IN-SERVICE DURABILITY OF uPVC WATER MAINS

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In order to determine whether uPVC pressure pipe performance is affected by time in service, sections of uPVC water mains of ages up to 16 years have been exhumed and tested. From a combination of quality and mechanical property tests it is shown that initial pipe quality is the overriding influence in determining pipe performance.

INTRODUCTION

uPVC pipes, which were first used as water mains over 25 years ago, currently have about 50% of the market share for pipe renewals and new works. This usage of uPVC is not spread evenly across britain, some engineers remain reluctant to specify it owing to its poor historical performance (1), whilst others are concerned that the pipes may age and become more susceptible to brittle failure with time in service. The work described in this paper was undertaken in collaboration with Severn Trent Water Authority, to determine whether the durability of uPVC water mains is affected by time in service.

uPVC is a viscoelastic material and therefore its properties are expected to change with time. Various research workers have investigated this phenomenon but they have used new pipes and artificially aged them by heat. In particular L C E Struik (2) found that the effect of artificial ageing on uPVC, using a variety of temperatures and times, is to make it stiffer and more brittle and to reduce the rate of stress relaxation of the material, whilst Schwencke (3) concluded that the effect of artificial ageing, which can be achieved by storing pipes at 60°C for 17 hours, is to increase their creep resistance and strength. A variety of preliminary tests carried out at WRc did not show artificially aged pipes to behave in the same way as pipes which had been in service for many years. It was decided that a study of properties of genuinely old pipes would provide results which could be interpreted more easily.

In this study pipes which had been in service for up to 16 years have been exhumed and tested in the ways described as follows.

In order to reduce the number of variables a single pipe size and class, 4 inch diameter class C (operating pressure 9 bar), from a single manufacturer was chosen for study. Pipes of a range of service ages which had experienced similar service conditions were exhumed. The manufacturer with the most extensive records of quality control and type testing for past production was chosen to allow this data to be compared with similar test data generated from tests on the exhumed pipes.

PIPES

Five 35m lengths of uPVC pipeline were exhumed from the Staffordshire area in the autumn of 1982. Their ages and operating pressures are given in Table 1. In addition samples of current production pipe were taken from Water Authority stockyards.

TESTING

The mechanical performance of uPVC is influenced by the degree of gelation and by the number and size of included particles. The gelation was assessed qualitatively by immersion of tapered samples in methylene chloride. The procedure in the draft revision of BS 3505 (4) was followed with the exceptions that the taper length was 120mm and the immersion time 30 minutes. Gelation was also measured quantitatively by the less well established techniques of DSC developed by Gilbert, Hemsley and Miadouye (5). The included particles were observed by X-radiography, although it is appreciated that this does not reveal particles of similar optical density to the uPVC polymer.

Routine tensile tests in accordance with Method 320C of BS 2782 (6) were carried out on samples cut longitudinally from the pipes, using a test speed of 3mm/minute.

Long term resistance to pressure of thermoplastic pipes has traditionally been assessed by stress rupture tests. The most useful of the manufacturer's records were those of pressure tests to 100 and 1,000 hour failure times for each production run on each extruder. Stress rupture regression curves for each exhumed pipe are being produced for comparison with this data. Each ruptured pipe sample has been examined for failure type (ductile or brittle) and initiation source. Failures have been classified as ductile if they show any signs of surface stress whitening or wall thinning.

The toughness of the pipes, which determines their resistance to slow crack growth is as important as their resistance to internal pressure. An assessment of pipe fracture toughness was made by testing notched C-rings of pipe, prepared in accordance with the draft revision of BS 3505 (4), to failure under a range of stress intensities (see Figure 1). Stress intensity regression lines were drawn for each pipe.

RESULTS AND DISCUSSION

Following exhumation the pipe diameters and wall thicknesses were measured and found to be within the specification limits in operation at the time of manufacture.

The gelation of the exhumed pipes was variable, and poor in comparison with pipes produced to the draft revised version of BS 3505 (4). From the photographs of the pipes after immersion in methylene chloride, it may be seen that pipe 2 has been attacked only slightly whilst pipe 4 shows severe attack both through the wall thickness and on the internal pipe bore. Gelation levels measured by DSC are given in Table 1. They correlate to a limited extent only with the methylene chloride attack; the new pipe and pipe 2 were significantly better gelled.

TABLE 1

PIPE NUMBER	PIPE AGE (Years)	NORMAL OPERATING PRESSURES (bars)	GELATION BY DSC (%)
1	16	3.7 - 4.9	52
2	13	4.7 - 5.1	64
3	9	4.5 - 5.5	51
4	7	2.0 - 2.5	49
5	4	2.9 - 3.4	49
New	0		65

X-radiography showed all the pipes to have included particles of sizes up to 0.5mm, i.e. approximately 10% of the wall thickness. From an examination of the failure initiation sites of the laboratory tested pressurised pipe samples, inhomogeneous regions up to 1.3mm were apparent, the larger ones being in pipes 1 and 4. Better gelled pipes would be expected to be more tolerant of defects, and therefore conversely pipe 4 with its low gelation and large defects would be expected to perform poorly. These differences in pipe quality must be borne in mind when examining the following mechanical test data.

The stress rupture results are shown in the standard format in Figure 3. The ductile and brittle failures are distinguished. Since it is not reasonable to relate the two failure types to a single regression line, only the ductile regression lines have been drawn. The dashed lines are regression lines of the original hydrostatic tests carried out by the manufacturer. It must be noted however that the manufacturer's test samples were end-restrained whilst those tested at WRc were unrestrained. For ductile failures, using Von Mise's yield criterion, it can be shown that pipe hoop stresses in restrained end tests are smaller than unrestrained by a factor of 0.87. Therefore to be directly comparable with the solid line, the dashed one should be shifted upwards. The dotted line shows this.

The slopes of the ductile regression lines and the manufacturer's lines are very similar for pipes 1 to 4 but there is substantial variation for pipe 5. If the samples of pipe 5 which are still on test and its tensile yield stress (see later) are taken into consideration it is clear that until further data is available, the line cannot be accurately plotted.

Still considering the ductile regression lines, the stresses which pipes 1 to 4 can withstand for a total lifetime of 50 years are slightly lower than those predicted from the manufacturer's regression lines but still significantly above the 23MPa required by BS 3505 (4). The scatter of the ductile failures about those regression lines is small such that the 97.5% lower confidence limit of the regression lines at 50 years is still greater than 23MPa. Until further data for pipe 5 is available it cannot be included in this comparison. The figures are given in Table 2.

Table 2 also compares the ductile regression line intercept with the tensile yield stress. The values are similar for pipes 1 to 4. The tensile yield stress for pipe 5 is close to the values for the other pipes which suggests that its ductile regression line will also be similar.

TABLE 2

PIPE NO.	STRESS FOR 50 YEAR LIFE (MPa)			TENSILE STRENGTH (MPa)		
	DUCTILE LINE	97.5% LOWER CONFIDENCE	MANUFACTURER'S LINE	DUCTILE LINE INTERCEPT	MANUFACTURER'S INTERCEPT	TENSILE YIELD STRESS
1	29.8	26.1	32.0	47.1	52.2	48.0
2	29.3	27.8	30.8	46.9	51.3	47.4
3	28.3	26.6	33.0	46.7	52.9	46.2
4	30.0	27.5	35.7	48.6	50.4	48.8
5			36.4	54.9	50.1	48.6

Having noted the similarities of the ductile line with the manufacturer's line, the important difference must now be considered. For all pipes 1 to 5 there have been a considerable number of totally brittle failures at relatively short times under test. Such failures would not be expected in new good quality pipe. Pipes 1 and 4 have shown the most brittle behaviour. This is likely to be attributable to their large defects and poor gelation. On the basis of the present data the brittle failures cannot be attributed to ageing since extrusion because all of them have occurred at pipe hoop stresses which are lower than the hoop stresses used by the manufacturer during type testing. The data shows no correlation of pipe age with mechanical performance. It is the opinion of the author that the pipes' initial quality is the most significant factor in influencing their subsequent performance.

In practice these five pipes were operating at low pressures (see Table 1) where the chances of failure due solely to the internal pressure are small. Unexpected surges or interference damage, should either occur, are likely to be far more detrimental.

The more limited data available from the C-ring tests is given in Table 3. From regression lines the stress intensity factors, K, for one hour and 50 years have been determined. The one hour stress intensity factor correlates with pipe quality as is expected from the work of Marshall and Birch (7). Notably pipe 2 has a high value of K whilst pipe 4 has a low value. The draft revision of BS 3505 (4) requires notched pipe C-rings to survive for 15 minutes at K = $3.25 MNm^{-3/2}$. Some of these pipes would not pass this standard.

In order to survive for 50 years the pipes should not be subjected to stress intensities greater than approximately $1 MNm^{-3/2}$. This would be equivalent to pipe with a defect of 25% of its wall thickness pressurised to 13.5 bar so long as there were no other stresses on the pipe. In practice a substantial safety factor is necessary to allow for other stresses. It must be noted that both the quantity of data and its distribution does not strictly permit valid regression to be carried out. Once again there is no trend due to age apparent, it is the pipe quality that is having the greatest effect on performance.

TABLE 3

PIPE NUMBER	STRESS INTENSITY ($MNm^{-3/2}$)		
	REGRESSION LINE SLOPE	ONE HOUR K	50 YEAR K
1	-11.2	3.4	1.1
2	-12.5	3.5	1.3
3	- 9.7	2.9	0.8
4	-13.1	2.4	0.9
5	-12.4	2.6	0.9
New		4.0	

CONCLUSION

Ageing has not been found to be a significant factor influencing uPVC pipe performance.

The material quality of uPVC pipes has an overwhelming effect. In particular there is a need to ensure good gelation and fracture toughness, and small inclusion size. The latest draft of BS 3505 has taken the first two points into account such that pipes manufactured to this standard should not show the same degree of service brittleness.

In general uPVC pipes are expected to last at least their design life of 50 years if they are left undisturbed but they will remain susceptible to interference damage if their material quality is not of a high standard.

A future study which involves the exhumation of fully characterised uPVC pipes will identify whether ageing will have a significant effect on the performance of modern production pipes.

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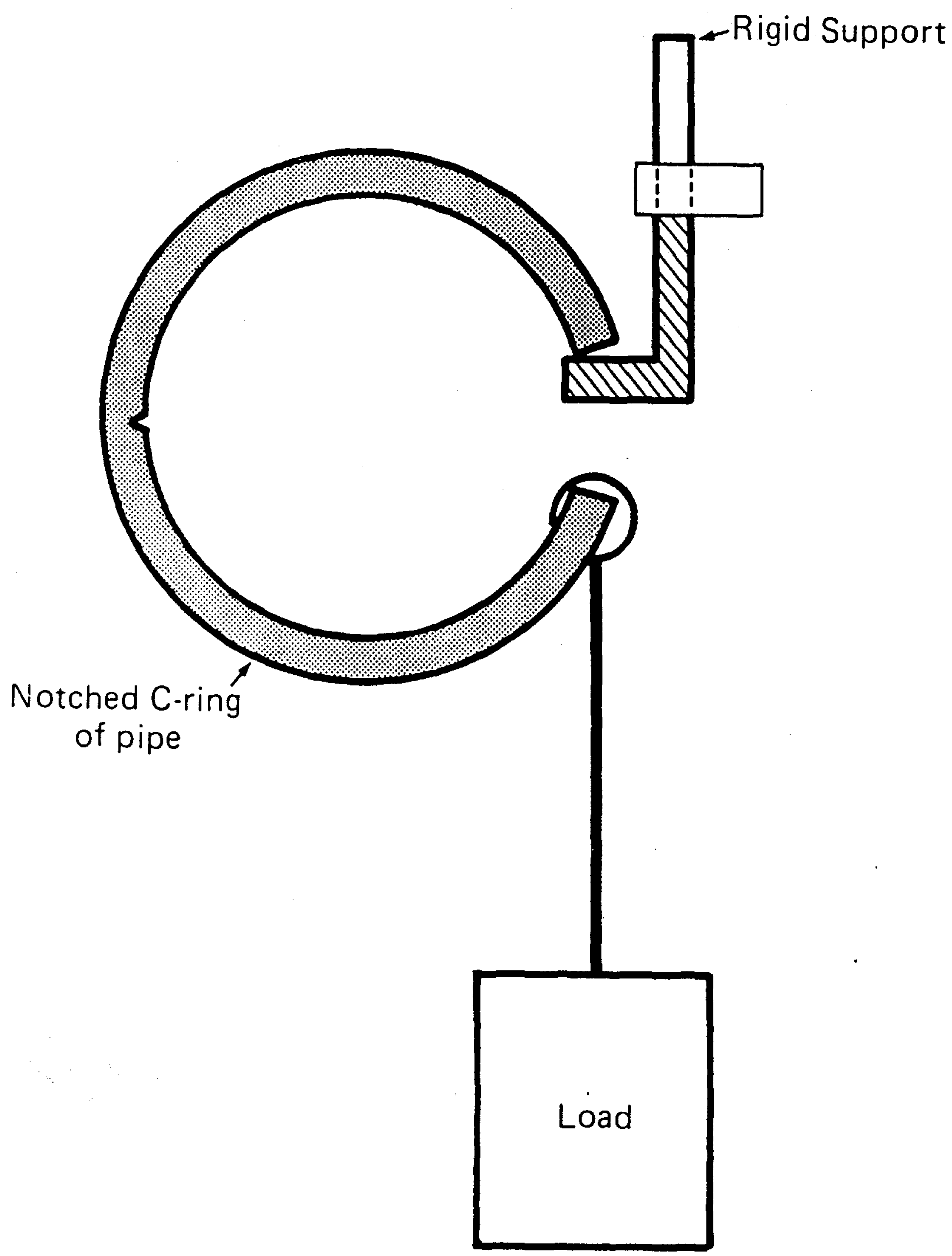
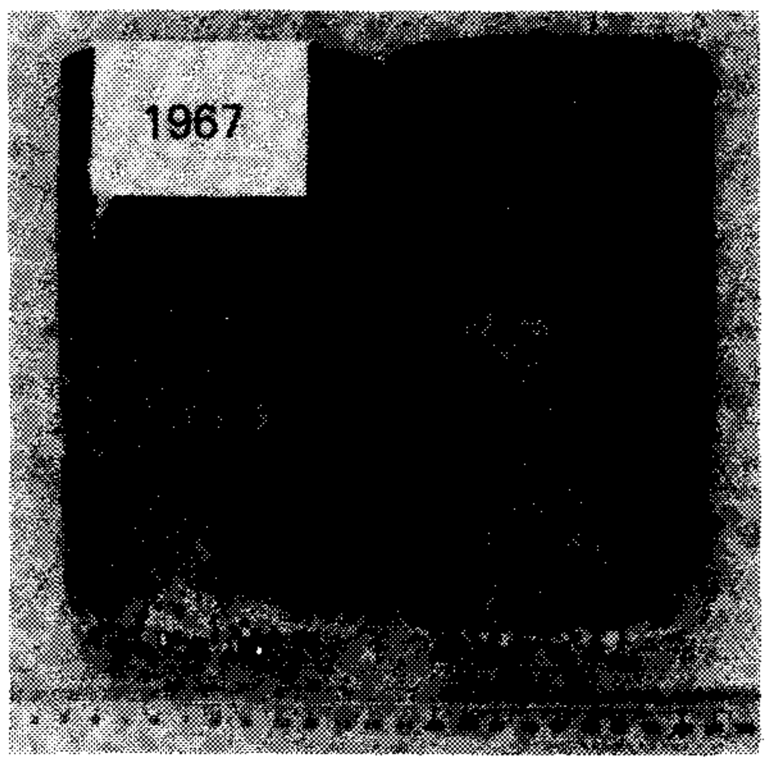
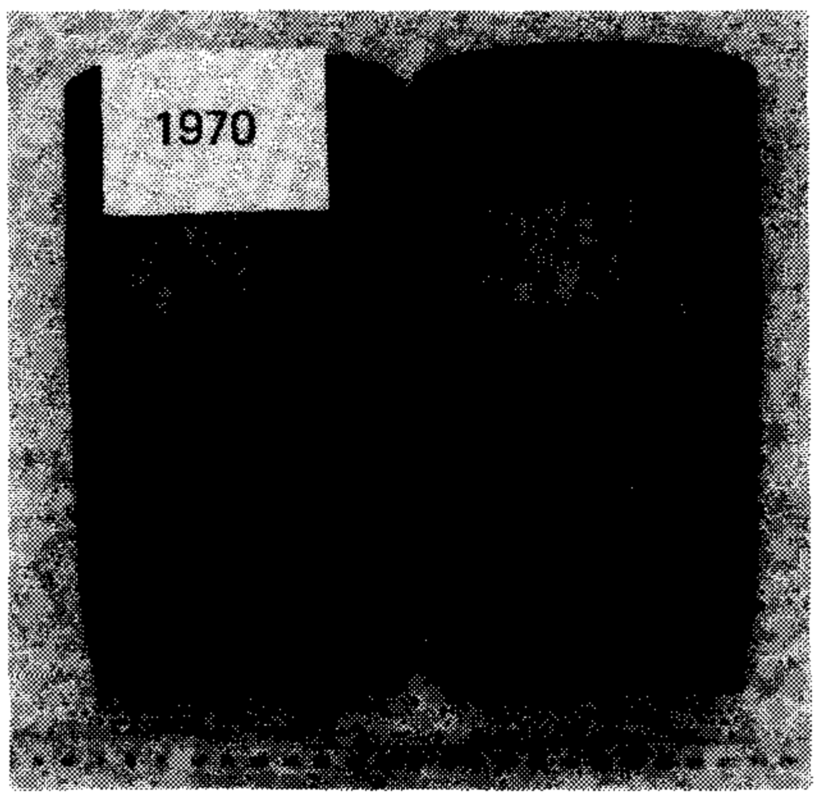


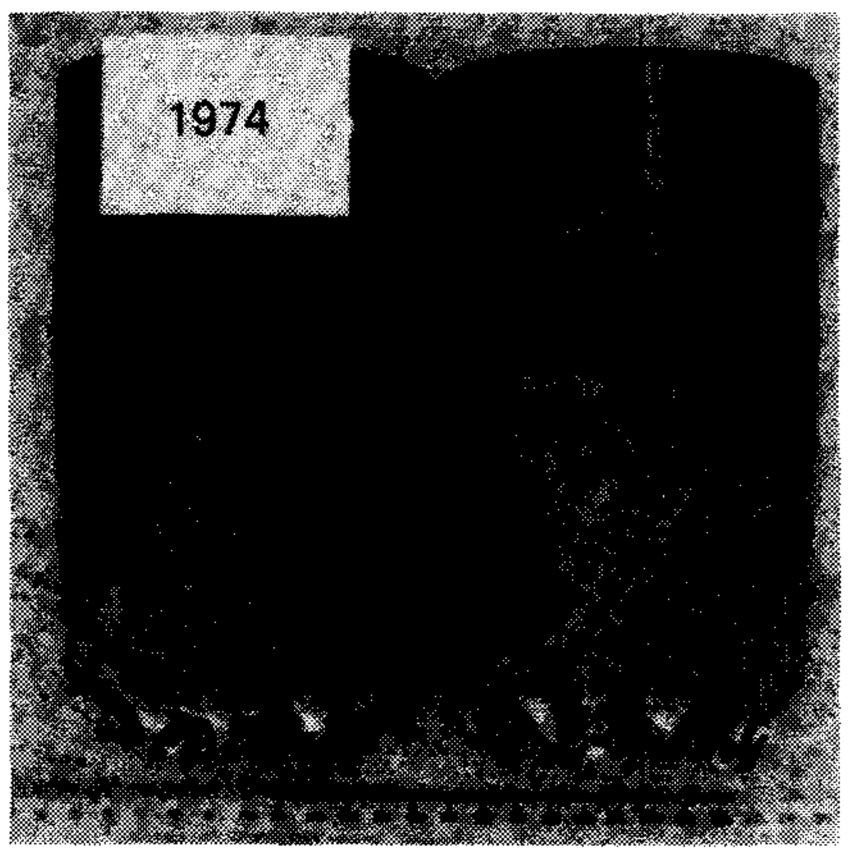
Fig. 1. Diagram of C-ring test.



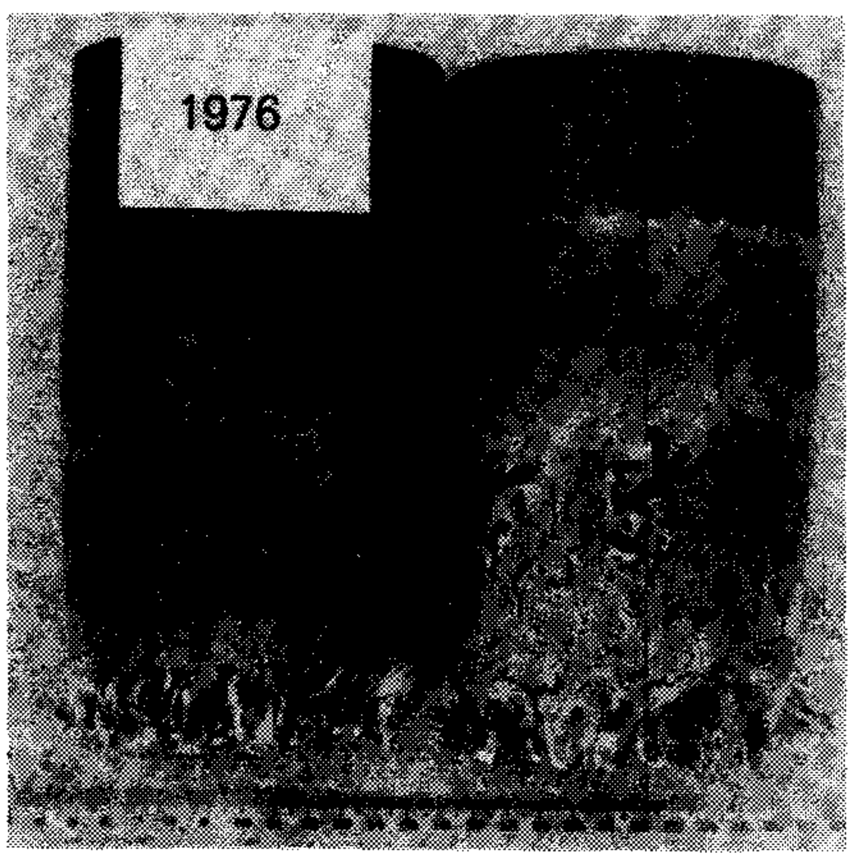
Pipe 1. Outside and middle of wall



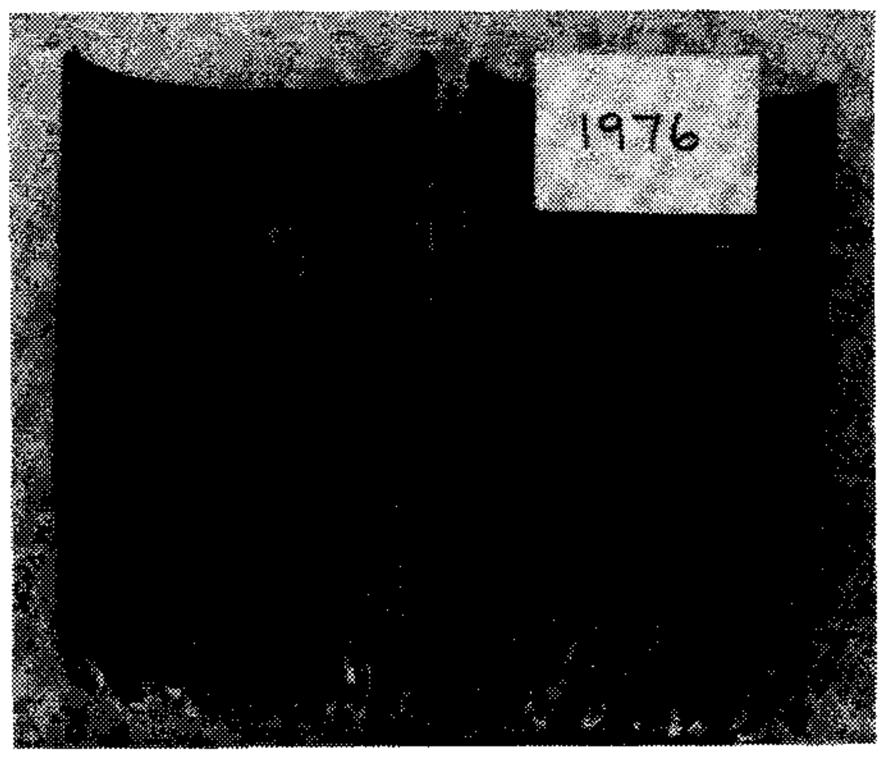
Pipe 2. Outside and middle of wall



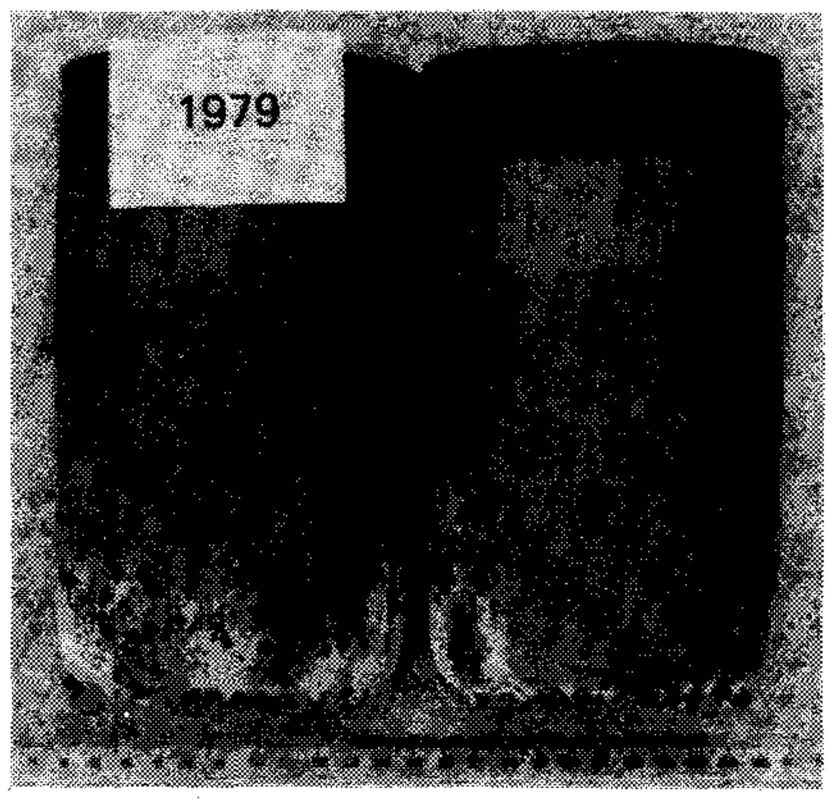
Pipe 3. Outside and middle of wall



Pipe 4. Outside and middle of wall



Pipe 4. Inside wall



Pipe 5. Outside and middle of wall

New pipe. Outside and middle of wall

Fig. 2. Pipes after tapering and immersion in methylene chloride at 20°C for 30 minutes.

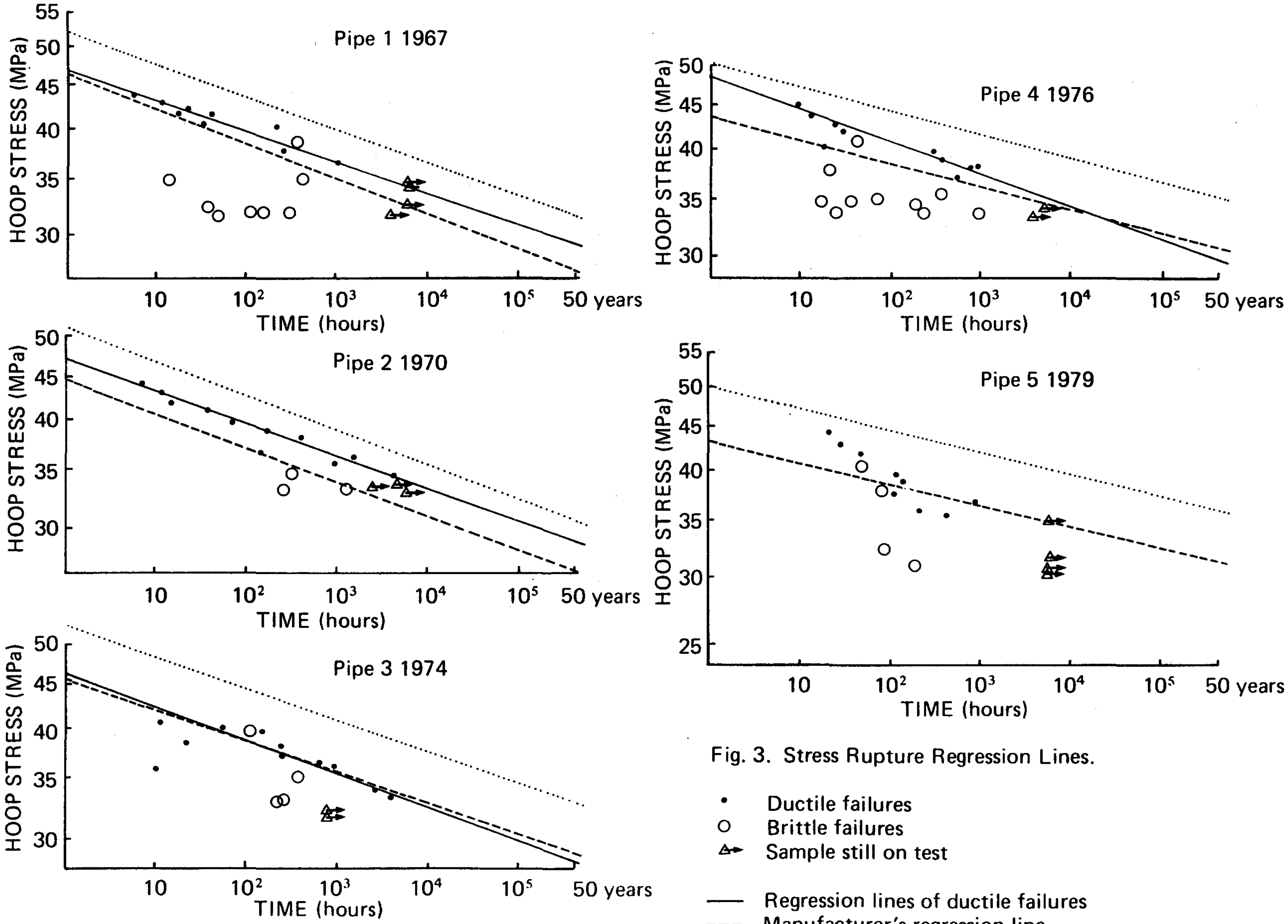


Fig. 3. Stress Rupture Regression Lines.

- • Ductile failures
- O Brittle failures
- △→ Sample still on test

- —— Regression lines of ductile failures
- – – – Manufacturer's regression line
- ······ Manufacturer's regression line shifted (see text)