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DESIGN AGAINST SURGE AND FATIGUE CONDITIONS FOR THERMOPLASTIC PIPES

FOREWORD

Past advice on dealing with transient pressures in plastic pipelines given in the Pipeline Materials Selection Manual (PMSM) issued for the Water Industry in 1995 by WSA, has been recognised as being extremely conservative. New experimental data obtained for UKWIR (ref. 1) now make it possible to establish more realistic rating criteria to cope with 'surge and fatigue' conditions for the full range of thermoplastic pipe materials that are currently used by the Water Industry.

This Information and Guidance Note, which offers new advice, has been prepared by the Pipeline Innovation Group of UKWIR acting on behalf of the Water Mains and Services and Engineering and Operations Committees of the UK Water Industry.

This document is not intended to be used as a specification. Information contained within it is given in good faith but neither UK Water Industry Research Ltd, Water UK nor WRc plc can accept any responsibility for actions taken as a result.

It has been found that high toughness Polyethylene materials may be considered not to need any de-rating to cope with repeated cycling, but they must still be designed to resist over-pressurisation and collapse. Hence, advice is given here to cope with Surge and Fatigue as separate phenomena. This is consistent with the CEN approach expressed in the Water System Standard prEN805 which requires suppliers to

quote a maximum pressure (PMA) inclusive of surge which can be tolerated by any pipe.

It is not possible to give absolute design criteria, which will apply to each and every pipe construction scheme. When new pumping mains are to be designed it is strongly advised that a separate hydraulic analysis be conducted to assess the magnitude and frequency of surges from pumps and valves which are to be used. The design advice offered in this IGN can be used to assist in the choice of pipe wall thickness that is needed for any plastic pipes that may be considered.

However, it is also recognised that much of the UK capital expenditure on pipes is for the replacement and rehabilitation of the existing network. It may not be possible or practicable to carry out a surge analysis in such cases. Therefore, outline design advice is offered to cover those situations where present operational experience suggests that there are no unusual surge and fatigue problems from existing pumps and valves. For these cases, it is generally assumed that the peak pressure will be no more than twice the steady state condition. The frequency with which such surges occur is a matter for local judgment.

The scope of the guidance is generally limited to only those materials which meet the requirements of BS3505 (PVC-U), WIS 4-31-08 (MOPVC), WISs 4-32-03/09 (PE80 water and sewer pipes), WIS 4-32-13 (PE100 pipes) and the BSI PAS 27 Specification for modified PVC-A pipes. GRP pipes are not covered by this IGN.

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Any pipe or ancillary equipment (e.g. valves, fittings and services) made from materials NOT included above (including anchoring devices, thrust blocks and clamps) must be designed to resist the expected peak pressures in the system, as per the recommendations given in the Pipeline Materials Selection Manual.

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SECTION A: BACKGROUND

A.1 General

For many years, it has been the policy of the UK Water Industry to recommend that PVC-U and PE pipes be derated where mains are expected to be subject to repeated surge pressures. The design advice outlined in BS CP312 for PVC-U has been incorporated in the 1995 edition of the PMSM.

New research on the behaviour of high toughness PVC and PE pressure pipes conducted for the UK Water Industry by UKWIR has shown that changes should be made to the recommendations. Surge alone is not considered to be a major cause of problems experienced in service and it has been determined that the new high toughness PE materials are apparently not affected by repeated cyclic loading.

The British Plastics Federation have been consulted on the contents of this IGN as have all UK consultants and academics who have historically been involved with the fatigue testing of plastics. They have all expressed their approval of the new initiative.

A.2 Historical Design for Surge and Fatigue

In all plastic pipe specifications, suppliers are required to generate long term design data by testing pipes at different static pressures until they burst. The design basis requires that the stress predicted to result in failure at 50 years is determined. The Design Stress is established by application of a factor of safety and the Design Pressures are derived for pipes of various wall thicknesses.

In spite of the use of large safety factors and extensive long-term static pressure testing, there have been historic failures of PVC-U pipe manufactured in the 1960/70s. Such failures were initially assumed to have been caused by repeated over-pressurisation by surge (ref. 1). Subsequently a number of research programmes have shown that repeated load cycling will cause an accelerated decay in the strength characteristics of PVC-U (e.g. refs. 2 to 6). Hence, to guard against cyclic pressure

failures in PVC-U pipes, BS CP312 was amended in 1977 (ref. 7) to limit the maximum stress level, which could be applied.

CP312 recommends that the maximum pressure amplitude of a surge event should always be less than half the static pressure rating of the pipe. In some pumping situations, the pressure variation can be twice the static pressure rating and thus pipe thickness would need to be quadrupled to protect against the pressure excursions. In pipe design manuals produced by WRc on behalf of the Water Industry, BS CP312 criteria have been adopted and applied to PVC-U. However, although CP312 strictly only applied to PVC-U pipes, the criteria have also been extended to include PE pipes in the PMSM. This has led to more limited use of plastics pipes for pumped mains and to significantly increased costs where plastics have been specified.

There is compelling evidence to suggest that the prime cause of poor PVC-U performance was poor resistance to static overloading from bending stresses generated locally by point loads. When new Water Industry and British Standards were introduced requiring suppliers to increase the fracture toughness of PVC-U pipes, the failure rates of pipes decreased. Water Company burst records show that PVC-U pipe made to the high toughness criteria into UK Specifications in 1986 (and adopted by British Standards in BS3505) have performed satisfactorily.

There have been few reported failures of any high toughness PVC, MOPVC or PE pipes due to surge or fatigue conditions.

A. 3 Definitions - Surge and Fatigue

A.3.1 Effects of Surge and Fatigue

'Surge and Fatigue' are often combined as a collective term. However although both phenomena arise from the same events (valves closing quickly, pump shut down etc.) they

should be considered separately since they describe different effects on the pipe material.

Surge generates pressures generally rising in excess of the static rating with the pressure being applied in very short timescales.

Fatigue is associated with cyclic pressure variation that is applied on a repeated basis over a long term. It is a condition often occurring below the rated pressure.

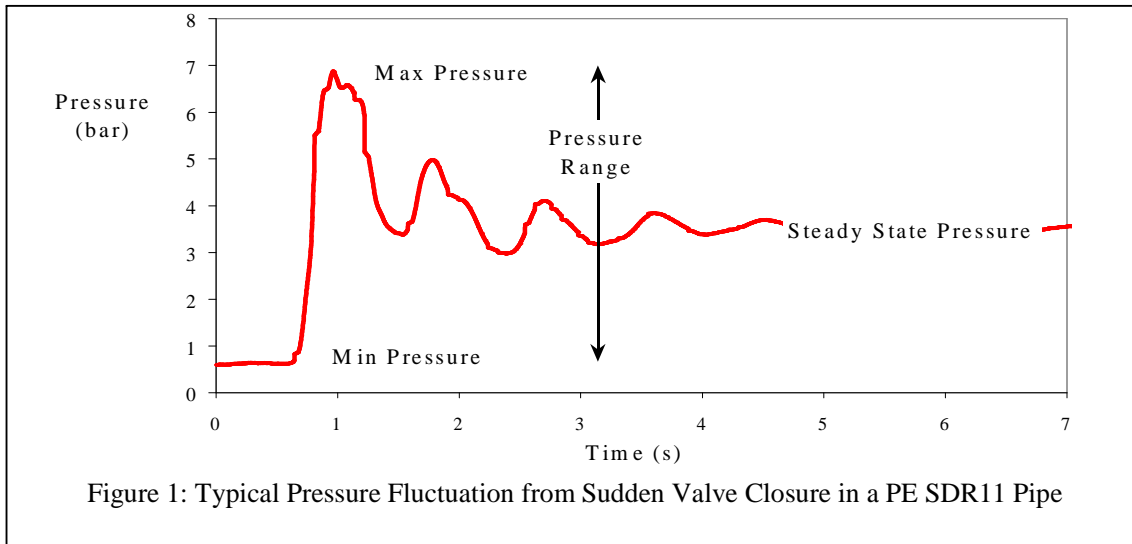
In a pumped system, the most frequent events that cause unsteady variations in pressure are pump start-up/shutdown. Secondary events such as air and line valves opening and closing could also generate pressure excursions. Generally, it is the fast closing of valves and uncontrolled pump shutdowns that cause the most severe changes and oscillations in pressure (ref. 8).

It should be noted that the stiffnesses of plastic pipes are lower than for metal/AC pipes and thus the pressure shock wave transmission speeds are lower. Consequently, the pressure rise rates and peak levels will be much reduced.

It is thus important that designers who are conducting hydraulic simulations use the correct short-term modulus for each material (as given in Table 1), so that realistic results are obtained.

A.3.2 Defining Surge

Surge creates fluctuations in pressure about the steady state level. The initial rate of pressure change is very high but of short duration. The fluctuations decay rapidly. An extreme pressure fluctuation trace caused by the instantaneous closing of a solenoid valve on a 25mm PE pipe is shown in figure 1. For larger distribution and branch mains, the rise rates will be lower but nevertheless, the peak pressure may be considerably in excess of the steady state case, and the minimum value may be sub-atmospheric. Extremes of both high and low pressure may cause damage. High-pressure peaks may cause pipe rupture.



If sub-atmospheric troughs occur, these may cause wall collapse by buckling and for a system joined by sockets and spigots there may be permanent problems with sealing ring displacements.

Problems with very low pressures will be less severe in a welded PE system since localised deformation caused by an extreme sub-atmospheric surge will be recovered when the pressure is restored.

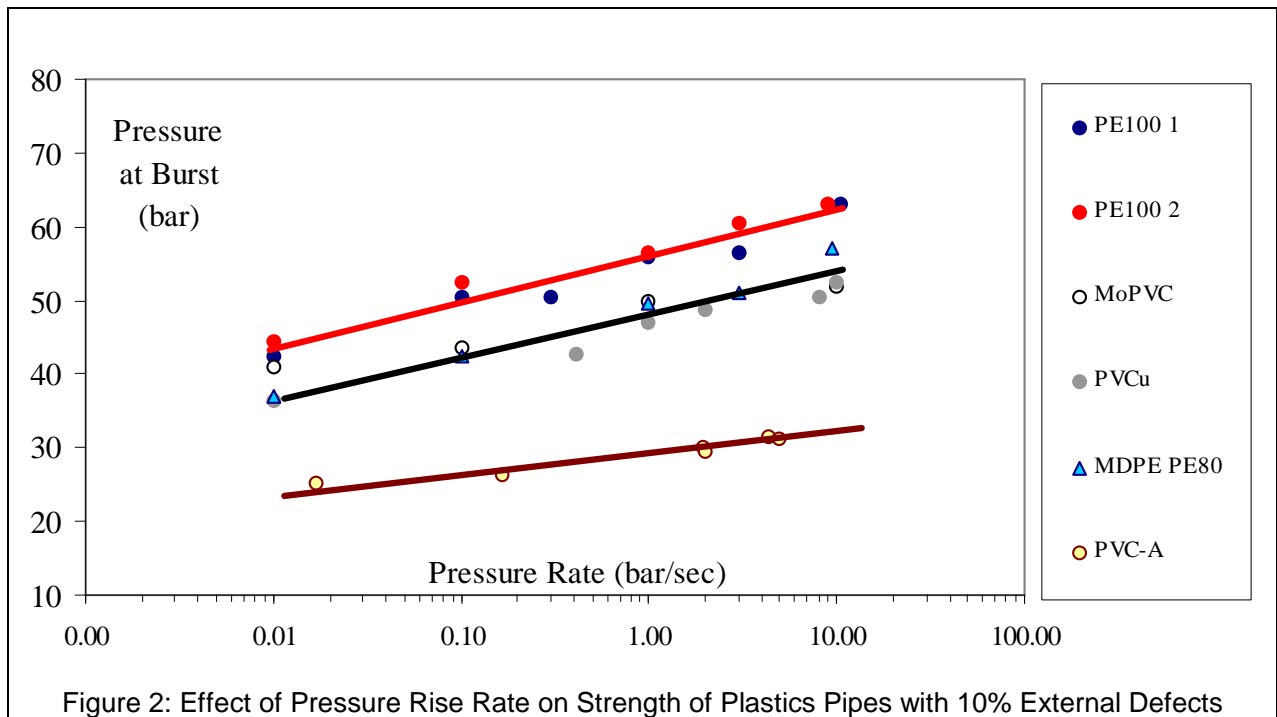
In both cases however, designers need to avoid difficulties by designing the wall section to give the pipe sufficient reserves of strength and stiffness to operate without fear of failure by over-pressure or collapse by buckling.

A.3.3 Response of Thermoplastics to High Rate Loading

Thermoplastics such as PVC and PE respond to high rates of loading by exhibiting greater strength and stiffness, since the materials' entangled molecular chain structure provides resistance to deformation. Hence, at high pressurisation rates pipes are better able to resist the higher stress levels generated by surge. Also, the strength of both materials will increase with high rates of loading.

Independent tests for UKWIR have been made on various pre-notched (10% of wall) PVC and PE pipes where the pressure was raised at different rates until failure occurred. The data are shown in figure 2 where pressures at failure for PVC and PE pipes are shown to increase as a function of loading rate.

Clearly, if a large crack has been growing due to long term static overloading (e.g. via point loading of a pipe resting on a boulder), then any surge may cause failure to occur prematurely. This often happened with low toughness PVC-U.



A.3.4 Defining Fatigue

Fatigue is often associated with repeated pressure variations about a mean value. The difference between the maximum and minimum pressures is defined as the 'range' (see figure 1). It is the cyclic loading condition that has caused brittle crack initiation and premature crack growth at low stress levels in metals in many applications.

This is not a problem with the slow diurnal pressure cycles which frequently occur in distribution systems, but in circumstances where short term surges may be repeated at frequent intervals, there is concern that there may be a weakening of pipes due to fatigue.

From experimental studies, it is commonly accepted that it is the total pressure range, which determines the decrease in lifetime in fatigue. Therefore, before considering choice of

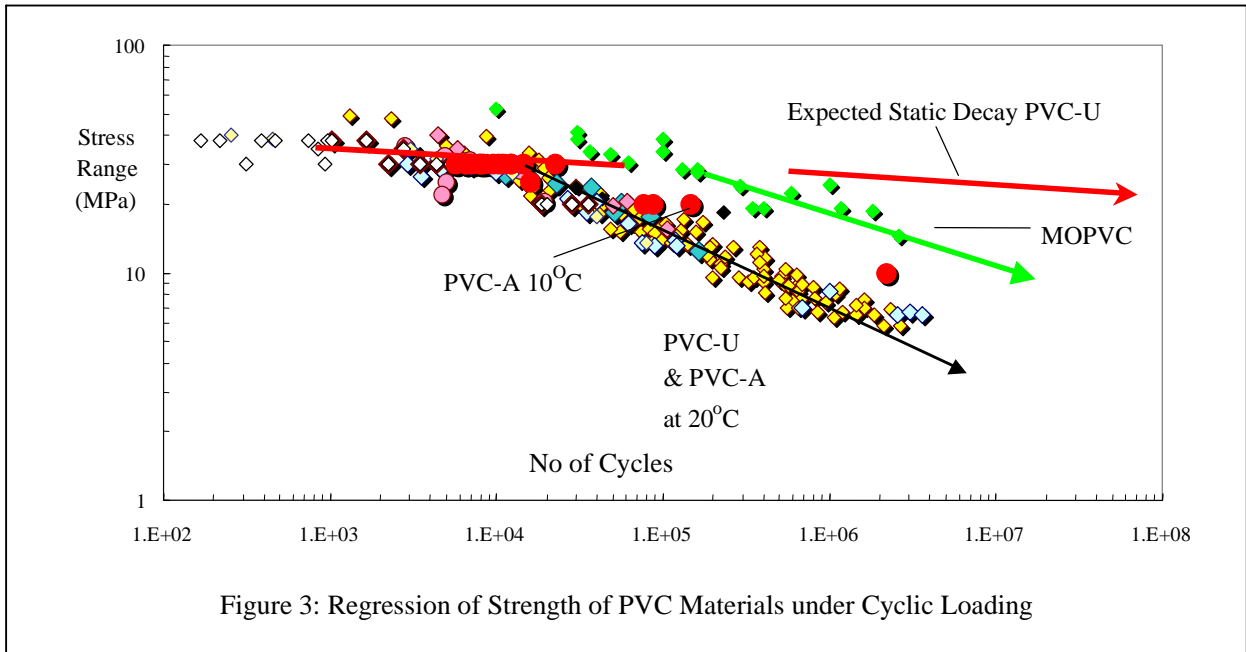
the appropriate pipe rating, the designer should know the maximum and minimum pressures, which are to be expected in a surge event. This may be determined by carrying out a formal surge analysis.

Designers of discrete pumped mains are recommended to conduct studies to determine expected pressure excursions – using moduli and stiffnesses relevant to the material concerned.

A.3.5 Materials Behaviour : Cyclic Loading

a) PVC Materials

Many historical research programmes have shown that:



- the long term properties of PVC-U and those with added impact modifiers (PVC-A) are reduced significantly by repeated cyclic loading.
- The presence of notches, scores and other defects in the pipe walls will further reduce the overall pipe lifetime.
- Different types of PVC-U and PVC-A have similar cyclic loading resistance. Adding the modifier does not increase resistance to cyclic loading.
- Increasing the static toughness of PVC-U also has no effect on improving the fatigue lifetime.
- Introducing molecular orientation into PVC pipe walls has been found to give significant improvements to the resistance to failure from cyclic loading.

b) PE Materials

For PE pipes, there is no reported history of service problems caused by long term failure due to fatigue. Moreover, research studies have shown that the fatigue resistance properties of various PE types can be significantly different.

The experimental data generated as part of the UKWIR programme (ref. 1) show that PE80 and PE100 materials which have satisfied the stress crack resistance requirements in current Water Industry Specifications do not have significant reductions in lifetimes under cyclic loading.

There is thus no need to de-rate their static pressure rating to account for fatigue. This is a significant change to the advice in the PMSM. However, other test data reported in the literature do indicate that PE materials with low long term static stress crack resistance below the requirements of WIS specifications can be made to fail prematurely under cyclic loading (see figure 4). As with PVCs, there is a need to de-rate (as recommended in the PMSM) for these types of PE.

A.3.6 Effect of Temperature

A recent study (ref. 10) has shown that altering the test/service temperature can significantly alter the lifetime of PVC-A pipes (see figure 5). Reducing temperature from 30°C to 5°C gives an order of magnitude increase in lifetime. PVC-U lifetimes are changed in the same way, but to a significantly lower degree.

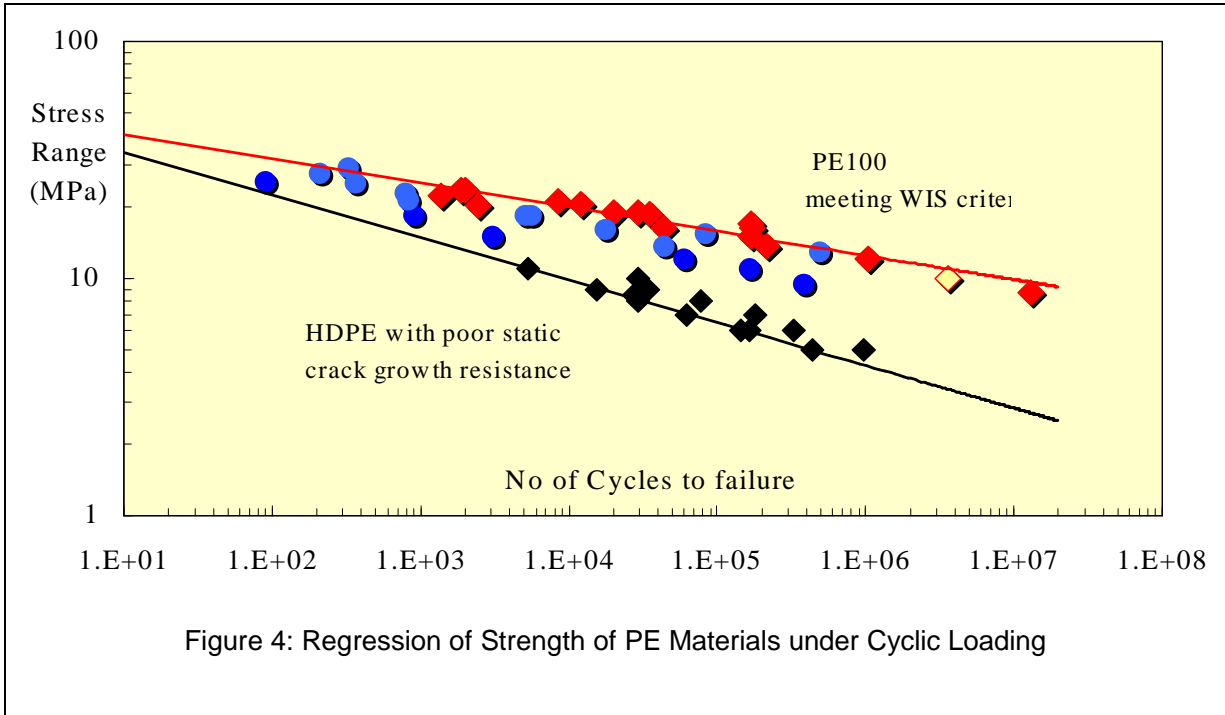


Figure 4: Regression of Strength of PE Materials under Cyclic Loading

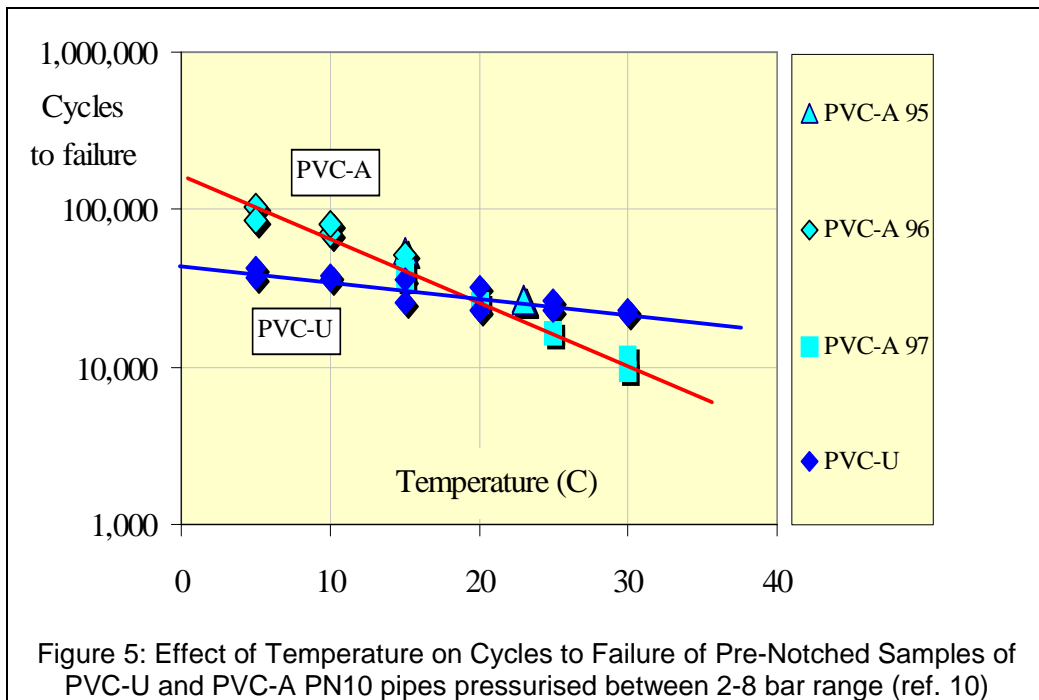


Figure 5: Effect of Temperature on Cycles to Failure of Pre-Notched Samples of PVC-U and PVC-A PN10 pipes pressurised between 2-8 bar range (ref. 10)

B. DESIGN FOR SURGE AND FATIGUE

B.1 Surge Design

During routine operation of a water pipe system, there are random, isolated events where pressures may surge to high levels without causing fatigue problems (e.g. emergency pump shut downs). It is necessary to specify the allowable pressure limits for each material to resist these peak surge events. A value for maximum pressure resistance including surge (PMA) will be an EN requirement when prEN805 is ratified.

It is also necessary to consider the effects of single surges on buckling resistance when the minimum pressure drops to sub-atmospheric levels.

B.2 Pressure Ratings to Resist Surge

It is the responsibility of the system designer to choose whether to conduct a formal surge analysis. For all rising mains, trunk mains and special pump/valve circumstances a detailed surge analysis should be conducted. For the identification of the peak surge, the worst anticipated event (e.g. emergency trip of all pumps) should be considered.

As part of a joint Water Industry and BPF research programme (ref. 8) and from detailed

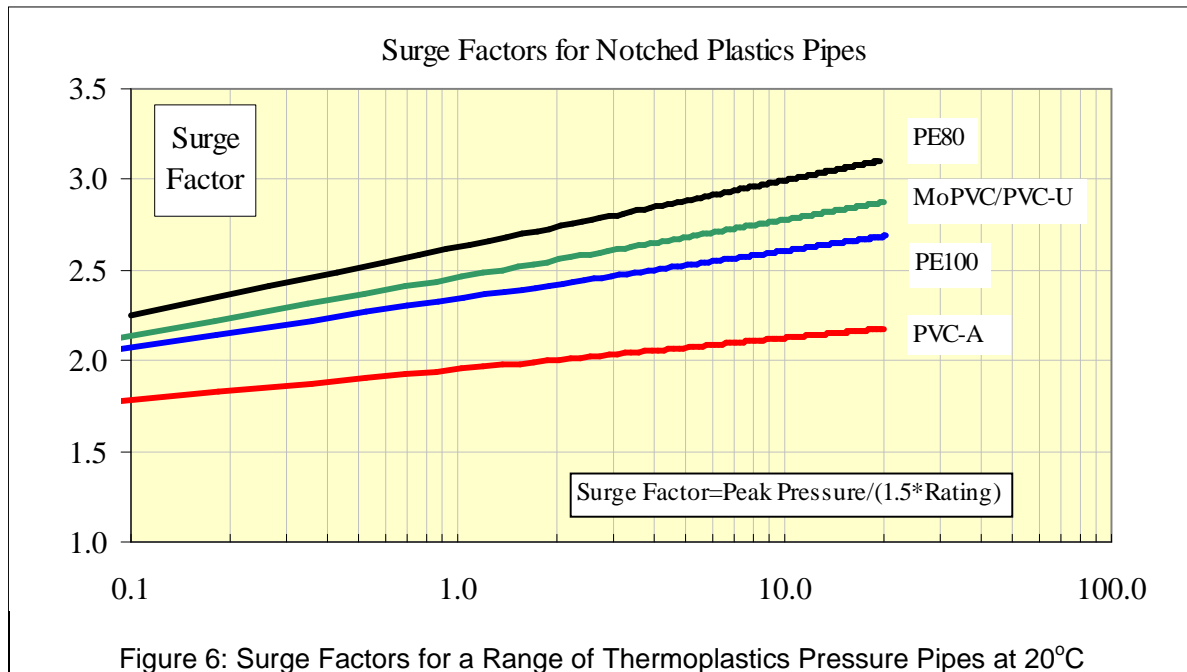
inspection of historical designs and field measurements by Hydraulic Analysis Ltd., it has been determined that for PE pipes in distribution systems, no surge event showed rise rates of more than 8 bar/sec.

The evidence from testing (figure 2) shows that standard thermoplastics used by the UK Water Industry will sustain pressures in excess of twice their static ratings at such high rates of pressure rise.

To determine the allowable pressure resistance of thermoplastic pipes, it is possible to use data relating pressure resistance to the rate of pressure rise (figure 2) to compute 'surge factors'.

Multiplying the pipe rating by the factors gives a good indication of the maximum pressure which can be sustained at any given pressure rise rate.

Note: The peak failure pressures in tests at all rise rates have been divided by a safety factor of 1.5 and then by the pressure rating to produce figure 6.



B.3 Example of Use of Surge Factors

Suppose the hydraulic analysis of a scheme indicated that:

- The steady state pressure was determined to be 6 bar.
- The pressure rise rate for the worst case 'event' was calculated to be 4 bar/sec and the peak pressure was predicted to be 12 bar.
- From figure 6, the surge factor for PE 100 at 4 bar/sec would be 2.5. Therefore a pipe rated at 6 bar (PN6) for static pressure would be capable of resisting a peak surge pressure of 15 bar (6*2.5). This would be secure.

Note: if the designer opts to increase the wall section to gain a greater safety factor, then the surge analysis should be repeated since the surge calculation itself is dependant on the SDR which is used. Stiffer pipes will cause higher wave speeds and peak values to be generated.

B.4 Resistance to Buckling

Where a surge 'event' creates a sub atmospheric pressure, the design should consider resistance to collapse. The backfill/native soil stiffnesses dominate all underground deformations of a flexible pipe and the new UK design procedure in the annex to EN1295 gives the appropriate formulae for calculating the safety factors for buckling resistance.

Where there are doubts about the potential site conditions, designers should carry out a detailed analysis both of the ground conditions as well as projected operational loadings.

The modulus of the native soil needs to be estimated and the type of in-fill and its compaction need to be specified to ensure adequate support to the pipe. Because pipe installations may be made in widely different soil types and using different in-fill materials, it is only appropriate to give general guidance for vacuum collapse for worst case burial conditions.

Using short term modulus values given in Table 1, specimen results are given for a range of different pipes and pressure classes where extreme conditions are assumed for pipes operating in conventional distribution systems.

It can be seen that for an assumption of pipe with typical ovality (10% for coiled PE, 5% for PVCs) there are adequate safety factors for a full vacuum generated by the surge 'event'. This should give confidence that buckling is not a problem for well installed pipes, since the calculations here assume poor ground and barely adequate backfill properties.

Where PE pipes are installed by slip lining an existing pipe or bursting out an old iron main such that there is no soil surround, calculations show that all pipes with ratings of SDR 26 or lower, retain safety factors of at least 2.

	E (MPa)	PN16	PN12.5	PN10	PN8	PN6
HPPE	1700	3.4		2.1	1.7	1.4
MDPE	1400		3.2		2.0	
PVC-A	3300	3.1	2.5	2.0	1.8	
PVC-U	3500		3.6		2.4	
MOPVC	3300	2.4	2.0			

Table 1: Safety Factors for resistance to transient vacuum for 'oval' thermoplastic pipes

For PE pipes installed by directional drilling, including beneath rivers with up to 5m depth, PE pipes with an SDR 17 or lower should be specified where negative surges up to 1 bar are expected. Higher SDRs should only be used where specific design calculations have been carried out.

To optimise pipe sizes on large single contracts, it is always wise to use data from surge simulations and to have local knowledge of specific ground conditions. The EN1295 design procedure can then be carried out - using material property data from the pipe supplier.

B.5 Design for Fatigue of Thermoplastic Pipes

It is now recommended that the design advice to cover cyclic loading conditions given in the PMSM should be modified for cases where frequent cyclic loading is to be expected:

1. There should be no de-rating at all for those PE materials, which meet the stress crack resistance requirements of WISs 4-32-03, 4-32-09 and 4-32-13.
2. For all other PE materials where WIS assessment has not been made, the pressure rating should be chosen to take account of the number of fatigue cycles to be expected.

To avoid this restriction, it is strongly advised that all procurement contracts ensure that only PE pipes which have excellent crack growth resistance are purchased and then de-rating is not an issue.

3. For all PVC based materials, there should be de-rating to allow for the decrease in strength as a function of repeated cyclic loading.

(N.B. The de-rating factors for all materials are based on test data obtained at 20°C).

4. Wherever de-rating is considered necessary, the fatigue data from laboratory tests (e.g. figures 3 and 4) have been fitted to power law functions to give the re-rating criteria in Table 2.

The predicted pressure/stress range should be multiplied by the tabulated re-rating factors to give the pipe rating required to safeguard against fatigue.

It should be noted that:

- a) MOPVC has lower re-rating factors because the stress carrying capacity is less sensitive to cyclic loading.
 - b) PVC-A materials have higher factors because the cyclic properties are the same as for PVC-U, but the static design stress is higher.
 - c) The factor of 0.5 for high toughness PE materials is indicative of no de-rating.
5. Where the pipeline is operated at other temperatures, the factors need multiplication by the coefficients given in section B.5.1.

Note 1: When considering fatigue, the range used should be the maximum value for the frequently repeated events (e.g. pump start/stop), but the frequency and total number should relate to all events (pump starts and stops, reflected transients etc.).

Note 2: The extreme emergency case of total pump shutdown should not be a repeated event and only needs to be considered in the surge design to ensure that extreme high and low pressures are considered.

Daily Frequency	Hourly Frequency	Total Cycles in 50 years	PVC-U	PVC-A	MOPVC	MDPE, HDPE	High Toughness PE80, PE100
			Rating Factor	Rating Factor	Rating Factor	Not tested to WIS	Tested to WIS
4	0.2	73,000	0.7	1.0	0.6	1.1	0.5
24	1.0	438,000	1.3	1.7	0.9	1.5	0.5
48	2.0	876,000	1.5	2.1	1.1	1.7	0.5
120	5.0	2,190,000	2.0	2.8	1.3	2.0	0.5
240	10.0	4,380,000	2.5	3.5	1.5	2.3	0.5
1200	50.0	22,000,000	4.0	5.6	2.0	3.0	0.5

Table 2: Recommended Fatigue Re-rating Factors for Plastics Materials

B.5.1 Effect of Temperature on Re-Rating

At temperatures below 20°C, the lifetime of PVC-A at a given stress range is enhanced to a significant degree. In clean water systems, the average water temperature in a buried PVC-U pipe in the north of England (measured over a two year period) has been found to be 11°C (ref. 11).

Thus, it is open to the design engineer to consider relaxation of the allowable de-rating if it is considered that the cyclic loading will occur over a long timescale where the average temperature is appropriate.

At higher temperatures, there is a reduction in lifetime for PVC materials and for pumped sewerage mains it may be appropriate to consider average operation at a higher than ambient temperature.

The coefficients which should be used to multiply the 20°C re-rating factors given in Table 2 are presented for a range of temperatures in Table 3.

It is a matter for the design engineer's judgement to decide the operating temperature. If temperatures below 20°C are appropriate, multiplying by the coefficients gives lower de-rating factors and vice versa for temperatures above 20°C.

Note: For MOPVC and PE materials, the allowable stress rating is recommended to be adjusted by 1.3% for every °C in excess of 20°C – to account for a simple loss in static strength.

Temperature (°C)	5	10	15	20	25	30
PVC-A	0.67	0.72	0.85	1.0	1.14	1.3
PVC-U	0.89	0.91	0.97	1.0	1.03	1.07

Table 3: Coefficients to Multiply Table 2 Re-Rating Factors to account for Temperature

B.5.2 Examples of Use of De-Rating Factors

If, for a pipe operating at 15°C with a static pressure of 3 bar, it was estimated that there would be 2 cycles/hr of pressures varying over a range of 0-6 bar, then the pipe pressure rating should be:

- at least 8.73 bar ($>0.97 \times 1.5 \times 6$) for PVC-U
- at least 10.84 bar ($>0.85 \times 2.1 \times 6$) for PVC-A
- at least 6.7 bar ($>1.1 \times 6$) for MOPVC and
- at least 10.2 bar ($>1.7 \times 6$) for PE which has not been assessed to WIS criteria
- at least 3 bar ($>0.5 \times 6$) for PE80 and PE100 which have passed WIS testing

For PVC-U, a PN10 rating would be selected,

For PVC-A, a PN12.5 rating would be needed,

For MOPVC, the lowest rating is PN12.5 and this is clearly secure,

For the PE with no WIS assessment, PN12.5 (SDR11 PE80) or PN10 (SDR17 PE100) ratings would be needed.

For high toughness PE80 and PE100 pipes, which have met all the strict long term crack growth requirements, no fatigue de-rating is needed and a PN4 (SDR 26) pipe could be used.

It should be noted that the pressure rating of selected pipe must always be greater than the maximum static steady state pressure.

C. REFERENCES

1. Marshall, G.P., Brogden, S: Final report of Pipeline Innovation Contract to UKWIR 1997.
2. Kirby P.C.; Plastic Pipes V, PRI, York, (1981).
3. Joseph S.H.; Plast. & Rubb. Proc. & Appl. 4, pp.325 (1984).
4. Stapel J. J.: Pipes & Pipelines Int., pp 11 & 33 February (1977).
5. Mandell J.F., Chevaillier J.-P.F., Poly. Eng. & Sci. 25, 170, February (1985).
6. Gotham K.V., Hitch M.J., Pipes & Pipeline Int., pp 10 February (1975).
7. Constable I., Williams J.G., Burns D.J., J. Mech. Eng. Sci., 12, 1, (1970).
8. British Standard Code of Practice 312, Part 2 (1973), Amendment AMD 2337 (September 1977), BSI, London.
9. Beech S.H., Headford A., Hunt S, Plastics Pipes IX, IOM, Edinburgh, 1995.
10. Lawrence, C., Teo, S., Potter, R.: Plastics Pipes X, pp743-752, IOM, Gotttenburg, 1998.
11. Birch, M.W., Marshall, G.P.: Final report of Pipeline Innovation Contract to UKWIR 1997.