EVALUATION OF METAL WATER PIPE LEAKS IN THE JOHANNESBURG MUNICIPAL AREA

J.S. Ramotlhola ● Dr C. Ringas

Advanced Engineering and Testing Services
Division of Materials Science and Technology, CSIR

WRC Report No. 587/1/99
ISBN 1 86845 480 0

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The objectives of this study were to critically examine the reasons for leaks of metallic water pipes in the Johannesburg area; to classify the causes of leaks and to recommend remedial strategies to minimise water losses. A better understanding of the failure mechanisms of potable water metallic pipes in this area would be of benefit to all local authorities and hopefully contribute to a reduction in water losses.

Significant water losses due to leaks (from burst pipes) and other causes are experienced by the Johannesburg City Council. The unaccounted for water losses (UAW) amounted to about 23% in 1989 of the bulk water purchased from the Rand Water Board by the Johannesburg City Council. It must be emphasised however that leakage from mains is but one component of UAW.

All authorities conveying and supplying water experience water leaks to a greater or lesser extent. There is however, little agreement as to the relative contributions of internal and external corrosion to the problems experienced. Significant water savings could be achieved by alerting municipal authorities to appropriate counter measures once the dominant reasons for water leaks have been determined.

Samples of failed pipes were received for metallurgical testing when cut-outs were made. Consequently, the samples received for testing represent only a fraction of the total number of leaks experienced during the period of this study since not all leaks are cut-out when repaired.

All samples received for testing were subjected to a detailed metallurgical examination including SEM and EDS analysis where necessary and microbiological testing for sulphate-reducing bacteria (SRB). During the second half of the study, pipe to soil potentials were taken when possible, in order to evaluate the effectiveness of cathodic protection.

The results of investigating 126 samples clearly showed that external corrosion was more of a problem than internal corrosion. In some cases however it was difficult to distinguish whether internal or external corrosion was responsible for failure and these failures were categorised as internal and external.

In terms of failure mechanisms, weld corrosion, was the predominant failure mechanism followed by corrosion by SRB (including both internal and external). Stray current corrosion was responsible for just over 7% of the failures. General thinning of samples attributed to general corrosion was also noted and thus was generally found on the older pipes. A few examples of galvanic corrosion were also noted and were due to carbon steel flanges being welded onto galvanised pipes.

The results reinforce the fact that unprotected carbon steel pipelines are prone to internal and external corrosion, primarily by SRB. External corrosion was more of a problem because a larger number of factors cause external corrosion. The main factors responsible for external corrosion however, were SRB and stray currents. An effective way to reduce the effect of both SRB and stray currents is to apply effective cathodic protection. The pipe to soil potentials showed that all but one of the pipe samples tested were not protected by CP. It is apparent that the application of effective CP could greatly reduce the number of external failures.

Although much research work has been carried out to investigate the corrosion of galvanised pipes at welds, the results show that this is still the predominant failure mechanism. However, most of the galvanised pipes tested were installed prior to 1980 when such problems hadn't been resolved.

It would appear that a course in corrosion basics to all plumbers involved in maintenance would be beneficial and would eliminate many failures by eliminating bad practices.

ACKNOWLEDGEMENTS

The research in this report was funded by the Water Research Commission and entitled:

EVALUATION OF METAL WATER PIPE LEAKS IN THE JOHANNESBURG MUNICIPAL AREA

The Steering Committee responsible for this project, consisted of the following people:

Mr H.C. Chapman	-	Water Research Commission (Chairman)
Mr J.P.V. Rodrigues	-	Durban Corporation
Mr J.M. Lamprecht	-	Rand Water Board
Mr D.W. Hodgkinson	-	Umgeni Water
Ms A. Bondonno	-	Formerly with the CSIR, now with Biodet Laboratories in New Zealand
Dr C. Ringas	-	CSIR
Mr A. Coetzee	-	Pretoria City Council
Mr K. Rohner	-	Johannesburg City Council
Mr D. Raymer	-	Port Elizabeth City Council
Mr F.P. Marais	-	Water Research Commission (Committee Secretary)
Mr D.S. Van der Merwe	-	Water Research Commission
Mr J.S. Ramotlhola	-	CSIR

The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is gratefully acknowledged.

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

CML	-	Cement Mortar Lined
CP	-	Cathodic Protection
CSIR	-	Council for Scientific and Industrial Research
EDS	-	Energy Dispersive Spectroscopy
G	-	Galvanised
HAZ	-	Heat Affected Zone
MIC	-	Microbiologically Induced Corrosion
MS	-	Mild Steel
SRB	-	Sulphate Reducing Bacteria
WRC	-	Water Research Commission

1. INTRODUCTION

Generally speaking corrosion failures of metallic potable water pipes of water distribution systems can be classified as being caused externally or internally. The internally initiated corrosion would be bursts or leaks caused by microbiological corrosion or breakdown of internal coating whether organic or inorganic in nature. External corrosion could result in leaks caused by a wider range of factors such as stray currents, incorrect or insufficient cathodic protection, microbiological corrosion, absence of, or defective coatings and mechanical damage such as the cutting of threads on galvanised piping.

According to previous studies, corrosion of potable water pipelines not only affects the integrity of the system but can also influence water quality by the release of corrosion products into the system (Bondonno, Ringas, 1993). Severe corrosion (internal or external) can lead to bursts with the associated costs of water loss and pipe repair or replacement.

This study had the following objectives:

- To critically examine the reasons for leaks of metallic water pipes in the Johannesburg Municipal Area.

- To classify the causes of leaks and recommend remedial strategies to minimise water losses in a cost effective manner.

- To identify areas where future research can be directed to assist water supply authorities in reducing water losses due to internal or external corrosion.

2. MATERIALS AND METHODS

2.1 Collection of Samples

Arrangements were made with the superintendents of the five sub-depots of the Johannesburg Water and Gas Department to contact the CSIR when cut-outs were being performed, so that the pipe section could be collected on removal from the distribution system. Alternatively, plumbers were instructed to keep the pipe section immersed in a bucket of water from the pipeline or wrapped in a wet material and return it to the depot for collection. It was very important that the pipe section and soil sample be kept moist for microbiological sampling. This took the form of swabbing beneath both internal and external tubercles on the pipe walls. A soil sample was also collected from the soil around the pipe.

It must be stressed that only pipe samples which were cut out for repair were received for investigation and that these are a small proportion of the total number of leaks experienced during the course of this study. On some occasions, pipe lengths which had not failed were received for investigation because of renewal of pipelines.

2.2 Processing of samples

2.2.1 Microbiological Analyses

The presence/absence of SRB was tested for by obtaining swab samples from beneath the corrosion product (tubercles) and soil samples outside the pipe. These were incubated in SRB medium at 30°C for up to 28 days.

2.2.2 Metallurgical Analysis

At the CSIR (COTTESLOE) laboratories, the pipe sections were systematically numbered and a detailed record of pipe location, date removed and condition of the pipe drawn up. An example of this form is shown in Figure 1. Detailed photographic records of the pipe sample, from the as-received condition through the various stages of examination, were also kept.

The pipe samples were sectioned longitudinally and when necessary, the corrosion product was analysed by Electron Dispersive Spectroscopy (EDS) for major chemical constituents. One half of the sectioned pipe was cleaned using inhibited hydrochloric acid, rinsed in water and ethanol then dried with warm air.

Both internal and external surfaces of the cleaned sections were examined using a stereo microscope. When necessary selected samples were examined at higher magnification by scanning electron microscopy (SEM). Samples of the cleaned and uncleaned sections were retained for possible cross-referencing.

Metallographic testing was carried out to examine the microstructure of selected mild carbon pipe samples and detailed analysis of weld failures. Metallurgical examination was carried out using standard grinding and polishing techniques. A 2% (v/v) nital (concentrated nitric acid in ethanol) etchant was used to show the different phases of microstructures in an optical microscope.

The chemical composition of selected mild steel pipe samples was determined using spectrographic analysis and is presented in Table 1.

2.3 Pipe-to-soil potential measurements

With the assistance from staff at the Johannesburg Water and Gas department, pipe-to-soil potentials have been carried out since February 1994, when possible. However at certain times the pipe sections had been brought back to the depot or backfilling was complete when the site was visited so these measurements could not be made.

The pipe to soil potentials were recorded using a standard copper/copper sulphate half cell and a high impendance voltmeter.

2.4 Age and Geographical information

A detailed list of the ages and geographical location of each pipe sample received for testing (when these were available), was compiled using burst sheet records from the Johannesburg Water and Gas Department and is shown in Table 3.

2.5 Classification of failure type

Other information which was obtained includes classification of pipe failures, such as SRB internal, SRB external, both internal and external, weld-attack, stray current, general corrosion, galvanic corrosion, unknown and good condition (unaffected). This information is recorded and categorized as shown in Figure 2(a).

3. RESULTS

3.1 Failure Mechanisms

A total of 126 pipe samples were received for examination during the period of this research (January 1993 - December 1994). Of these 81% were carbon steel, 17% were galvanised steel mainly of small diameter (20 - 50mm) and 2% were cement mortar lined steel pipes.

The categorisation of corrosion damage was as follows:

External	-	41%
Internal	-	25%
Both internal and external corrosion	-	32%
Good condition	-	2%

3.2 Causes of failures

Figure 2(a) shows a graphic representation of the location of corrosion. External corrosion at 34% accounted for the highest number of failures. However, the failures caused by stray currents were also external so in fact the failures which were clearly due to external corrosion amount to 41% of the total.

The category external and internal amounting to 33% was due to the fact that some pipe samples showed signs of both internal and external corrosion and it was not clear which had caused the failure. However, if one were to take half of this category (say 16%) and add it to the external category then the number of failures due to external factors would rise to 57% of the total. This is a clear indication that the bulk of the corrosion problem experienced by Johannesburg Municipality Area is predominantly due to external factors as 41% of the failures were due predominantly to external factors.

Figure 2(b) summarises the type of corrosion mechanism and the figures are expressed as a percentage. The single largest cause of failure was corrosion at the weld. It was found that this occurred in almost all the galvanised steel samples evaluated. The ages of the galvanised steel pipe samples varied, with the oldest dating from the 1920's and the youngest from the 1980's.

The next largest cause of failure was external microbiologically influenced corrosion (MIC) followed by internal MIC. The bacterial tests carried out only tested for the presence of SRB and hence all the MIC failures in this study are attributed to SRB. However, it is well known and accepted that MIC is due to a variety of organisms living in a biofilm and hence it is not strictly correct to attribute all the failures to SRB. However, for the purposes of the present study it was sufficient to only test for SRB since for classification purposes (of failures) it is immaterial whether the corrosion was caused by only SRB or SRB and iron bacteria (for example) working synergistically.

It was also evident in some cases that there was SRB growth both internally and externally and such samples amounted to 11% of the total. A figure of 45% for SRB is obtained if all the SRB segments are added and clearly this is a significant amount.

General corrosion amounted to 13% of the total. This figure does indicate that a significant portion of the corrosion of the pipelines occurs fairly slowly and is due to dissolved oxygen in the ground or aggressive soils or corrosive water on the inside of the pipeline. A typical example of general corrosion is shown in Figure 3.

Figure 4 shows a failure attributed to stray currents. Failures attributed to stray currents amounted to 7% of the total and were certainly significant in terms of numbers.

One example of galvanic corrosion was noted and is shown in Figure 5. A carbon steel flange was welded to a galvanised steel pipe, resulting in corrosion at the joint between the flange and the pipe.

3.3 Geographical considerations

PAGEVIEW PIPELINE

A detailed study of a pipeline in 12th Street, Pageview, between De la Rey and Krause Streets was undertaken in 1993. The whole pipeline was being replaced with PVC piping. A detailed study of three sections from the entire pipeline length was carried out by a visit to the site. Figure 7 shows the area of pipeline sampled and the results obtained. The pipe to soil potential readings showed that the pipe was actively corroding at all three sites tested. The resistivity, which changes from one end of the pipe to the other, indicated that the soil was fairly aggressive. It did, however, highlight the variations in soil type that can occur even over a short length of pipe (±300m). Although SRB were not isolated from the interior of section A, they were present in other samples tested. It is possible that the bacteria were killed by heat during the cutting process as the section removed was not long enough to prevent heating effects at the centre. The nature of attack does seem to be due to SRB, and these organisms were most likely present along the whole length of the pipe. Severe external corrosion only occurred at the site where SRB were isolated from the soil, which strongly suggests that they were responsible for the external corrosion as well.

From the literature reviewed, it seems that the majority of failures of potable water pipelines are external. The major factors influencing external corrosion are (i) the dissolved oxygen content of the soil which can influence formation of anaerobic regions and concentration cells, (ii) the presence of stray currents, (iii) microbiological activity in the soil. The results of the present study also show that corrosion is predominantly external.

3.4 Cathodic Protection

The pipe to soil potentials presented in Table 2 clearly show insufficient protection of the pipelines. Only one sample in Commando Road, Longdale, showed a potential more negative than - 0.850mV versus $Cu/CuSO_4$.

It is probable however, that the smaller diameter pipelines (i.e. less than 300mm diameter) are not protected by CP and the fact that a large number of the samples examined in this study were from this category may explain the low potentials.

Nevertheless, some of the potentials in Table 2 were taken on pipelines of 300mm diameter and larger (up to 900mm diameter) and from this it would appear that there is generally inadequate CP in the Johannesburg Municipal Area.

One of the most commonly used criteria for cathodic protection is -0.850mV versus a $Cu/CuSO_4$ reference electrode. It would appear that since the bulk of the failures by corrosion were external that a greater emphasis on achieving adequate protection would reduce the external corrosion problem.

4. DISCUSSION

The impact of microbiological corrosion as well as general corrosion on water distribution systems can show significant physical damage to pipes, service connections and fittings. The potable water industry has not escaped this problem irrespective of measures taken to protect water distribution systems such as mild steel pipes and galvanised pipes.

SRB are the organisms most commonly associated with MIC in industry. Their presence in potable water systems is no exception and this can seriously affect the life of pipelines. The effect of SRB in potable water systems has been evaluated in two recently completed studies funded by the WRC (2), (3).

From the samples tested, the Johannesburg Municipality mostly uses mild steel pipes with a diameter range of 60 - 300mm, galvanised pipes of diameter 20 - 50mm and mortar-lined steel pipes. The chemical composition of the pipe materials used had a carbon content of 0,03 - 0,18 weight percent and parental microstructures of ferrite and pearlite for all ages of pipes. The microstructure varied widely as far as the grain size was concerned. Although from the microstructural level the grain sizes looked satisfactory, one does find exceptions in pipes from different age groups.

Steel pipes suffered mostly from pitting corrosion which initiated internally or externally and in some cases it initiated both internally and externally. The causes of this kind of corrosion vary from one pipe to another and location of the pipe. Steel pipes that were corroding externally were due to both SRB and aggressive soils. The pitting morphology on the outside suggested that SRB were quite active and microbiological analysis supported this fact. Internal corrosion of the steel pipes was mainly due to SRB attack.

On carbon steel pipes, corrosion induced by SRB has several characteristic features. Usually the metal surface is distinctly tubercular, the nodules consisting mainly of iron and sulphur species. Beneath the tubercles, the metal is clearly pitted in a localised fashion. Tubercles formed by iron-depositing bacteria, may or may not contain SRB in their interior. The metal beneath the tubercles normally has semi-spherical pitting attack in the absence of SRB. Corrosion beneath the tubercles is in the form of shallow, saucer-shaped pits. As corrosion proceeds, the pipe wall thickness is reduced, eventually the material perforates.

Galvanised steel piping underwent both general corrosion and pitting which was mostly initiated externally. The inside of these pipes had thick scaling which may have acted as a protective layer. The scale-forming ability of water depends on hydrogen ion concentration (pH value), total calcium content and total alkalinity. The corrosion rate of zinc in hard water may be 15μm/yr but in soft water it can be 150μm/yr. Soft waters, with their high content of dissolved oxygen and CO_2, generally attack zinc more vigorously than fairly hard waters. The normal corrosion product on zinc in water is $ZnCO_3$, and on removal of this corrosion product (chemically cleaned), the surface of the pipe looked good. Most of the galvanised steel pipe failures were along the weld-line. The metal was attacked from both the inside and outside with the inside attack being moderate when compared to the outside.

Preferential Weld Corrosion was found in both the galvanised steel pipes and the carbon steel pipes. This type of corrosion is mostly associated with aqueous environments. There is clearly a microstructural dependence and it has been shown that the presence of impurities and hardened structures can accelerate the corrosion around the weld.

The presence of electric railways, direct current generators and electric cables are common features of a highly developed city like Johannesburg. Of the total number of pipes, 7% failed by stray currents, which illustrates the importance of effective CP to minimise this type of corrosion.

The effects of galvanic corrosion were noted on some pipelines in localities where two dissimilar metals were joined together either by ignorance or being irresponsible.

The joining of a mild-steel flange to a galvanised pipe without protection may lead to adverse effects on the pipes as was found in this investigation.

General corrosion was very common as one would expect, because of the number of variables present underground. This type of corrosion could not be accounted for by any one particular effect. The most common feature of this corrosion was general thinning of the pipe both internally and externally.

The pipe to soil measurements that were recorded and documented range from -1024 to -15 mV. This would indicate that active corrosion was occurring at some localities.

5. CONCLUSIONS

The following conclusions can be drawn from this study.

- Unprotected mild steel pipes in potable waters are susceptible to MIC, both internally and externally.
- SRB play a major role in the corrosion process.
- The majority of corrosion failures of the potable water pipeline sections studied were external.
- Preferential weld corrosion was prevalent.
- Stray currents are active and contributed to 7% of the total failures.
- The levels of cathodic protection in the Johannesburg municipal area were generally ineffective or non-existent which indicates that active corrosion of metallic pipelines is occuring.

6. RECOMMENDATIONS

6.1 Guidelines for prevention of failures -

(a) Improve Cathodic Protection of all pipelines (this will reduce both stray current effect and external MIC by SRB).

(b) Improve protective coatings on metallic pipes.

6.2 Guidelines for corrosion audits -

(a) Each local authority/municipality should log all failures in the way that was done in this study in order to build up their own data base with historical information. The booklet described in 6.3(c) will describe how this can be done.

6.3 Guidelines for corrosion education of water supply authorities -

(a) Introduce seminars/workshop to address common potable water distribution problem.

(b) Attend and present basic corrosion courses.

(c) The WRC should print a booklet summarising the main findings of this study and include colour photographs showing each type of failure and guidelines on how to build up such a database.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

- It is recommended that the same research be extended to other municipalities in GAUTENG.
- Extension of the study to areas where soft waters are used.
- Research to increase our understanding of the effects of stray currents and better ways to reduce their impact on steel pipelines.

8. REFERENCES

1. Ringas, C.; Callaghan, B.G.; Straus, F.J. and Gnoinski, J. - **The effects of varying water quality on the corrosion of different pipe materials in the PWV/Klerksdorp areas.** WRC Project No. K5/254.

2. Bondono, A.; Ringas, C.; Ramotlhola, J.S. and Prinsloo, C. - **Microbial corrosion of common piping materials in the PWV area.** Project No. K5/432 (1994).

Table 1: CHEMICAL ANALYSIS OF SOME PIPES SECTIONS RECEIVED FOR TESTING

Spectrographic percentage analysis of pipe samples labelled according to decade installed.

Period	ELEMENT										
	C	Mn	S	P	Si	Cr	Mo	Ni	Cu	Al	Fe
1920	0,08	0,4	0,052	0,024	≤0,01	≤0,01	≤0,01	0,009	0,16	≤0,005	Bal
1930	0,16	0,48	0,027	0,008	0,05	≤0,01	≤0,01	≤0,01	≤0,01	≤0,005	Bal
1940	0,04	1,14	0,025	0,013	0,28	0,05	0,02	0,04	0,24	≤0,005	Bal
1950	0,18	0,49	0,023	0,014	≤0,01	≤0,01	≤0,01	≤0,01	≤0,01	≤0,005	Bal
1960	0,04	0,39	0,011	≤0,005	≤0,01	≤0,01	≤0,01	≤0,01	≤0,01	≤0,005	Bal
1970	0,14	0,54	0,015	0,018	≤0,01	≤0,01	≤0,01	≤0,01	≤0,01	≤0,005	Bal
1980	0,03	0,33	0,029	0,014	≤0,01	≤0,01	≤0,01	≤0,01	≤0,01	≤0,067	Bal
1990	0,05	0,36	0,011	≤0,005	≤0,01	≤0,01	≤0,01	≤0,01	≤0,01	≤0,005	Bal.

TABLE 2: **PIPE TO SOIL POTENTIALS**

DATE	DEPTH (m)	DIAMETER (mm) (OD)	POTENTIAL (mV)	ADDRESS
09/02/94	1	220	- 234	Cor. Village & Usher **SELBY**
"	2	750	- 700	Cor. 3rd Ave. & 11th **KEW**
"	2	150	- 463	Cor. 3rd Ave. & 11th **KEW**
"	0,3	150	- 355	Cor. Napier & Guild **MILLPARK**
"	0,3	150	- 245	Cor. Napier & Guild **MILLPARK**
08/03/94	1,5	100	- 290	173 Barry Str **BRUMA**
09/03/94	1	150	- 835	Cor. Federation & 3rd Ave. **PARKTOWN**
05/07/94	-	-	- 480	Cor. Gerard & Steyn **OBSERVATORY**
11/07/94	1	100	- 168	Cor. Mercury & Jeffrey **MAYFAIR**
"	1	100	- 341	Cor. Janson & Mercury **BRIXTON**
"	1	100	- 328	10th Str. Vrededorp **BRAAMFONTEIN**
12/07/94	1	300	- 246	Cor. Central & 9th Ave. **HOUGHTON**
13/07/94	1	250	- 412	Cor. Rockcliff & Hollywood **NORTHCLIFF**
"	1	250	- 358	Cor. Rockcliff & Hollywood **NORTHCLIFF**

TABLE 2 (continued): **PIPE TO SOIL POTENTIALS**

DATE	DEPTH (m)	DIAMETER (mm) (OD)	POTENTIAL (mV)	ADDRESS
13/07/94	1	250	- 363	Cor. Rockcliff & Hollywood **NORTHCLIFF**
"	1	100	- 482	Cor. Simmonds & Fox **CBD**
14/07/94	1	150	- 237	Cor. Svewright & Market **NEW DOORNFONTEIN**
"	1	150	- 379	Cor. Sirewright & Market **NEW DOORNFONTEIN**
				Cor. Bree & Queen **NEWTOWN**
05/07/94	1	150	- 466	Cor. Bree & Queen **NEWTOWN**
"	1	150	- 432	Cor. 1st Str & Bezuidenhout **BEZVALLEY**
19/07/94	1	450	- 342	Cor. Poviosonal & Wolta **LENZ**
"	1	300	- 532	Cor. De Malan & Judith **EMMARENTIA**
20/07/94	1	300	- 235	Power Park Res. **PARKTOWN NORTH**
16/09/94	2	600	- 127	Central Avenue **FAIRWAY**
"	1	20	- 15	27 9th Avenue **MAYFAIR**
29/09/94	1	100	- 336	Cor. Rudd & Chaplin **ILLOVO**
05/10/94	1	900	- 43	Cor. 7th Ave. & Main Rd **MELVILLE**

TABLE 2 (continued): **PIPE TO SOIL POTENTIALS**

DATE	DEPTH (m)	DIAMETER (mm) (OD)	POTENTIAL (mV)	ADDRESS
11/10/94	1	150	- 249	Commando Rd **LONGDALE**
17/10/94	1	150	- 1024	Commando Rd **LONGDALE**
17/10/94	1	150	- 301	Cor. 8th Ave. & 4th Str **BEZ. VALLEY**
26/10/94	1	100	- 371	18 Karin Ave. Velardin **NORTHCLIFF**
04/11/94	1	75	- 165	Cor. Ascot & Viljoen **BERTRAMS**

N.B.: All potentials were taken with a $Cu/CuSO_4$ reference electrode.

TABLE 3: SUMMARY OF LOCALITY AND AGE OF CUT-OUTS

Address	Material	Year	Pipe No.	Diameter (mm)	Type of Failure
Cnr. Brick Lane & Stephen Road, Ophirton	MS	1959	1	110	Ext
Second Street & Third Avenue, Booysens Reseve	MS	1961	2	165	Ext
No address	MS		3	150	Int
Stand (1/55) Booysens Road, Booysens	MS	1969	4	165	Ext
Cnr. Springs & Bossman Road, Ophirton/Booysens	MS	1927	5	90	Both
Cnr. Brick Land & Stephen Road, Ophirton	MS	1959	6	100	Ext
Roberts Street, Kensington	CML	1967	7	150	Ext
Cnr. Leyds & Quarts Street, Doornfontein	MS	1926	8	50	Ext
Cnr. Cumberland & Miabo Street, Kensington	MS	1950	9	150	Ext
Cumberland Road, Kensington	MS	1950	10	150	Int
No address	MS		11	110	Ext
Cnr. de Wet Road & Swazi Road, Waterval Estate	G	1948	12	25	Ext
Watt Road, Industria	MS	1966	13	25	Ext
Cnr. Carter & Club Road, Forest Hill	MS	1957	14	75	Both
No address	MS		15	75	Ext
49, 9th Street, Vrededorp	MS	1960	16	15	Ext

TABLE 3 (continued)

Address	Material	Year	Pipe No.	Diameter (mm)	Type of Failure
Cumberland Road, Kensington	G	1950	22	20	Ext
Cnr. Collins & Guildford Street, Brixton	G	1925	23	15	Ext
15 Buchan Road, Stafford	MS	1939	24	90	Both
Cnr. Tullray & Tullray West Street, Crown Gardens	MS	1949	25	90	Int
Cnr. Helens & Bellona Street, Mayfair West	MS	1935	26	150	Good
Cnr. St. Ives & Bellona Street, Mayfair West	MS	1935	27	90	Good
28 Fairways Road, Linksfield North	MS	1953	28	90	Int
174 8th Street, Mayfair	G	1926	29	25	Ext
Cnr. Corlett Drive & High Street, Bramley	MS	1933	30	90	Both
No address	MS	-	31	90	Int
Cnr. Market & Van Beck Street, New Doornfontein	MS	1958	32	150	Both
Cnr. 10th Street & 6th Avenue, Bezvalley	MS	1936	33	150	Ext
3 Orchards Streets, Orchards	CML	1958	34	90	Ext
77 Ascot Street (off Bertrams Road), Judith Paarl	MS	1929	35	90	Int
127 Westcliff Drive, Westcliff	MS	1966	36	90	Both

TABLE 3 (continued)

Address	Material	Year	Pipe No.	Diameter (mm)	Type of Failure
Cnr. Park & Ferreira Street, West Turffontein	MS	1929	37	90	Int
Turffclub Street, Turffontein	G	1965	38	25	Ext
Cnr. St. Ives & Bellona Street, Mayfair West	MS	1935	39	100	Both
35 12th Street (Cnr. de la Rey), Vrededorp	G	1960	40	25	Ext
Cnr. Fairways & Stoneway, Linksfield North	MS	1953	41	100	Int
Cnr. The Valley & Lawrence Road, Westcliff Ext.	MS	1922	42	90	90
Cnr. Barry Hertzog & Muirfield, Emmarentia	MS	1936	43	225	Ext
Price Street Extension, Industria	MS	1936	44	150	Ext
Cnr. 4th Avenue & Momouth, Westdene	MS	1944	45	90	Ext
20 Umgeni Road, Emmarentia	MS	1954	46	90	Ext
118 Corlett Drive, Birnam	MS	1942	47	90	-
No address	G	-	48	50	Ext
Cnr. Oxford Road & Tyrwhitt Avenue, Rosebank	MS	1957	49	150	Ext

TABLE 3 (continued)

Address	Material	Year	Pipe No.	Diameter (mm)	Type of Failure
Cnr. Ramsay Street & Poulton, Booysens	MS	1974	50	150	Ext
35 Stamford Street, Forest Hill	MS	1947	51	100	Both
Nicole Street, Kensington	MS	±1951	52	100	Int
Cnr. Kei Road & Umgeni, Emmarentia	G	1954	53	25	Ext
Cnr. Barry Hertzog & Gleneagles, Greenside	MS	1974	54	100	Ext
Cnr. Lyndhurst & Hare, Lyndhurst	G	1979	55	50	Ext
Clare Street, Between Mint & Central, Mayfair	G	1986	56	20	Ext
30 Burns Street, Waverley	MS	1933	57	100	Ext
Cnr. 11th Avenue & 6th Street, Houghton	MS	1934	58	100	Both
11 Swansea Road, Parkwood	MS	1969	59	100	Int
Cnr. Market & End Street, City Centre	G	1925	60	25	Ext
13th Avenue between Krause & de la Rey, Pageview	MS	1960	61A	100	Both
13th Avenue, Pageview	MS	1960	61B	100	Both
13th Avenue, Pageview	MS	1960	61C	100	Int
37 Springbok Road, Mayfield Park	MS	1973	62	150	Both
12th Street between Krause & de la Rey, Pageview	MS	1960	63A	100	Int
12th Street, Pageview	MS	1960	63B	100	Int
12th Street, Pageview	MS	1960	63C	100	Both
Cnr. Church Street & 10th Avenue, Mayfair	MS	1937	64	90	Ext

TABLE 3 (continued)

Address	Material	Year	Pipe No.	Diameter (mm)	Type of Failure
Cnr. Ley & Tana, Victory Park	MS	1965	65	100	Ext
29B Cnr. Commissioner & West Street, CBD	MS	1940	66	150	Ext
11 Harley Street, Yeoville	G	N/A	67	50	Ext
Esselen between Twist & Edith Cavell, Hillbrow	G	1963	68	50	Ext
Cnr. Market & Kort Street	MS	1963	69	150	Both
10 Sattle Street, Northcliff	MS	1971	70	90	Both
Cnr. Loveday & Webber Street, City Centre	MS	±1970	71	50	Ext
Cnr. Wemmer Jubilee & Salisbury, Wemmer	MS	1960	72	100	Both
7 Rocky Ridge Road, Parktown	MS	N/A	73	150	Int
Cnr. Burton & Beit Road, Doornfontein	G	1961	74	20	Ext
Cnr. Miller & Link South, Triomf	MS	1964	75	150	Int
Cnr. Central & Fountain Street, Fordsburg	G	1946	76	25	Ext
Alex du Toit Street, Bellavista	G	1984	77A	50	Ext
Alex du Toit Street, Bellavista	G	1984	77B	50	Ext
No address	MS	-	78	90	Good
Cnr. Tilray & Ring Road, Crown Gardens	MS	1949	79	150	Int
Inlet Chamber, Crown Gardens	MS	1972	80	110	Ext

TABLE 3 (continued)

Address	Material	Year	Pipe No.	Diameter (mm)	Type of Failure
Cnr. Kafue Road & 11th Street, Melville Koppies	MS	1937	81	150	Ext
No address	G	-	82	50	Both
68 Athlone Avenue, Sandringham	MS	1946	83A	110	Int
True North Road, Mulbarton	MS	1970	83B	150	Int
Cnr. Rifle Range & Vincent, Forest Hill	MS	1964	84	90	Both
10 Sherwell Road, New Doornfontein	MS	1930 - 1932	85	50	Both
Cnr. Carvendish & Webb, Yeoville	MS	1966	86	110	Ext
Cnr. Carvendish & Webb, Yeoville	MS	1963	87A	100	Ext
Cnr. 13th Avenue & Bird, Mayfair	MS	1963	87B	100	Ext
Cnr. London Lane & Armsterdam, Park Central	MS	1957	88	150	Ext
Cnr. Joubert & Fox Street, Johannesburg	MS	1935	89	150	Ext
Stand 827, Parktown	MS	1924	90	150	Int
Cnr. Maidstone & Lyndhurst, Lyndhurst	MS	1973	91	150	Ext
No address	MS		92	110	Int
Cnr. Elandsburg & Boekkevelds Drive, Eldorado Park	MS	1973	93	80	Ext
No address	MS		94	110	Ext
Cnr. Solomon & 12th Street, Vrededorp	MS	1935	95	110	Ext
No address	G		96	25	Ext
No address	MS		97	150	Ext

TABLE 3 (continued)

Address	Material	Year	Pipe No.	Diameter (mm)	Type of Failure
Tywhitt Road, Birdhaven	MS	1938-1943	98	110	Int
Stand 922, Emmarentia	G	1955	99	60	Ext
10th Street, Vrededorp	MS	1960	100	100	Ext
1314 Christopher Street, Eldorado Park West Ext. 2	MS	1973	101	100	Int
Cnr. Gerald & Steyn Street, Observatory	G	1964	102	20	Both
Cnr. Central & 9th Avenue, Houghton	MS	1936	103	300	Both
Cnr. Rockcliff & Hollywood Street, Northcliff	MS	1971	104	250	Both
Cnr. Sivewright & Market Street, Doornfontein	MS	1963	105	150	Both
Bangalore Drive, Lenasia Ext. 11	MS	1992	106	150	Ext
No address	MS	1987	107	90	Good
9th Avenue & Salisbury (Claim) Street, City Centre	MS	1945	108	225	Both
Kruis & Salisbury (Claim) Streets, City Centre	MS	1935	109A	100	Good
Kruis & Salisbury (Claim) Streets, City Centre	MS	1935	109B	100	Good
Kruis & Salisburty (Claim) Streets, City Centre	MS	1935	109C	100	Both
Bree Street, Newtown	MS	-	110	100	Ext
Chaplin & Atherstone, Illovo	MS	-	111	100	Ext
Cnr. Ascot & Viljoen Streets, Bertrams	MS	-	112	75	Ext
No address	G	-	113	50	Ext

TABLE 3 (continued)

Address	Material	Year	Pipe No.	Diameter (mm)	Type of Failure
Rede Street, Forest Hill	MS	-	114	90	Ext
Prairie Street, Rosettenville	MS	-	115	90	Both
Rietfontein Hospital	MS	-	116	90	Ext
Zeilion Street, Bellavista	MS	-	117	90	Ext

TABLE 4: **GALVANISED PIPES (SMALL DIAMETER)**

PIPE NUMBER	DIAMETER (mm)
8	50
12	25
13	25
16	15
22	20
23	15
29	25
40	25
48	25
53	25
56	20
60	25
67	50
68	50
72	25
73	50
74	25
76	25
77	50
77B	50
82	25
96	25
99	50
102	20

JR/frs/misc/galpipes

TABLE 5: AGE ANALYSIS OF SAMPLES RECEIVED FOR TESTING PERIOD (1920's - 1990's)

1920's	1930's	1940's	1950's	1960's	1970's	1980's	1990's	UNKNOWN
5	24	12	1	2	50	56	106	3
8	26	19	6	4	54	77A		11
23	27	20	9	7	55	77B		15
29	30	21	10	13	62			17
35	33	25	14	16	70			31
37	39	45	22	18	71			48
42	43	47	28	36	80			67
60	44	51	32	38	83B			73
90	57	66	34	40	91			78
	58	76	41	59	93			82
	64	79	46	61A	101			92
	81	83A	49	61B	104			94
	85	98	52	61C				96
	89	108	53	63A				97
	95		88	63B				110
	103		99	63C				111
				65				112
	109			68				113
				69				114
				72				115
				74				116
				75				117
				84				

TABLE 5 (continued):

1920's	1930's	1940's	1950's	1960's	1970's	1980's	1990's	UNKNOWN
				87A				
				87B				
				86				
				100				
				102				
				105				

* The dates refer to the decade in which the pipe was installed.

WRC/JHB MUNICIPALITY PIPE FAILURE SURVEY

PIPE NUMBER: ....

STAND NUMBER: ....

ADDRESS: ....

TOWNSHIP: ....

DATE REMOVED: ....

REMOVED BY: ....

EXTERNAL APPEARANCE: ....

....

....

....

INTERNAL APPEARANCE: ....

....

....

....

SOIL TYPE: ....

BACTERIAL ANALYSES:

SRB External: ....

SRB Internal: ....

Slime formers: ....

EDS: ....

METALLURGICAL RESULTS: ....

....

MODE OF FAILURE: ....

....

....

Figure 1: Form for recording pipe sample data

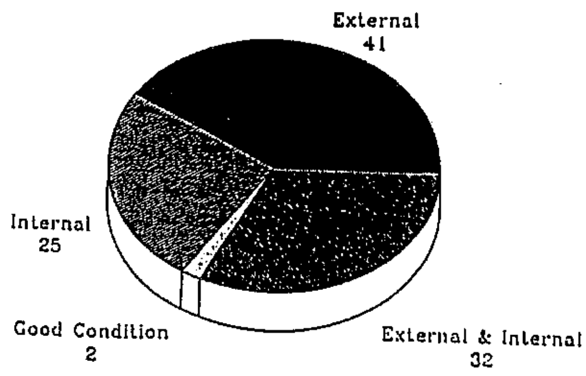


Figure 2(a): 3-D pie-chart showing percentage location of corrosion

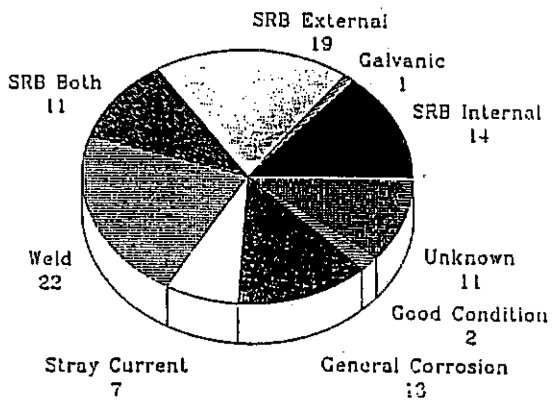


Figure 2(b): 3-D pie-chart showing percentage type of corrosion.

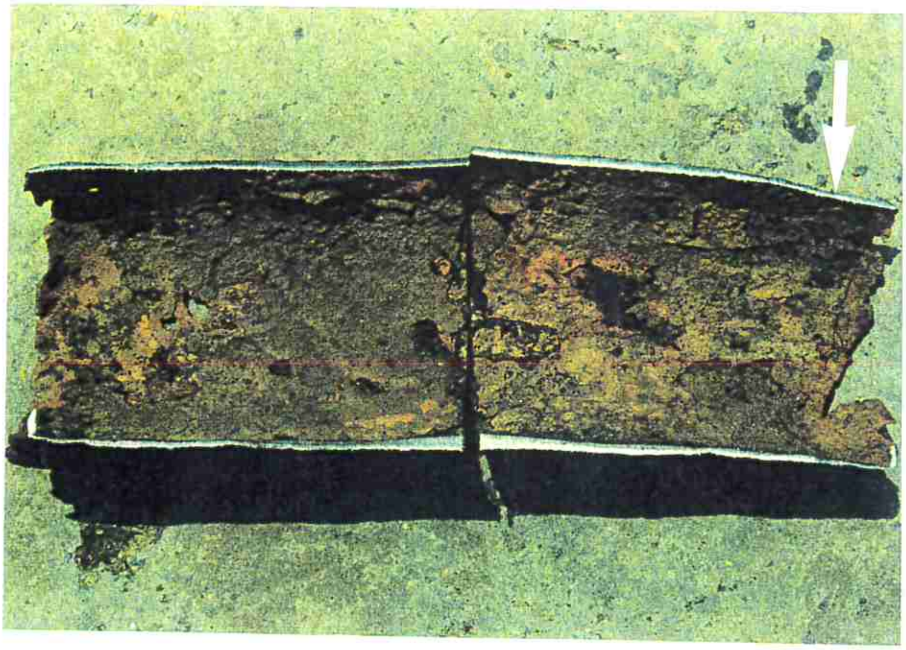


Figure 3: General type corrosion (N.B. thinning wall arrowed). Magnification: X0,4.

Figure 4: Stray current on pipe samples after cleaning (note - melted parts). Magnification: X0,5.

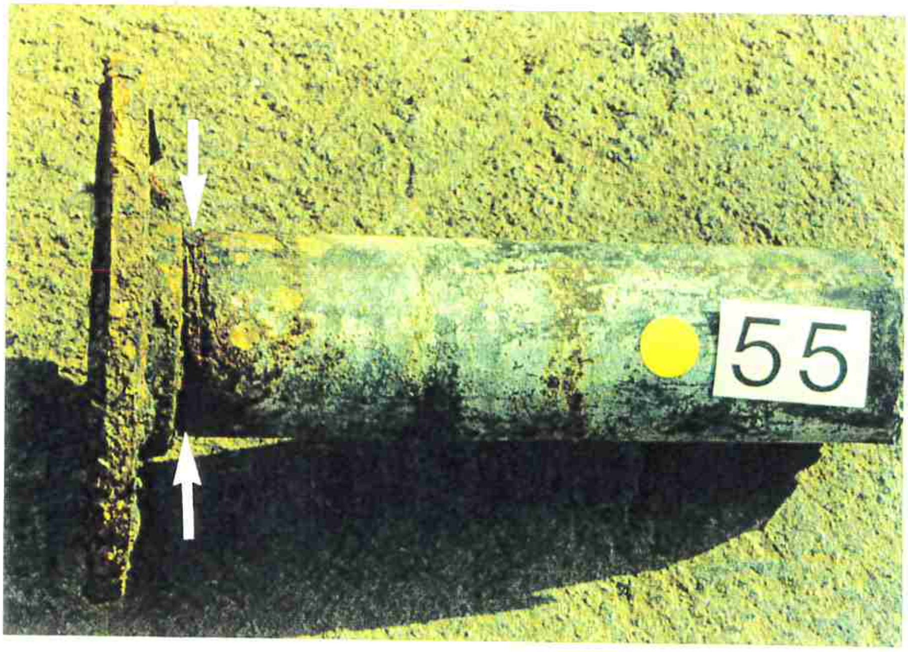


Figure 5: Galvanic corrosion - (Mild steel flange and galvanised pipe (Note -corrosion attack arrowed). Magnification: X0,5.

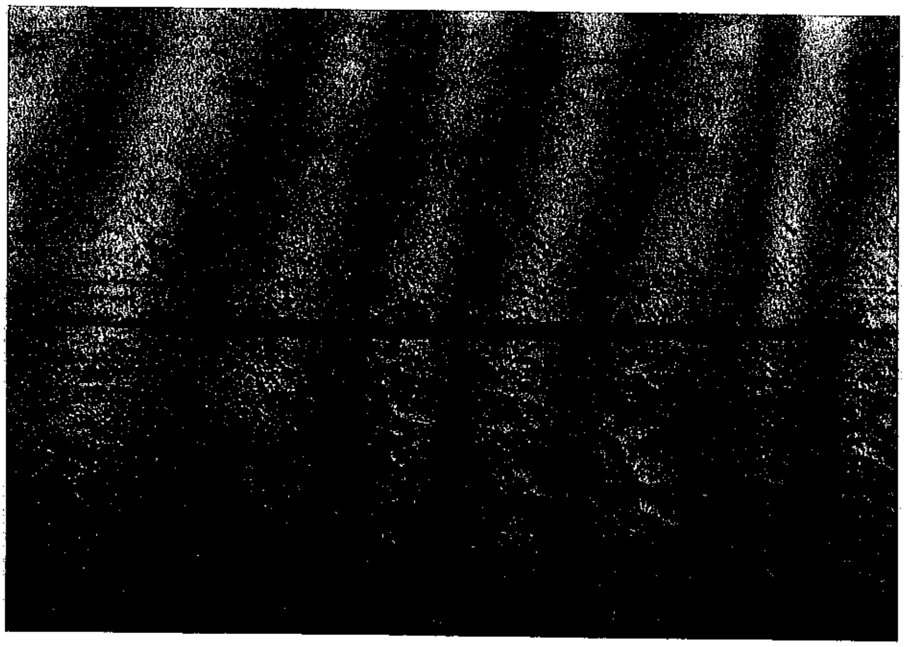


Figure 6(a): Weld attack galvanised pipe (outside). Magnification: X0,6.

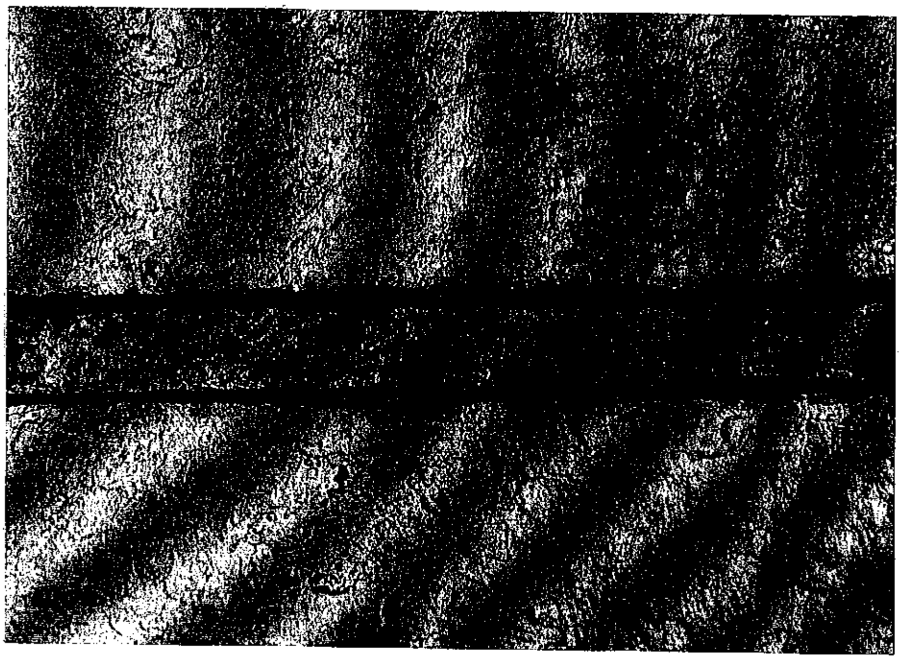
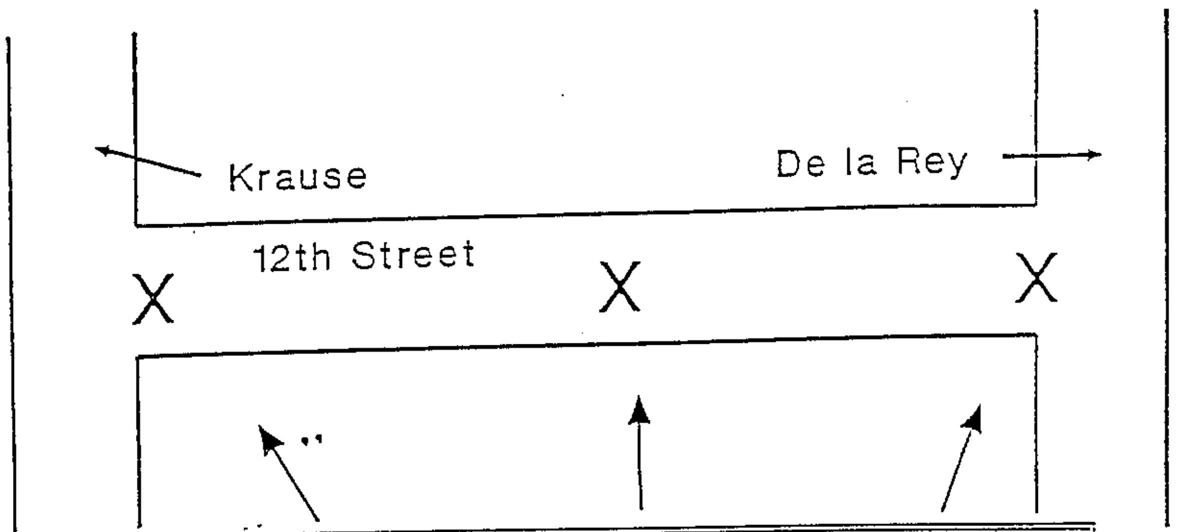


Figure 6(b): Weld attack (HAZ) mild steel pipe (inside). Magnification: X0,6.

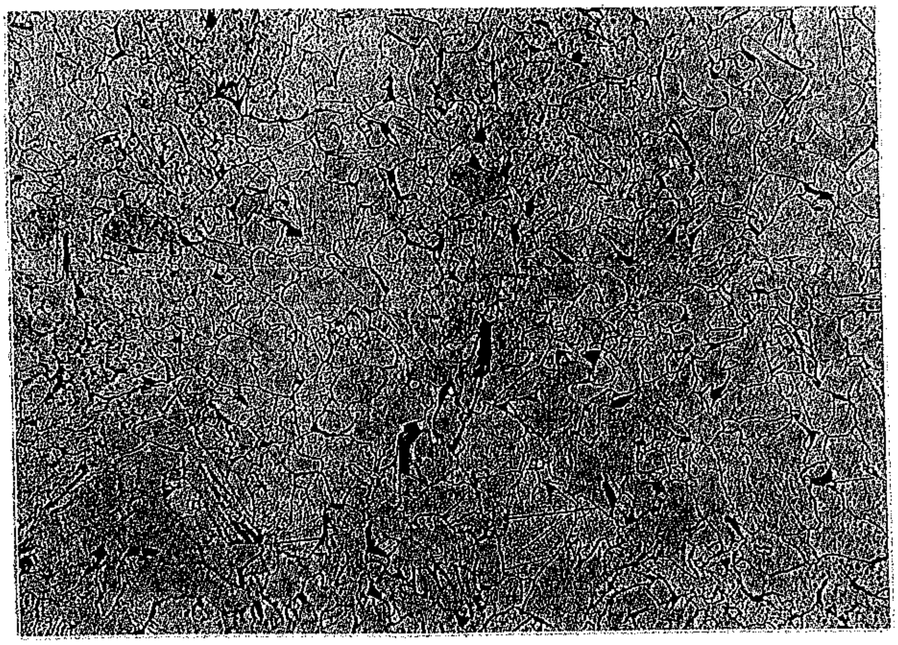


	A	C	B
SRB INT	—	+	+
SRB SOIL	—	+	—
PITTING INT	deep, saucer	shallow saucer	corr on weld
PITTING EXT	none	deep with penetration	shallow at weld
RESISTIVITY	7351 Ωcm	5906 Ωcm	4021 Ωcm
PIPE:SOIL POT	-387 mV	-401 mV	-381 mV

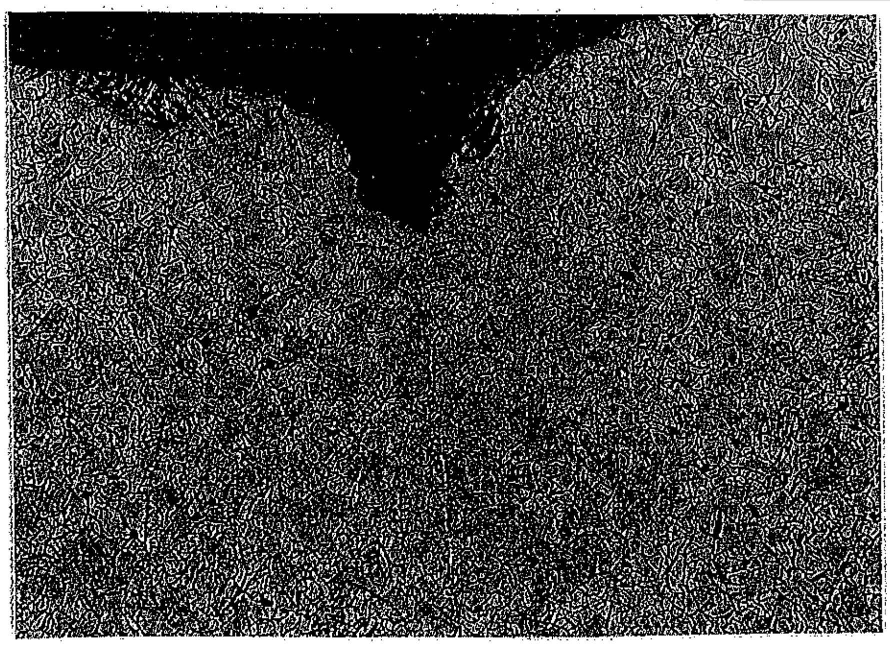
Figure 7: Results from study of Pageview pipeline. (Diagram not to scale)

APPENDIX 1

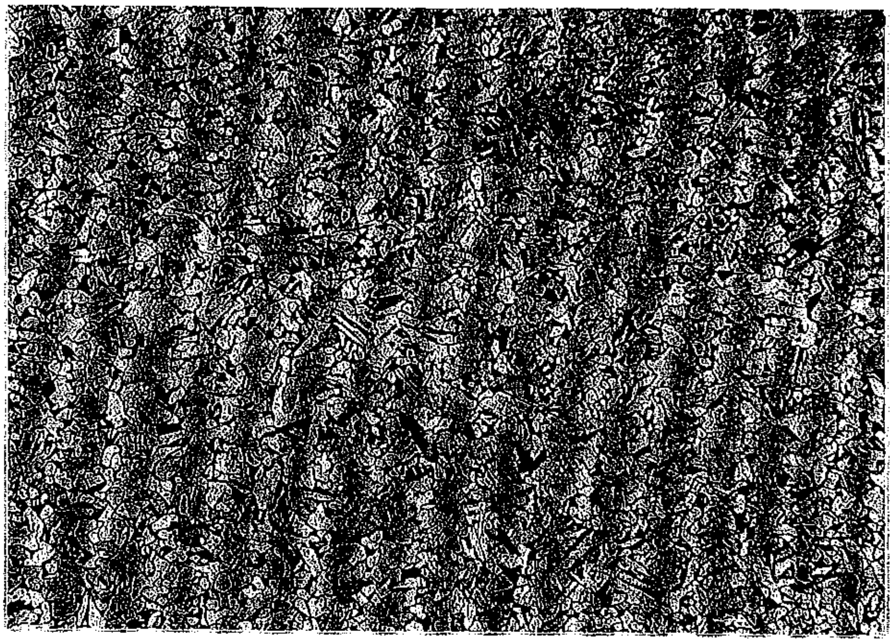
PARENT AND WELD ANALYSES



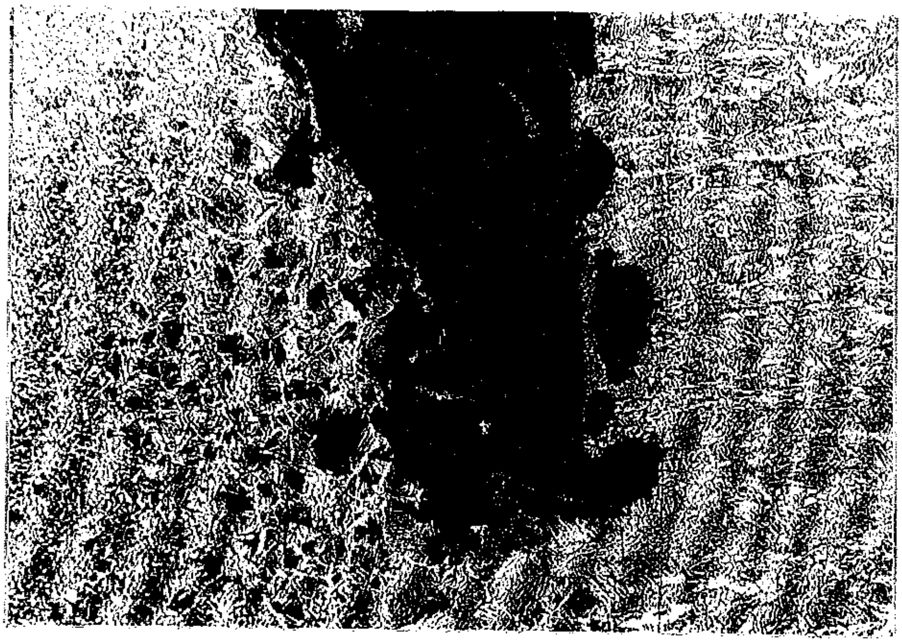
PIPE NUMBER:	23 (GALVANISED)
SECTION:	PARENT MICROGRAPH
MAGNIFICATION:	X116
YEAR:	1920



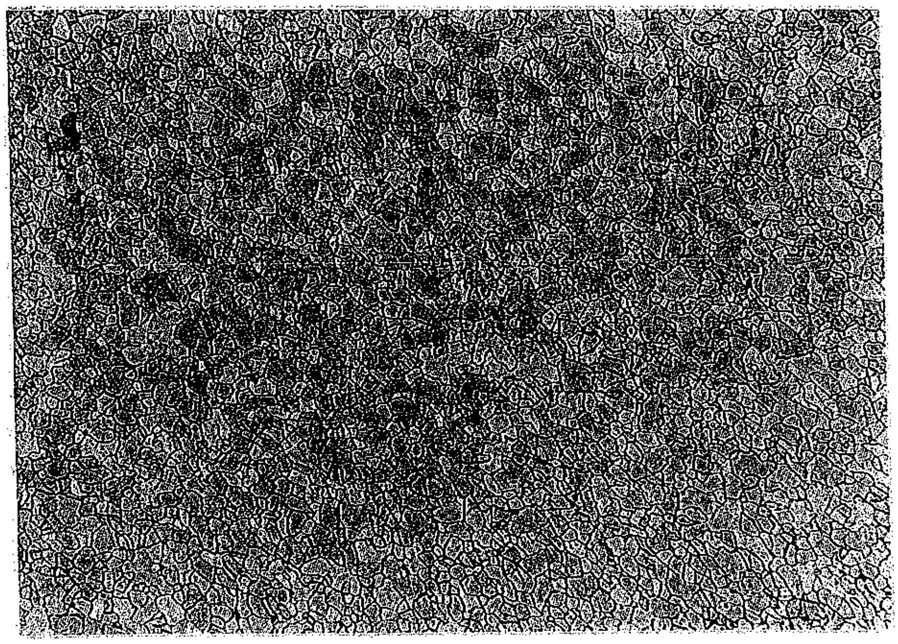
PIPE NUMBER:	23
SECTION:	WELD (ATTACK FROM INSIDE) MICROGRAPH
MAGNIFICATION:	X57
YEAR:	1920



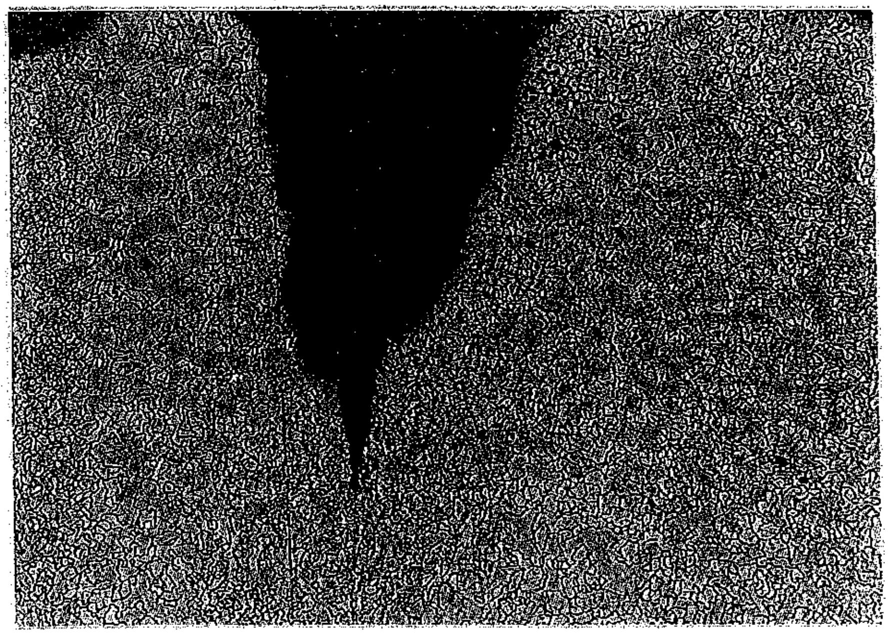
PIPE NUMBER: 89 (MILD STEEL)
SECTION: PARENT
MAGNIFICATION: X116
YEAR: 1930



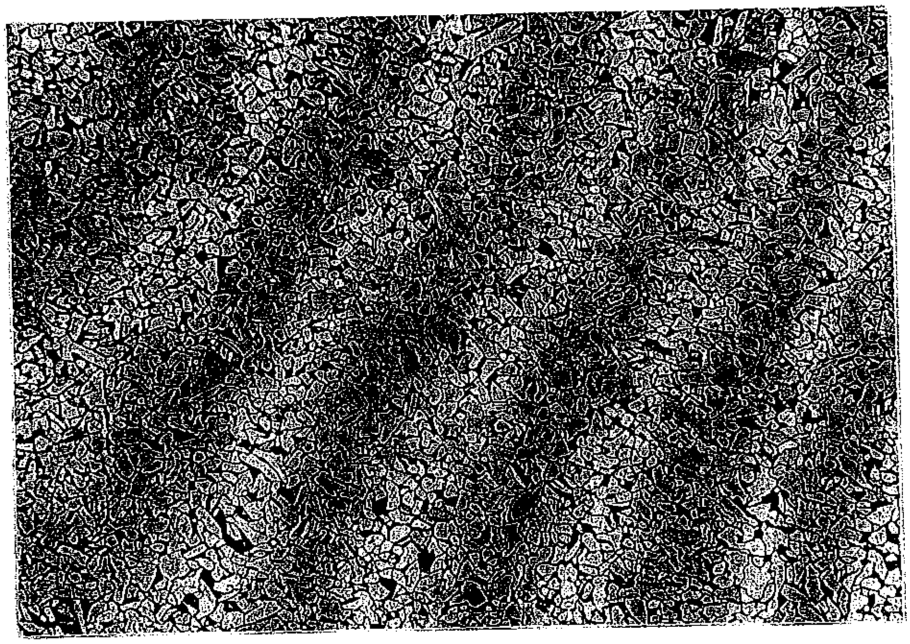
PIPE NUMBER: 89
SECTION: WELD ATTACK
MAGNIFICATION: X57
YEAR: 1930



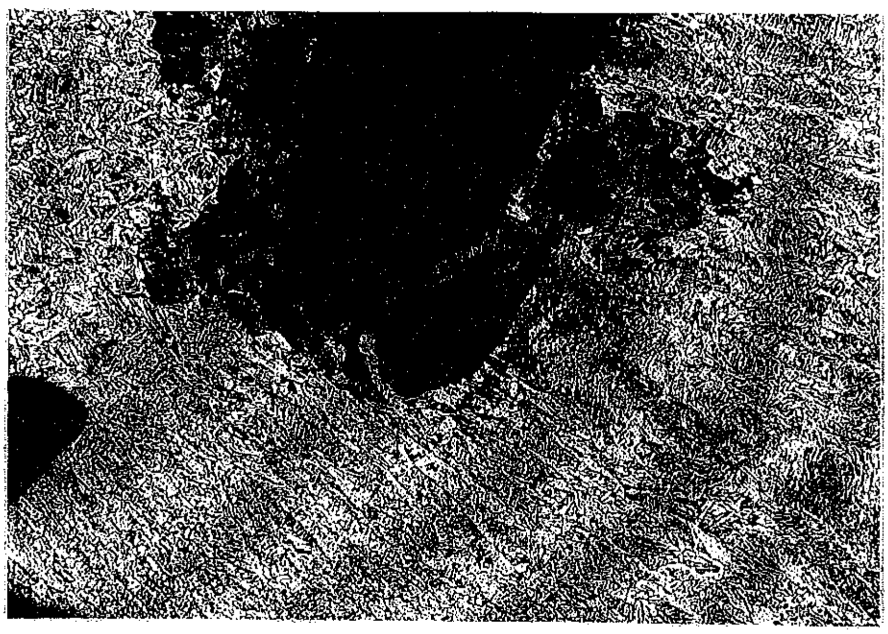
PIPE NUMBER: 76 (GALVANISED)
SECTION: PARENT MICROGRAPH
MAGNIFICATION: X116
YEAR: 1940



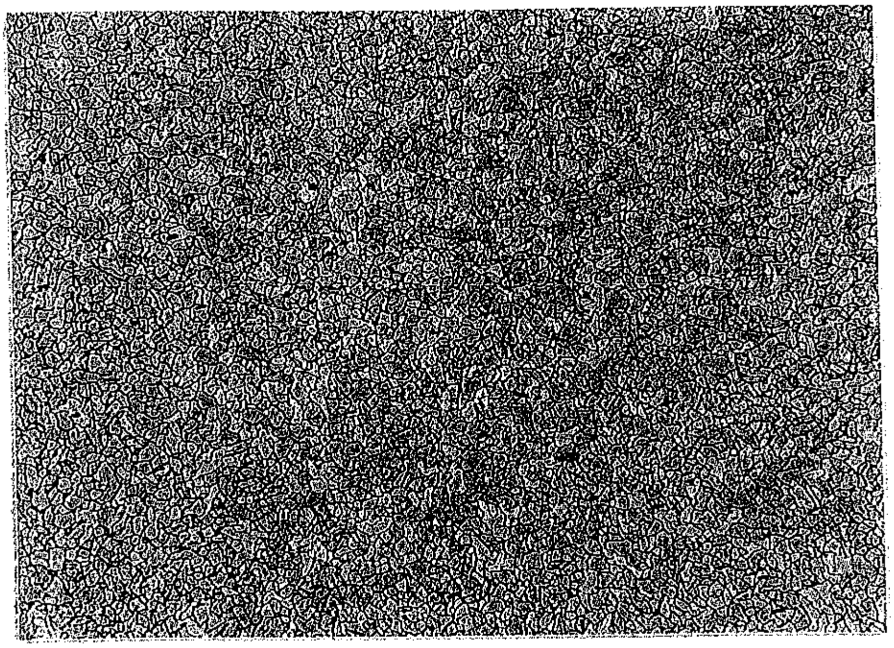
PIPE NUMBER: 76
SECTION: WELD (ATTACK FROM OUTSIDE)
MAGNIFICATION: X57
YEAR: 1940



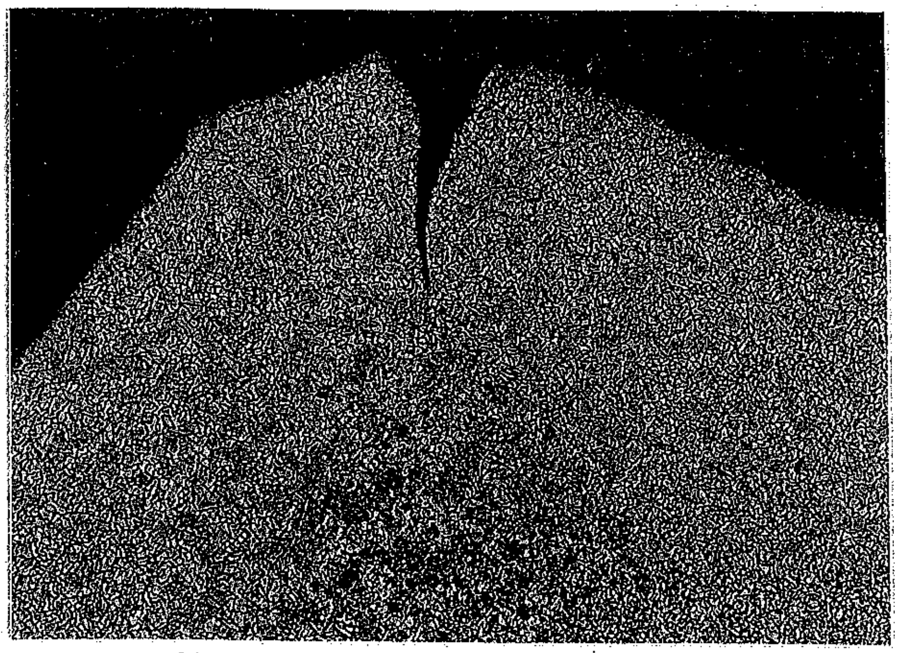
PIPE NUMBER:	79 (MILD STEEL)
SECTION:	PARENT MICROGRAPH
MAGNIFICATION:	X116
YEAR:	1940



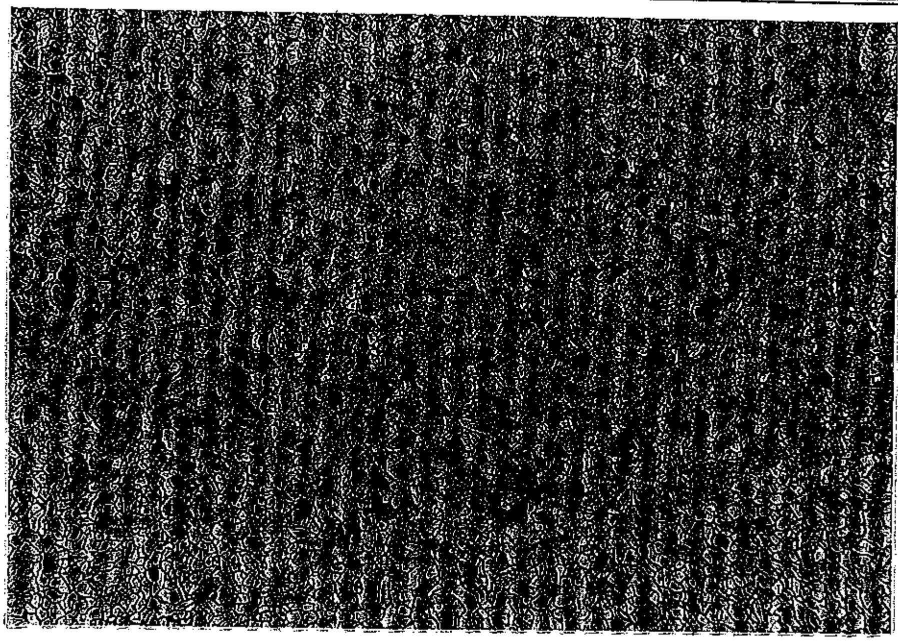
PIPE NUMBER:	79
SECTION:	WELD MICROGRAPH
MAGNIFICATION:	X57
YEAR:	1940



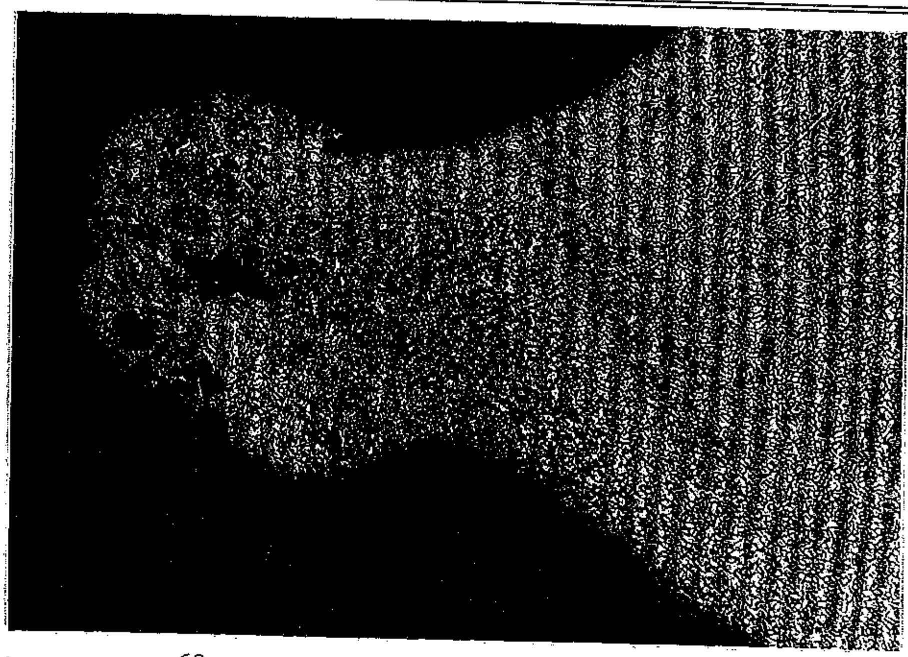
PIPE NUMBER:	99 (MILD STEEL)
SECTION:	PARENT MICROGRAPH
MAGNIFICATION:	X116
YEAR:	1950



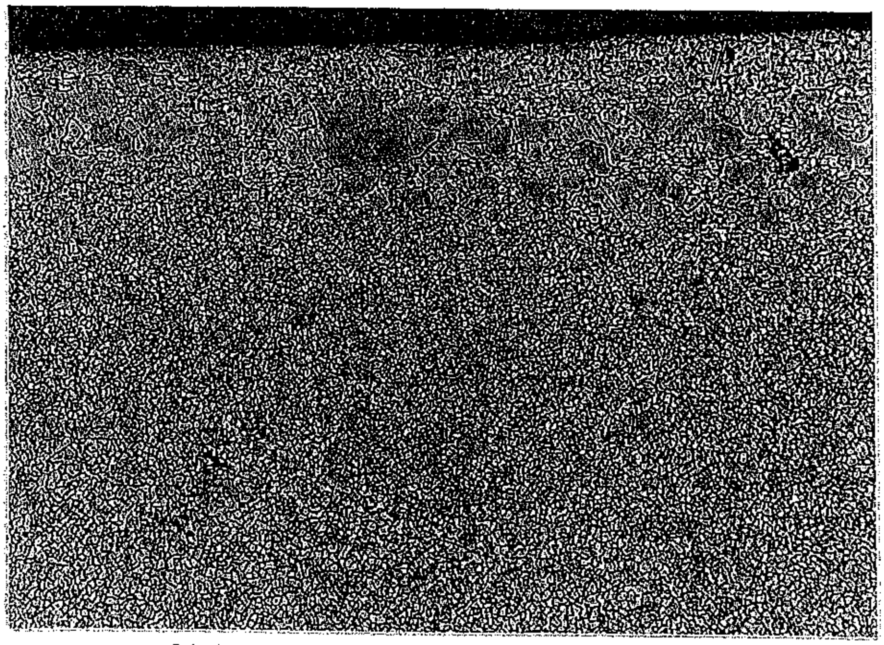
PIPE NUMBER:	99
SECTION:	WELD (ATTACK FROM BOTH INSIDE AND OUTSIDE)
MAGNIFICATION:	X57
YEAR:	1950



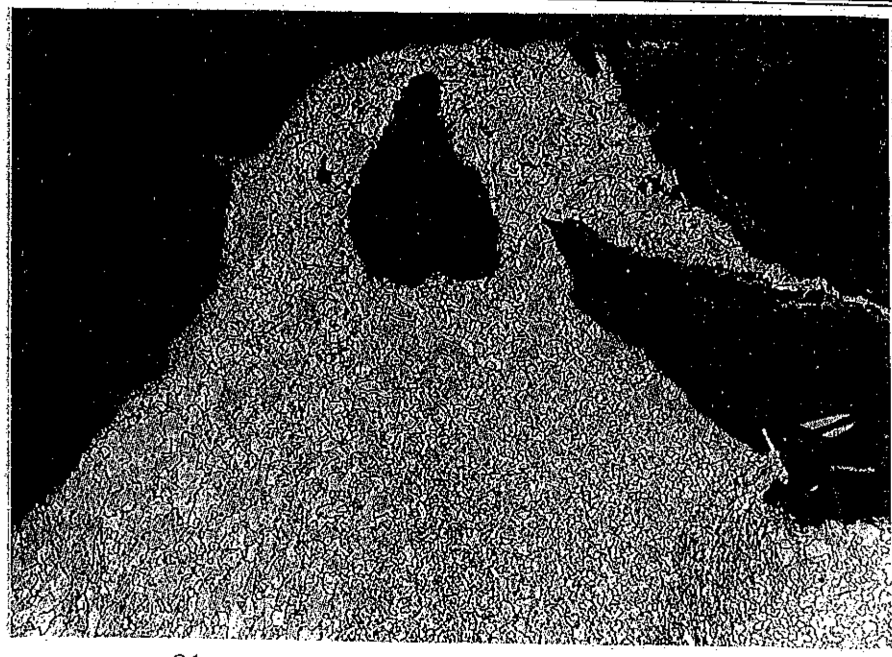
PIPE NUMBER: 68 (MILD STEEL)
SECTION: PARENT
MAGNIFICATION: X116
YEAR: **1960**



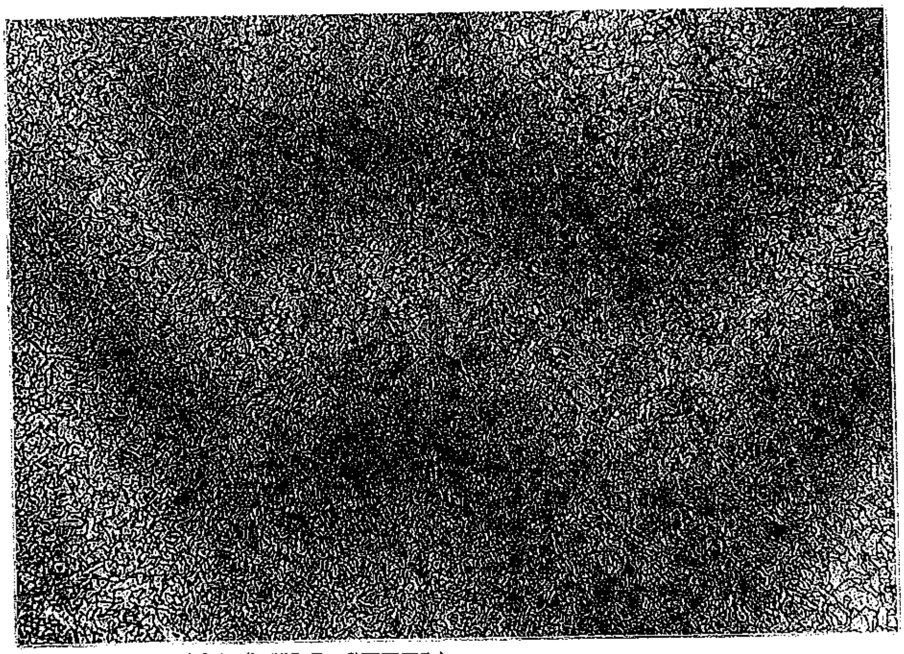
PIPE NUMBER: 68
SECTION: WELD ATTACK
MAGNIFICATION: X57
YEAR: 1960



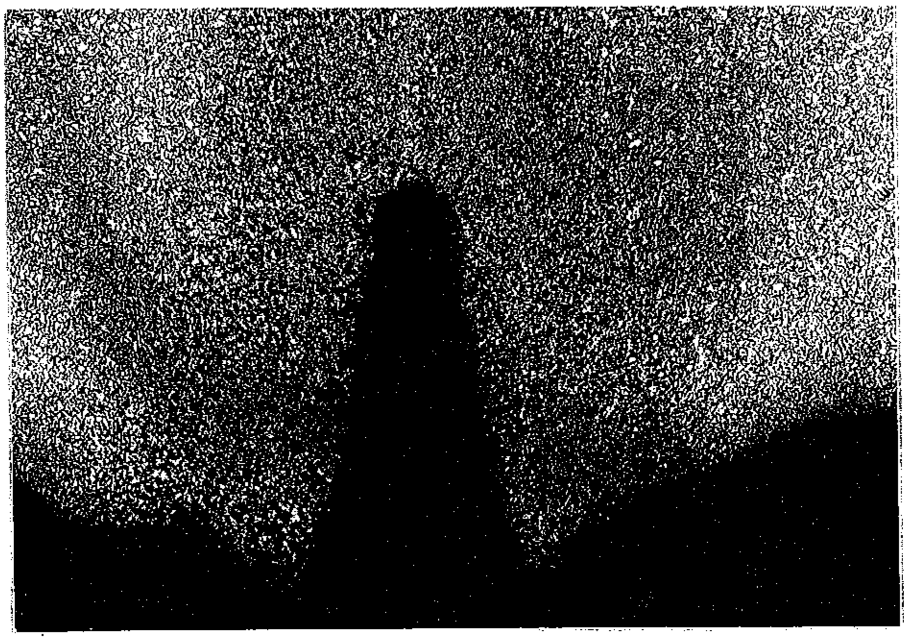
PIPE NUMBER:	91 (MILD STEEL)
SECTION:	PARENT MICROGRAPH
MAGNIFICATION:	X116
YEAR:	1970



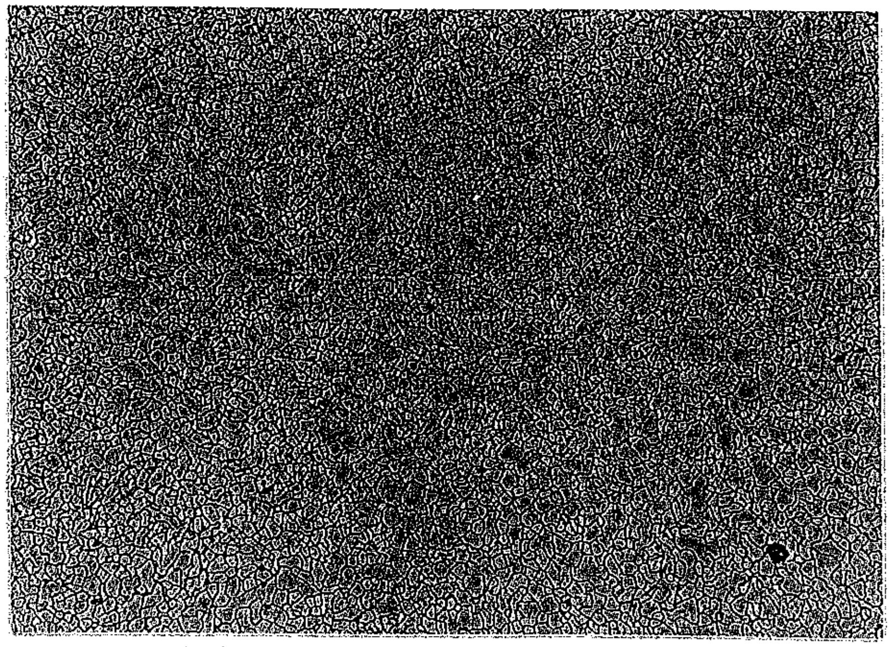
PIPE NUMBER:	91
SECTION:	WELD (POROSITY) ATTACK MICROGRAPH
MAGNIFICATION:	X57
YEAR:	1970



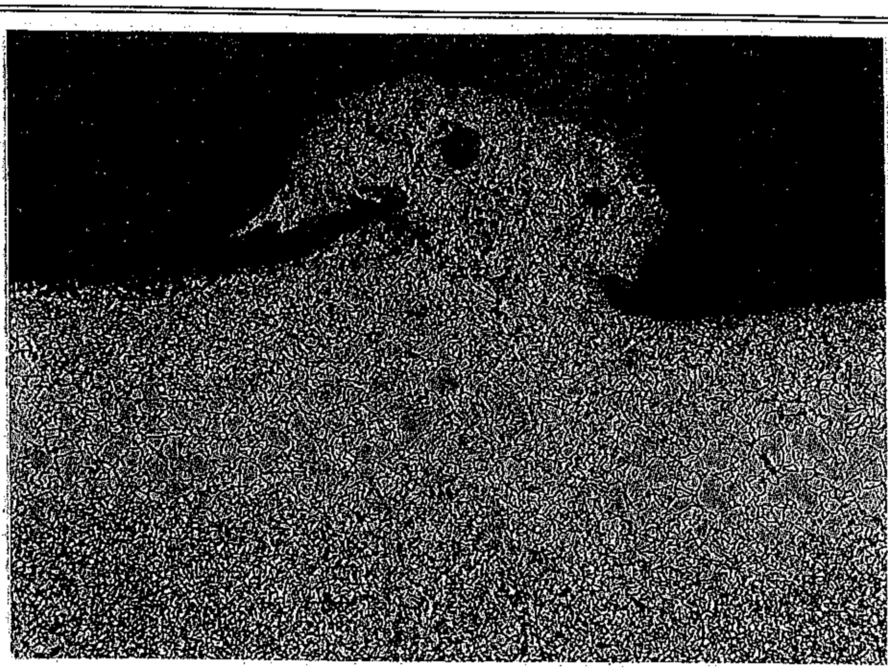
PIPE NUMBER: 101 (MILD STEEL)
SECTION: PARENT
MAGNIFICATION: X116
YEAR: 1970



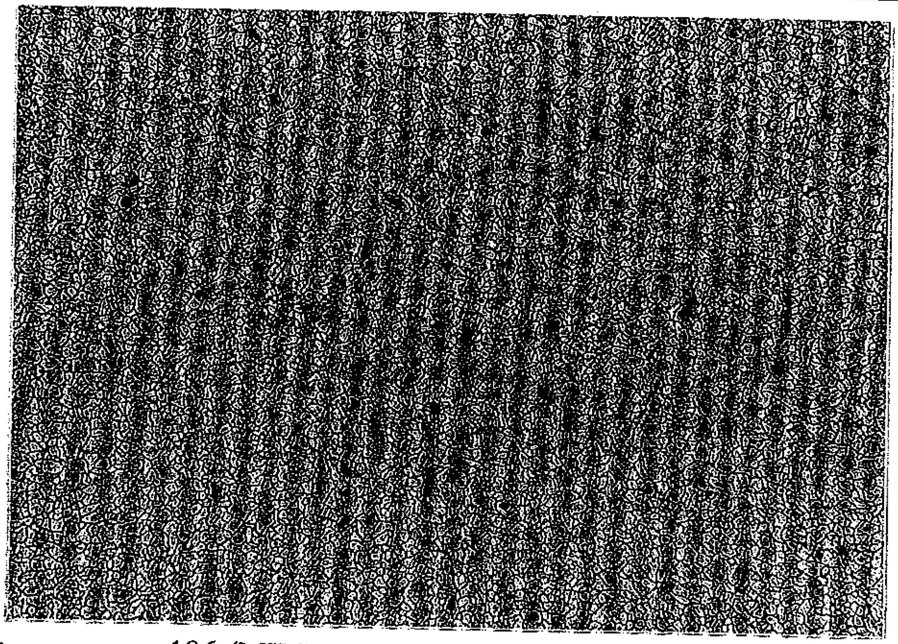
PIPE NUMBER: 101
SECTION: WELD (ATTACK) INSIDE
MAGNIFICATION: X57
YEAR: 1970



PIPE NUMBER: 77 (GALVANISED)
SECTION: PARENT MICROGRAPH
MAGNIFICATION: X116
YEAR: 1980



PIPE NUMBER: 77
SECTION: WELD (POROSITY AND FILLER METAL ATTACK)
MAGNIFICATION: X57
YEAR: 1980



PIPE NUMBER: 106 (MILD STEEL)
SECTION: PARENT MICROGRAPH
MAGNIFICATION: X116
YEAR: 1990

PIPE NUMBER: 106
SECTION: WELD (ATTACK) MICROGRAPH
MAGNIFICATION: X57
YEAR: 1990

APPENDIX 2

LITERATURE REVIEW

LITERATURE REVIEW

CORROSION OF POTABLE WATER DISTRIBUTION SYSTEMS

CONTENTS

1. INTRODUCTION

A corrosive environment is defined as one in which a pipe is weakened by corrosion to such an extent that it fails during normal operation at a time period less than the specified economic life of the pipe. In the case of steel, this amounts to through penetration of the pipe wall by corrosion. (Ferguson & Nicholas, 1992).

Corrosion has caused extensive damage in water mains by thinning the wall over large areas or by localized pitting. External corrosion can be accelerated by galvanic effects, stray current and microbiological activities in the soil. Internal (waterside) corrosion also has an unfavourable influence on the structural integrity of water mains. As corrosion reduces the pipe wall thickness, the water main will be prone to fracture from internal and external loads (Zamanzadeh et al, 1990).

Corrosion effects can lead to a number of problems in drinking water distribution networks and house installations, not only by damages to the transport system itself, but also by deteriorating drinking water quality (Wagner, 1990). Great increases in operational costs can result due to pitting corrosion which leads to pipe failures, increase in water leakages and pressure loss due to voluminous tubercles. Deterioration of the drinking water quality due to corrosion products from internal corrosion causes both negative health aspects and aesthetic problems. (Moen, 1990). By improving material qualities and corrosion protection technologies in combination with the knowledge and recommendation of the correct material for the correct location, a great number of these problems can be reduced or even avoided (Wagner, 1990).

2. METALLIC CORROSION REACTIONS

For corrosion to occur, an electrochemical cell is required. This cell consists of an anode (negatively charged anions move towards it), a cathode (positively charged cations more towards it), a connection between the anode and cathode for electron transport, and an electrolyte that will conduct ions (Le Chevalier et al, 1993).

Corrosion of buried metallic pipe is a result of electric current flowing from the metal into the soil. Where the current leaves the metal, it takes small particles of metal with it, causing corrosion. The current that flows is a direct current and may be produced by galvanic action or by electrolysis - stray current. Galvanic corrosion is generally the primary type of corrosion encountered (Yampolsky, 1983).

2.1 Galvanic Corrosion

In a galvanic corrosion cell direct electric current is generated within the cell itself due to the difference in electrical potential between the anode and cathode. A driving force is created between the two when in contact with a common electrolyte, such as soil or water, and when they are electrically connected. Current leaves the anode, travels through the electrolyte to the cathode and returns to the anode through the metallic connection. At locations where the current leaves, corrosion occurs. The cathode which receives the current is protected.

Galvanic corrosion can occur when two dissimilar metals are connected (eg. steel and copper) or it can occur on a single metal due to variations in the metal itself or due to variations in the electrolyte (eg. dissimilar soils). On a pipeline anodic and cathodic areas may be microscopic and in close proximity causing general uniform corrosion, or the electrodes may be large and somewhat remote from one another, causing pitting. Impurities in the metal, sediment accumulations and attached bacterial biofilms can all lead to the development of galvanic cells. The rate of corrosion is determined by the relative size of the anode and cathode and by the resistance of the electrolyte. (Smith, 1989, Yampolsky, 1983, Le Chevalier, 1993).

2.2 Electrolytic Corrosion (Stray Current Corrosion)

In an electrolytic corrosion cell direct current is generated outside the cell. Corrosion occurs at the point or points of current discharge from the anode. The anode and cathode may be of the same material. Possible outside sources of direct current include stray currents from cathodic protection systems, electric railways, manufacturing plants and mines. (Smith, 1989).

2.3 Polarization

Polarization is a reduction in the corrosion rate (and current flow) resulting from reducing voltage difference, or increasing resistance, between the anode and cathode. Polarization tends to retard the corrosion activity and rate (Smith 1989).

3. CORROSION CELLS APPLICABLE TO WATER DISTRIBUTION MAINS

3.1 Dissimilar Soils

A pipeline passing through dissimilar soils can create galvanic corrosion cells. The difference in potential between the metal and soil A may vary from that of soil B because of differences in composition of the two soils and their ability to serve as electrolytes. Some causes of dissimilar soil conditions include low resistivity vs higher resistivity soil, wet soil vs drier soil, clay vs silt, dense soil vs loose soil, alkaline soil vs neutral or acid soil. The anodic areas occur in the first soil type of each pair mentioned. (Smith, 1989). These cells, also called concentration cells and often associated with differential aeration cells, can also be set up by local variations in the chemical composition, in the concentrations, pH, redox potential etc of the soil in contact with the pipeline. They can result from the mixing of backfill material with elements such as mortar, plaster, cinders, slag, coal residues and organic materials. (Marchal & Poirier, 1992). A condition where the soil above the pipe is lose and well-aerated, while the bottom of the pipe is resting on undisturbed moist soil can lead to corrosion at the bottom. This is a common condition since the majority of corrosion leaks occur on the bottom of a pipeline. (Yampolsky, 1983). In some cases the installation of an insulated fitting in the pipeline at the junction of the two different soils can reduce corrosion by breaking up the corrosion circuit.

3.2 Differential Aeration

This is one type of a dissimilar soil cell. Differences in oxygen supply to different points of the metal/soil interface create differential aeration cells (Marchal & Poirier, 1992). The well-aerated metal regions become cathodic with respect to areas where oxygen has little or no access and which become anodic. The degree of oxygen penetration in a soil depends on its microstructure, level of water saturation, drainage conditions and the depth to which the pipe is to be laid.

3.3 Pitting Attack

Point localization of attack resulting in pitting corrosion, can give rise to enormous ratios of cathode area to anode area and thus to extremely high rates of dissolution. This most often occurs as a result of soil conditions or at sites of paint or coating flaws, mill scale disruption, or points of impact or abrasion, exposing bright metal (Rothwell, 1979; Smith, 1989). The exposed metal becomes anodic with respect to the rest of the pipeline and will therefore corrode in these sites. Threaded areas on a pipe also become anodic due to the exposure of bright metal (Yampolsky, 1983).

Of all modes of corrosion in a distribution system, pitting is probably the most damaging. Depending on the strength of the corrosion cell, metal involved and capability of the environment to serve as an electrolyte, pitting usually progresses to penetration of the metal faster than other forms of corrosion (Smith, 1989). An additional complication in pitting processes is the fact that chemical changes in the environment within the pit frequently militate against self-healing, so that once pitting has started, it is unlikely to stop until penetration has occurred (Rothwell, 1979).

3.4 Crevice Corrosion

This is a severe form of localized attack often caused by the low rate of oxygen transfer into crevices. These may thus become sites for rapid dissolution while the balancing cathodic reaction occurs over a much larger area to which oxygen has ready access (Rothwell, 1979). This type of corrosion occurs most frequently at overlaps of metal, crevices under bolt and rivet heads, in bolt holes, under surface deposits and even at gasket surfaces. Prevention of this type of corrosion involves elimination of crevices where possible. Methods may include use of butt welding rather than bolting or rivetting, closing crevices by welding, use of non-absorbent gaskets and designing to avoid sharp bends that can retain stagnant material (Smith, 1989).

3.5 Galvanic/Bimetallic Corrosion

A galvanic cell can be established whenever different metals are used in pipeline construction, provided there is an electrical contact between them and they are in contact with a common electrolyte (soil or water). Any two dissimilar metals may produce an electrical potential between them (Dittmer, 1975). The cathodic reaction generally tends to become localized on the more noble of the couple, the anodic on the more base. The severity of attack depends on a number of factors including the extent of dissimilarity of the metals in the couple, the relative areas of the two metals and the conductivity of the electrolyte (Rothwell, 1979). In the case of distribution systems, the most common example of galvanic corrosion is the coupling of copper household pipes to unprotected iron or steel mains. Optimum conditions for corrosion are the presence of a dry top soil and saturated salty soil at pipe depth between a long length of copper and steel. This form of corrosion is easily controlled by electrically insulating or separating the copper pipe from the steel mains. This has the effect of either eliminating copper - steel contact or minimising the surface area of copper in contact with the steel (Ferguson and Nicholas, 1992).

3.6 Differential Exposed Surface Area

In a corrosion cell with a small anode and large cathode, corrosion at the anode will progress rapidly. This is partly caused by the slow polarization of the large cathodic area. Examples of this situation in distribution systems include: rivets used to fasten structural members or plates, bolts and nuts in pipe joints, valves, sleeves and other equipment, small pipes electrically connected to large pipes. If the metals can be arranged such that the anode is large and the cathode small, polarization occurs rapidly and diminishes corrosion. If the materials of mechanical joint bolts in contact with pipe of a much larger surface area, are of about the same potential, the bolts will be anodic to the pipe if the environment acts as a suitable electrolyte. In addition, the bolts are under stress. The bolts (small anodes) sacrifice readily to the pipe. To overcome this, bolts and nuts should be of greater nobility so that the cell is reversed by making the bolts cathodic (Smith, 1989).

3.7 Direct Connection of New Pipe and Old Pipe

This situation frequently arises in the water supply industry when, due usually to corrosion damage, a section of old steel pipeline is replaced with new steel. The new pipe becomes anodic with respect to the old pipe and will corrode provided there is electrical connection between the pipes and the electrolyte is sufficiently conductive to support the cell. The situation develops because corrosion products collected on the older pipe, cause it to be cathodic with respect to the clean metal surface of the new pipe. This problem can be overcome by insulating the new pipe section from the old pipe section and isolating the pipes from the electrolyte (Dittmer, 1975; Smith, 1989).

3.8 Microbiological Corrosion

Microorganisms can be classified into two important groups, aerobic and anaerobic microbes. Both groups can affect the corrosion of water distribution mains in the following ways:

- by influencing cathodic and anodic reactions.
- by influencing protective surface films.
- by creating corrosive conditions.
- by producing deposits (Dittmer, 1975).

Steel water mains are susceptible to microbiologically influenced corrosion (MIC) as a result of their exposure to soil and water (Zamanzadeh et al, 1990).

The electrochemical corrosion mechanisms can be harnessed and accelerated by microorganisms by four modes of action (Gregoire, 1992).

a. by the formation of adherent deposits on the metal. Bacterial slime deposits on pipe walls set up a differential aeration cell leading to pitting attack beneath the deposit (anode);

b. release of aggressive chemical reagents. In the course of their metabolism, microorganisms release organic acids into the environment. This leads to the local lowering of the pH and inevitable attack of unprotected metals. Bacteria of the genus Thiobacillus can produce corrosive sulphuric acid;

c. anodic activation by oxidation of metallic ions. Many microorganisms metabolize ferrous iron and therefore assist its anodic dissolution through contact with an aqueous medium. Furthermore certain microorganisms transform the ferrous iron into the hydrated ferric hydroxide found in mucilaginous secretions. Genera commonly associated with this form of corrosion include Gallionella, Siderocapsa Sphaeratilus and Leptothrix. Their secretions are so abundant that they can cause pipe blockages;

d. stimulation of cathodic reactions. This type of corrosion mainly involves anaerobic sulphate reducing bacteria (SRB). These bacteria can unsymmetrically depolarize the cathode by releasing hydrogen present there. The absence of inhibition of the anodic reaction has also been confirmed. In all cases, the activity has been measured in the presence of sulphate. SRB may also utilize hydrogen from organic matter, with the release of corrosive hydrogen sulphide. A purely electrochemical mechanism which takes place simultaneously is the formation of iron sulphide. This is cathodic with respect to the steel pipe, thus forming a cell which will remain active even after microbial activity has ceased. This type of corrosion particularly affects buried pipes but can coexist with the development of other microbial colonies inside water carrying pipework.

The necessary environment for SRB corrosion requires a supply of sulphate (available in most natural waters and soils), an organic source of carbon and anaerobic conditions. This type of corrosion may thus develop virtually anywhere where free access of oxygen is occluded. The attack may be found under slimes and debris and the environment within tubercles (Rothwell, 1979).

The corrosion behaviour of ductile and grey iron pipes in environments containing SRB was studied (King et al, 1985). It was found that both metals suffered extensive was studied (King et al, 1985). It was found that both metals suffered extensive corrosion by SRB with corrosion rates higher in soils (50-60 mpy) than in aqueous media (20-22 mpy). The oxide films and protective bitumen coating both delayed the onset of corrosion, which occurred when these deteriorated or were damaged. The process of SRB corrosion appeared initially to be intermittent pitting attack resulting from the formation and breakdown of sulphide films on the metal, followed by the establishment of more stable active sites on the metal and a continued localized attack. The adherent sulphide films are cathodic to the anodic substrate metal.

The serious and costly damage to underground structures attributable to SRB is now well established and widely accepted (Dittmer, 1975). Field observations and tests in Wisconsin (Patenaude, 1985) indicated that nearly one half of the corrosion of steel culvert pipe in that area was related to the activity of SRB. In the Johannesburg Municipality, failure of steel water mains during the drought period in the early 1980's was strongly suspected of being due to internal corrosion by SRB (Osborne).

3.9 Stray Current Corrosion

Stray direct current can have a damaging effect on buried steel pipelines. It occurs when direct current from an outside source enters the pipeline, then leaves to complete its intended circuit. This is a typical electrolytic cell with the cathode as that portion of the pipeline receiving direct current and the anode the location from which the current leaves. The source of the direct current can be from electric railways, a direct current generator, manufacturing plant, mines or other metallic structures protected by impressed direct current. In these situations, the ground is often used as a return path for the current. However, the current often strays to the pipeline if it is in the vicinity because of its lower resistance to current flow (Smith, 1989; Yampolsky, 1983).

Factors affecting the rate of corrosion include:

- potential difference of external supply.
- electrical resistance of soil between pipe and supply (significantly influenced by moisture content).

- electrical resistance of pipe (as influenced by joints).
- current density.

Of primary importance is the total charge transfer, not the maximum potential difference or maximum current, that occurs between the anode and cathode of the structure (Ferguson and Nicholas, 1992). Long, electrically continuous pipelines are vulnerable to stray current problems because the current in a large area is accumulated to higher levels and discharged at a point or points of lower resistance. Pipelines consisting of short segments, each separated from the next by a rubber - gasketed joint, actually discourage the accumulation of stray current (Smith, 1989).

3.10 Erosion Corrosion

This type of corrosion may be encountered in pipes, valves, fittings and pumps. Most metals have protected surfaces, either from the manufacturing process or from corrosion products such as oxide scale. Impingement corrosion is most often observed in tees and elbows or at other changes in high flow direction. The eroding action of the water wears away any protective film and this becomes the site of accelerated corrosion. Excessively high water flow velocities can increase corrosion action on pipe interiors by eroding protective films. Such velocities assure a constant exposure of eroded areas to fresh electrolyte water (Smith, 1989).

4. EFFECT OF THE ENVIRONMENT ON WATER DISTRIBUTION MAINS CORROSION

4.1 Water Composition

The main determinative factors in assessing the corrosivity of potable water to distribution mains are pH, hardness and/or alkalinity, aggressive anions, dissolved gases (O_2 and CO_2) and organic matter (Rothwell, 1979). If iron or steel pipe which is uncoated internally is exposed to aggressive water, corrosion may result. The effects of corrosion are:

- tuberculation and reduction in flow capacity;
- red water;
- weakening of the pipe structure.

Corrosive water provides an adequate electrolyte for the development of corrosion cells, with the anodes located at flaws in the internal surface of the pipe. The eroding action of flowing water, together with dissolved oxygen, removes the hydrogen which usually polarizes the surface so that corrosion progresses. Corrosion products tend to build up around the corrosion cell area, creating a tubercle. At times a membrane of iron hydroxide or iron oxide forms over the tubercle and activity stops. This membrane can be broken by erosion or porosity, and the cell reactivates and builds another layer. While the tubercle is being built, iron is being removed from the interior of the pipe wall. The risk of perforation is further increased if iron bacteria are present in the water in the system. These bacteria can proliferate in the tubercles of ferric hydroxide where they oxidize enzymatically the divalent iron that appears next to the metal. This oxidation of bacterial origin adds to the chemical oxidation that takes place at the periphery of the tubercles in contact with the system water. The rate of the anodic reaction and consequently the corrosion rate are thus increased. The dissolved oxygen may be entirely consumed inside the ferric hydroxide tubercles. Anaerobic bacteria are then likely to appear and proliferate in these tubercles. Some of them may be SRB. The corrosion is then accelerated owing to the formation of FeS (Legrand et al, 1992). Tubercle formation is less uniform than scale formation and may be quite localized, frequently at threaded joints (TPC Publication, 1980).

4.2 **Soil Composition**

Corrosiveness of soil varies over a wide range because of the variety of compositions. Factors affecting corrosiveness of soils are moisture, pH, permeability of water and oxygen, dissolved salts and bacterial content. Most of the factors affect the resistivity of the soil. It generally appears that soils of low resistivity containing significant concentrations of chloride and sulphate ions are usually the most corrosive (Dittmer, 1975; Compton, 1979). Underground corrosion of unprotected ferrous metal is often most severe in wet, clayey soils of about neutral pH, and takes the form of pitting attack.

When removed from the soil, the pipe is covered by loose, black corrosion product containing H_2S and pitting beneath. Such evidence indicates the presence of SRB which can usually be isolated from the corrosion product and surrounding soil.

Several attempts have been made to determine the physical and chemical factors that influence corrosion in soils (Dittmer, 1975). Characteristics which have been proposed include: anaerobic bacteria, differential aeration, chemical nature, formation of concentration cells, soil resistivity and redox potential.

5. STUDIES OF DISTRIBUTION MAINS CORROSION

A number of studies have been undertaken to determine the failure mechanisms of distribution mains. Zamanzadeh et al (1990) reported that the majority of failures were caused by joint and tap leaks, fracture and internal and external corrosion. The fracture, however, was often induced by corrosion damage.

A survey in 1982 of the distribution network in Barcelona (Sauvalle and Coll, 1982) to determine the causes of corrosion of cast iron piping, concluded that there was corrosive attack from the outside in. No clear link was established, however, between various degrees of aggressivity of the soil and the condition of the piping.

Most reports seem to suggest that corrosion occurs mainly externally. Ferguson and Nicholas (1992) obtained information of corrosion mechanisms from a substantial data base of exhumed pipe. They proposed that the major intrinsic soil corrosion processes occur due to either the activity of anaerobic bacteria or localised differential aeration cells. The corrosion behaviour of ductile and grey iron pipes was studied in soil and water environments containing SRB (King et al, 1985). It was found that the soil environment was the most corrosive to both metal types.

Microbially induced corrosion is a common mechanism of pipeline failure. In a study carried out on steel culvert pipes in Wisconsin, Patenaude (1985) reported that field observations and tests indicated that nearly one half of the corrosion damage was due to the activity of SRB. In more than 80% of the cases in which corrosion damage was discovered by close-interval potential surveys of pipelines. Prinz (1986) reported that anaerobic soil and the presence of SRB were the cause of the corrosion. Kasahara and Kajiyama (1985) found from field experience that most corrosive attacks on buried pipes were more or less localized. High SRB activity at anodic areas was proposed to play an important role in the corrosion process. O'Conner and Banerji (1984) observed that in the presence of microorganisms, more localized pitting of cast iron occurred. Corrosion influenced by other microorganisms viz. iron - and sulphur-oxidizing bacteria, was reported from field and laboratory studies of ductile iron. It was proposed that sulphuric acid, produced by these bacteria, was responsible for the accelerated corrosion (Kasahara and Kajiyama, 1990).

An investigation of water mains corrosion in the Johannesburg municipality was carried out in the early 1980's due to the large number of bursts which were occurring. Although the water quality was suspected of being aggressive due to increased chloride and sulphate levels arising from recycling and reuse, this was not the major factor. Some pipes were externally corroded due to aggressive soils, but the failures were mainly internal. Strong evidence suggested that the pipes were corroding internally due to SRB activity. These bacteria were found beneath tubercles on the pipe walls and all pipe samples examined contained sulphide which is indicative of SRB.

Hedberg et al (1990) summarised conclusions from a workshop held to discuss corrosion and corrosion control in drinking water systems and in which a number of countries participated. Steel piping suffered mainly from pitting corrosion which led to the formation of tubercles (which reduced water flow) and dissolved iron and suspended particles. Cast iron underwent mainly uniform-type corrosion with the formation of tubercles, while ductile iron suffered from graphitization and pitting corrosion. Galvanised steel underwent both general corrosion and pitting. It seemed that most attention was focused on the adverse effects of corrosion on water quality due to internal attack (Oliphant; van den Hoven and van Eekeren; Vik and Weideborg; Ljunggren, 1990). In Germany it was found that corrosion problems occurred mainly in old networks without internal corrosion protection and in systems with very low alkalinity. Corrosion was exacerbated by stagnant conditions especially in steel, ductile and cast iron pipes (Wagner, 1990). In Norway, pitting corrosion of cast and ductile iron pipes led to pipe failures and increased water and pressure loss (Vik and Weideborg, 1990). External corrosion causing failures and leaks seemed to be a bigger problem in Sweden (Ljunggren, 1990). In Finland the most severe corrosion problems occured in steel, ductile and cast iron due to the fact that the bitumen layer applied for protection was insufficient (Pääkkönen, 1990).

6. CORROSION PREVENTION AND CONTROL IN DISTRIBUTION SYSTEMS

The various types of corrosion cells which can occur in water distribution systems were outlined in Section 3. Theoretical prevention and control procedures for these cells are presented in the table below. Specific procedures will be discussed in more detail thereafter.

TABLE 1 **Corrosion cells and their prevention or control (Smith, 1989).**

CELL TYPE	ITEMS MOST FREQUENTLY AFFECTED	PREVENTION OR CONTROL, GENERAL (SPECIFIC METHODS APPEAR IN CHAPTER 4)
Bi-Metallic	Pipe, valves, repair sleeves, meters, bolted connections	Insulation between metals; material selection
Dissimilar Soils	Underground pipe	Create uniformity of the electrolyte
Pitting Corrosion	Internal and external surfaces of pipe, tank wall surfaces, valve bodies, well casings, structural steel members and plates	Material selection, improvement of environment or isolation from electrolyte, creation of cathodic conditions on affected metal
Differential Aeration	Underground pipe	Provision of uniform environment
Bacteriological Corrosion	Underground metals	Isolation of metal from soil altering the environment to exclude anaerobic conditions
Differential Mass and Surface Area	Rivets, bolts (and other fasteners), brackets and hangers	Insulate metals apart, create large anodes and small cathodes
Crevice Corrosion	Bolt holes, gasket faces, plate overlaps	Eliminate crevices that can harbor entrapped solids or water
Differential pH	Pipe passing through concrete to soil, pipe exposed to non-uniform pH soil due to contamination	Insulate at junction of high and low pH materials; isolate pipe from environment
New Pipe-Old Pipe	Transmission and distribution pipelines	Insulate new pipe section from old pipe sections; isolate from electrolyte; create cathodic conditions on new pipe
Soil Contamination	Pipe, service lines, valves	Isolate underground metals from soil; select backfill
Erosion Corrosion	Pipe and fitting interiors, pump impellers	Material selection; linings; flow velocity reductions

6.1 Isolation from Corrosive Environments

Isolation may involve relocation of the threatened pipeline from a corrosive to a non-corrosive environment or provision of barriers such as coatings and wrappings.

Relocation is usually feasible when a planned underground pipeline will traverse an area proximate to an impressed current cathodic protection anode bed. It is more economical and reliable than shielding operations. Rerouting should avoid areas of contaminated soil, such as waste dumps, land fills, coal storage areas and water logged areas (Smith, 1989).

Isolation from the environment most often takes the form of coating or wrapping. The coating required will depend on the type of pipework and on the aggressivity of the medium (soil or water). Capoulade et al (1989) have made a distinction between active and passive coatings. In the case of passive protection, the coating has the effect of shielding the substrate from the surrounding electrolyte. It acts as an inert barrier between the external medium and the substrate. To do this the coating must meet the following requirements:

- have a high, insulating electrical resistance to block electrochemical processes;
- be able to shield the pipe from stray currents;
- be able to maintain the negative potential necessary for cathodic protection when this is applied;
- be sufficiently impermeable to water and water-vapour;
- have great chemical inertia;
- be unaffected by bacteria;
- possess good mechanical properties;
- be adequately adherent to the substrate metal;
- have good shock resistance in order to limit damage during transport, laying and backfilling;
- have suitable hardness to hinder penetration by backfill material, plant roots or in the case of internal lining, to avoid damage by erosion.

Examples of passive coatings include: thermoplastics, Polyolefins, Polyvinyl chloride, Polyamides, Epoxy resins and derivatives, Polyester resins and polyurethanes and derivatives.

In the case of active protection, the protective mechanism places the substrate in a non-corrodible domain either through the use of appropriate coatings (galvanic, cementation), or through a complementary protection system (cathodic protection). In the case of cementation, the reaction of the water with the cement mortar tends to create a protective carbonated layer at the surface of the latter. The pH of the water permeating the coating is made more alkaline and thus less corrosive. Doherty (1990) reported a decrease in failures in water mains with the use of internal cement lining of ductile iron pipes.

Active and passive protection are commonly used simultaneously:

- passive coating and cathodic protection for buried structures;
- passive coating applied on top of an underlying active coating.

6.2 Insulation

Two connected metals, one more noble than the other, exposed to a humid atmosphere, water or soil, should be electrically separated using gaskets or other non-conducting devices. The degree of corrosion will depend on the anode to cathode ratio (large anode, small cathode is more favourable) and on the resistivity of the soil. Insulation is accomplished by installing an insulating device and wrapping the line with dielectric material. If a new section of pipe replaces an older pipe section effective insulating couplings should be used to connect the two sections so that a corrosion cell cannot develop between them.

6.3 Environmental Control

Environmental control with regard to soil is limited to knowledge of soil characteristics and location of underground pipelines away from severely corrosive soil. The bedding backfill materials are also important. The former should be a granular material to ensure good drainage while the latter should be uniform in composition and non aggressive (e.g. a chalk-sand mix).

The effective treatment of water involves the addition of non-toxic chemicals. Addition of lime may aid the scaling properties, while inhibitors will control tuberculation and rust scale. Biocides may be added to control microorganisms (Smith, 1989).

6.4 Materials Selection

In materials selection, strength considerations must include not only sufficient capacity to handle predictable internal pressure, earth, traffic and impact loads, but also the unpredictable loads from expansive clays, differential temperatures and proximate construction. When considering possible strength loss due to corrosion or deterioration of pipe material, it must be assumed that any of the available materials can corrode under certain circumstances. Effective and economical corrosion prevention procedures must thus be followed (Smith, 1989).

Non-metallic materials, despite poor mechanical properties, such as asbestos cement, PVC and polyethylene frequently exhibit high resistance to corrosion. Plastics should not, however, contain plasticizers as these are biodegradable. Cost-wise no material can approach the tensile strength of mild steel and it is likely to remain the most used structural material for many decades (Dittmer, 1975).

6.5 Cathodic Protection

Cathodic protection is the positive use of galvanic or electrolytic corrosion to protect a metallic structure by creating cathodic conditions on its entire surface (Smith, 1989). Galvanic anode cathodic protection involves the use of sacrificial anodes. These are most often magnesium or zinc anodes (for protection of iron and steel pipes). The anodes are electrically connected to the pipe. Current flows from the anode through the soil to the pipeline (cathode) and returns to the anode via the connecting wire to complete the circuit. The current required to protect the pipeline depends of whether the surface is bare or coated, and if coated, the condition of the coating. The galvanic anode is gradually corroded in the process of generating current and the rate of corrosion is directly related to the level of current produced. The hazard of creating stray currents with this type of system is virtually non existent (Yampolsky, 1983; Smith, 1989).

Impressed current cathodic protection is more suitable than sacrificial anodes for protection of pipelines in high soil resistivities and long sections of lines in uncongested areas. This system involves an electrolytic corrosion cell, created by direct current from an outside source. This is normally a rectifier which converts alternating current to direct current. The latter is impressed into the electrolyte (soil) into an anode or anode bed. The cathodically protected structure accepts current from the electrolyte and the circuit is completed through a metallic connection back to the rectifier (Yampolsky 1983; Smith, 1989). The universally accepted measurement of the effectiveness of cathodic protection on an iron or steel pipeline is the pipe-to-soil potential. If this potential (with reference to a copper - copper sulphate electrode) is maintained at -850 mV at all times, full protection is provided (Smith, 1989). In the case of the presence of SRB, the pipe-to-soil potential should be -950 mV for effective protection. As the soil condition is generally unknown, it is recommended to set the potential to this value in all soils other than sand (Prinz, 1986).

7. REFERENCES

Bondonno, A. and Ringas, C. (1993). **Microbial Corrosion of common piping materials in the PWV area**. WRC Project No. K5/432/0/1.

Capoulade, A. et al (1992) ***Protective Coatings.*** In: Water and Gas Mains Corrosion, Degradation and Protection. Ed, C. Basalo, Ellis Horwood, New York, pg 229-298.

Compton, K.G. (1979). ***Corrosion of buried pipes and cables Techniques of study, Survey and Mitigation.*** In: Underground Corrosion. ASTM Special Technical Publication 741. Ed E. Escalonte pg 141-155.

Dittmer, C.K. (1975). ***Microbiological aspects of pipeline corrosion and protection***: PhD Faculty of Technology of the Victoria University of Manchester.

Doherty, B.J. (1990). ***Controlling ductile - iron water mains corrosion.*** Materials Protection January 1990 pg 22-28.

Ferguson, P.H. and Nicholas, D.M.F. (1992). ***External Corrosion of buried iron and steel water mains.*** Corrosion Australasia 17; 7-10.

Gregoire, G. et al (1992). ***Corrosion Theory***. In: Water and gas mains corrosion, degradation and protection. Ed, C. Basalo, Ellis Horwood, New York, pg 3-62.

Hedberg, T. et al (1990). ***The influence of water quality on different pipe materials and house installations - Conclusions from the Workshop***. In: Corrosion and corrosion control in drinking water systems. Workshop and seminar, Oslo, Norway, March 1990, pg 1-4.

Kasahara, K. and Kajiyama, F. (1985). ***Role of sulphate reducing bacteria in the localized corrosion of buried pipes.*** Proc. International Conference on Biologically Induced Corrosion, Maryland pg 171-183.

Kasahara, K. and Kajiyama, F. (1990). ***Electrochemical aspects of microbiologically influenced corrosion of buried pipes.*** In: Microbiologically Influenced Corrosion and Biodeterioration. Eds. N.J. Dowling, M.W. Mittelman and J.C. Danko. Papers from

International Conference on MIC, Oct. 1990, Knoxville, pp 2-33 - 2-39.

King, R.A. et al (1985). ***Corrosion behaviour of ductile and grey iron pipes in environments containing sulphate reducing bacteria.*** Proc. International Conference on Biologically Induced Corrosion, Maryland pg 83-91.

Le Chevalier, M.W. et al (1993). ***Examining the relationship between iron corrosion and disinfection of biofilm bacteria.*** Journal American Water Works Assoc. 85; 111-123.

Legrand, L., Leroy, P. and Poirier, G. (1992). ***Water in public distribution systems.*** In: Water and gas mains corrosion, degradation and protection. Ed C.

Basalo, Ellis Horwood, New York, pg 63-148.

Ljunggren, O. (1990). ***The user's problem and need for corrosion monitoring and control.*** In: Corrosion and corrosion control in drinking water systems. Workshop and seminar, Oslo, Norway, March 1990, pg 7-10.

Marchal, R. and Poirier, G. (1992). ***Corrosivity of soils to ferrous metals.*** In: Water and gas mains corrosion, degradation and protection. Ed C. Basalo, Ellis Horwood, New York. pg 151-181.

Moen, S.E. (1990). ***Corrosion problems and strategy in Norwegian Waterworks.*** In: Corrosion and corrosion control in drinking water systems. Workshop and seminar, Oslo, Norway, March 1990, pg 5-6.

O'Conner, J.T. and Banerji, S.K. (1984). ***Biologically mediated corrosion and water quality deterioration in distribution systems.*** Report No. EPA-600/2-84-056, University of Missouri, Columbia.

Oliphant, R. (1990). ***Corrosion control in drinking water systems in the UK.*** In: Corrosion and corrosion control in drinking water systems. Workshop and seminar, Oslo, Norway, March 1990, pg 33-36.

Osborne, D.W. ***Corrosion in potable water systems: The Johannesburg experience.*** Paper from the Johannesburg Municipality.

Pääkkönen, J. (1990). ***Corrosion research in Finland.*** In: Corrosion and corrosion control in drinking water systems. Workshop and seminar, Oslo, Norway, March 1990, pg 47-48.

Patenaude, R. (1985). ***Microbial corrosion of culvert pipe in Wisconsin.*** Proc. International Conference on Biologically Induced Corrosion, Maryland pg 92-95.

Prinz, G.P. (1986). ***Close-interval potential surveys of buried pipelines: method and experience.*** Proc. UK Corrosion '86, Vol 2, Birmingham, 1986, pg 67-77.

Rothwell, G.P. (1979). ***Corrosion mechanisms applicable to metallic pipes.*** Pipes and Pipelines International 24; 16-20.

Sauvalle, R. and Coll, J. ***Corrosion behaviour of buried metal piping.***

Smith, W.H. (1989). ***Corrosion Management in Water Supply Systems.*** Van Nostrand Reinhold, New York.

TPC Publication 7 (1980). ***Prevention and control of water - caused problems in building potable water systems.*** Publ. NACE, Houston, Texas.

van Hoven, T.J.J. and van Eekeren, M.W.M. (1990). ***Corrosion and Corrosion control in drinking water systems in the Netherlands.*** In: Corrosion and corrosion control in drinking water systems. Workshop and seminar, Oslo, Norway, March 1990, pg 43-46.

Vik, E.A. and Weideborg, M. (1990). ***Corrosion and corrosion monitoring in low alkalinity waters - Norwegian experience.*** In: Corrosion and corrosion control in drinking water systems. Workshop and seminar, Oslo, Norway, March 1990, pg 55-62.

Wagner, I. (1990). ***Corrosion and corrosion control in drinking water systems in Germany.*** In: Corrosion and corrosion control in drinking water systems. Workshop and seminar, Oslo, Norway, March 1990, pg 37-41.

Yampolsky, M.E. (1983). ***Corrosion of piping.*** Plumbing Engineer, July/August 1983, pg 24-33.

Zamanzadeh, M. et al (1990). ***Analysis of failures in water mains.*** Materials Protection, 29; 50-53.

APPENDIX 3

RAM DATA SHEETS

PIPE NO	MAT	DIAM (mm)	TUB	SRB INT	SRB EXT	HOLE INT	HOLE EXT	PITS INT	PITS EXT	SURFACE INT	SURFACE EXT	P-S (mV)	SOIL RES	TYPE
1	MS	110	✓			✓	✓	few small shallow	large shallow		E/S → pits from outside in			O
2	MS	165	✓					few shallow		bit of shallow pitting	corr. through at weld surface good			O W
3	MS	150	✓					large, deepish		Elongated hole	good.			I ?SRB
4	MS	165	✓				✓	few shallow	large shallow					O.
5	MS	90				✓	✓	large deepish	irregular deep					B
6	MS	100	✓	+	soil +				large shallow & some deep	good	pitting			O SRB
7	CML	storm H_2O 150									badly thinned pressure burst			O t
8	MS	50								good.	Some thinning			O t
9	MS	150	✓					shallow		shallow pitting & some thinning	Irregular & melt on outside outer surf good			?SC
10	MS	150	✓				✓	large shallow & some deep	mainly shallow some deep	large hole from inside	mainly shallow few deep, small pits & penetration			I SRB
11	MS		none							good	deep pitting & melted holes from inside out			?SC
12	G	25	✓	+	−				badly	good	thinned & pitted weld corr			O W
13	MS	25	few	−	soil + +		✓			generally good	general thinning & pitting			O SRB
14	MS	75	✓	+	−			shallow		gen corr & shallow pits	mainly general corr			B t
15	MS	75	few	+	−	✓		few shallow	shallow extensive	general type corr	extensive pitting & thinning & penetration			O t

SC – Stray Current
t – thinning
W – welding
O – outside/external
I – internal

PIPE NO	MAT	DIAM (mm)	TUB	SRB INT	SRB EXT	HOLE INT	HOLE EXT	PITS INT	PITS EXT	SURFACE INT	SURFACE EXT	P-S (mV)	SOIL RES	TYPE
16	MS	15	scale	+	+		✓		severe	gen corr in patches	badly corroded + pitted			O SRB
17	MS					✓	✓	shallow ext	shallow ext.	pitting + thinning	pitting + thinning			B t
18	MS	90	few					shallow			gen corr ō one large irregular hole + smaller holes			I t
19	MS		✓	+					extensive shallow	good	general corr + ext. shallow pitting			O
20	MS			+			✓	few shallow	badly	fairly good ō some shallow pits	few small holes + bad pitting			O
21	MS	90	✓	+			✓	few shallow	extensive shallow some deep		gen corr + pitting crack along weld			O W
22	G	20			+		✓		badly	good	badly pitted ō penetration / weld corr			O W SRB
23	G	15	scale	+	−		✓		bad	good	extensive pitting + weld corr			O W
24	MS	90	✓	+	soil + +	✓		shallow	shallow	shallow pitting not too extensive	general corr ō some shallow pitting			B SRB
25	MS	90	✓	−	−					good; pitting on weld - failed	good ? remains of bitumen			I W
26	MS	150	✓	−	soil +			small shallow	small shallow	generally good	generally good.			good
27	MS	90	✓	−	soil +			few small shallow		generally good	generally good some gen. cor			good
28	MS	90	✓	+	soil +	✓			large shallow	pitting + thinning				I SRB
29	G	25	scale	+	soil +		✓		bad	good.				O SRB
30	MS		✓	+	+	✓			small shallow		generally good			B SRB

PIPE NO	MAT	DIAM (mm)	TUB	SRB INT	SRB EXT	HOLE INT	HOLE EXT	PITS INT	PITS EXT	SURFACE INT	SURFACE EXT	P-S (mV)	SOIL RES	TYPE
31	MS	90	✓ heavy	—	—	✓		quite bad			generally good ō gen corr			I t SRB
32	MS	150	✓	+	soil +	✓		large shallow			severely thinned			B t SRB
33	MS	150	✓	+		✓	mainly ✓		deep					O SRB
34	CML	90			—						burst where other section joined			O
35	MS		✓ heavy			✓		not many		thinning	millscale thinning			I t
36	MS		✓	+				bad	bad	badly thinned + pitted.	badly thinned + pitted			B t
37	MS	90	✓	+		✓		badly	shallow	badly thinned + pitted	good			I t SRB
38	G	25	✓				✓		pitted		pitting ō penetration			O
39	MS	100	✓	—						badly thinned	badly thinned			B t
40	G	25	scale	—			✓		badly	good	badly pitted			O ?SRB
41	MS		✓		—	✓		deepish		deepish ō penetration	good.			I
42	MS		✓	—	+			deep pits	few shallow	corr on thread.				I
43	MS	225	✓	+	+		✓	. . .	bit	good — some mill scale	only bit of pitting			O SRB
44	MS	150		—	—	small	✓	shallow saucer			quite good melted area around big hole			SC
45	MS		–	–				none	some pits + small holes	still good.	failure along welded joint			O W

PIPE NO	MAT	DIAM (mm)	TUB	SRB INT	SRB EXT	HOLE INT	HOLE EXT	PITS INT	PITS EXT	SURFACE INT	SURFACE EXT	P-S (mV)	SOIL RES Ω.cm	TYPE
46	MS		✓	–	–			few shallow			badly corr on thread by pitting			O
47	MS			–										
48	G		scale	dry H_2O –			✓		bad	good	bad pitting c̄ weld corr.			O W ?SRB
49	MS	150	✓	–	soil + +			few shallow	bad	quite good	bad pitting c̄ penetration	–435		O SRB
50	MS	150	✓	–	+		✓		quite deep	good ? mill scale/bitumen		–541		O SRB
51	MS	100	✓	+	soil + +	✓	✓	quite bad	quite bad	pitting	pitting & thinning + "exfoliation"	–390		B SRB
52	MS	100	✓	+	soil + +			few shallow		good & some shallow pitting	good	–222		I SRB
53	G	25	✓							good	slight gen corr	–135		O t
54	MS	100	✓	–			✓		bad	? millscale	badly corr grooved attack	–238		? SC
55	G	50	scale	–	soil +					good	galv pipe c̄ MS Flange – galvanic	–460	28000	O galvanic
56	G	20	scale	–					bad	good	badly pitted c̄ weld corr.			O W SRB
57	MS	100	✓	–	soil +			shallow		quite good.	burst near coupling corr on thread pipe OK	–271	14 388	O SRB
58	MS	100	✓	–	soil +	✓	✓	bad	bad	bad pitting c̄ penetration	bad pitting c̄ penetration.	–494	3644	B SRB
59	MS	100	✓	+	soil –	✓					good	–240		I SRB.
60	G	25	scale	–	soil +	none	none		bad	good	weld corr	–300		O W SRB

PIPE NO	MAT	DIAM (mm)	TUB	SRB INT	SRB EXT	HOLE INT	HOLE EXT	PITS INT	PITS EXT	SURFACE INT	SURFACE EXT	P-S (mV)	SOIL RES Ω.cm	TYPE
61A	MS		✓	+	soil +			saucer deep	saucer deep.				—	B SRB.
61B	MS		✓	+	soil —	✓	✓	deep saucer	extensive				—	B SRB
61C	MS		✓	—	soil +			large gouge-like			good		—	I SRB.
62	MS	150	✓	+	soil +	✓	none		shallow saucer	corrugated surf		-333	3330	B SRB
63A	MS	100	✓	—	soil —	none	none	deepish saucer	none		good cond not much metal loss	-387	7351	I SRB.
63B	MS	100	✓	+		none	none	none	shallow	corr at welded joint. Surf good no weld line corr	shallow pits at welded joint surface good	-381	4021	I SRB.
63C	MS	100	✓	+	soil +	none	pinhole penetr.	shallow saucer	shallow & deep			-401	5902	B SRB
64	MS			+						shallow pits but quite good cond.	pipe good but thread badly corr		—	O
65	MS	100	scale	—			✓	shallow few	deep	quite good cond			—	O
66	MS	150	✓	—	soil +		✓	shallow saucer	severe		severe pitting + thinning. Pits mainly ext	-266	—	O SRB
67	G	Fire m.	scale					none	few small shallow	good	weld failure		—	O W
68	G	Fire m. 50	scale						shallow		weld failure	-456	—	O W
69	MS	150	✓	—	soil +	✓		deep	deepish saucer			-509	—	B SRB
70	MS		✓	+	soil +			deepish saucer		Thread- shallow saucer pits. Pipe deepish saucer	hole in thread weld failure but metal cond good		—	B SRB
71	MS	Fire m 50			soil +		✓	shallow saucer	deepish saucer			+261	—	O SRB

PIPE NO	MAT	DIAM (mm)	TUB	SRB INT	SRB EXT	HOLE INT	HOLE EXT	PITS INT	PITS EXT	SURFACE INT	SURFACE EXT	P-S (mV)	SOIL RES	TYPE
72	MS	100	scale	+	soil +		✓		few deep saucer	mainly general corr	mainly severe general corr	-224	—	B E SRB
73	MS	150		—		✓		deepish saucer	small shallow		good		—	I
74	G	20	scale		soil +				bad	good cond	weld failure	-308	—	O W SRB
75	MS	150	✓	—	soil +			deepish saucer	few shallow small	weld corr	quite good	-228	—	I W
76	G	25	scale		soil +				severe	good	weld corr	-282	—	O SRB
77A	G	50	scale		soil +		✓		bad	good.	weld starting to corr	-203	—	O SRB
77B	G	50	scale		soil +				slight	good	weld corr	-140	—	O W SRB
78	MS	110	✓					Slight	shallow	weld-corr, good	Fair/weld		—	I W
79	MS	150	✓	—				shallow	shallow	weld corr	weld corr	-101	—	I W
80	M/S	110	✓				✓	shallow	no	shallow pits peg from outside	Good		—	O
81	M/S	150	✓	—	+	✓		scattered	scattered	Thinning	Thinning	-336	—	O t
82	G	25	scale	—	+				shallow	Good	Weld failure		—	B W
83	MS	110	✓	+	—	✓		bad deep	none	Weld-corr. Pits (many)	Good		—	I W
83B	MS	150	✓			✓	✓	deepish (many)	shallow (many)	Gen. Corrosion	Shallow Pits		—	I SRB
84	MS		✓	—	+	1	✓	"		Gen. Corros[illegible]	Thinning hole (across)		—	B t

PIPE NO	MAT	DIAM (mm)	TUB	SRB INT	SRB EXT	HOLE INT	HOLE EXT	PITS INT	PITS EXT	SURFACE INT	SURFACE EXT	P-S (mV)	SOIL RES	TYPE
85	MS	50	✓			✓	✓	Shallow	Shallow & General	General corrosion	General corrosion		–	B
86	MS	110	✓				✓	Shallow pits	General shallow pits	"	"		–	O
87	MS	110	✓	+	–				Shallowish pits	Fair/Erosion like	Fair		–	O
87B	MS	100	✓	+	–					Erosion	Good	-224 -352 375	–	O
88	MS	150	✓	+	+	✓	✓	Shallow pits	deepish pits	Pitted Surf.	General Corr.		–	O SRB
89	MS	150	✓	+	+		✓			Weld attack	Weld attack		–	O SC
90	MS	150	✓	–		✓		deep/ Shallow pit	deepish pit	General corr.	General corr.		–	I SRB
91	MS	150	✓	✓					deep pit	Weld attack	Weld attack		–	O [illegible]
92	MS	110	✓	✓		✓	✓	deep pits	Shallow pits	Erosion Pit-Like	General corr.		–	I
93	MS	80	✓	+		✓	✓	deep	deep	Highly Corroded	Highly Corroded		–	O SRB
94	MS	110	✓			✓	✓	deepish saucer	deepish saucer	beel	bad		–	O
95	MS	110	✓				✓	Threaded area	✓	Highly Corroded	Highly Corroded		–	O SRB
96	G	25	Scale				✓		deep saucer	Good	Weld Attack		–	O
97	MS	150	✓				✓	Shallow pits	Shallow pits	Bad	Stray Current		–	O SC
98	MS	110	✓			✓		Very/very deep		General Corrosion	General Corrosion		–	I

PIPE NO	MAT	DIAM (mm)	TUB	SRB INT	SRB EXT	HOLE INT	HOLE EXT	PITS INT	PITS EXT	SURFACE INT	SURFACE EXT	P-S (mV)	SOIL RES	TYPE
99	G	60	✓				✓		✓	Highly corroded	Good		—	O
100	MS	100	✓			✓			Shallow pits	Erosion	General corr.	-328	—	O
101	MS	100	✓							Weld attack	Good		—	T W
102	G	120								Thinning/Corr.	Gen. Corr.	480	—	B t
103	MS	300	✓			✓			Shallow pits	Weld attack	Weld attack		—	B w
104	MS	250	✓					shallow pits		Weld attack	Weld attack (mild)		—	B W
105	MS	150	✓					shallow pits	shallow pits	"	" (Good)		—	B
106	MS	150	✓				✓ From there	Shallow pits	Shallow pits	Weld attack	Weld attack Stray Current		—	O sc
107	MS							Shallow		Pitted	Good		—	G ?
108	MS	225	✓				✓	Shallow pits	Shallow pits	Weld attack	Weld attack		—	B W
109A	MS	100	✓					Shallow saucer		Gen. Corrosion	Good		—	G ?
109B	MS	100	✓					deepish pits			Good		—	G?
109C	MS	100	✓							Gen. Corrosion	Gen. Corrosion		—	G?
110	MS	150	✓			✓		Shallow pits	Shallow pits	Weld attack	Stray current.		—	O sc
111	MS		✓			✓	✓	Deepish saucers	Shallow saucers	Corroded	Thinning/Gen. corr		—	O

PIPE NO	MAT	DIAM (mm)	TUB	SRB INT	SRB EXT	HOLE INT	HOLE EXT	PITS INT	PITS EXT	SURFACE INT	SURFACE EXT	P-S (mV)	SOIL RES	TYPE
112	MS	75	✓				✓	Shallow saucers	Shallow saucers	Bad	Thinning / Bad		—	O
113	G	50					✓		deep / shallow pits	Good	Gen. Corr.		—	O
114	MS	110	✓				✓	Shallow sauce	deep pits	~~Good~~ Bad	~~Gen. Corr.~~ Bad		—	O
115	MS	110	✓			✓	✓	"	"	Gen. Corr.	Gen. Corr.		—	B
116	MS	110	✓			✓	✓	Shallow pits "	deep pits	Gen. corrosion	Slight Current		—	O
117	MS	110	✓				✓		deep pits	Bad	Bad		—	O