Industry Guidelines

PVC PRESSURE PIPES
DESIGN FOR DYNAMIC STRESSES

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PVC Pressure Pipes
Design for Dynamic Stresses

This guide is intended to assist in the selection of PVC-U, PVC-M and PVC-O pipes in applications involving cyclic operating pressures.

Introduction

PVC pressure pipes are designed on the basis of a burst regression line for pipes subjected to constant internal pressure. From this long term testing and analysis, nominal working pressure classes are allocated to pipes as a first indication of the duty for which they are suitable. However, there are many other factors which must be considered, including the effects of dynamic loading. Whilst most gravity pressure lines operate substantially under constant pressure, pumped lines frequently do not. Pressure fluctuations in pumped mains result from events such as pump start-up and shutdown and valves opening and closing. It is essential that the effects of this type of loading be considered in the pipeline design phase to avoid premature failure. This note is intended to assist in the selection of pipe class for PVC pipes in applications involving transient and cyclic operating pressures.

The approach adopted for pipe design and class selection when considering these events depends on the anticipated frequency of the pressure fluctuation. For frequent, repetitive pressure variations, the designer must consider the potential for fatigue and design accordingly. For random, isolated surge events, for example, those which result from emergency shutdowns, the designer must ensure that the maximum and minimum pressures experienced by the system are within acceptable limits.

Definitions

Surge

For the purposes of this document, surge is defined as a rapid, very short-term pressure variation caused by an accidental, unplanned event such as an emergency shutdown resulting from a power failure. Surge events are characterised by high pressure rise rates with no time spent at the peak pressure.

Fatigue

In contrast, fatigue is associated with a large number of repetitive events. Many materials will fail at a lower stress when subjected to cyclic of repetitive loads than when under static loads. This type of failure is known as (cyclic) fatigue. For thermoplastic pipe materials, fatigue is only relevant where a large number of cycles are anticipated. The important factors to consider are the magnitude of the stress fluctuation, the loading frequency and the intended service life. Where large pressure fluctuations are predicted, fatigue design might be required if the total number of cycles over the intended lifetime of the pipeline exceeds 25,000. For smaller pressure fluctuations, a larger number of cycles can be tolerated.

Pressure Range (amplitude)

Pressure range is defined as the maximum pressure minus the minimum pressure, including all transients, experienced by the system during normal operations

Diurnal pressure changes

Diurnal pressure changes are gradual pressure changes which occur in most distribution pipelines as a result of daily demand variation. It is generally accepted that diurnal pressure changes will not cause fatigue. The only design consideration required for this type of pressure fluctuation is that the maximum pressure should not exceed the pressure rating of the pipe.

Surge design

It has long been recognised that PVC pipes are capable of handling short-term stresses far greater than the long-term loads upon which they are designed. That is, PVC pipes can cope with higher pressures than they are designed for provided the higher pressures are of only a short duration. However, this characteristic feature is not utilised in design in Australia and design recommendations advise that the peak pressure should not exceed the nominal working pressure of the pipe. This recommendation is based on the fact the pipes should not be considered in isolation but as part of a system. Whilst the pipes themselves might be capable of withstanding occasional, short duration exposure to pressures in excess of the design pressure, the same assumption may not apply to the complete pipeline system.

Where the generation of negative pressures is anticipated, the possibility of transverse buckling should be considered. This topic is addressed elsewhere.

Fatigue design

The fatigue response of thermoplastics pipe materials, particularly PVC, has been extensively investigated (1-18). The results of laboratory studies can be used to establish a relationship between stress range, defined here as the difference between the maximum and minimum stress (see Fig 1), and the number of cycles to failure. From these relationships it is possible to derive load factors that can be applied to the operating pressures, to enable selection of an appropriate class of pipe.

This type of experimental data inevitably has a degree of scatter and it has been Australian practice, after Joseph (3), to adopt the lower bound for design purposes. This approach is retained here because it ensures the design has a positive safety factor and recognises that pipelines may sustain minor surface damage during installation, which could promote fatigue crack initiation. Note that for fatigue loading situations, the maximum pressure reached in the repetitive cycle should not exceed the static pressure rating of the pipe. Recommended fatigue cycle factors for PVC-U, PVC-M and PVC-O are given in Table 1.

TABLE 1

Total Cycles	Approx. No. Cycles /day for 100y life	Fatigue Cycle Factors, f		
		PVC-U	PVC-M	PVC-O
26,400	1	1	1	1
100,000	3	1	0.67	0.75
200,000	5.5	0.81	0.54	0.66
500,000	14	0.62	0.41	0.56
1,000,000	27	0.50	0.33	0.49
2,500,000	68	0.38	0.25	0.41
5,000,000	137	0.38	0.25	0.41
10,000,000	274	0.38	0.25	0.41

Using Table 1, the Maximum Cyclic Pressure Range for a given class of pipe can be calculated from the following formula:

$$\text{MCPR} = \frac{\text{PN}}{10} \times \text{f}$$

Charts plotting the MCPR versus the number of cycles for a range of pressure classes of PVC-U, PVC-M and PVC-O pipes are plotted in Appendix A.

Procedure

To select the appropriate pipe class for fatigue loading, the following procedure should be adopted:

1. Estimate the likely pressure range, ΔP, i.e., the maximum pressure minus the minimum pressure.
2. Estimate the frequency or the number of cycles per day which are expected to occur.
3. Determine the required service life and calculate the total number of cycles which will occur in the pipe lifetime
4. Using the appropriate chart in Appendix A draw a vertical line from the x-axis at ΔP and a horizontal line from the y-axis at the total number of cycles in the pipe lifetime.
5. Find the intersection point between the horizontal and vertical lines.
6. Select the pipe class that bounds the region of this intersection point as the minimum required for these fatigue conditions.

Definition of Pressure Range

For simplicity, the pressure range is defined as the maximum pressure minus the minimum pressure, including all transients, experienced by the system during normal operations as shown in Figure 1. The effect of accidental conditions such as power failure may be excluded.

Figure 2 also illustrates the definition of a cycle as a repetitive event. In some cases, the cycle pattern will be complex and it may be necessary to also consider the contribution of secondary cycles.

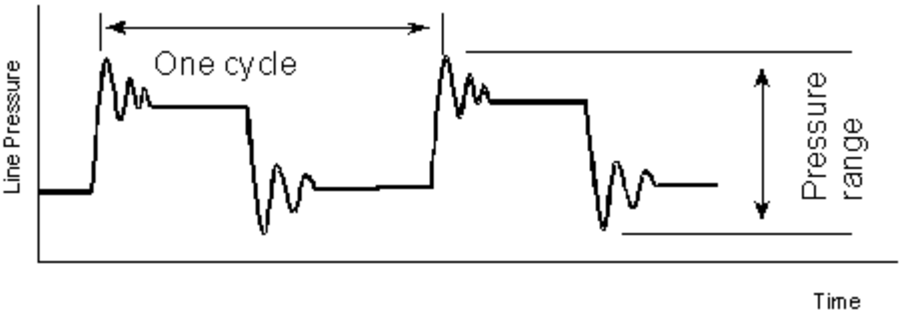

Figure 1 : Pressure Cycle

Complex Cycle Patterns

Pumping systems are frequently subject to surging following the primary pressure transient on switching. Such pressure surging decays exponentially, and in effect, the system is subjected to a number of minor pressure cycles of reducing magnitude. In order to take this into account, the effect of each minor cycle is related to the primary cycle in terms of the number of cycles which would produce the same crack growth as one primary cycle.

Using this technique, it is shown in Reference (3) that a typical exponentially decaying surge regime is equivalent to 2 primary cycles. Thus for design purposes, the primary cycle amplitude only is considered, with the frequency doubled.

In general, similar technique may be applied to any situation where smaller cycles exist in addition to the primary cycle. Empirically crack growth is related to stress range according to $(\Delta\sigma)^{3.2}$. Thus, n secondary cycles of magnitude $\Delta\sigma_1$ may be deemed equivalent in effect to one primary cycle,

where
$$n = \left(\frac{\Delta\sigma_0}{\Delta\sigma_1}\right)^{3.2}$$

For example, a secondary cycle of half the magnitude of the primary cycle:

$$n = \left(\frac{2}{1}\right)^{3.2} = 9.2$$

so it would require 9 secondary cycles to produce the same effect as one primary cycle. If they are occurring at the same frequency, the effective frequency of primary cycling is increased by 1.1 for the purpose of design.

Example

A sewer rising main has a pump pressure, including static lift and friction losses, of 400 kPa. When the pump starts up, the pressure rises rapidly to 950 kPa before decaying exponentially to the static pumping pressure.

On pump shut down, the minimum pressure experienced by the system is 100 kPa. On average, the pump will start up 8 times per day. A minimum life of 100 years is required.

The maximum pressure experienced indicates that a minimum class of PN10 will be required. A fatigue analysis is now needed in order to determine suitability or otherwise of PN10.

In this system, the pressure range is 850 kPa. The pump will start up approximately 292,000 times in a 100 year lifetime. However, the exponential cycle pattern means that this should be doubled for design purposes. Therefore, the system should be designed to withstand approximately 584,000 cycles in a 100 year lifetime.

Using Table 1 to determine the fatigue load factors for PVC pipes at 5.8×10^5 cycles gives the following class selection:

Material	Fatigue Cycle factor, f (Table 1)	Maximum Cyclic Pressure Range (MPa)	Minimum Pipe Class selection
PVC-O	0.54	PN12.5 = 1.25 x 0.54 = 0.675	PN16
		PN16 = 1.6 x 0.54 = 0.86	

The graphical procedure is demonstrated in Figure 2. Using the charts in Appendix A, draw a vertical line from the pressure range on the x axis and a horizontal line from the number of cycles on the y axis. Find the intersection of these two lines and read off the pipe pressure class that bounds this region. In this example, the intersection point lies in the region bounded by the PN16 curve so PN16 is required for PVC-O pipe for fatigue loading.

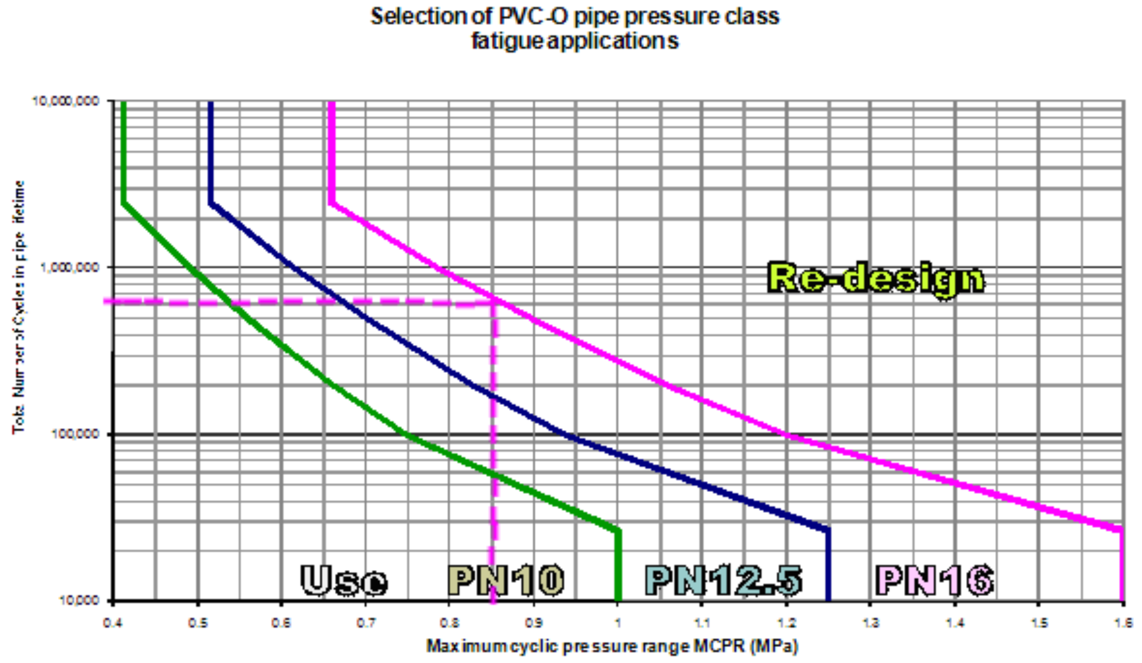

Figure 2

The fatigue analysis thus determines that although PN10 is adequate for the maximum pressure, a minimum PN16 pipe is needed for PVC-O, in order to cope with fatigue effects.

Effect of Temperature

Few data have been established concerning the relationships between fatigue performance and temperature. Reference 3 suggests that effects are marginal if any within the range of normal pipeline operating temperatures.

Normal temperature de-rating principles should be applied in class selection for maximum operating pressure. Fatigue should then be considered separately and the highest pressure class selected.

That is, select the highest class arrived via:

a) Static design including temperature derating; or
b) Dynamic design as covered herein.

Safety Factors

The fatigue design guidelines presented in Table 1 and Appendix A are based on the lower bound of laboratory test data or have a safety factor incorporated. They are therefore considered conservative and no additional safety factor need be applied in general. However, where the magnitude or frequency of dynamic stresses cannot be estimated in design with any reasonable degree of accuracy, appropriate caution should obviously be applied. This judgement is in the hands of the designer.

Whilst it is always possible to predict the steady operating conditions with good accuracy, it will occasionally be the case, in complex systems, that it is impossible to predict the extent of surge pressures. In such circumstances, relatively low cost surge mitigation techniques, for example solid-state, soft-start motor controllers, should be considered. It is of course recommended that actual operating conditions for all systems should be measured, as a matter of routine, when the system is commissioned. Should surge pressure amplitudes in the event exceed expected levels, it is relatively easy matter to retrofit control equipment to ensure that they are kept in check.

Design Hints

To reduce the effect of dynamic fatigue in an installation, the designer can:

- Limit the number of cycles by:
  - Increasing well capacity for a sewer pumping station;
  - Matching pump performance to tank size to eliminate short demand cycles for an automatic pressure unit; or
  - Using double-acting float valves or limiting starts on the pump by the use of a time clock when filling a reservoir.
- Reduce the dynamic range by:
  - Eliminating excessive water hammer; or
  - Using a larger bore pipe to reduce friction losses.

Fittings

Thermoplastics fittings present a special problem. The geometry of fittings can result in complex stress patterns which 'amplify' the apparent stress cycle. An apparently harmless pressure cycle can thus produce a damaging stress cycle leading to a shortened fatigue life. This is particularly important in the case of branch fittings such as tees. In addition, the situation can be aggravated further by the existence of stresses from other sources, for example bending stresses induced by flexing under hydraulic thrust in improperly supported systems.

Since the design of fittings is not standardised, the fittings manufacturer should be consulted for recommended de-rating factors for cyclic loading conditions. It is therefore necessary to consider fittings separately from pipe.

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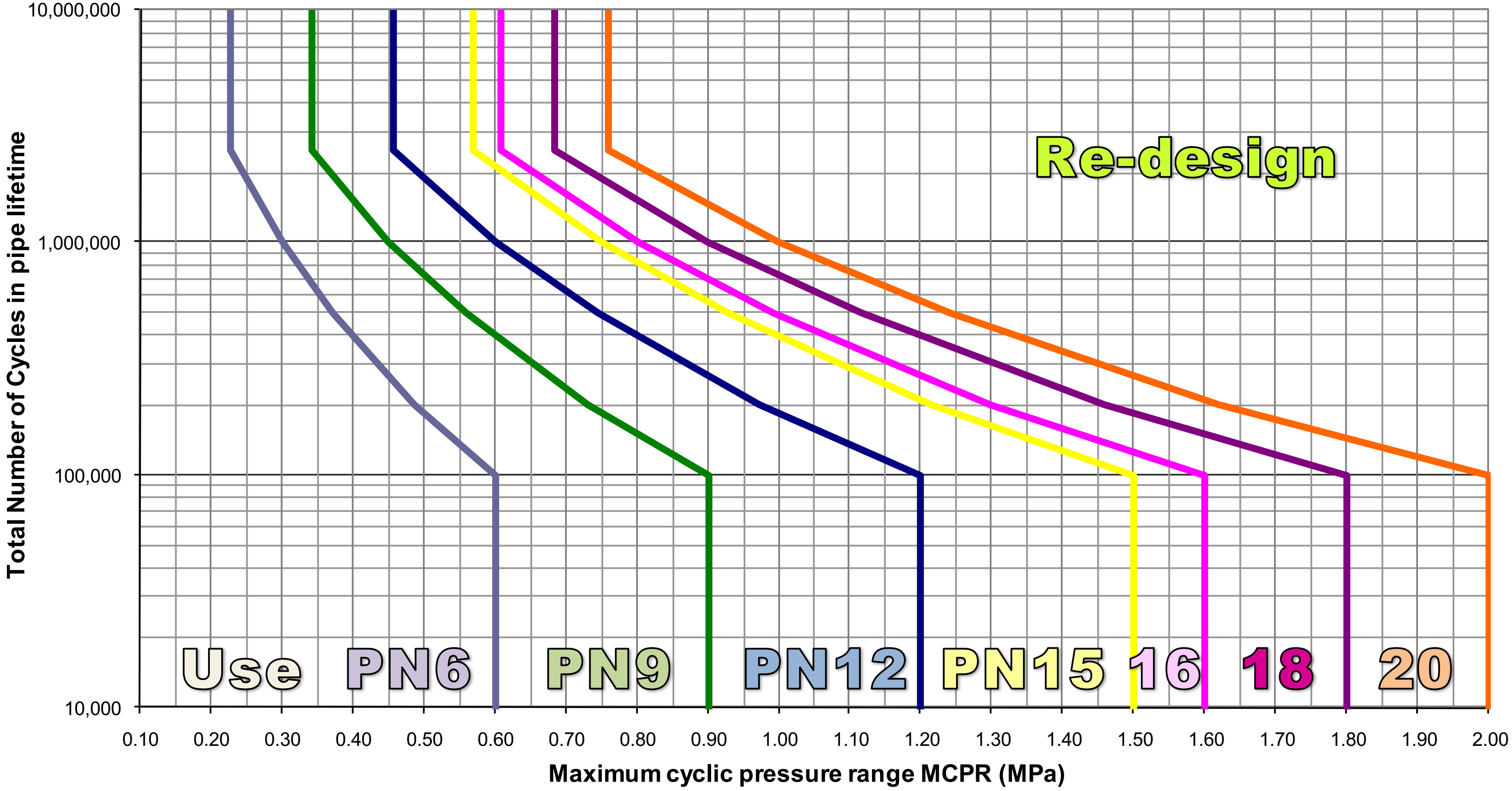
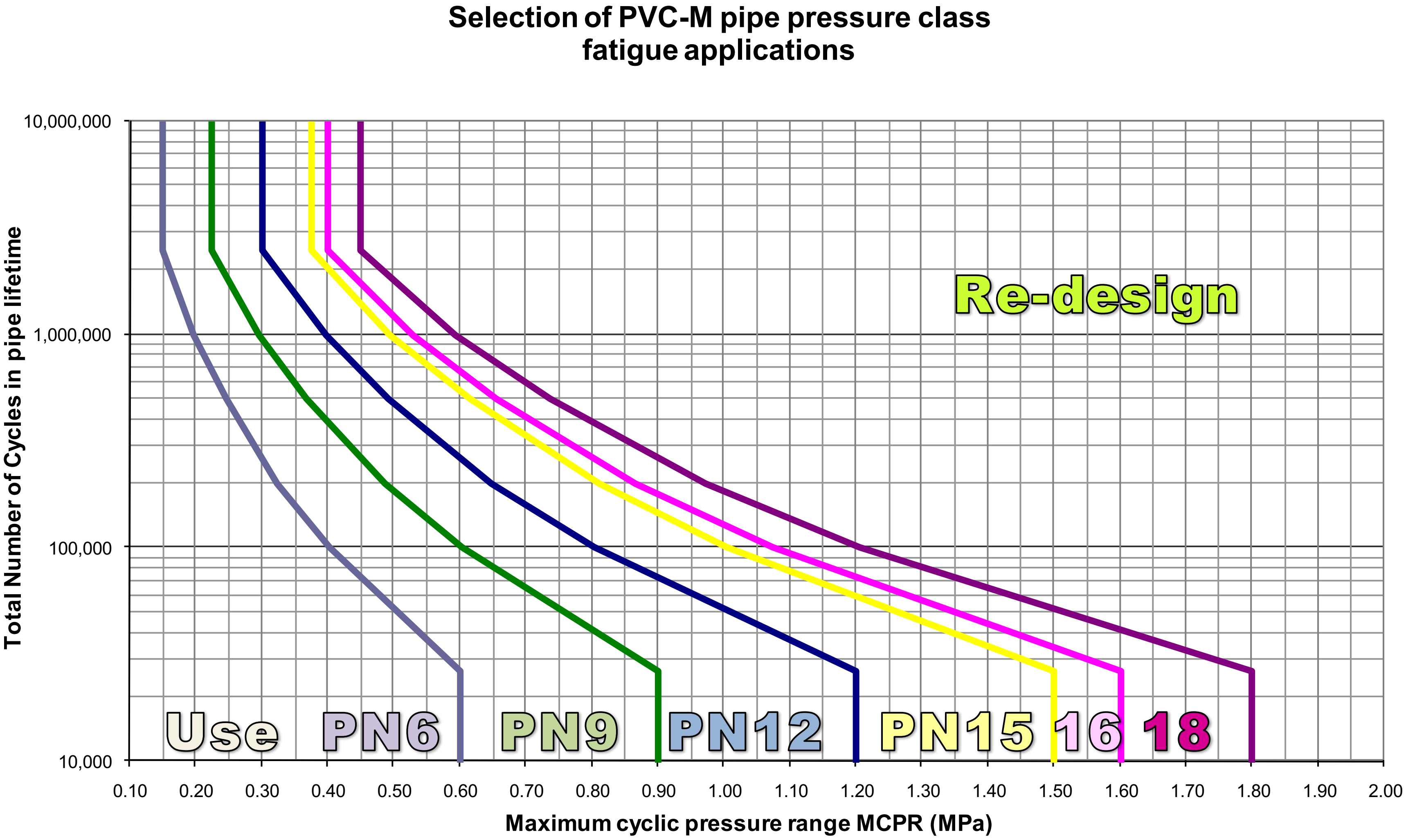
Appendix A

Selection of PVC-U pipe pressure class fatigue applications

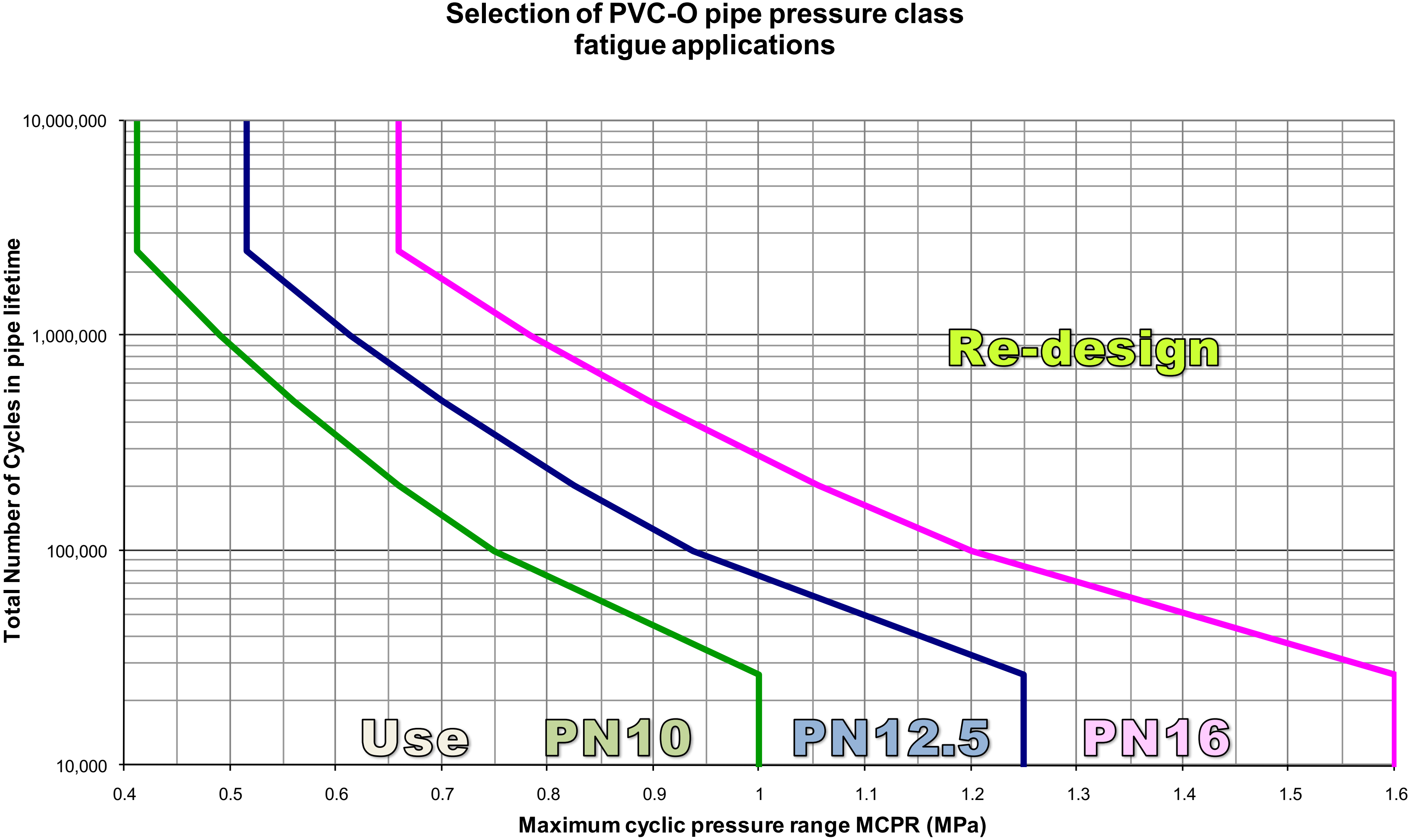


Appendix A



Selection of PVC-M pipe pressure class
fatigue applications
Total Number of Cycles in pipe lifetime
10,000,000
1,000,000
100,000
10,000
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
Maximum cyclic pressure range MCPR (MPa)
Re-design
Use
PN6
PN9
PN12
PN15
16
18

Appendix A


Selection of PVC-O pipe pressure class
fatigue applications
Total Number of Cycles in pipe lifetime
10,000,000
1,000,000
100,000
10,000
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
Maximum cyclic pressure range MCPR (MPa)
Re-design
Use
PN10
PN12.5
PN16