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Publisher's version / Version de l'éditeur:
https://doi.org/10.1016/S1350-6307(99)00005-9
Engineering Failure Analysis, 7, February 1, pp. 43-53, 2000-02-01

A Preliminary Analysis of Failures in Grey Cast Iron Water Pipes

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Abstract:

Most water utility engineers are familiar with the typical failure modes of grey cast iron pipes such as circumferential breaks and split bells. However, while researchers have examined the forces that are likely responsible for these failures, the failure mechanisms that link those forces with the observed failures have not been thoroughly investigated. Understanding these mechanisms is important for finding ways of detecting damaged pipes and preventing their ultimate failure. This paper presents a failure analysis of five different pipes that show four different failure modes. The analysis suggests that some of these failures occurred in at least two stages, raising the possibility that non-destructive testing could be used to detect pipes that are part way through the failure process.

Résumé

La plupart des spécialistes des services publics d'eau connaissent les modes typiques de rupture des conduites en fonte grise, par exemple la rupture annulaire et la cassure de l'embout femelle. Les chercheurs ont étudié les forces qui sont probablement à l'origine de ces ruptures, mais ils n'ont pas examiné en détail la façon dont elles provoquent effectivement les ruptures. Il importe de comprendre ces mécanismes pour trouver des manières de déceler les conduites endommagées et empêcher leur rupture finale. Ce document analyse quatre modes de rupture de cinq conduites. L'analyse porte à croire que certaines de ces ruptures se sont produites en au moins deux étapes, ce qui permet de penser qu'on pourrait recourir aux essais non destructifs pour déceler les conduites qui sont à mi-chemin dans le processus de rupture.

Introduction:

Although it is no longer being used for new installations, grey cast iron is the most common material used in in-service water distribution pipes in North America[1]. It is also the material that has the highest number of failures per kilometre per year[2], with typical rates of as 39 breaks/100km of pipe per year in Canada. In part, this is due to the age of the pipes, which have installation dates ranging from the 1870s to the early 1970s. However, the susceptibility of the pipes to corrosion and their brittle nature are largely responsible for their failure. In general, the external forces that induce grey cast iron pipe failures are understood[3,4] and the physical appearance of those failures are known[3]. Most grey cast iron pipes fail because of a combination of factors that may include external loading, internal pressure, manufacturing flaws and corrosion damage[3,4]. These failures usually result in one of the standard types of breaks: bell splitting, consisting of an longitudinal break starting at the bell; through-hole corrosion pits; circumferential cracking, where the pipe splits in a circle across its axis; and longitudinal cracking, where the pipe breaks along its axis[3]. Figures 1 to 4 show schematic diagrams of each type of failure.

However, while the external forces and the final failure modes are understood, the mechanisms that link the application of the force to the actual failure have not been as thoroughly investigated. Failure analysis has been performed by a number of different authors on cast iron pipes[5-14], but in many cases the emphasis has been on the corrosion aspects of the failure[6,8-12], rather than complete examination of the failure process. Other studies have dealt with specific types of failures, including those due to blasting[9], air pockets[14] and external forces[5,7]. In addition to this work there has also been statistical analysis of failures in water systems, including those caused by such sources as earthquakes[15-16] and temperature effects[17].

Despite this body of work, little research has been done on the actual relationships between corrosion, applied mechanical forces and the failure process. These relationships are particularly important for grey cast iron pipe, where the dominant failure modes are related to external forces[3], as opposed to ductile iron pipe, where corrosion pit failures are the most common[10]. Of the studies that do describe this type of failure, one simply differentiates between mechanical and corrosion failures[5], while another states that most failures are due to combined mechanical and corrosion effects[7]. This paper describes the first results of a study that is intended to investigate the details of the mechanical failure process. Five separate pipe failures were investigated in detail and the implications of the results for water utility practice are described.

Experimental Details

Four samples of failed pipes were obtained from the Regional Municipality of Ottawa-Carleton (RMOC) in Ontario. The pipes were all 150 mm (6”) in diameter and made of grey cast iron. Two pipes had failed by circumferential cracking, one by a bell split and the fourth by a blow-out of part of the pipe wall. The pipes were delivered for examination immediately upon excavation and repair once the failures had been identified by RMOC staff. Their installed ages are given in Table 1.

The pipe fractures were examined visually for evidence of the cause of fracture. Where the nature of the fracture warranted, Energy Distribution Analysis of X-rays (EDAX) was used to qualitatively identify the chemistry of the corrosion products on each pipe surface. One half of each pair of fracture surfaces for the circumferential and bell split pipes were then sand blasted to remove all corrosion products and determine the size of the corrosion pits in the pipe wall at the fracture surface. Grey cast iron pipes are frequently corroded through the process of graphitisation[5,12], which occurs when the metal of the cast iron is corroded and leached away, leaving a network of graphite flakes behind. Although they are much weaker than the intact metal, areas of graphitisation adhere to the remaining metal in the pipe and are difficult to detect. Sand blasting removes the material, making evaluation of the corrosion pitting in the pipe possible. However, sand blasting completely removes the other evidence of the causes of the failure and should therefore only be used after the failure analysis is otherwise complete.

A fifth pipe supplied by the city of Minneapolis, Minnesota for a separate, American Water Works Association Research Foundation/National Research Council Canada funded project[18] was also examined. That project had shown that the pipe had a very low tensile strength (33 MPa) and the pipe was examined to determine the causes of the weakness. In this case sections were cut from the pipe and examined visually. The fracture surfaces were then also examined visually and the observed inclusions chemically analysed using EDAX.

Results and Discussion

a) Bell split pipe

This pipe had failed at the bell with a 30 cm long crack that initially ran longitudinally at the bell end and then curved in a clockwise direction around the pipe circumference, producing an appearance similar to that in Figure 1. The seal material inside the bell was “leadite”, a sulphur based compound used in the 1930s and 1940s as a replacement for earlier lead seals[19]. Rope was wrapped around the pipe to fill up the joint between the bell and the spigot of the next pipe. Molten leadite was then poured in the joint to complete the seal. Localised tuberculation was observed on the inside of the pipe surface and there were small regions of graphitisation on the inside of the pipe. The spigot of the pipe inside the bell had not been damaged by the failure.

The fracture surface at the bell end showed a significant deposit of corrosion products (up to 0.4 mm in depth) on each fracture surface. The colour of this deposit ranged from yellow-orange to yellow-gray. By the pipe end of the bell the corrosion products on the fracture surface had become too thin to measure with vernier calipers and had a deep brownish red colour. For much of the length of the fracture in this region the graphite flakes along the fracture surface could still be seen. These flakes could not be seen through the corrosion products at the bell end of the fracture.

Figure 5 shows EDAX spectra from this pipe failure with the results of the spectra normalised against the larger (K_α) iron peak. The spectra from the clean metal shows a strong iron peak and a weak silicon peak. The carbon content of the pipe and the oxygen content of the corrosion products will not appear in an EDAX spectrum. The spectra from the lightly corroded fracture surface also shows small amounts of calcium and a larger proportionally larger silicon content. These constituents have been taken up from the surrounding earth as part of the corrosion process. Finally, the spectra from the fracture surface near the end of the bell shows aluminum, sulphur and potassium in addition to proportionally much higher amounts of silicon and calcium.

The top surface of one half of the pipe was sand blasted to remove graphitisation and corrosion products. This treatment revealed the presence of a small corrosion pit at the outside surface of the bell where the fracture had initiated. Examination of the pit showed that it occurred on both sides of the fracture, indicating that it had formed before the fracture had taken place. Graphitisation had also occurred along the surface of the crack at the end of the pipe.

Bell splits are frequently associated with the presence of leadite seals in the pipes[19]. Leadite is rigid but non-metallic. As a result it has a different coefficient of thermal expansion than the cast iron pipes that surround it. Failures in these pipes are often considered to be due to the stresses that develop when the temperature of the pipe is either much lower or much higher than when it was installed. Analysis of the above evidence suggests a more complex failure process. The pipe appears to have failed because the small corrosion pit caused a localised weakness. The pipe then split at the bell, presumably because of the previously mentioned differences between the leadite seal and the pipe metal. However, the differences in the corrosion products along the fracture surface suggest that this split travelled only a short distance down the pipe, stopping once the internal stresses in the pipe had been reduced. This initial splitting was not enough to cause the pipe to fail.

At this point corrosion began to take place along the fracture surface. At some time later a significant amount of corrosion products had built up along the fracture surface. A second split in the pipe then occurred, extending the crack farther along the pipe axis. This second split was the cause of the failure that resulted in the pipe being taken out of service. It may have been caused by the forces exerted by the gradual build-up of expansive corrosion products along the pipe surface or by a second incident of thermally induced stress. Since the pipe was removed from service quickly once it had failed, only a thin coating of iron oxide formed along most of the fracture surface.

b) Pipe failure by blow-out

Pipe blow-outs tend to occur when corrosion or graphisation has reduced the strength of the pipe wall in a local area to point where a pressure surge causes wall to rupture. Most such corrosion pits in grey cast iron pipes are roughly circular or in nature[12], but this pipe showed long, thin corrosion pitting that paralleled the pipe axis, similar to that shown in Figure 2b. It failed when one area of corrosion pitting had only

0.5 mm of wall thickness left. It then fractured along the length of the pit and broke open, leaving a 20 cm long, 23 cm wide hole.

This particular pipe was covered with a bituminous protective coating. There was no evidence of widespread corrosion or graphitisation along the body of the pipe. Instead the corrosion damage was restricted to several smaller regions and was primarily in the form of long corrosion pits of the type that caused the failure. This suggests that the protective coating had been damaged by scratching along the length of the pipe. Once the coating had been penetrated, external conditions would have been favourable for corrosion to take place along the scratches while being inhibited elsewhere. This accelerated corrosion would then have resulted in the observed failure.

c) Circumferential breaks

Most grey cast iron pipes fail by circumferential cracking (Figure 3). Unlike the blow-out and bell split described previously, this type of break is considered to be at least partially due to external forces as bending moments are required to produce a circumferential crack. Issues such as bedding supporting the pipe and the backfill that was used to fill in the trench in which the pipe was placed may therefore be important in determining the cause of failures. The first pipe that was examined had been installed in a rock bed and was backfilled with gravel with a maximum aggregate size of 15 mm. The pipe joints were sealed with lead.

Approximately half the surface of this pipe is covered with a very thin layer of brownish red iron oxide, while the remaining part of the pipe is covered in corrosion products that range from yellow orange to yellow grey in colour. In one region of the pipe the fracture surface showed evidence of graphitisation. The fracture surface is relatively flat and smooth, typical of a brittle fracture, but rises slightly in the region of yellowish corrosion before falling into a dip at the graphitised corrosion pit. The yellowish corrosion product is thicker than the red-brown iron oxide. Finally, a second corrosion pit exists in the pipe directly opposite the graphitised pit.

Figure 6 shows EDAX spectra for this pipe failure. In this case the lower ends of the spectra have been examined to show the differences between the regions of the fracture surface. The spectra have again been normalised against the K_α iron peak, which is not shown on the figure. The clean metal of this sample shows the presence of silicon and a small amount of phosphorus. The dark red corrosion region also shows aluminum, silicon, calcium and sulphur. The orange-grey region shows a much lower relative silicon content, sulphur, phosphorus, calcium and chlorine. The phosphorus in the latter two spectra is due to the pipe metal, while the calcium and sulphur content has come from the surrounding soil. The chlorine is likely due to the salt put on roads in the Ottawa region during winter. The EDAX spectra indicates that the orange-grey region of corrosion in the pipe was immersed in salt water long enough for the chlorine to become part of the corrosion products on the fracture surface.

The change in colour, thickness and chemistry of the corrosion products along the fracture surface all suggest that this pipe also failed in a two stage process, with a lapse of a considerable amount of time between the two stages. The break appears to have initiated at the graphitised corrosion pit. It then propagated approximately half way around the pipe before stopping. Corrosion build-up then occurred along the fracture surface and then, at some later time, the rest of the pipe failed.

The second pipe with a circumferential break also had a rock bedding, but was covered with a mixed backfill of clay and granular material. It was connected to the adjacent pipes with mechanical joints rather than with a lead or leadite seal. The top of the pipe had been marked before removal. The fracture surface of this pipe showed a more uniform colour and depth of corrosion product than the previous pipe. The surface of the fracture was slightly curved relative to the circumferential direction. There were two exceptions to the uniform corrosion products. At the top of the pipe the bare metal of the fracture surface could still be seen. At the bottom of the pipe a dark area was observed that proved to be graphitisation. This corrosion pit penetrated approximately 6.1 mm,. or 56% through the thickness of the 10.9 ± 0.1 mm thick pipe.

The shape of the fracture surface, the extent of corrosion on the fracture surface and the depth of the corrosion pit at the bottom of the pipe suggest that this pipe failed by a crack initiated at the corrosion pit. This would imply that sagging or external loading from above the pipe produced the forces that were responsible for the failure. The crack then propagated most of the way around but the pipe did not completely fail at this time. Some time later the final failure took place, severing the remaining metal.

The analysis of both pipe failures indicates that circumferential breaking can be at least a two stage process. This view of the failures was confirmed by the examination of six grey cast iron pipes that had been delivered by the City of Toronto to the University of Toronto's Department of Civil Engineering. Each pipe had been removed from service part way through this two stage process and showed a circumferential break that had propagated most of the way around the circumference before stopping.

d) Manufacturing flaws in older pipe

Many of the older pipes in use in North America were made using the pit casting process, in which the molten cast iron was poured into upright sand molds and left to slowly cool[20]. In some cases the manufacturing process had poor metallurgical control and the result was a pipe with flawed metal and reduced strength. Figure 7 shows a cross-section from such a pipe, which dates from 1885 and was excavated from Minneapolis. The machined surface of the sample shows a network of pits that indicate that the pipe cooled with internal air pockets. This sample was fractured in the lab so that a fresh fracture surface could be examined. The fracture surface also showed evidence of visible pores, with the largest seen being approximately 2 mm across or 14% of the thickness of the pipe. A number of black, non-metallic inclusions were also seen on the fracture surface. These inclusions were approximately 1 mm across in width. An EDAX examination of the inclusions indicated that while they had a high iron content, they also had a much higher silicon content than the metal around it. This result suggests that the inclusions were un-dissolved ferrosilicon. Silicon is often added to cast iron in this form, suggesting that the metal in this pipe was not held at temperature longer enough for all of the ferrosilicon used to dissolve. Other fracture surfaces showed similar inclusions, suggesting a widespread problem.

Both the pores and inclusions in this sample produce weaknesses in the metal. As a result, it had a much lower tensile strength than is typical of pipes of its manufacturing type (33 MPa versus 130 MPa) and an equally low fracture toughness. Similar porosity has been described as the cause of the failure of a larger diameter cast iron pipe[13], while two of the pipes excavated by the City of Toronto similar but larger porosities. These results suggest that high porosity may be a frequent problem in older grey cast iron pipes.

Conclusions

Corrosion has long been identified as a major cause of failure in cast iron and other metallic pipes. In each case analysed above, corrosion pits were associated with the failure of the pipes, although in the case of the Minneapolis pipe it was not possible to determine if the corrosion pit was directly associated with the failure or if its proximity to the failure was only coincidental. However, the results also indicate that the failure process is more complex than has previously been believed. While the blow-out detailed above was a single stage process where the pipe failure occurred all at once, the circumferential and bell split failures occurred in two stages. The first stage involved an initial crack, while the second stage produced that final cracking that actually caused the pipe to fail and be removed from service.

If this failure pattern can be confirmed as being true for most or all grey cast iron water pipe failures, it may be possible to identify damaged areas during the failure process. If damaged pipes can be identified before they completely fail, water utilities will be able to repair or replace them on a scheduled rather than an emergency basis, significantly reducing their operating costs.

Some pipes have been observed to fail due to manufacturing defects. If utility records shows a specific vintage of pipe from a specific manufacturer has a higher failure rate than might otherwise be expected, a metallurgical examination or failure analysis may be warranted. The porosity and inclusions seen here indicate that the pipe itself was partly the cause of the failure, rather than external conditions or forces. Utilities with similar, low quality pipes may wish to schedule them for early replacement or rehabilitation.

The number of failures presented here is quite small. While the failure processes in these pipes has been identified, it would be incorrect to assume that the same processes take place in all grey cast iron pipe failures. A further study with a larger number of samples is necessary to determine whether the conclusions drawn here hold true in general.

Acknowledgements:

This research was funded by the National Research Council Canada. The assistance of the Regional Municipalities of Ottawa-Carleton and the City of Minneapolis in supplying the pipes examined for this study is gratefully acknowledged. The analysis of the pipe from the City of Minneapolis was partially funded by the American Water Works Association Research Foundation as part of a separate project . EDAX work was carried out by Jeffrey Fraser of the Institute for Microstructural Studies and Ed Quinn of the Institute for Research in Construction. Sample preparation by Richard Desnoyers is gratefully acknowledged, as is the assistance provided by Professor Jeffrey Packer and Michael Seica of the University of Toronto Department of Civil Engineering.

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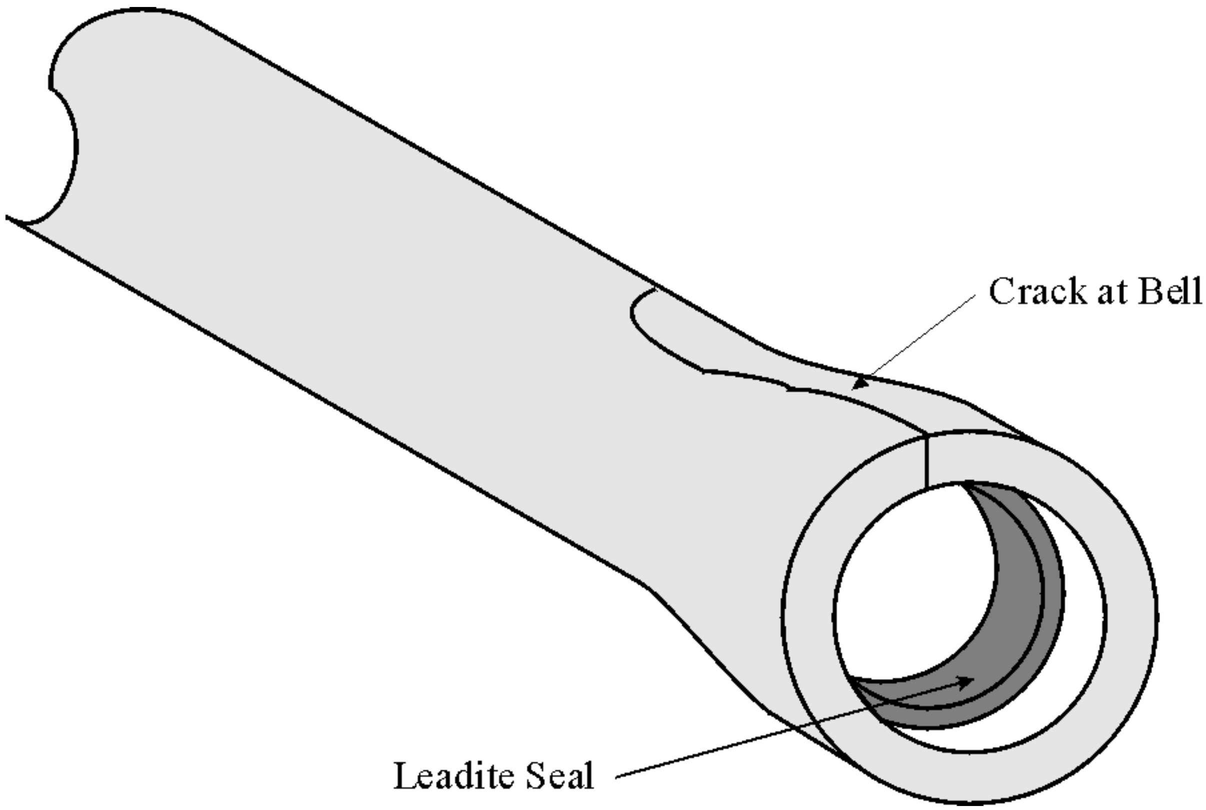
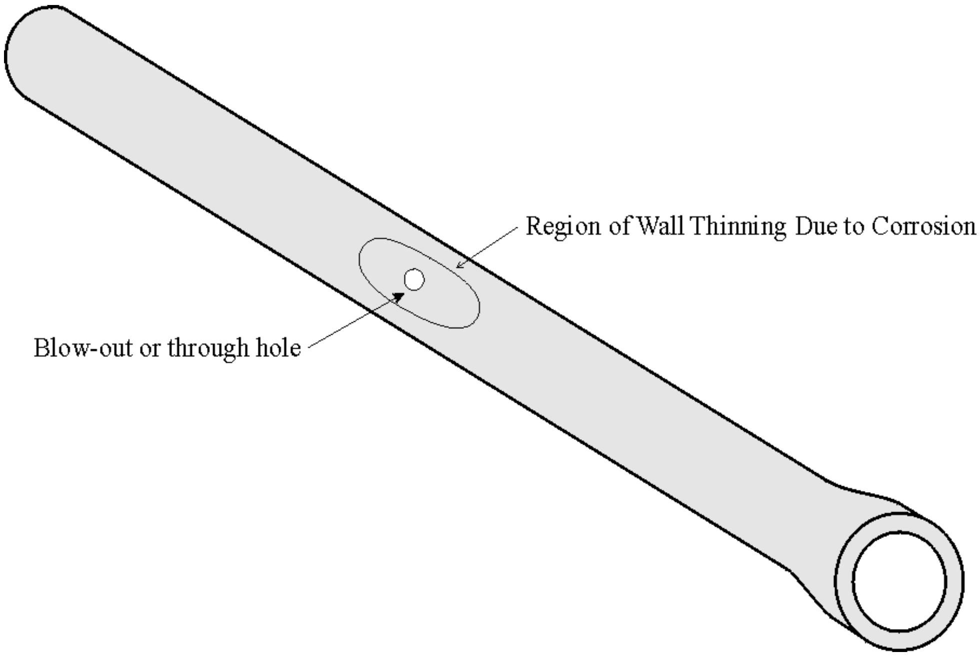
Table:

Sample Number	Water System	Year of Installation	Failure Type
1	Regional Municipality of Ottawa- Carleton	Unknown (1930s - 1940s)	split bell
2	Regional Municipality of Ottawa- Carleton	1961	blow-out
3	Regional Municipality of Ottawa- Carleton	1932	circumferential
4	Regional Municipality of Ottawa- Carleton	1955	circumferential
5	Minneapolis	1885	circumferential

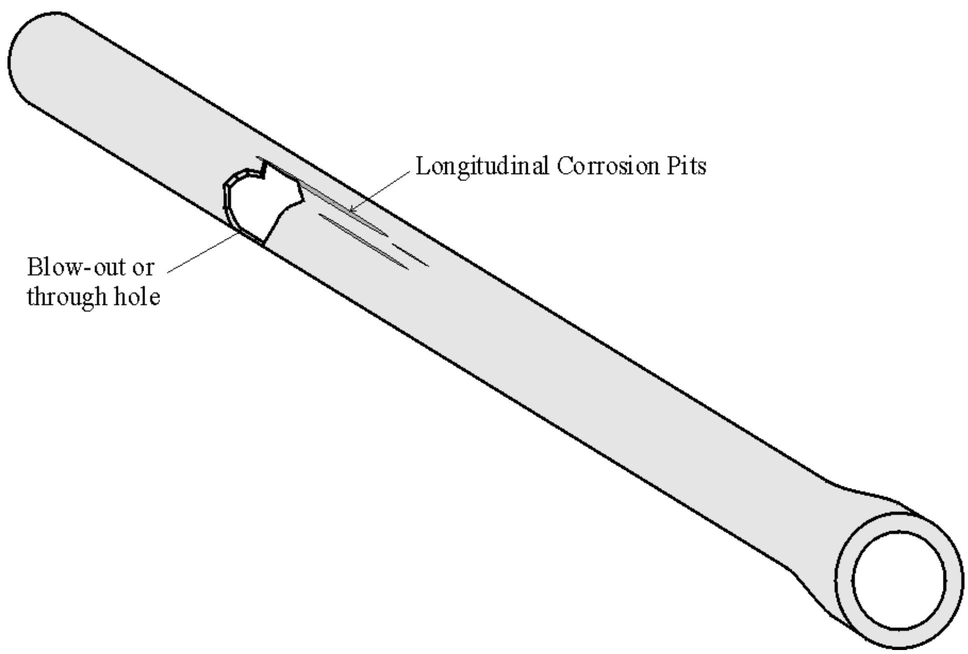
Figures:



1. Split bell type failure, showing the bell end of the pipe. Differential thermal expansion between the bell and the leadite pipe seal causes this type of failure.

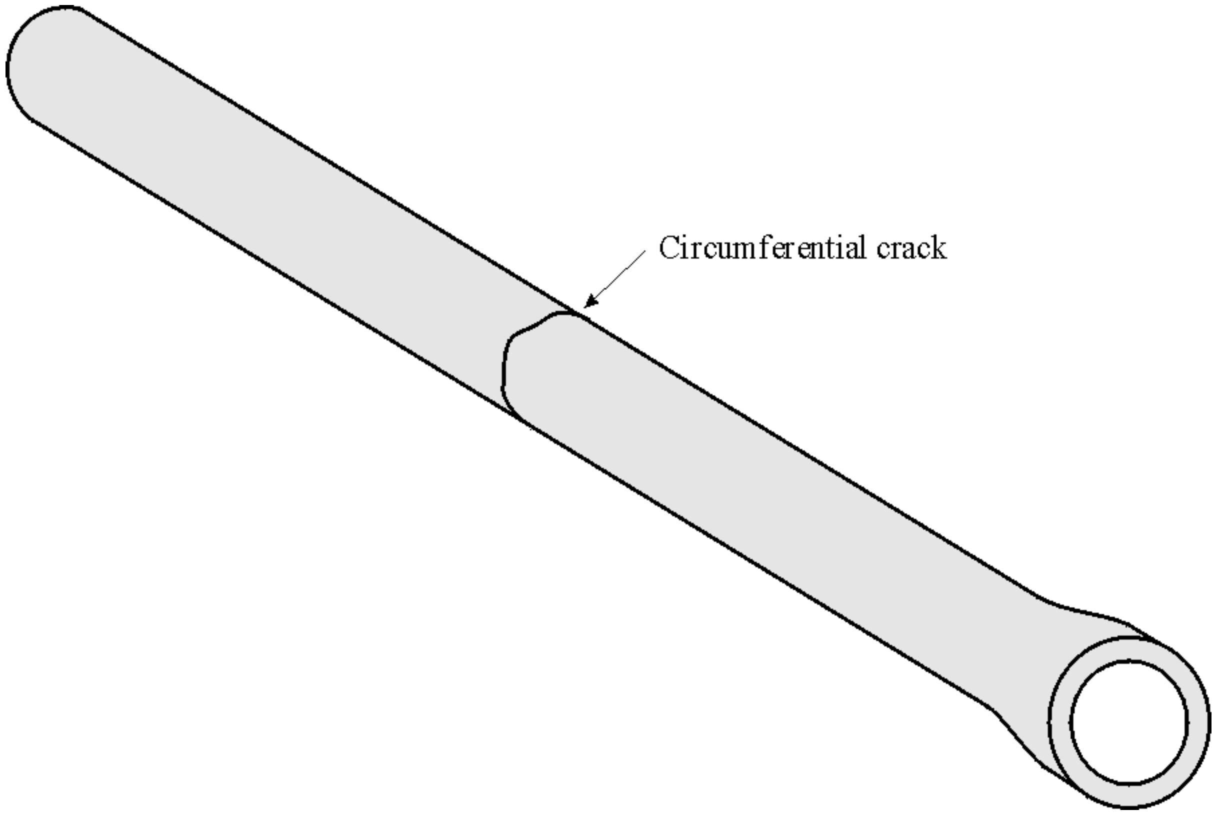


a)

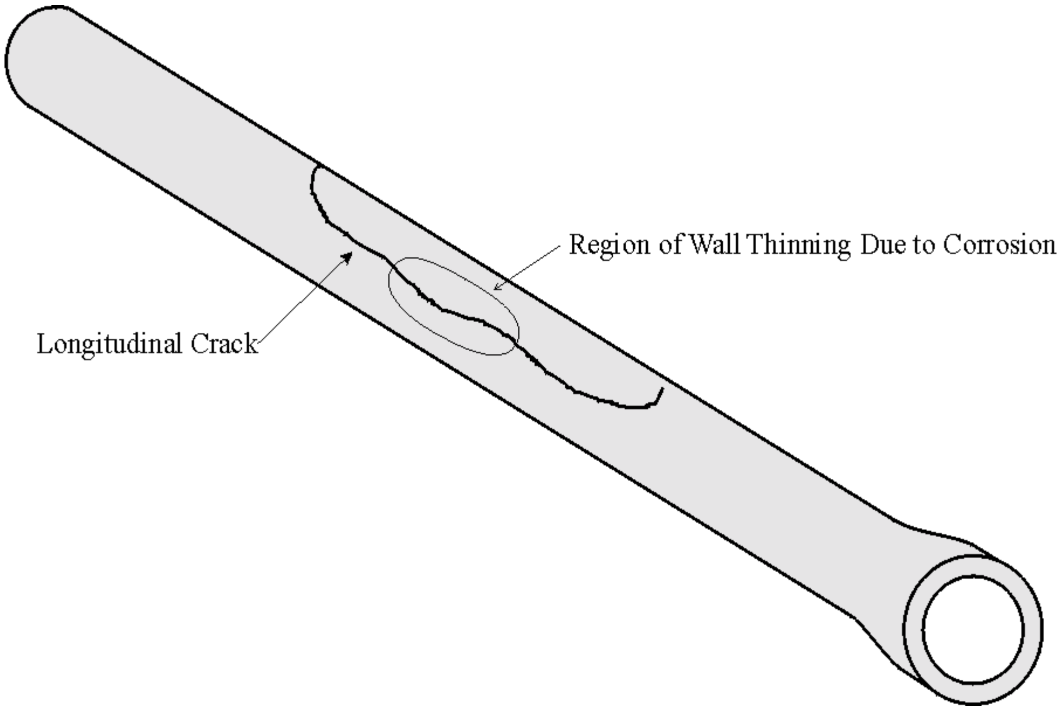


b)

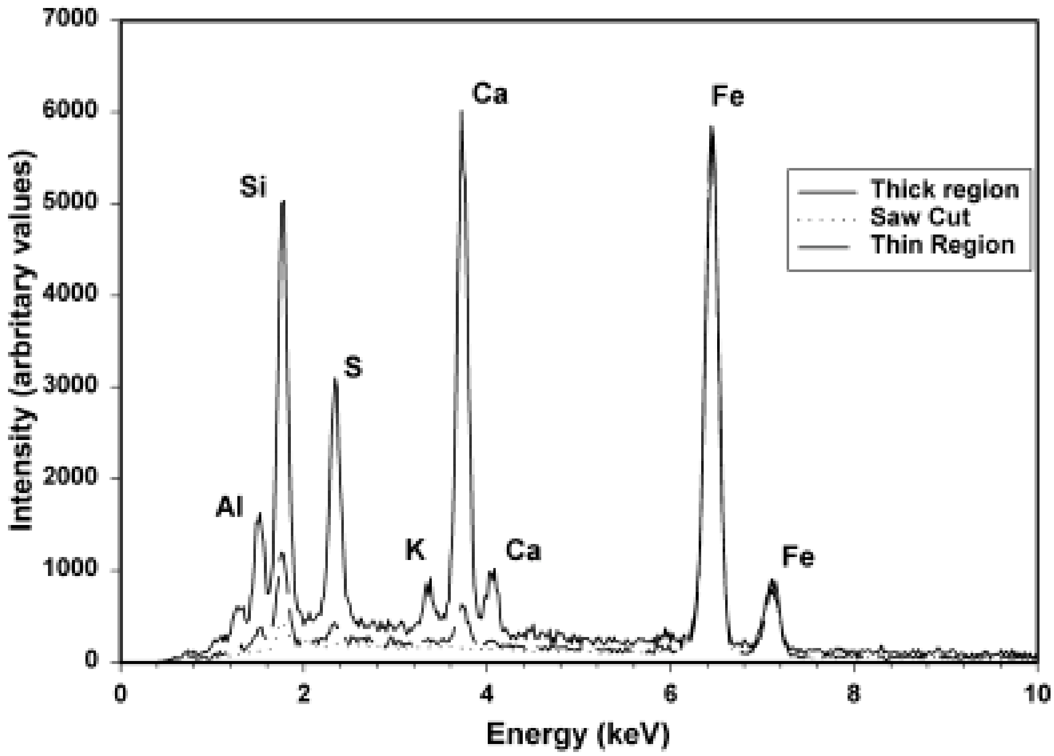
2. Blow-out type failure. Localised wall corrosion weakens the pipe wall until internal pressure surges cause the failure. Figure a) shows the typical form of a blow-out, while Figure b) shows the form discussed in this paper.



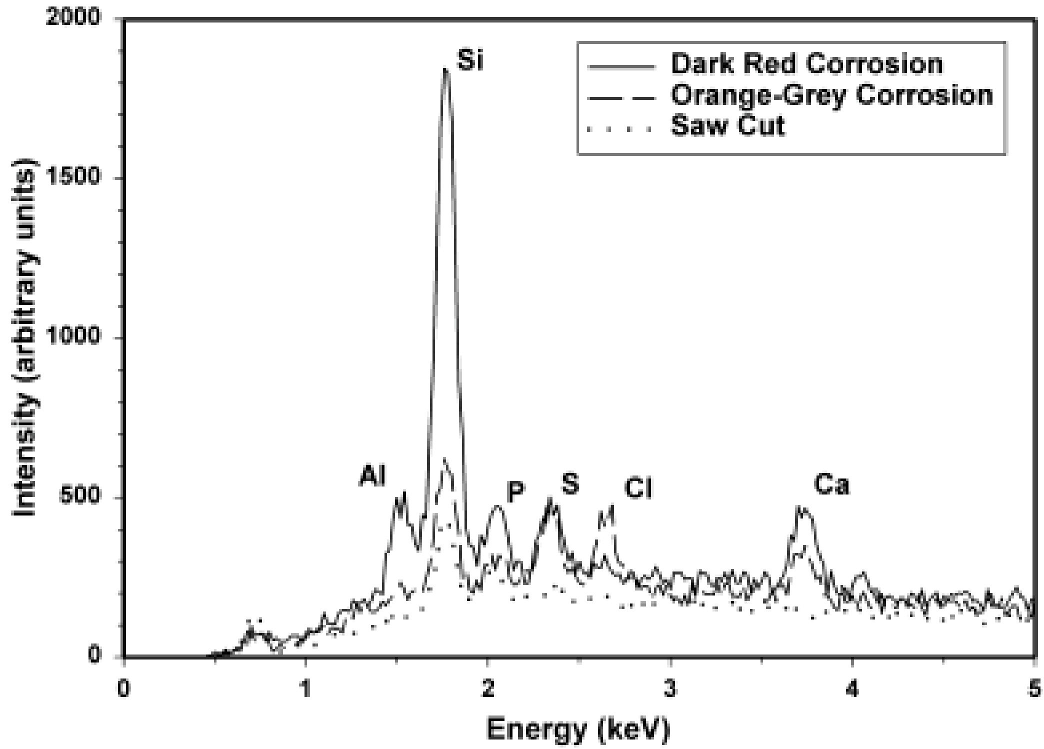
3. Circumferential failure. External bending forces in combination with corrosion pitting cause this form of failure.



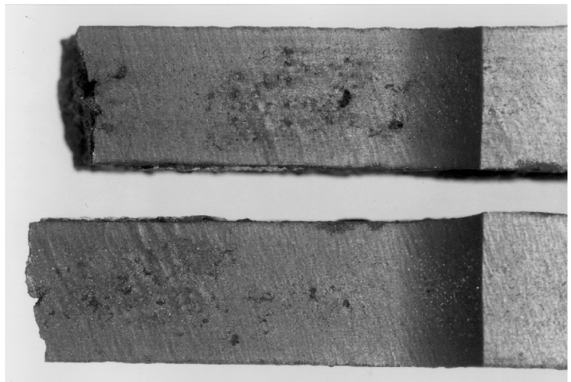
4. Longitudinal splitting. This type of failure is also caused by pipe wall thinning and pressure surges. The thinning can be produced corrosion or through pipe wall porosity. In some cases the crack will extend the length of the pipe.



5. EDAX spectra of the pipe that had failed by a bell split. These spectra have been normalised against the iron K_α signal.



6. EDAX spectra of a pipe that had failed by a circumferential split. These spectra have been normalised against the iron K_α signal.



7. Pores in the machined surfaces of the Minneapolis pipe sample. These pores and the inclusions that accompanied them produced a pipe that was much weaker than is typical for its class of pipe.