphite separation layer tapered off and terminated at the outer wall which, under the microscope, is a smooth surface depression. At this point a second graphite separation layer started beneath the surface as shown in Figure 31. Within the surface layer of metal the dendritic graphite cells were present up to approximately 70 1/2 inches where the graphite separation layer and the dendritic graphite disappear. Here, fine flake graphite aggregates predominated up to the lap at 71 inches shown in Figure 30. From these observations, it is apparent that the thin layer of surface metal was formed during the cast.

The change in graphite across the graphite separation layer from dendritic cells to fine flakes leads one to believe that a stationary solid-liquid interface occurred near the outer wall. According to Ruddle (51) in his discussion on the formation of a solid-liquid interface for gray cast iron, a "skin" or region of active solidification will form at the mold surface, setting up a thermal barrier. This thermal barrier delays further solidification from taking place through the remaining thickness of the molten metal. Such barriers come from the heat released during solidification. This wall of thermal energy must be dissipated through the solid metal and the mold wall before solidification can continue. Until this is overcome, a stationary solid-liquid interface will exist.
Figure 31. Formation of graphite separation lines at 70 inches. Graphite separation line nearest the outer wall ends at a surface flow line. Note also a second graphite separation line starts to form away from the outer pipe wall.
When the heat is dissipated, the solidification wave moves inward and the process of continuous solidification proceeds again.

In centrifugal casting, the pulverulent powder retards heat extraction and prevents rapid solidification, which would produce white cast iron. It also allows sufficient time for fusion to take place between laps of successive layers of metal. (59, 60) However, a continuous solidification did not take place in the Pendleton pipe and laps occurred. The lack of fusion within the metal lapping zone indicates that the outer surface of the first spiral of molten metal solidified before the next spiral of molten metal was laid. Cavities within the lapping zones, as shown microscopically in Figure 30 and macroscopically in 32, adds credibility to this statement. Note also that the gas cavities shown in Figure 32 were open to the outside surface as seen by the formation of an oxide or bituminous coating within the cavities.

The formation of semi-spherical shape gas cavities shown microscopically in Figure 23 and blowholes shown macroscopically in Figure 33 were commonly found along the graphite separation layer. Note that the larger blowhole penetrates into the thickness approximately one quarter of the cross sectional thickness. The blowholes were seen in the radiographs as the distinct white spheres. The formation of these cavities at the separation layer indicates that this layer was apparently at one time a solid-liquid interface. It is normally expected that gas evolved during the solidification of the liquid phase in the pipe casting, starting at the mold wall, migrates through the pipe wall thickness and escapes at the inner surface.
Figure 32. Macrograph showing the formation of gas cavities within the pipe's lapping zones. Penetration of the bituminous coating or the formation of an oxide within the gas cavities indicates the cavities were open at the surface.
Figure 33. Macrograph showing blowholes penetrating into the pipe's wall thickness. Blowholes were commonly found along the graphite separation layer.
This movement of the gas to the inner surface is made possible by the centrifugal force being exerted on the pipe material. However, in the case of the Pendleton pipe, solidification at the mold wall was not continuous. It appears a temporary thermal barrier occurred at the mold wall to create a solid-liquid interface. When the barrier was removed, the gas evolved at this interface or separation layer was trapped by the subsequent solidification of the liquid phase taking place across the pipe wall thickness.

The defects analyzed during this investigation, i.e., a surface layer of metal separated from the rest of the pipe wall by a layer of graphite, laps in fusion zones, semi-spherical gas cavities and blowholes, and a poor surface appearance are obviously produced during the manufacture of this pipe. It appears that the defects are attributable to one of two causes. The first is pouring the metal at a temperature below the optimum. This results in the formation of separated layers, porosity, poor casting detail and laps. (2) The second is casting in a cold mold. Defects attributed to this are laps, separated layers, shrinks, and the presence of outside diameter carbides. Standard practice requires that molds are pre-heated, prior to their use, into the temperature range of 500 F to 800 F. The preheat is accomplished by heating the molds in ovens or by gas burners. Once achieved, this mold temperature is maintained during production by heat absorption from the casting. Therefore, the mold temperature is dependent on the casting cycle (pouring to pouring). It also must be noted that an increase in the mold coating thickness has the affect of reducing the temperature
of the mold. (2) The Pendleton pipe may have been the first pipe to be cast in a mold that was not adequately preheated.

3.4.6 Microhardness Test

The hardness of the matrix was measured across the pipe's thickness. This was done to determine the trend in matrix hardness and the existence of any unusual hardness gradient. Particular attention was given to the area of surface discoloration between 71 inches to 88 inches found on the fracture surface.

The apparatus used for this purpose was the Tukon Hardness Tester. This tester utilizes a diamond shaped indenter. Each indentation was made in a polished specimen using a load of one kilogram. The indentation was then measured in Filar units under a 16 mm objective lens (250X), corrected, and then interpreted in Knoop hardness numbers (KHN). A filar unit is equivalent to one micron.

Gray cast iron, as previously observed in the section on Metallography, contains graphite which is very brittle, and a matrix structure consisting of ferrite intermixed with pearlite colonies and steadite. Ferrite is relatively soft, and pearlite, which is a composite of ferrite and cementite layers, is relatively hard. With this variation in microstructure, hardness variations were expected. Specimens taken at 8, 24, 40, 58, 75 1/2, and 82 inches were evaluated. Microhardness tests were made across the cross sectional thickness of the pipe wall.

Figure 34 shows the hardness curve for each specimen. Each of these curves was obtained by plotting the best visual fit through
FIGURE 34. Microhardness Test Results.
54 data points. While there were numerous erratic readings, approximately 70% of the hardness readings fell within ± 10 KHN of the average curves. The erratic readings were randomly distributed on each side. As a result, the appropriate positions for the curves were rather well defined. Comparison of the hardness curves shows that each specimen exhibits the same general trend in hardness across the cross sectional thickness. Hardness values averaging about 230 KHN, were found in most cases on the outer surface. This is associated with the pearlitic layer observed on the outer pipe wall during metallographic examination. From the outer surface, a decrease in hardness was noted as the traverse approached the graphitic separation layer from .4 mm to .6 mm. The average KHN in this region was about 200 KHN. Beyond .6 mm hardness values increased to a maximum of approximately 210 KHN at about 2 mm before gradually decreasing towards the center. Hardness values at the center averaged about 160 KHN. No noticeable changes in hardness values were recorded as the hardness traverses continued until the inner surface was approached. At this point a slight increase in hardness was noted in three of the six specimens. This was attributed to the pearlitic layer found on the inner surface. The average hardness value near the inner surface was about 150 KHN.

These results were compared with the hardness test results previously discussed under Quality Determination. KHN were converted to Rockwell B hardness numbers using a conversion chart for gray cast iron. (32) The average hardnesses of approximately 200, 160 and 150 KHN
near the outer surface, the center, and the inner surface respectively, corresponds to Rockwell B 90, 79, and 75. In the previous tests the average hardness in these approximate locations were found to be Rockwell B 88, 78, and 78. This is a fairly good correlation for the two sets of test results.

Specimen 5 and 6 taken at 75 1/2 inches and 82 inches respectively, covered the area of surface discoloration found on the fractured surface. Metallographic analysis covered in the previous section did not reveal any unusual features and as shown in Figure 34, no unusual hardnesses were recorded. Their hardness traverses were comparable in all respects to the hardness traverses for specimens 2, 3, and 4.

3.4.7 Corrosion Layer Analysis

The investigation next focused on the black surface discoloration on the longitudinal fracture surface between 71 inches and 88 inches. Metallographic specimens sectioned from positions at 75 1/2 inches, 76 inches, 76 1/2 inches, 81 inches, 84 inches, and 87 inches, were polished to evaluate the thickness of the corrosion layer. A sample was also sectioned from 57 inches for comparative purposes. The fracture surface of each prepared specimen was observed at 100X. Thickness measurements of the corrosion layer starting at the pipe's outer wall and traversing across the pipe's thickness to the inner wall are reported at the quarter distances.

Examination of the metallographic specimens taken from points at 75 1/2 inches to 87 inches showed that there were two distinct corrosion zones. The fracture surface was completely covered with a layer of
solid corrosion product. This was zone one. Zone two consisted of corrosion that penetrated into the base metal below zone one. In many cases, this penetrating corrosion consisted of clusters of corrosion products that appeared to form around graphite flakes.

The specimen from the 75 1/2 inch position showed no signs of penetrating corrosive attack either at the outer wall surface or the inner wall surface. Zone one thicknesses at these sites were approximately .001 inch and .0015 inch, respectively. The thickness of the zone one corrosion layer was observed to increase from .001 inch at the outer wall surface to .003 inch at the quarter distance. From here, the thickness increased to a maximum of .006 inch near the center. It remained at .006 inch until the three quarter mark before decreasing to .0015 inch at the inner surface. The greatest corrosion build up occurred between the center of the pipe wall and the inner wall surface.

The specimens taken from positions at 76 inches and 76 1/2 inches exhibited the greatest effect of corrosive attack. Observations of three specimens at the intersection of the fracture surface and the outer wall surface, showed a heavy corrosion of both types one and two. This is shown in Figure 35 photographed at 200X and in Figure 36 at 100X. In these figures the fracture surface is at the top of the pictures. The depth of zone two penetration in Figure 35 was .008 inch. In Figure 36, the greatest depth of penetration was .04 inch and occurred along the graphitic separation layer.

Zone one thickness of the specimens prepared from positions at 76 inches and 76 1/2 inches measured from .003 inch to .007 inch at
Figure 35. Micrograph of specimen sectioned at 76 1/2 inches. Note the heavy build up of Zone 1 corrosion at the outer pipe wall and deep penetration of Zone 2 corrosion.
Figure 36. Micrograph of specimen sectioned at 76 inches. Heavy build up of Zone 1 corrosion is shown on the fracture surface located at the top. Zone 2 corrosion is prevalent in several areas and is also shown penetrating along the graphite separation layer.
the outer pipe surface. At the quarter distance, the thickness increased to approximately .006 inch and remained at this thickness up to the center. From the center, the layer again increased to a maximum thickness of .008 inch before decreasing to .003 inch at the inner wall surface. No corrosive penetration into the metal matrix was observed at the inner wall surface. Across the traverse, zone two corrosive attack was noted. It appeared primarily in the center and towards the inner wall surface. Similar in appearance to the clusters found on the outer pipe wall, these clusters of corrosion products outlined the graphite colonies beneath the zone one corrosion layer as shown in Figures 37 and 38.

At 81 inches, the specimens showed a similar penetrating corrosive attack at the outer wall surface, and down the graphitic separation layer. However, the zone one corrosion was not as thick as observed between 76 inches and 76 1/2 inches. The thickness near the outer wall surface measured from .001 inch to .002 inch. Between the quarter distance and the center, it measured from .003 inch to .004 inch with a high point of .006 inch near the center. From the center, the thickness decreased to .0015 inch and remained constant to the inner pipe wall. The zone two penetrating corrosive attack, as noted between 76 inches and 76 1/2 inches, was not observed at 81 inches.

Specimens taken at 84 inches and 87 inches revealed a decreasing trend in layer build up and a mild corrosive attack. At 84 inches a fairly uniform zone one thickness of .0005 inch to .001 inch was observed across the wall thickness. The zone two penetrating type of corrosive attack, peculiar to the specimens between 76 and 76 1/2 inches
Figure 37. Micrograph of Zone 2 corrosion attack centering around graphite flakes. Zone 1 corrosion layer is on top and does appear to contain graphite flakes.
Figure 38. Micrograph of Zone 2 corrosion around graphite in a rosette structure. Note also that graphite flakes are found in the Zone 1 corrosion layer.
was not detected. There was, however, some penetrating type corrosion in which penetration had been inward from the outer wall surface, rather than from the fracture surface. This is shown in Figure 39 at 100X.

The specimen taken at 87 inches also showed no signs of the zone two corrosive attack from either the inner or the outer wall surface and none below the fracture surface. Zone one thickness, like the specimen at 84 inches, measured .0005 inch to .001 inch across the pipe wall thickness. Between the quarter distance and the specimen's center, it was observed that a crack or metal separation started from the center and paralleled the fracture surface approximately .01 inch below the surface towards the outer part of the pipe wall, as shown in Figure 40. There was no sign of zone two corrosion in this area. This is a good indication that this metal separation was caused by the final catastrophic pipe failure.

The control specimen taken at 57 inches was found to be free of any penetrating corrosive attack. The red rust layer measured to be approximately .001 inch thick from the outer wall surface as shown in Figure 41 to the inner wall surface.

The area of greatest corrosion layer thickness was associated with the black surface deposit. The color of this deposit indicates two possibilities. The first is hydrous ferrous ferrite (Fe₃O₄) better known as magnetite which forms a black layer between ferrous hydroxide (Fe(OH)₂) or hydrous ferrous oxide (FeO·nH₂O), and ferric hydroxide (Fe(OH)₃), or hydrous ferric oxide (Fe₂O₃·nH₂O). (11) The
Figure 39. Corrosive attack originating at the outer pipe wall and penetrating into the wall thickness.
Figure 40. Metal separation found in the center thickness of the specimen taken at 87 inches. No sign of heavy build up of Zone 1 or 2 corrosion indicates the separation was caused by pipe failure.
Figure 41. Micrograph of control specimen taken at 57 inches shows no heavy Zone 1 corrosion on the fracture surface or the presence of Zone 2 corrosion.
second possibility is the black porous structure rich in graphite produced by graphitization or graphitic corrosion of gray cast iron in relatively mild corrosive environments.

The results of studies conducted by Corey and Finnegan (14) on the corrosion of iron in water at room temperature showed that $\text{Fe}_3\text{O}_4$ formed as a solid product of reaction according to the following equation:

$$3\text{Fe} + 4\text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4 + 4\text{H}_2$$

The water was free of dissolved oxygen and carbon dioxide. In the discussion portion of this study reference was made to a study by A. Krause in explanation of the formation of $\text{Fe}_3\text{O}_4$ in a media which contains little oxygen. According to Krause, as cited by Corey and Finnegan (14, p. 1244), when the dissolved oxygen supply is low enough, ample time is available for the reaction between $\text{Fe(OH)}_2$ and $\text{Fe(OH)}_3$ to form magnetite, $\text{FeO} \cdot \text{Fe}_2\text{O}_3$. The equation of formation that was given was:

$$\text{Fe(OH)}_2 + 2\text{Fe(OH)}_3 \rightarrow \text{FeO} \cdot \text{Fe}_2\text{O}_3 + 4\text{H}_2\text{O}$$

However, for the case when the supply of oxygen is plentiful, nearly complete oxidation to $\text{Fe(OH)}_3$ will occur. Ewing (21) in his discussion on the corrosion of iron in soils also presents the same information. Uhlig (66), in his discussion on the mechanism of corrosion of iron fully immersed for long periods in water, referenced the published works of E. Herzog in 1936 and 1938. Herzog, as cited by Uhlig (66), stated that when iron was placed in soft or distilled
water, it became covered with a film of magnetite that was fairly adherent, but not to the extent of preventing attack on the iron below. Thus, in turn, the black magnetite was covered with a layer of hydrated ferric oxide, or yellow rust. From this information, the corrosion layer between 71 and 88 inches could quite well be composed of hydrous ferrous ferrite, or magnetite, and hydrous ferric oxide.

The second possibility, peculiar to gray cast iron, is graphitization which was previously discussed during Visual Inspection. This corrosion mechanism involves the electrochemical action between ferrite (anode) and graphite (cathode) in a suitable corrosive environment. The removal of ferrite in the corrosion process leaves behind a black porous structure rich in graphite, carbides, and usually a considerable amount of free iron which forms iron oxides. (72) Wesley in his discussion on graphitic corrosion of cast iron states three possible effects associated with the formation of a graphitic layer in the corrosion of the metal. The first possible effect is that this layer may decrease or prevent further corrosion of the base metal when the layer has reached a certain thickness. This is due to the pores in the layer being filled with solid corrosion products and other solid matter, provided the environment permits the deposition of such material. In this case, a passivating layer is formed.

The second possible effect is that the graphitic layer may increase the corrosion rate of the base material. The pores of the thickening corrosion layer, in this case, are not being filled with
corrosion products and the attack has provided a larger graphite surface area to accelerate the electrochemical process.

The third possible effect is that the graphitized layer on one part of the metal in galvanic contact with an ungraphitized area may accelerate the rate of corrosion on the ungraphitized area.

At present the first possible effect fits the description of the examined corrosion layer. In particular, note the formation of corrosion products around graphite flakes and the presence of graphite flakes within the corrosion layer as shown in Figure 37 and Figure 38.

The transverse crack found at 82 1/2 inches and discussed in the section on Visual Inspection, exhibited the same type of corrosion layer appearance as seen on the longitudinal fracture surface. Color comparison at the intersection of the longitudinal and transverse fracture surfaces as shown in Figure 12, showed them to be the same. It therefore appears that the corrosion on both fracture surfaces was formed at the same time. In addition, the corrosion layer thickness, as discussed previously, showed a substantial decrease from 81 inches to 87 inches.

The results of this investigation show that the corrosion layer thickness on the fracture surface builds up from 75 1/2 inches to a maximum at 76 - 76 1/2 inches before decreasing at 81 inches. The area of greatest build up occurred at the center of the pipe's wall thickness towards the inner surface. Although it is most likely that failure initiated first at the inner surface of the wall, it
is not likely that fracture initiation was the result of interaction with the transported water. No penetrating corrosive activity was noted at the inner wall surface, nor was there any significant build up of corrosive products such as tubercles. In addition, the cement lining was found pretty well intact along the fracture line.

Likewise, the cause of the longitudinal failure could not be attributed to a corrosive attack by the pipe's underground environment. According to Ewing (21), as soon as a pipe is buried, anodic and cathodic areas are established on the pipe outer wall surface. Attack by different soils was shown to vary from concentrated pits in well drained soils to blotches in poorly drained soils. In both extremes, the attack was by penetration into the pipe's wall thickness with deposits of corrosive products being formed in and around the pits. This was not observed on the Pendleton pipe's outer wall along the longitudinal fracture line. No corrosive activity in the form of pits penetrating into the pipe wall was found.

The longitudinal fracture in the Pendleton pipe, therefore, does not appear to have been initiated by either an internal or external corrosion process. Instead, the results indicate that corrosion occurred on an already existing surface.

3.4.8 Summary of Results

Metallographic analysis provided further proof of a poorly manufactured pipe. The investigation indicated that during solidification of the spirals of molten metal, a thermal hold occurred near
the mold wall that caused a temporary stationary solid-liquid interface. A graphite separation layer formed along this interface which separated the outer wall metal, of approximately 1/32 inch thickness, from the rest of the pipe wall. Gas, evolved during the subsequent continuation of the solidification process across the wall thickness, was trapped between the solid interface and the solidifying body of metal.

Examination of fusion zones where the layers of molten metal overlapped revealed laps open at the outer wall. These features, in addition to a poor casting surface, indicated that the molten metal was poured into a cold mold or cast at a lower than optimum temperature.

There was an area of surface discoloration indicating a typical corrosion behavior between 68 inches and 88 inches but the appearance of the microstructure of the wall metal as shown by specimens taken at 75 1/2 inches and 82 inches was the same as observed in the specimens taken between 8 inches and 75 1/2 inches. In addition, there were no unusual hardness gradients in the area of the surface discoloration that would indicate unusual structures that could cause failure. However, evaluation of the corrosion layer thickness between 71 inches and 88 inches showed the corrosion in this region to be quite different. The greatest layer thickness and corrosive attack was observed to occur between 75 inches and 81 inches. Clusters of what appeared to be products of corrosion were found beneath the corrosion layer, in the metal matrix, in this region. Their cores appeared to be graphite flakes. At no other area across the entire
longitudinal fracture surface were such products to be found. The corrosive attack across the pipe's wall thickness in this area was uniform. No signs of an externally or internally initiated attack were found.

The evidence suggests strongly that failure started in the region from 71 to 88 inches. The corrosion layer on the fracture surface was much thicker in this region, and the only cases of corrosion penetration into the base metal, zone two type corrosion, were found in this region. Furthermore, the color of the corrosion deposit, black - indicative of stagnant water in a part through crack, as well as its greater thickness near the inner wall surface, both suggest strongly that there was a crack part way through the pipe wall, from the inside, in this region for an extended time before the final pipe failure. It does not appear that this crack was directly related to any of the metallurgical defects.

3.5 ELECTRON MICROPROBE ANALYSIS

The results obtained by metallographic analysis revealed an area on the longitudinal fracture surface from which it appeared likely that the catastrophic failure initiated. This area, between 75 inches and 81 inches, exhibited a very thick layer of corrosion products found nowhere else on the entire fracture surface. These corrosion products varied in color from black to yellowish red, as shown previously in Figure 6. Their composition was not known. In an attempt to learn more about these surface deposits, an investigation was made by electron microprobe.
3.5.1 Method of Analysis

Basically, an analysis by the electron microprobe method is conducted by subjecting a polished flat metallographic specimen in a vacuum to a beam of high energy electrons. Each type of atom in the area under irradiation by the electron beam will emit its own characteristic x-ray wavelengths. The intensity of each element's response is dependent on the amount of that element present in the irradiated area. Differentiation of the different elements by x-ray wavelengths, and measurement of their respective intensities, are accomplished by x-ray spectrometers. The electron beam can also be used to scan the surface for areas of element concentrations. Electron pictures, or scanning electron micrographs, for each element may also be obtained on Polaroid film by photographing the display of the cathode ray tube (CRT).

3.5.2 Investigation

Two specimens taken at 57 inches and 76 inches respectively, were taken to the U.S. Bureau of Mines Albany Metallurgy Research Center, Albany, Oregon, to have the corrosion layers examined by electron microprobe. The specimens were mounted so that the polished surface was a cross section through the pipe wall fracture surface and corrosion deposits.

The specimen taken at 76 inches was the first to be analyzed. Two different areas were selected as sites to be scanned. The first area was located at the corner of the fracture surface and the outer
pipe wall. A light micrograph of this area is shown at 300X in Figure 42a. The second area was selected, and shown in Figure 43a, was located between .3 inch and .4 inch from the pipe wall's outer surface.

In Figure 42a, the corrosion layer on the fracture surface is located in the upper left hand corner of the micrograph. The oxide layer, observed on the outer surface of the pipe wall was later determined by x-ray diffraction to be $\alpha$-$\text{Fe}_2\text{O}_3$, hematite. Note that this layer is continuous along the outer wall and along the outside of the corrosion layer. Formation of this oxide layer most likely occurred during manufacture of the pipe at the foundry prior to the application of the outer protective coating. Elements analyzed, and their concentrations, are shown in Figures 42b to 42g at magnifications of 300X.

The corrosion layer on the fracture surface, the $\alpha$-$\text{Fe}_2\text{O}_3$ oxide layer on the outer pipe wall, and the clusters of what appear to be corrosion products within the metal matrix were found to have much lower iron concentration than the wall matrix metal, and were high in oxygen content. Most noticeable in the case of iron, Figure 42b, is the drastic change in iron concentration between the corrosion layer away from the pipe wall as compared to the corrosion layer next to the oxide layer at the pipe wall. The microprobe scan for silicon revealed areas of concentration that were just the opposite of that shown for iron, Figure 42c. In particular, the silicon was concentrated in a thick layer at the corrosion layer-metal matrix interface. According to Speller, silicon as well as carbon, phosphorous, and sulphur are less
Figure 42a. Light micrograph at 300X of the intersection between the outer pipe wall, on the right, and fracture surface, at the upper left hand corner of the specimen taken at 76 inches. Note continuous layer of oxide along the outer wall and along the outside of the corrosion layer.

Figure 42b. Scanning electron micrograph of iron at 300X. Note lower concentration of iron in corrosion layer away from the pipe wall as compared to the layer at the pipe wall.
Figure 42c. Scanning electron micrograph of silicon at 300X. Note high concentration at corrosion layer - base metal interface.

Figure 42d. Scanning electron micrograph of carbon at 300X. Carbon concentration appears higher in corrosion layer and in corrosion cluster.
Figure 42e. Scanning electron micrograph of sulphur at 300X. Large cluster at lower left hand corner was not analyzed successfully.

Figure 42f. Scanning electron micrograph of phosphorous at 300X. Phosphorous concentration in the corrosion layer at the outer wall and in the metal matrix appear uniform. Clusters of phosphorous concentration most likely are iron-phosphorous compounds.
Figure 42g. Scanning electron micrograph of oxygen at 300X. Note heavy concentration in corrosion layer and in corrosion clusters.
soluble than pure iron. Therefore, in the corrosion of cast iron, an increase in concentration of these elements occurs due to the removal of iron. (58) Note also in Figures 42b and 42c that the area of highest iron concentration in the corrosion layer, the area next to the oxide layer at the outer wall surface, has a fairly uniform silicon content, which is of about the same concentration shown in the metal matrix. This tends to indicate that corrosion near the outer wall has not progressed to the extent that it has in the interior. At least, the iron content in the outer region is higher.

Carbon was found to exhibit only a slightly greater concentration in the corrosion layer than in the metal matrix. However, in the matrix it centered primarily within the center of the clusters of corrosion products, as shown in Figure 42d. The high concentration of carbon present in the crevices of the corrosion layer is probably due to specimen mounting material, which contains carbon, being trapped in the crevices.

Phosphorous and sulphur, two other elements commonly found in cast iron, provided additional information in this analysis. The sulphur content was higher in the corrosion layer near the oxide layer at the outer pipe wall and within the clusters of corrosion than in the metal matrix. The large cluster of sulphur shown in the lower left hand corner of Figure 42e was not analyzed successfully, but it was determined that it was not manganese sulphide. The phosphorous content in the corrosion layer next to the oxide layer and in the metal matrix were comparatively the same, Figure 42f. The concentration pattern in the layer of corrosion products was
somewhat similar to that of iron with a region of relatively high concentration near the oxide layer at the outer wall surface. Quite noticeable in Figure 42f is the clusters of phosphorous compounds, most likely Fe₃P, which appear to form along a straight line near the outer wall surface. They extend from the metal matrix through the corrosion layer. During microstructural examination covered in Metallography, it was pointed out that a pearlitic layer existed on the outer wall of the pipe before graphite flakes or colonies were observed. It is at about the boundary of this region that the clusters of phosphorous concentration occur. The corrosion solubility of pearlite, which is composed of ferrite and cementite, Fe₃C, is less than that of ferrite, which comprises the bulk material in the metal matrix. (58) Therefore, it would be expected that the time required for pearlite to corrode would be much longer than for ferrite. As shown in Figure 42b to 42g the chemical composition of the corroded layer next to the oxide layer at the outer wall surface is less changed from the matrix composition than is the remainder of the corrosion deposit.

The corrosion clusters seen in Figure 42a revealed a high carbon center which is most likely graphite. Graphite flakes and colonies although not always interconnected throughout the matrix do branch out into the matrix. (8) Water, the most logical electrolyte involved in the corrosion process apparently penetrated into the metal matrix along these avenues to set up the galvanic cells around the graphite clusters. Shrinkage cavities, also present in the center of the pipe wall would provide additional avenues by which the electrolyte could penetrate into the metal matrix. The presence of a high oxygen concentration
and in turn a high iron depletion within these clusters as shown in Figures 42b and 42g are evidence that these clusters are in fact corrosion products and not material trapped in the casting. Sulphur was also found in higher concentration within the corrosion clusters as well as within the corrosion layer near the outer wall. Its presence in a somewhat higher concentration near the outer wall may indicate attack by leachants produced by sulfate reducing bacteria from the soil in this area. This attack could have followed pipe failure, occurring during the period between shut down, after failure, and excavation of the pipe.

It is apparent that the metal at the initial fracture surface was corroded away, Figure 42a. The continuity of the oxide layer on the outer pipe wall next to the corrosion layer; the row of phosphorus clusters extending from the metal matrix through the corrosion layer; and the segregation of elements across the defined pearlite-metal matrix boundary in the corrosion layer substantiate this finding.

Electron Microprobe analysis of the corrosion layer on the fracture surface between .3 inch and .4 inch from the outer wall surface revealed similar results. Figure 43a shows the area with the corrosion layer at the upper right hand corner. Electron micrographs of each element are shown in Figures 43b to 43g at 300X. Iron was found once again to be decreased in the corrosion layer and in the clusters of corrosion products which formed below the fracture surface. These clusters of corrosion products formed
Figure 43a. Light micrograph at 300X of the Zone 1 corrosion, at the upper right hand corner, and Zone 2 corrosion between .3 inch and .4 inch from the pipe's outer wall of the specimen taken at 76 inches.
Figure 43b. Scanning electron micrograph of iron at 300X. Depletion of iron in corrosion layer and corrosion clusters is evident.

Figure 43c. Scanning electron micrograph of silicon at 300X. Note heavy build up of silicon at the corrosion layer-metal matrix interface.
Figure 43d. Scanning electron micrograph of carbon at 300X. High concentration in corrosion cluster is due to the presence of graphite flakes.

Figure 43e. Scanning electron micrograph of sulphur at 300X. Sulphur concentration appears higher in the corrosion layer and corrosion cluster.
Figure 43f. Scanning electron micrograph of phosphorous at 300X.

Figure 43g. Scanning electron micrograph of oxygen at 300X. Note heavy oxygen concentration in corrosion clusters.
around graphite flakes as shown in the micrograph for carbon, Figure 43d. The electrolyte for the corrosion process, as in the case of the clusters found at the outer wall, also penetrated through the graphite network. This is verified in the micrograph for oxygen, Figure 43g which shows that paths of high oxygen concentration existed between the corrosion layer and the corrosion clusters. This supports the previous findings that the clusters are not exclusively graphite colonies or inclusions, but are products of corrosion. A relatively higher concentration of sulphur is also noted within these clusters and in the corrosion layer as observed in Figure 43e.

As found in the investigation at the outer pipe wall, silicon concentrated very heavily near the corrosion layer-metal matrix interface. This can be seen in Figure 43c. Such a high concentration near this interface tends to indicate that the build up occurred over a period of time by the steady leaching away of iron and the formation of the layer of corrosion products. It should be noted that the layer of high silicon concentration was much thicker here than near the outer wall. Phosphorous on the other hand, was found to be of a lower concentration in the corrosion layer than in the metal matrix.

The specimen taken from the point at 57 inches was from an area exhibiting red rust on its fracture surface. Figure 44a shows the part of this specimen near the outer wall surface. The fracture surface is located at the top of the micrograph. Located on the
right is the outer pipe wall surface with a thick oxide coating of \( \alpha-\text{Fe}_2\text{O}_3 \). The corrosion products on the fracture surface are much thinner than in the specimen from 76 inches. Micrographs for each selected element, with the exception of Phosphorous, are shown in Figure 44b to 44f at 300X.

Analysis of this relatively "new" fracture surface showed a heavy concentration of oxygen in the corrosion products as well as some iron depletion. Quite noticeable in Figure 44c was the lack of a heavy silicon build up near the fracture surface, but this time it was observed on the outer wall next to the \( \alpha-\text{Fe}_2\text{O}_3 \) layer. This concentration was believed to have been caused by the formation of the oxide layer during manufacture of the pipe. It is noted here that any build up on the fracture surface or along the outer wall is nowhere near the concentration observed at 76 inches. Therefore, time is certainly a factor in the creation of the silicon layer.

Sulphur showed a surprisingly heavier concentration near the fracture surface. The most common source of sulphur would be from the soil. In Mr. Ray Struthers failure report, it was related that after the failure was detected, the water line was shut down and the pipe left underground overnight before being excavated the next day. This would be sufficient time for the mixture of water and soil to come in contact with the fracture surface, and hence become involved in the corrosion process. It is not likely that sulphur of this concentration came from the decomposition of the base metal.
Figure 44a. Light micrograph at 300X of the specimen taken at 57 inches. Fracture surface is at the top. Note the formation of a thick oxide coating of hematite on the outer pipe wall on the right.

Figure 44b. Scanning electron micrograph of iron at 300X. Iron loss at fracture surface is minimal.
Figure 44c. Scanning electron micrograph of silicon at 300X. Concentration of silicon at the pipe wall is quite noticeable and is believed to have been caused by the formation of the oxide layer.

Figure 44d. Scanning electron micrograph of carbon at 300X.
Figure 44e. Scanning electron micrograph of sulphur at 300X. The heavy concentration on the fracture surface is being attributed to soil and water mixture in contact with the fracture surface after pipe failure.

Figure 44f. Scanning electron micrograph of oxygen at 300X.
3.5.3 Chemical Analysis

Chemical breakdown of the base metal, corrosion layer, and corrosion clusters by weight percent of six elements is shown in Table IV for each of the areas investigated. These values are obtained by microprobe analysis. Since the microprobe focuses on a very small area, a spot perhaps two microns in diameter, and since both the corrosion products and the base metal are rather gross conglomerates of various phases, including ferrite, cementite, iron oxide, and flakes of graphite, the analysis should not be considered as representative of overall compositions of either the corrosion products or the base metal. The probable material on which the beam was focused is indicated in the last column of Table IV.

Comparison of the amount of elements present in the specimens taken at 57 inches and at 76 inches gives further evidence that the fracture surface in the area of 76 inches was not the result of the catastrophic failure but was the likely origin of it.

Oxygen content in the corrosion layer at 76 inches was 36% at the outer wall surface and 57% between .3 inch and .4 inch of the wall thickness. The depletion of iron, or the leaching away of iron, in the corrosion process complemented the high oxygen content at 76 inches. Iron content near the outer wall surface was 43% while the iron content near the middle of the wall thickness was 33%. This compares with the adjacent base metal where the iron content was 96%. Note also that the heavier concentration of oxygen and the greater
<table>
<thead>
<tr>
<th>Location</th>
<th>Section</th>
<th>Fe</th>
<th>Si</th>
<th>C</th>
<th>S</th>
<th>P</th>
<th>O</th>
<th>Phase(s)</th>
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<tbody>
<tr>
<td></td>
<td>Base Metal</td>
<td>96</td>
<td>2</td>
<td>neg</td>
<td>neg</td>
<td>.5</td>
<td>neg</td>
<td>Ferrite</td>
</tr>
<tr>
<td>76 INCHES</td>
<td>OUTER WALL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corrosion Layer</td>
<td>43</td>
<td>13</td>
<td>.1</td>
<td>.2</td>
<td>.6</td>
<td>36</td>
<td>Iron Oxide</td>
</tr>
<tr>
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<td>Cluster</td>
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<td>6</td>
<td>60</td>
<td>.3</td>
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<td>2</td>
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<td>96</td>
<td>2</td>
<td>neg</td>
<td>neg</td>
<td>neg</td>
<td>neg</td>
<td>Ferrite</td>
</tr>
<tr>
<td>76 INCHES</td>
<td>INNER WALL</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corrosion Layer</td>
<td>33</td>
<td>9</td>
<td>neg</td>
<td>.2</td>
<td>neg</td>
<td>57</td>
<td>Iron Oxide</td>
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<tr>
<td></td>
<td>Cluster</td>
<td>54</td>
<td>14</td>
<td>2</td>
<td>.5</td>
<td>neg</td>
<td>30</td>
<td>Predominantly Iron Oxide</td>
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<tr>
<td></td>
<td>Base Metal</td>
<td>95</td>
<td>1.3</td>
<td>2.8</td>
<td>neg</td>
<td>-</td>
<td>neg</td>
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</tr>
<tr>
<td>57 INCHES</td>
<td>OUTER WALL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corrosion Layer</td>
<td>85</td>
<td>1.1</td>
<td>6</td>
<td>.8</td>
<td>-</td>
<td>1.2</td>
<td>Ferrite, Graphite, Iron Oxide</td>
</tr>
</tbody>
</table>
depletion of iron occurs in the middle of the wall rather than at the outer wall surface.

The concentration of silicon found near the corrosion layer-metal matrix interface in the specimen at 76 inches was 13% near the outer wall surface and 9% near the middle of the wall. Its presence in such heavy concentrations indicates that the crack at this point had existed for a considerable time in order for the silicon to have had time to build up in concentration.

The sulphur content found at 57 inches of .8% was much higher than the content of .2% found at 76 inches. Its presence is believed to be the result of the overnight settling of the soil-water mixture on the fracture surface prior to the pipe being excavated. This contrast in sulphur content indicates that corrosion at 76 inches did not occur by the sulphate reduction or bacteria process.

The formation of corrosion clusters found beneath the fracture surface at 76 inches revealed the progressive nature of corrosion in this area. Penetration of the electrolyte along graphite networks was found nowhere else as determined by the corrosion layer investigation covered under Metallography. The carbon content of 60% found in the corrosion cluster at the outer wall at 76 inches helps to substantiate the findings made previously that the centers around which corrosion took place were graphite. The low carbon value shown in the analysis for the corrosion cluster in the middle of the wall, however, is misleading. The area on which the electron beam focused did not include graphite flakes as was the case for the cluster analyzed at the outer wall.
The composition of the black surface deposit represented by the analysis at 76 inches, is very low in carbon content, less than .1%. This value does not correspond to the high carbon content of approximately 11% found by other investigators in graphitic corrosion deposits. (56, 58, 72) However, observations of the corrosion layer, as shown in Figure 37 and Figure 38, shows that in this case the graphite flakes are preserved intact in the corrosion layer. The matrix around the graphite consists of corrosion products. Since the chemical analysis is restricted to the scanning area of the probe, it is possible that the probe was focused on materials between graphite flakes. The low carbon content would not be representative of the carbon content normally found in graphitic corrosion products.

The fairly uniform amount of corrosion across the pipe's wall thickness, the tight bonding of the corrosion products observed in the corrosion layer, and the formation of corrosion clusters around graphite flakes are all consistent with Wesley's description of graphitic corrosion mentioned earlier. (72) The tight bonding and thickness of the layer of corrosion products would tend to indicate that the layer formed under stagnated conditions. In stagnated or poor circulation areas on the fractured surface it is feasible that magnetite and hydrated ferric oxide would form to add to the black surface appearance. The presence of a tight crack in the pipe would in all likelihood create crevice corrosion conditions or prevent free circulation of oxygenated water. At a later time the crack may have propagated sufficiently to relieve this stagnated condition and expose new areas on the fracture surface to an ample supply of oxygenated
water. The oxides formed during the corrosion process of iron would then be primarily Fe₂O₃, red rust.

3.5.4 **Summary**

The microprobe analysis presented corroborating evidence that the fracture surface covered by the black corrosion deposit, between 75 inches and 81 inches, had been present for some time and in all probability was the site where the catastrophic failure initiated. A heavy concentration of silicon along the corrosion layer-metal matrix boundary and the high oxygen content in the corrosion products in this region, 36% at the outer wall and 57% in the middle of the wall thickness, was not found at 57 inches. The specimen at 57 inches appeared to be typical of most of the fracture surface.

Corrosion by bacterial or sulphate reduction, which normally indicates exposure of the metal to a moist soil environment, was absent prior to failure of the pipe. This was substantiated by the higher sulphur concentration found at 57 inches as compared to the content found at 76 inches. Graphitic corrosion, peculiar to cast iron due to the presence of graphite, was the apparent mode of corrosion with the dissolved iron reacting with water to form iron oxides. It was determined that the tight adherent layer of corrosion products consisted of graphite flakes, magnetite, and hydrous ferric oxide.
3.6  **STRESS ANALYSIS**

Determinations of the types of loading that would cause pipe failure during service operation are attempted in this section.

3.6.1  **Analysis of Stresses In Cast Iron Water Pipe**

External loads on a buried pipe arise from soil cover which creates vertical forces at the top of the pipe and reactive forces at the bottom. Horizontal forces are produced on the sides of the pipe by the compression of the backfill due to deformation of the pipe under vertical loading. In analyzing the combinations of external loads and internal pressures that will cause the pipe to fail, it is assumed that the pipe acts as an elastic ring, modulus of elasticity being constant.

External loads applied at the top and bottom of the pipe cause the pipe to deform into an elliptical shape with the short diameter parallel to the line of applied loading. The maximum bending moments in the pipe wall are created at the point of loading and reaction. (62) Horizontal forces created by resistance of the tamped backfill to compression are smaller than the vertical forces but also create bending moments in the pipe wall. The bending moments created in the pipe wall by vertical and horizontal forces at any point in the pipe are of opposite direction and tend to oppose one another. Therefore the maximum moment created in the pipe by vertical forces is partially offset by the moment created by the horizontal forces. (53, 73)
Internal pressure in a pipe produces uniform outward radial forces on the pipe wall. Under this radial force the pipe wall is placed in circumferential tension. If these "hoop" stresses are of sufficient magnitude, the pipe will fail in the longitudinal direction. It is noted here that the hoop stress created by internal pressure is twice the stress created in the longitudinal direction, hence failure favors a longitudinal crack rather than a circumferential. (43, 53, 73)

Under vertical loads, deformation in the pipe increases the horizontal diameter while decreasing the vertical diameter. The uniform radial pressure force is thereby varied and there is resistance to pipe deformation. However, this effect is considered to be negligible since the magnitude of the unbalanced internal forces are considered small. (53) Hence, the solution for the maximum wall stresses in a pipe under external vertical load and internal pressure is found by considering the combination of flexural stresses due to external load and the hoop stresses due to internal pressure at the point of maximum moment. However, the direct addition of hoop tensile stresses and flexural stresses is not exactly correct for cast iron pipes.

Tests on cast iron rectangular beams (53) showed that cast iron is stiffer in compression than in tension. The elastic stress-strain relationships for cast iron under all types of loading are not equal except at very low loads, hence the value of the modulus of elasticity is not constant. The neutral surface of the rectangular beam in bending tends to move towards the compression face. According to Schlick (53), it is due to this feature of cast iron that the flexural stresses
calculated by using the flexural formula $Mc/I$ is not additive to the circumferential stress, but it is used as a good approximation in normal design. For this problem, Schlick derived a mathematical relationship which best describes the behavior of pipe under both external load and internal pressure.

Tests conducted by Schlick (53) showed that when a pipe is subjected to an external load, $w$, lb/ft, applied by the "three edge bearing" method, and to internal pressure, $p$, psi, the breaking loads $p$ and $w$, were represented with sufficient accuracy by the formula given below for various combinations of internal pressure and trench load. The three edge bearing method of applying an external load mentioned above consists of a concentrated load applied vertically to a wood block resting on the pipe or pipe ring section that is laying on a lower bearing support. The upper block and lower bearing support extend the full length of the pipe or ring.

$$w = W \sqrt{\frac{p-p}{p}}$$

$W$ = ring test crushing load with no internal pressure (lb/lin ft)

$P$ = bursting pressure with no external load (psi).

$p\&w$ = any combination of internal pressure and external load which will cause failure.

It is this mathematical relationship that is the basis of the whole system of water pipe thickness calculations in use today.
3.6.2 Determination of Required Pipe Thickness

The pipe ordered from the Pacific States Cast Iron Pipe Company was a pressure class 150, 12 inch diameter pipe. According to the Company, when a pipe is specified by internal pressure without additional information, the Company assumes that the pipe will be installed under field condition B, with a five foot depth of cover and manufactured with 18/40 strength iron. Field condition B specifies that the pipe is to be laid in a flat bottom trench, backfilling tamped. The 18/40 iron strength designation is equivalent to the pipe having a minimum Bursting Tensile Strength of 18,000 psi and a minimum Ring Modulus of Rupture of 40,000 psi.

To illustrate how one would determine the minimum wall thickness for a 12 inch diameter pipe to meet the requirements for the above mentioned loading conditions and pipe specification, the USA Standard USAS A21.1-1967 entitled USA Standard for Thickness Design of Cast Iron Pipe published by the AWWA was used for Case 1. Case 1 consists of "trench load (earth load but no truck superload) in combination with internal pressure (working pressure plus surge pressure) and with a 2.5 factor of safety applied to both trench load and internal pressure."

Values for ring test load, w, equivalent to the trench load including a 2.5 safety factor, and for internal pressure, p, with a 2.5 safety factor with surge pressure allowances included were selected from tables. (12) The value of w was 2,100 lb/lin ft and the value of p for a class 150 pressure pipe was 650 psi. For a pipe
under these two conditions, the minimum required pipe thickness was determined to be approximately 0.32 inch from a thickness nomogram (12) for a 12 inch pipe of 18/40 strength. To this minimum thickness is added a standard corrosion allowance of 0.08 inch. The minimum manufacturing thickness is now 0.40 inch. A casting tolerance of 0.06 inch for a 12 inch pipe is now added to the minimum manufacturing thickness to obtain a total thickness value of 0.46 inch.

In the purchase of a pipe however, selection is made by pipe size and thickness class number which conforms to USA Standards. Since no class number exists for a wall thickness of 0.46 inch, the nearest class number is specified. This class number is 22 which corresponds to a pipe wall thickness of 0.48 inch. The determined thickness of 0.48 inch correlated relatively well with the thickness of the pipe under investigation, which measured approximately 0.46 inch.

3.6.3 Load-Pressure Relationship

Using Schlick's equations, combinations of external load and internal pressure that would be expected to cause failure have been calculated for Case 1 and are presented graphically in Figure 45. A pipe wall thickness of 0.46 inch was used. Equations and calculations involved in determining the curves of Figure 45 may be found in the Appendix III.

From the thickness determination in the previous section it was shown that pipe thickness is calculated with surge pressure consider-
Figure 45. External Load - Internal Pressure Relationship.
ations, corrosion tolerance, casting tolerance, and a 2.5 safety factor all included. As shown in Figure 45, if this pipe were subjected to the conditions it was designed to withstand, a ring test load of 2,100 lb/lin ft and internal pressure of 650 psi, it would be very much below the maximum load and pressure that would probably be required to cause failure. For a constant pressure of 650 psi, a load of 6,150 lb/lin ft would be the estimated external load required to initiate failure, while an internal pressure of 1,300 psi is the estimated pressure required to initiate failure for a constant external load of 2,100 lb/lin ft. Equations (4) and (5) in the appendix are used to determine equivalent earth loads and working internal pressure that would cause pipe failure.

Equivalent earth load for the three edge bearing loads of 2,100 lb/lin ft and 6,150 lb/lin ft are calculated to be 1,159 lb/lin ft and 3,394 lb/lin ft, respectively. The corresponding working pressure are 410 and 150 psi. This analysis is of course based on a defect free pipe that is properly bedded. Basically, earth loads per lineal foot of pipe length correspond to the weight of a column of earth equivalent to the depth of cover to top of pipe by trench width at top of pipe by lineal foot of pipe length.

During sectioning of the ends of the water pipe to reveal the fracture surface, it was noted that the crack, already possessing a fracture opening of 1/16 of an inch, opened to approximately 1/4 inch when the unbroken pipe ends were removed. This established the presence of residual hoop stresses due to casting. Since the ultimate
tensile strength of the metal is utilized in resisting hoop tension as well as flexural tension, residual hoop stress of substantial magnitude could result in combined stress that exceed the strength of the pipe and hence cause an unexpected failure.

In Appendix III calculations of residual stress based on the observed crack opening are shown using Crampton's formula. (17, 48) A circumferential residual stress of approximately 4,500 psi was calculated. By subtracting this stress from the bursting tensile strength and the modulus of rupture, also known as the ultimate flexural stress, a value for bursting pressure, P, of approximately 1,030 psi and a value for ring crushing load, W, of approximately 7,600 lb/lin ft, respectively, was obtained. The new graphical presentation of external load, applied under three edge bearing conditions, versus internal pressure to failure, is also shown in Figure 45. For a constant three edge bearing load of 2,100 lb/lin ft, a pressure of 950 psi is now required to cause failure while a load of 4,600 lb/lin ft is required to cause failure at a constant internal pressure of 650 psi. Based on this information the pipe would still have sufficient strength under the design conditions.

It was reported by Mr. Struthers that a pressure test made after the defective pipe was removed read a maximum of approximately 40 psi over a 24 hour period. Therefore, a properly bedded pipe under five feet of cover, with a 40 psi internal pressure, would require one of the following conditions to rupture the pipe: a water hammer causing surges of internal pressure of more than 900 psi, a transient external load of about 7,500 lb on a lineal foot of the pipe (three edge bearing
load) or some combination of the two. Transient service loads of this magnitude seem very unlikely.

4.0 ANALYSIS AND CONCLUSIONS

From the results of this study it is concluded that:

1. The 12 inch diameter cast iron pipe, although meeting all of the acceptance specifications set forth by the American National Standards Institute, Inc., exhibited poor casting qualities in the form of blowholes, gas porosity, lapping zone discontinuities, and a poor casting surface. In addition, the metallurgical structure at the pipe's outer surface exhibited two abnormal types of graphite flake formation as well as a discontinuous solidification pattern which produced a thin separated metal layer at the outer wall surface. The formation of these defects could be explained by the casting of the pipe in a cold mold. The failure, however, did not initiate from any of these casting defects, as was determined by visual inspection and radiographic examination.

2. The design strength of a 12 inch diameter pipe, with a wall thickness of .46 inch, under bedding condition B, was found to be more than adequate to withstand the loading condition produced by a five foot depth of soil cover and internal working pressure of 150 psi. Also taken into consideration were residual hoop
stresses of more than 4,000 psi created by the manufacturing process. The loading condition that the Pendleton pipe was reported to be subjected to consisted of a five foot depth of soil cover and an internal working pressure of approximately 40 psi. Based on the design expectations for the 12 inch diameter pipe, one of three conditions would have had to occur to cause failure as a result of service stresses: a water hammer producing a pressure greater than 900 psi, an external impulse loading over 7,500 lb/lin ft (three edge bearing load), or a combination of the two. It is highly unlikely that loads of this magnitude could have taken place in the Pendleton water line to cause this pipe failure.

3. During the examination of corrosion deposits on the fracture surface, an unusual black surface appearance was observed between 71 and 88 inches. Microscopic examination of the surface deposits in this area revealed a very thick adherent layer of corrosion products with a corrosion attack that penetrated into graphite clusters in the base metal. The greatest corrosive activity was observed between 75 and 81 inches with the greatest build up occurring between the center of the pipe and inner wall surface. Nowhere else along the longitudinal fracture surface was such a heavy build up of corrosion products, or comparable penetrating attack found.
This corrosive attack was determined to be characteristic of graphitic corrosion, which is peculiar to gray cast iron. The thick layer build up and penetrating attack indicated that corrosion had taken place over a long period of time before final failure, as compared with the rest of the fracture surface, which was covered with a thin corrosion layer. Therefore, it was concluded that corrosion had taken place on an already existing crack surface between 75 and 81 inches. Additional evidence came from examination of the inner and outer wall surfaces in the area. No signs were found of a penetrating corrosive attack in the form of pits into the pipe wall thickness caused by a chemical reaction between the pipe and its internal or external environment.

4. It appears that failure was not initiated by metallurgical defects, or by service stresses, or by corrosion acting alone. Since there is evidence of a sizeable hairline crack of long duration in the pipe wall, it appears that this crack was the probable origin and primary cause of the final failure.

5. The formation of the hairline crack in the cast iron water pipe was most likely caused by external impact with a hard object. On impact, the wall was bent inward and the inner wall surface was placed in
tension and the outer wall surface in compression. If the severity of impact exceeded the tensile strength of the inner wall surface, a hairline crack would form. (60, 62, 63) If the impact was not sufficiently severe, the crack would not penetrate through the pipe wall. It would not be visible until something caused it to propagate through the pipe wall. These statements are confirmed by impact tests performed by several investigators interested in the effects of impact on cast iron water pipes and were discussed earlier under the section External Impact by Trench Filling. (60, 62, 63, 73)

In the case of the Pendleton pipe, the thickness of the corrosion deposits on the darkened area was greater near the inner wall surface than near the outer wall surface. This tends to indicate a crack that initially was open to the inside of the pipe and only partially penetrated the pipe wall. This condition would be consistent with the above observations on the effect of external impact in causing hairline cracks.

Therefore, it is concluded that a hairline crack existed in the Pendleton pipe due to an impact loading received sometime during transportation, handling or installation.
6. Over the four and one-half years that the pipe was in service for the City of Pendleton, Oregon, the effects of corrosion and service stresses increased the depth and length of the hairline crack. The pipe finally became so weakened in this area that it was unable to resist the loads applied in service by internal water pressure and external earth loads. The result was a seven feet four inch longitudinal crack that opened all the way through the pipe wall over a short period of time.
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APPENDIX I

TITLE: Talbot Strip Test - Modulus of Rupture Calculation

1. Problem: Determine the Modulus of Rupture for the beam loading shown in Figure 1.

![Figure 1](image)

A. Solving for reaction forces:

\[ \sum F_{vertical} = R_1 - W/2 - W/2 + R_2 = 0 \]

\[ W = R_1 + R_2 \]

\[ \sum M_{R_1} = -W/2(3) - W/2(6) + R_2(9) = 0 \]

\[ R_2 = W/2 \]

hence, \[ R_1 = W/2 \]
B. Solving for the moments in the beam:

Using free body diagrams, the moment in the beam are:

\[ \Sigma M_x = M - \frac{W}{2}(x) = 0 \]

\[ M = \frac{W}{2}x \]

(1) For condition:

0 < x < 3 inch \hspace{1cm} \Sigma M_x = M - \frac{W}{2}(x) = 0

\[ M = \frac{W}{2}x \]

(2) 3 < x < 6 inch \hspace{1cm} \Sigma M_x = M - \frac{W}{2}(x) + \frac{W}{2}(x-3) = 0

\[ M = \frac{W}{2}(3) \]

(3) 6 < x < 9 inch \hspace{1cm} \Sigma M_x = M - \frac{W}{2}(x) + \frac{W}{2}(x-3) + \frac{W}{2}(x-6) = 0

\[ M = -\frac{W}{2}x + 9 \frac{W}{2} \]
C. Shear and Moment Diagram are then:

\[ \text{Shear} \]
\[ \begin{array}{c}
W/2 \\
0 \\
3W/2 \\
-W/2
\end{array} \]

\[ \text{Moment} \]
\[ \begin{array}{c}
0 \\
3" \\
3" \\
3" \\
9"
\end{array} \]

D. Solving for Modulus of Rupture:

\[ R = \frac{Mc}{I} \] (flexural formula)

\[ R = \text{Modulus of rupture} \]
\[ M = \text{Bending moment} \]
\[ c = \text{Distance from neutral surface (N.A.)} \]
\[ I = \text{Moment of inertia}. \]

\[ R = \frac{3(W/2)(d/2)}{1/12 td^3} \quad \text{I = 1/12 } td^3 \]

\[ R = \frac{9W}{td^2} \]

\( d = \text{depth of beam} \)
\( t = \text{width of beam} \)
## APPENDIX II

ROCKWELL B HARDNESS TEST DATA

<table>
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<th>Specimen No.</th>
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<th>Middle of Thickness</th>
<th>Inner Pipe Wall</th>
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</tr>
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<td>76/79</td>
<td>80/80</td>
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<td>90/85</td>
<td>66/75</td>
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<td>Right End</td>
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<td>81/76</td>
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<td>94/88</td>
<td>76/81</td>
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<td>Left End</td>
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<tr>
<td></td>
<td>Right End</td>
<td>86/84</td>
<td>75/74</td>
<td>73/76</td>
</tr>
</tbody>
</table>
APPENDIX III

I. Title: Design Load-Pressure Equations and Calculations (12, 53)

A. Equations:

1. Schlick's equation for combining external loading and internal loading pressure to failure.

\[
 w = W \sqrt{\frac{P - p}{P}} \tag{1}
\]

\( W \) = ring test crushing load with no internal pressure, lb/lin ft.
\( P \) = bursting pressure with no external load, psi
\( p\&w \) = any combination of internal pressure, psi, and external load, lb/lin ft, which will cause fracture.

2. Equations to solve for parameters given above

a. \( W = \frac{Rt^2}{0.0795 (d+t)} \) \tag{2}

\( R \) = ring modulus of rupture (determined by crushing tests), psi
\( t \) = net thickness of pipe wall
\( d \) = nominal pipe size

b. \( P = \frac{2St}{d} \) \tag{3}

\( S \) = bursting tensile strength (determined by burst test), psi

c. \( w = \frac{2.5 We}{L_f} \) \tag{4}

\( w \) = ring test load equivalent of trench load (lb/lin ft) including a 2.5 safety factor
\( We \) = earth load, lb/ft
\( L_f \) = load factor dependent on laying condition
2.5 = factor of safety
d. \[ p = 2.5 \left( p_w + p_s \right) \] \hspace{1cm} (5)

\( p = \) internal pressure (psi) including a 2.5 factor of safety
\( p_w = \) working pressure, psi
\( p_s = \) allowance for surge pressure, psi
2.5 = factor of safety

B. Calculation of design loads and pressure:

Given:

1. pipe thickness, 0.46 inch
2. pipe size, 12 inch
3. Iron strength, 18/40 (bursting tensile/ring modulus) of rupture
4. Depth of cover, 5 feet
5. Laying condition, B
6. Working pressure class, \( p_w = 150 \) psi
7. Surge or water hammer, \( p_s = 110 \) psi for 12 inch diameter pipe
8. Load factor for laying condition B, 1.38
9. Earth load at 5 feet depth and laying condition B, 1159 lb/lin ft.
10. No impulse loading

1. Solving for \( W \)

\[ W = \frac{Rt^2}{0.0795 \left( d+t \right)} \] \hspace{1cm} (2)

\[ W = \frac{(40,000)(0.46)^2}{0.0795 (12 + 0.46)} \text{ lb/lin ft} \]

\[ W \approx 8,500 \text{ lb/lin ft} \]

2. Solving for \( P \)

\[ P = \frac{2St}{d} \] \hspace{1cm} (3)

\[ P = \frac{2(18,000)(0.46)}{12} \text{ psi} \]

\[ P \approx 1,380 \text{ psi} \]
3. Solving for $w$ and $p$

$$w = W \sqrt{\frac{p - p_p}{p_p}} \quad (1)$$

<table>
<thead>
<tr>
<th>$w$</th>
<th>$p$, psi</th>
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<tr>
<td>$1/4$ W</td>
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<tr>
<td>$1/2$ W</td>
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<td>$3/4$ W</td>
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<table>
<thead>
<tr>
<th>$p$</th>
<th>$w$, lb/lin ft</th>
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<td>$3/4$ P</td>
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</table>
II. Title: Residual Stress Equation and Calculation (48)

A. Equation:

1. Crampton's formula for solving circumferential residual stress in thin walled tubes

\[
\sigma_c = E' t \left( \frac{1}{D_0} - \frac{1}{D_1} \right)
\]  

\(\sigma_c\) = circumferential residual stress, psi  
\(E\) = modulus of elasticity  
\(t\) = thickness of pipe wall  
\(D_0\) = diameter of pipe outer wall  
\(D_1\) = diameter of pipe after sectioning pipe longitudinally  
\(E' = E/(1-v^2)\)  
\(v\) = Poisson's ratio

B. Calculation for \(\sigma_c\):

[Note: Calculated value of \(\sigma_c\) is only an approximate value and used here for investigative purpose]

Given:

\(E = 12 \times 10^6\) psi  
\(v = 0.29\)  
\(D_0 = 12.92\) inches  
\(D_1 = 13.045\) inches  
\(E' = E/(1-v^2)\)  
\(E' = 12 \times 10^6/(1-(0.29)^2)\)  
\(E' = 13.1 \times 10^6\) psi

\[
\sigma_c = E' t \left( \frac{1}{D_0} - \frac{1}{D_1} \right)
\] (6)
\[ \sigma_c = 13.1 \times 10^6 (0.46) \left( \frac{1}{12.92} - \frac{1}{13.045} \right) \text{ psi} \]

\[ \sigma_c \approx 4,500 \text{ psi} \]

C. Calculation of Design Loads and Pressure with Residual Stress Added:

Given:

1. Pipe thickness, .46 inch
2. Pipe size, 12 inches
3. Specification bursting tensile strength, 18,000 psi
4. Specification ring modulus of rupture, 40,000 psi
5. Residual stress, 4,500 psi

1. Solving for \( W \):

\[ W = \frac{(R-\sigma_c)t^2}{0.0795 (d+t)} \tag{2} \]

\[ W = \frac{(40,000 - 4,500)(0.46)^2}{0.0795 (12+.46)} \text{ lb/lin ft} \]

\[ W = 7,600 \text{ lb/lin ft} \]

2. Solving for \( P \)

\[ P = 2t \frac{(S-\sigma_c)}{d} \tag{3} \]

\[ P = 2(0.46)(18,000-4,500) \psi \]

\[ P = 1030 \psi \]

3. Solving for \( w \) and \( p \)

\[ w = W \sqrt{\frac{P - p}{p}} \tag{1} \]
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