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PVC PIPE PERFORMANCE IN WATER MAINS AND SEWERS

P.C. Kirby[1]

Abstract. The performance of PVC pressure pipe is assessed after over 15 years experience in Britain of its use for water mains and pumped sewers. Burst records kept by Water Undertakings have been used to compare the burst rates of PVC and iron pipe under similar conditions of use and an analysis of PVC pipe failure investigations has established some of the principal causes of bursts and leakages. It was found that the service performance has improved considerably with increased familiarity. The effect of surge in pumped sewage mains on the dynamic fatigue limit in PVC pipe is discussed together with the need for more relevant test procedures and the use of alternative plastics.

Introduction. Unplasticised PVC pressure pipes have been in general use for over 15 years in Britain for water supply and pumped sewage applications. They have taken a large share of the market in sizes up to 12-14 inch diameter. These pipes have proved attractive in terms of cost and ease of installation and have overcome problems of corrosion, discoloured water and frictional head losses. There have, however, been a number of bursts and leaks in PVC pipelines, often associated with brittle fractures, which were not anticipated by the users who expected a plastic material to be tough and resilient. The economic and other advantages of plastic pipe ensures its continued use despite occasional bad publicity but, now that plastics other than PVC are available in a range of pipe diameters, an objective assessment of the service performance of PVC pressure pipe was considered opportune in order to gauge the seriousness of these problems.

In order to assess the overall performance of PVC pipe, burst records maintained by Water Undertakings were utilised to determine failure rates for PVC pipe and compare these with the failure rates for equivalent cast iron services. In the course of this work, the opinions and experiences of a number of users were recorded. A detailed analysis of burst frequencies in exactly corresponding sections of PVC and of cast iron water mains was carried out in one district with particularly detailed installation and burst records. At the Water Research Centre, work has been carried out for a number of years on the identification and classification of pipeline failures and detailed case histories of 332 PVC pipeline failures were analysed to identify the most common causes.

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[1] Principal Materials Engineer, Water Research Centre, Swindon, England.

History of use in Britain. Manufacture of PVC pipe in Britain began in 1955 and the first pressure pipes were produced in 1957. The first important water project was a 675 yard pipeline of 6 inch diameter between Queenborough and Sheerness(1). The use of PVC pipe for buried water mains was confined to special situations until about 1962 when the first British Standard was introduced(2) and the flexible push-fit joint became available. It has since been widely adopted, particularly in sizes up to 12 inch. In 1975, Banks(4) estimated that PVC pipe had taken 25% of the clean water market for pressure pipes and the figure is now thought to be around 40%. The flexible push-fit socket introduced in 1962 was a moulded coupling cemented to a straight pipe. The first integral joint socket was marketed in 1965. The British Standard, BS 3505, was revised and updated in 1964 and 1968 and a Code of Practice(3) for handling and laying the pipe was produced in 1973.

General Survey. A preliminary survey of private Water Companies and public Water Authorities was carried out to locate suitable performance records(5). The attitude of these undertakings towards record keeping varied considerably. Some considered that the cost of maintaining burst records could not be justified economically; others kept burst records but did not have accurate records of the lengths of different types of pipe material in use, so that burst rate per unit length could not be evaluated; while in many undertakings continuity of records had been lost during widespread reorganisation in 1974.

Fifteen Water Companies and 18 Water Authority Divisions were found, however, to have some suitable records. Details of these Undertakings are given in Table 1 together with a résumé of their reasons for selecting PVC pipe. Table 2 gives details of the year when PVC pipe was first laid in these areas together with the maximum diameters laid to date, the pressure classes selected and the water pressures actually found in these areas. Table 3 gives failure statistics for cast iron and PVC water mains in these areas for the year 1978.

The general level of satisfaction with the performance of PVC pipe was found to be as follows:

Generally satisfied with PVC for all situations	:	20 (62.5%)
PVC acceptable for special situations (corrosive conditions or small diameter only)	:	9 (28.1%)
PVC no longer acceptable	:	2 (6.3%)
PVC never laid	:	1 (3.1%)

In 17 cases where it was possible to calculate the burst rate per mile for cast iron and PVC water mains for the year 1978, the burst rate for PVC was lower than for iron in 11 areas, equal in one area and higher in 5 areas (Table 3).

Some Water Undertakings impose an additional safety factor by purchasing pipe to a higher pressure class than that calculated from the pressure requirements of the system, as can be seen from Table 2. In this group the satisfaction profile is higher than that for the Water Undertakings as a whole but the difference is not great enough to to be statistically significant.

Table 1. Water Undertakings and their Selection Criteria

Ref. No.	Undertaking		Reason for Choosing PVC Pipe Material cost	Laying cost	Corrosive conditions
Water Companies					
1	Bristol			*	*
2	Cambridge		*	*	*
3	Chester		*	*	
4	Colne Valley			*	*
5	Folkestone		*		*
6	North Surrey		*		
7	Sunderland		*	*	
8	Tendring Hundreds				*
9	West Kent		*	*	*
10	Wrexham		*	*	
11	York		*		
12	Jersey				
13	Mid Sussex				
14	Portsmouth				
15	East Surrey				
Water Authorities					
	Authority	Division			
16	Anglian	Northampton	*		
17	Northumbrian	Tees	*	*	
18	Southern	Hampshire	*	*	*
19	Severn-Trent	Soar	*	*	*
20	Thames	Chiltern			*
21	Thames	Cotswold	*	*	*
22	Thames	Vales	*		*
23	Wessex	Avon		*	*
24	Wessex	Bristol		*	*
25	Yorkshire	North Eastern	*	*	
26	Southern	East Sussex			
27	Severn-Trent	Tame			
28	South West	Exeter			
29	Welsh	Gower		*	
30	Yorkshire	Eastern			
31	Yorkshire	West Central			
32	Yorkshire	South Western			
33	Yorkshire	South Eastern			
		Total	15	15	13
		Overall response	22	22	22
		%	68%	68%	59%

Table 2. Authority Laying Details

Authority Ref. No.	Year first laid	Maximum diameter inch	Pressure class Maximum	Pressure class Minimum	Normal pressure ft head
1	1968	8		C	290 max
2	before 1963	24	D	C	200-200
3	1963	10	D	C	50-150
4	1962	20		C	150-300
5	1964	24		C	150-400
6	1965	18		C	100 max
7	1964	12	D	C	50-200
8	1962	16			100 max
9	1960	14		C	350 max
10	1960	12	E	B	200 max
11		18		B	150 max
12	1963	10	C	C	225 max
13	1961				
14		24	C	B	
15					
16		12		C	100-200
17	1969	24	D	C	200 max
18	1963	18		C	100-200
19	1964	16		C	150 av
20	1960	20		C	180 max
21	1967	24		C	350 max
22	1964	18		C	
23	1963	14			350 max
24	1960	20		D	350 max
25	1963	16			400 max
26	1966	14			350 max
27	1964				
28	1960				
29					
30					
31					
32					
33					
Overall	1960-1969				

Key: Class B = Maximum working pressure 6 bar (200 ft head)
Class C = Maximum working pressure 9 bar (300 ft head)
Class D = Maximum working pressure 12 bar (400 ft head)
Class E = Maximum working pressure 15 bar (500 ft head)

Table 3. PVC and Cast Iron Failure Statistics 1978

Authority Ref. No.	Number of failures in 1978 Cast iron	PVC	Failure rate - Bursts/mile/year Cast iron	PVC
1	482	144		
2	150	53	0.46	0.23
3				
4	782	6	0.53	0.05
5	81	6		
6	131	19		
7	499	85	0.42	0.40
8	102	6	0.32	0.07
9				
10	206	5	0.52	0.10
11				
12	23	17	0.13	3.51
13	258	25	0.26	0.17
14				
15	674	5	0.53	1.18
16				
17	756	154		
18	38	6	0.16	0.25
19	1221	96	0.70	0.20
20	82	11		
21	77	9	0.17	0.08
22				
23			0.17	0.73
24				
25	284	60	0.40	0.18
26				
27				
28				
29				
30	550	46	0.28	0.28
31	1333	24	0.55	0.42
32	931	82	0.77	0.85
33	372	4	0.37	0.02

In general, the users perceive the advantages of using PVC pipe (in order of importance) to be:

(1) lower pipe cost in sizes up to 12 in
(2) lightness and ease of installation
(3) corrosion resistance and the maintenance of flow characteristics in service
(4) ability to install by mole ploughing in boggy areas.

The only disadvantage of using PVC pipe noted is the occurrence of unexpected failures.

Some causes of failure are categorised by the users themselves and most frequently mentioned are failures connected with joints, including the fracture of moulded socket couplings, poor performance of solvent welded joints and displacement of rubber rings. Failures due to pressure tapping for house connections are frequently mentioned and accidental damage from adjacent excavations is also cited as a frequent cause of failure, especially when the pipes are newly laid. In this case it might be thought that the pipe material itself could not be blamed but some users contend that PVC is in fact more damage-prone than iron because it cannot be easily detected after burial. Other factors mentioned include surge problems in pumped mains, poor handling and laying practice and manufacturing defects.

Other points of interest which were noted by the users are that (a) there is often a very high initial burst rate when the main is brought into service, (b) that there is often a higher incidence of failures with large diameter pipes (over 12 inch) and (c) that the incidence of pipeline failures is not uniform but confined to a small number of problem mains with the majority giving no trouble after installation. This latter experience was shared by a large number of the Authorities questioned.

Although traffic loading was only cited by one Water Undertaking as a major cause of failure, there is a more widespread reluctance to lay PVC in main roads and streets and iron is often chosen for these sections of the main, with the PVC pipe reserved for rural areas.

Storage conditions on site and in the stockyards of users were found to be fairly good although many pipes exhibited surface scratches; and sunlight bleaching was usually ignored. On the other hand, there was a reluctance to use imported or screened backfill material for pipelaying unless the soil was very rocky or stony.

Analytical Study of Comparative Failure Rates. In order to study the comparative failure rates of PVC and iron pipes and the effect of pipe variables on failure more closely, a more refined statistical experiment was carried out(6). This compared the performance of a range of PVC pipes laid over a certain period of time with that of a range of iron pipes of the same diamter laid over the same period of time and subject to similar operational conditions. This investigation was carried out in collaboration with the Colne Valley Water Company(4), an organisation which maintains excellent main laying and burst records and which had laid iron and PVC pipes in the same diamter ranges between 1962 and 1972. The Company's statutory supply area is to the north of London and stretches from Harrow in the south to Harpenden in the north, taking in the towns of St Albans and Watford as well as parts of the London Boroughs of Barnet, Brent and Hillingdon. The area thus covers a range of urban and semi-rural situations. The water supply in the area is not aggressive to cast iron. The gravel/chalk soil in the northern section is also non-aggressive but the London clay in the southern section is highly corrosive under certain conditions and prone to seasonal variation in moisture content.

Mains laid since the commencement of PVC laying in 1962 were studied and the study was restricted to 3, 4 and 6 inch distribution mains. Mains were divided into sectors and 799 sectors of PVC main with a total length of 71 miles were compared with 295 sectors of cast iron main with a total length of 27 miles. Main laying data recorded for each sector was compared with mains failure data for the same sector using multi-variate analysis.

Overall results indicate that the burst rate per mile-year is higher for PVC than for cast iron (Table 4). If the data is examined on a year-by-year basis, however, a somewhat different picture emerges (Fig. 1). The average burst rate for all cast iron pipes is 0.22 bursts per mile-year over the whole period. The burst rate for PVC in 1965 was over 4 bursts per mile-year but has fallen steadily since that time until in 1973 it fell below the rate for cast iron. Between 1973 and 1979 the burst rate for PVC pipe has been consistently at or below the burst rate for iron pipe. That this is not an isolated trend is indicated in Fig. 2 where the Colne Valley data on PVC pipe failures is compared with similar data obtained from another Water Company (Sunderland and South Shields(7)). The fall in failure rate with time shows a closely similar trend in both sets of data.

Table 4. Summary of the Data Sample for the Colne Valley Experiment

PVC

Diameter (inches)	Sample length (miles)	Sample exposure (mile-years)	No. of bursts	Failure rate No./mile-year
3	10.9	81.0	27	0.33
4	52.3	380.9	156	0.41
6	8.1	55.0	14	0.25
Total	71.3	516.9	197	0.38

Cast Iron

Diameter (inches)	Sample length (miles)	Sample exposure (mile-years)	No. of bursts	Failure rate No./mile year
3	9.9	135.7	34	0.25
4	14.9	190.0	41	0.22
6	1.8	23.4	1	0.04
Total	26.6	349.1	76	0.22

This improvement in performance may well represent, in part, the improvement in pipe manufacturing techniques which must have occurred over this period but it is also thought to be due to a greater extent to the increased realisation that handling and installation of PVC pipes affect their service performance. The pipes were originally sold on the premise that they were light, foolproof and unbreakable on site compared with the brittle cast iron pipes they were meant to replace. Later the manufacturers began to emphasis the care required in handling and installation and finally in 1973, the National Code of Practice(3)

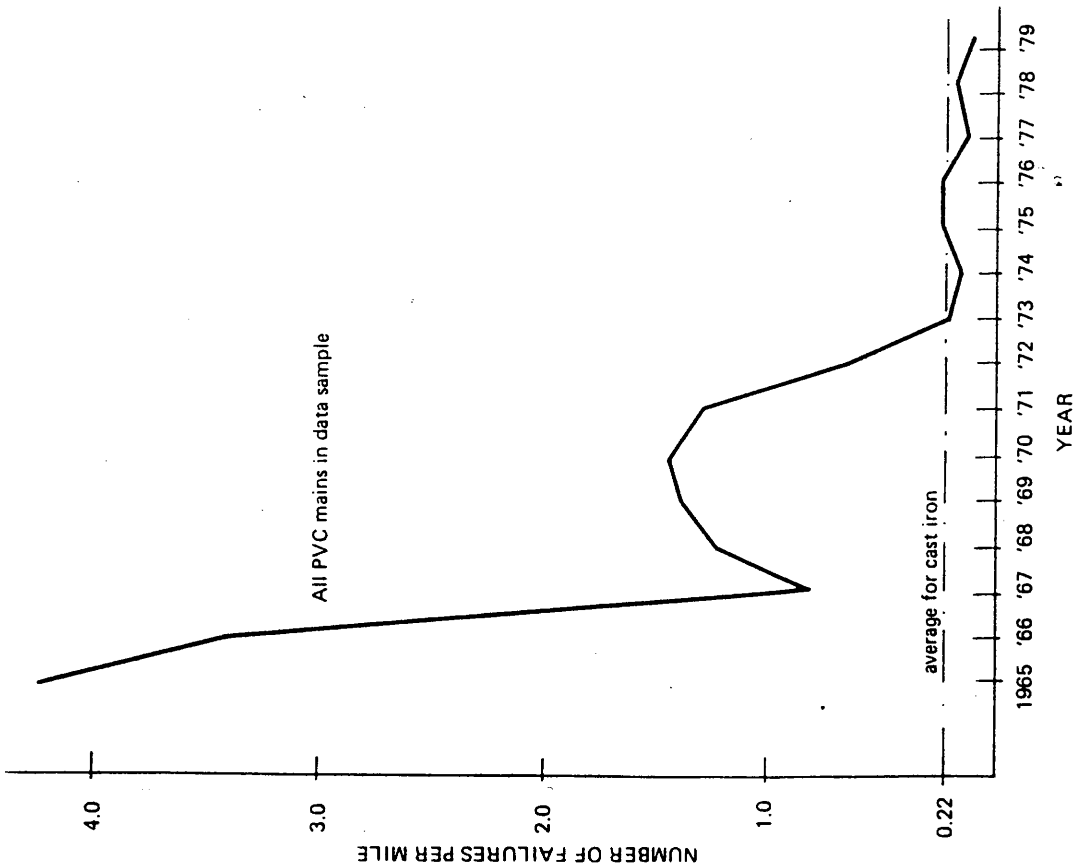

Fig. 1. Annual failure rates of PVC pipe

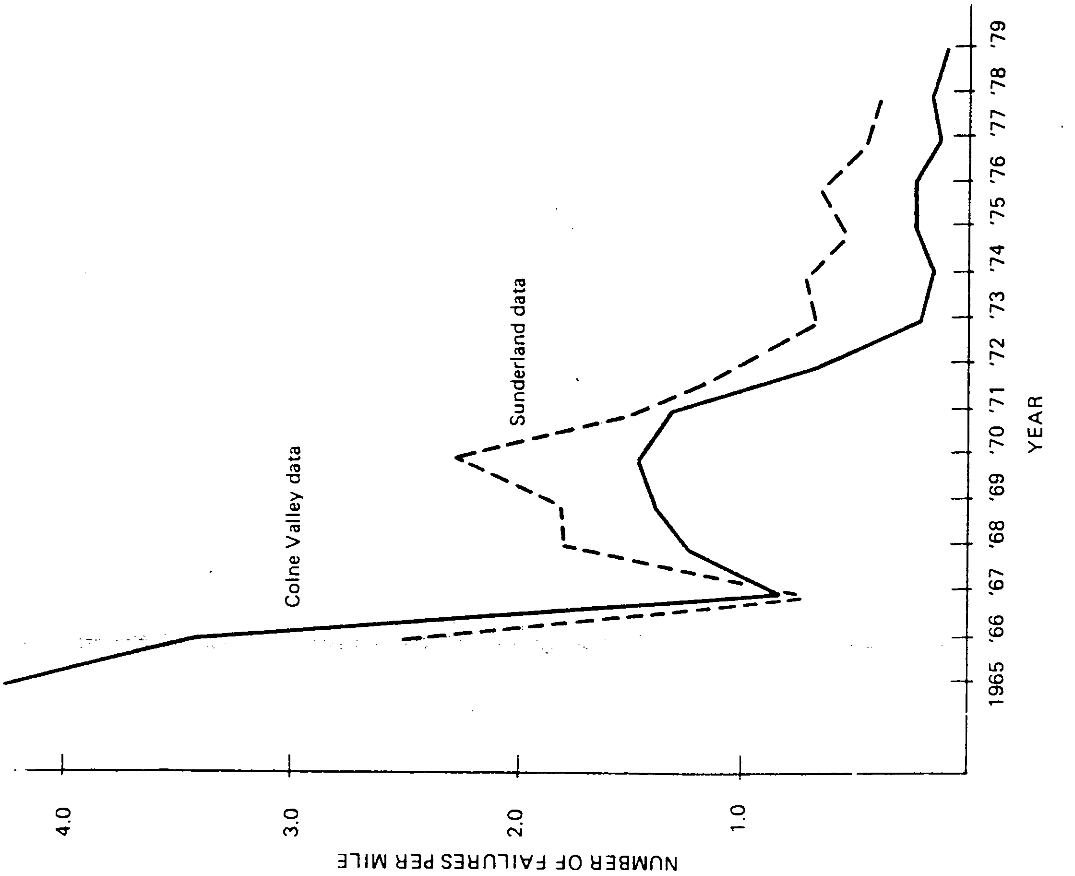

Fig. 2. Comparative failure rates for PVC pipe in Colne Valley and Sunderland.

was issued giving detailed instructions on storage, handling, installation and backfilling requirements. For instance, in the area under study, native soil was used as a backfill material prior to 1970. 1970-1974 was a transitional period and, since 1974, pea shingle has been imported for backfill with PVC pipes.

Another factor which the analysis brought out is that the high failure rates generally occur within the first two years of life of the main. Figure 3 shows the variation of failure rate with time for PVC mains laid in each year between 1965 and 1977. In this early high risk category between 1965 and 1971 the average failure rate is about 2.1 per mile-year whereas for the rest of the data the average failure rate is about 0.2 per mile-year. While it is to be expected that faulty material and improper jointing will show up early in the history of the pipeline, other factors to be taken into account are that the pipeline may be subject to a greater degree of mechanical damage from adjacent excavation while building work is still in progress and may also be subject to heavy traffic loading from site vehicles before the road surfaces are made up.

The data analysis revealed that in the 0-2 year high-risk period, 59% of the failures were reported as due to mechanical interference while in failures which occurred after 2 years or more, mechanical interference was blamed in only 19% of the cases.

Analysis also showed that the failure rates of mains in the Southern (clay soil) area were consistently about three times as high as the failure rate in the Northern (gravel-chalk soil) area. The implications of this are still being considered. No other statistically significant correlations were found at the 95% confidence level but the use of subcontract labour for pipelaying instead of the users' own staff was associated with an increase in failure rate which is not quite significant at this level of confidence. About 30% of the failures logged were found to be due to joint problems of various sorts.

Investigation of Causes of Failure. In many cases the causes of PVC pipeline failures are apparent. Examples of this are mechanical damage due to interference from adjacent excavations and badly displaced joint rings. In other cases the pipe may fracture in a brittle manner in service and the cause is not immediately obvious. To throw more light on this aspect, data on 332 laboratory investigations of PVC pipeline failures carried out by the Water Research Centre were analysed to ascertain the most common causes of failure(7). Samples submitted for laboratory investigation would not have included the obvious examples of mechanical damage, etc. where no investigation is warranted but are otherwise broadly representative. The pipes examined covered the entire size range of PVC pipes available from 2 to 24 inch diameter, the most common size ranges being 7 to 10 inch (25.4%) and 4 to 6 inch (23.2%). All pressure classes were also represented. The pipes had failed in normal operational service in all parts of Britain. All the pipes were pressure pipes but included both water mains and pumped sewage mains.

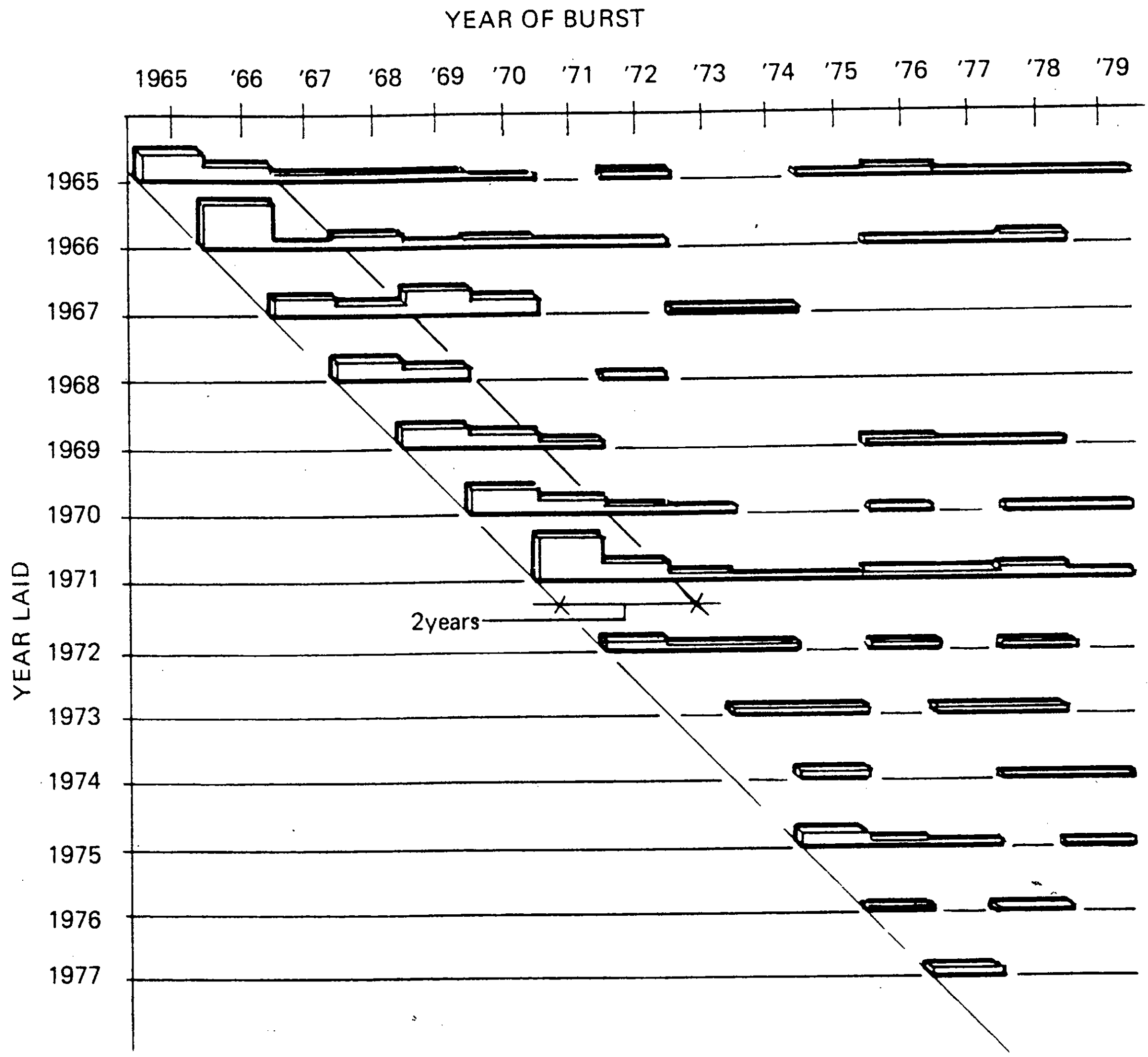

Fig. 3. Annual burst rate vs. year laid and year of burst.
(height of block represents failure rate)

The results of the analysis are shown in Table 5. The overall breakdown is as follows:

Manufacturing faults	23.2%
Laying and jointing faults	51.4%
Operational factors	15.2%
Unknown	10.2%

Table 5. Principal Causes of PVC Pipeline Failure (Analysis of 332 laboratory investigations)

Manufacturing Defects		
Inclusions		11.2%
Voids		3.5%
Spider line defects		2.5%
Dimensional or surface defects		6.0%
	Total	23.2%
Laying and Jointing Defects		
Ring displacement or seal fault		5.5%
Excess solvent cement		4.0%
Insufficient solvent cement or poor joint preparation		10.7%
Over-insertion		6.7%
Angularity or other bending moment		5.7%
Faulty backfill (point loading)		13.7%
Impact (on site)		5.1%
	Total	51.4%
Operational Factors		
Solvent attack (from pipe contents)		3.2%
Surge fatigue		5.7%
Tapping failures		2.6%
Miscellaneous known causes		3.7%
	Total	15.2%
Unknown Causes		10.2%

The most important single cause was found to be faulty backfill leading to point loading with large stones pressing against the pipe wall. This accounted for 13.7% of all the failures examined. The most common manufacturing defect was found to be inclusions either of unmixed additive or of burnt polymer in the pipe material, acting as internal stress raisers from which cracks developed (11.2%). Problems with solvent-cemented joints accounted for 14.7% of the failures. The most important operational factor found was fatigue due to surge pressure fluctuation. This accounted for 5.7% of all failures but was found to be particularly associated with pumped sewage systems and accounted for a much higher percentage of failures in this type of application. Failures which occurred during the tapping of a main under pressure for a service connection accounted for only 2.6% of the total but are nevertheless important because of possible hazard to personnel involved.

Surge Problems with Sewage Rising Mains. Where possible, sewage flows by gravity in unpressurised systems but must be pumped uphill where the terrain demands. PVC pressure pipes are used for this application which has been considered similar in requirements to that of pressurised water supply. Our investigations into pipeline failures established that pumped sewage systems are more liable to surge and are more severely stressed than equivalent water systems because of the occurrence of dynamic fatigue due to surge(8). Although surge can and does occur in water systems also(9) the essential difference is that the sewage system is designed to pump intermittently and the closing of the non-return valve when pumping ceases can generate large surge waves which are repeated at frequent intervals (Fig. 4) so that a large number of dynamic fatigue cycles can be built up rapidly. Gotham and Hitch(10) found in their laboratory tests that the maximum surge amplitude should not exceed 50% of the rated pressure of the pipe and that the peak positive surge pressure should not exceed the maximum rated pressure of the pipe in order to avoid reducing the PVC hoop strength safety factor. Our own investigation showed that these limits were being generally exceeded on sewer rising mains where PVC pipe failures had occurred. It has been found possible in most cases to reduce the slamming of the non-return valve to a safe level by a simple modification to the pumphouse control gear.

Conclusions. PVC pipe has now been in service for some 18 years in Britain for water supply pipes and pumped sewage applications and has gained widespread acceptance. Our researches indicate that earlier installations had a poor performance record due in part to lack of knowledge on the handling and installation of the new material. Pipes installed more recently have a failure record which is probably as good as, or even somewhat better than, cast iron pipes. Paradoxically, because of the time lag in communications, the performance of the pipes is being questioned at a time when their reliability is on the increase. Because pipelines have such a long life, many of these early problem installations will be making their presence felt for many years to come.

Although the performance of PVC pressure pipes may now be considered stable, water users feel justified in pointing out that, without corrosion problems, the service record of plastics pipes ought to be very much better than that of iron pipes and look for still further improvement in PVC pipe service reliability. Although many failures are due to handling and installation errors a greater tolerance of mishandling, which must inevitably occur to some extent in practice, would be appreciated.

This improvement may come through the adoption of a tougher specification for PVC pipe with tests related to the performance criteria recognised in service. The adoption, for instance, of a fracture toughness test(11) would have a considerable impact in boosting user confidence. Alternatively, there is a growing interest in other plastics pipe materials such as polyethylene and ABS which may offer greater toughness and resistance to crack propagation(12). There is,

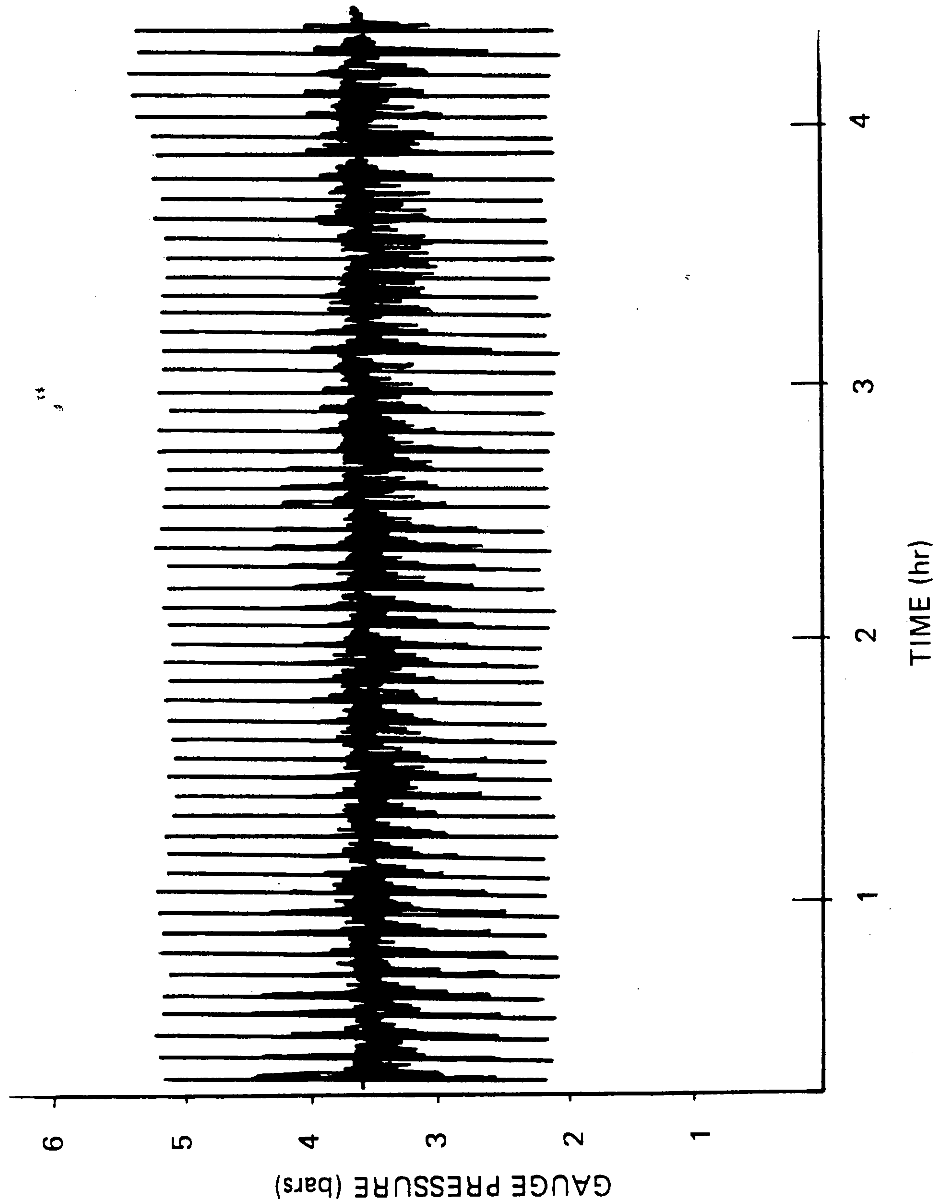

Fig. 4. Four hours in the life of a 24in. diameter uPVC Class B sewer rising main.

however, the prospect that, in the event of the introduction of another plastics pipe material we might have to live through another ten-year learning period such as we have already experienced, brought about by overselling the robustness of the product to the point where slipshod handling and installation practices are encouraged.

In any event the next few years look like being a period of considerable interest in the field of plastics pipe for water applications.

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