# TECHNICAL NOTE

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# PVC PRESSURE PIPES - DESIGN FOR DYNAMIC STRESSES

## Introduction

Nominal Working pressures assigned to the various classes of PVC pressure pipes in AS/NZS 1477 are based on the burst regression line for pipes subjected to constant internal pressure. Whilst most gravity pressure lines operate substantially under constant pressure (within the context of this note), pumped lines frequently do not. It is well known that a form of failure due to material fatigue can arise if stress fluctuations of sufficient magnitude and frequency occur, in any material and PVC is no exception.

PVC pipes, in fact, are very competent in handling accidental events, such as pressure fluctuations due to a power-out. A single pressure surge at twice working pressure for one minute is handled with the same factor of safety as the constant working pressure for fifty years. This is because the short term tensile strength of PVC is much higher then the long term rupture load. It is of course not recommended that this allowance be used in design - peak design pressures should not exceed the nominal working pressure - but it is nice to know the margin of safety exists.

However, if repetitive surges are likely to exceed about 100,000 occurrences during the life of the pipe, then fatigue is a possibility and a fatigue design should be carried out.

Oriented PVC (OPVC) is also dimensioned according to a static pressure regression line. However, molecular orientation results in a significant improvement in ultimate tensile strength in the hoop direction. This means that pipes can be designed to operate at hoop stresses typically twice that of standard PVC pipes without reducing the safety factor. Like the static strength, the dynamic performance or fatigue strength of PVC is also enhanced by orientation. Nevertheless design for fatigue should still be carried out where operating conditions are relevant.

## Fatigue Response of PVC

The response of PVC to cyclic stresses has been intensively investigated (see references). A fatigue crack initiates from some flaw in the material matrix, usually towards the inside surface of the pipe where stress levels are highest, and propagates or grows with each stress cycle dependant on the magnitude of the cycle. Ultimately the crack will penetrate the pipe wall and the resultant crack, from a few millimetres to a few centimetres long in the axial direction, will produce a leak. On occasion, particularly with larger diameter pipes containing air entrained in the line, the crack may reach a critical length prior to penetrating the wall and a large surge may result in the pipe bursting.

Rates of crack growth have been well researched under a range of experimental conditions and readers are referred to the literature for a detailed coverage of the subject.

The performance of OPVC under fatigue loading has been evaluated mainly by comparison with standard PVC. It is important, when reviewing the relative performance, to bear in mind that the operating stress of OPVC is typically twice that of standard PVC. Thus for a fair comparison it is essential to consider the performance at equivalent stress ranges relative to their respective maximum operating stress rather than at the same stress. In general, researchers have concluded that OPVC has improved resistance to fatigue at equivalent stress cycle amplitudes. It is also interesting to note that unlike standard PVC, the crack propagation path in OPVC occurs at an angle to an introduced notch and not directly through the specimen. It appears that the molecular orientation inhibits the growth of a fatigue crack in the radial direction thus lengthening the crack path before failure occurs.

It is important to appreciate that the growth of a fatigue crack is largely unrelated to the average stress level, or the peak stress level, but principally to the stress cycle amplitude. Thus a pipe subjected to a pressure cycle of zero to half working pressure is just as much in danger of fatigue as one subjected to a pressure cycle from half to full working pressure. This manifests itself in the field as the somewhat puzzling phenomenon that pipe fatigue failures occur just as frequently at high points in the system as low points, where the total pressure is greater.

## Design Criteria for Fatigue

It can be appreciated from the above that a design for fatigue must involve:

A: An estimate of the size of pressure fluctuations likely to occur in the pipeline ie., the difference $\Delta P$ between maximum and minimum pressures.

B: An estimate of the frequency, usually expressed as cycles per day, at which such fluctuations will occur.

C: A statement of the required service life expected from the pipe.

## Standard PVC pipes

Design proceeds on the basis of the established relationship between stress amplitude and number of cycles to failure. Laboratory data from many sources is collated by S.H. Joseph, Reference (1) and a lower bound established. This lower bound can be expressed as the following design relationship.

$$\Delta\sigma = \frac{352}{N^{\log 2}} \quad \text{or} \quad \frac{352}{2^{\log N}} \qquad ....(1)$$

where N is the total number of cycles in the life of the pipe

(The two expressions are identical and either may be used for convenience in computation).

From B and C the total life cycles N is calculated, and hence the allowable stress cycle amplitude.

From there, the allowable pressure cycle amplitude is most simply derived by ratio from the allowable static working stress $\sigma$ and pressure P.

$$\frac{\Delta P}{\Delta\sigma} = \frac{P}{\sigma} \quad \text{or} \quad \frac{\Delta P}{P} = \frac{\Delta\sigma}{\sigma} \qquad .....(2)$$

Thus for AS 1477 pipes $\sigma = 11$ MPa

and

$$\frac{\Delta P}{P} = \frac{32}{N^{\log 2}} \quad \text{or} \quad \frac{32}{2^{\log N}} \qquad .....(3)$$

This delightfully simple relationship says that the dynamic pressure ratio;

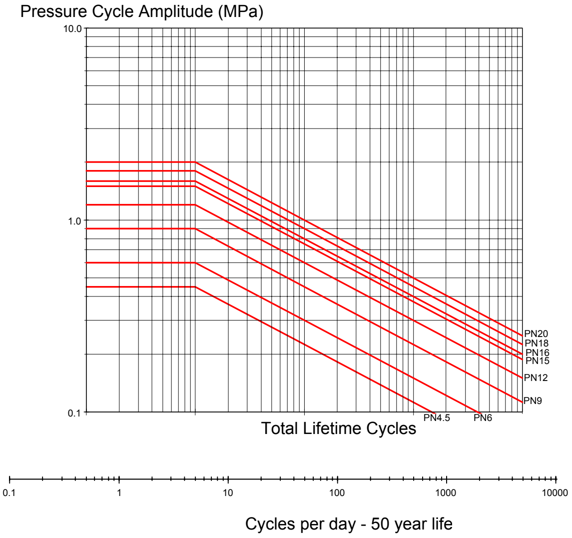
$$\frac{\text{Allowable dynamic pressure amplitude}}{\text{Allowable static pressure}}$$

should not exceed the following values.

| Number of life cycles | Dynamic pressure ratio |
|---|---|
| $10^5$ | 1.0 |
| $10^6$ | 0.5 |
| $10^7$ | 0.25 |
| $10^8$ | 0.125 |

NOTE: The dynamic pressure ratio should not exceed 1. Therefore, the dynamic pressure amplitude should not exceed the maximum allowable static working pressure of the pipe even for lower number of life cycles than given above.

The specific relationships for all pipe classes are plotted in Figure 1.



## Example of Use:

A sewer rising main with a pumping pressure of ninety metres, static head at the pump thirty metres, is designed to service a population of 400 growing to 2000 in 50 years. Throughput is 300 litres/head/day average, and well capacity is 20,000 litres:

Average throughput is 360,000 litres/day and assuming half the well capacity is utilised then the average switching rate will be 36 cycles/day. The dynamic range is 60m. Consulting the design chart, a class 12 pipe is required. Note that only class 9 is required to cope with the maximum pumping head but this inadequate from the fatigue standpoint.

It is noteworthy also that doubling the well capacity would double the life of the system, and an economic balance here must be considered.

## Oriented PVC (OPVC)

For simplicity, the technique used by Joseph was duplicated in the evaluation of OPVC. The results presented in several sources were collated onto one graph and a lower bound established. Using a similar analysis to that shown above for a design stress of $\sigma$ = 23.6
MPa this lower bound can be expressed by the following relationship:

$$\frac{\Delta P}{P} = \sqrt{\frac{32}{2^{\log N}}} \qquad .....(4)$$

which means that for OPVC, the dynamic pressure ratio, ie

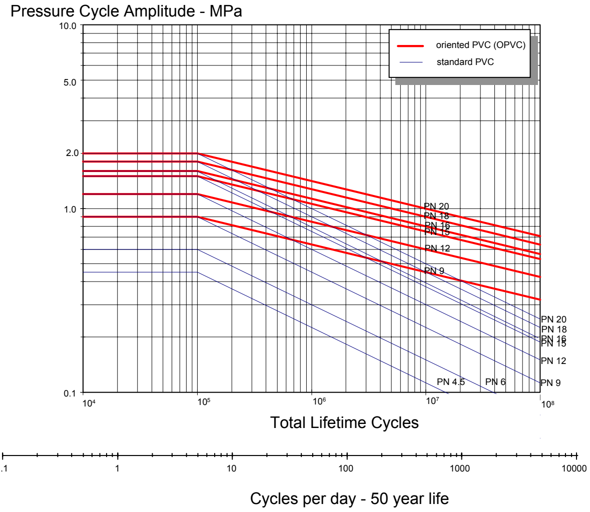
$$\frac{\text{Allowable dynamic pressure amplitude}}{\text{Allowable static pressure}}$$

should not exceed the following values.

| Number of life cycles | Dynamic pressure ratio |
|---|---|
| $10^5$ | 1.0 |
| $10^6$ | 0.71 |
| $10^7$ | 0.5 |
| $10^8$ | 0.35 |
| $10^9$ | 0.25 |

NOTE: As for standard PVC the dynamic pressure ratio for OPVC should not exceed 1.

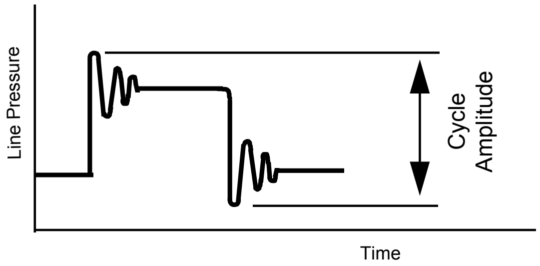
The specific relationships for all pipe classes are plotted in Figure 2.



For ease of use, a larger Figure is presented in Appendix A

## Definition of Pressure Amplitude and Effect of Surges

For simplicity, the pressure cycle amplitude is defined as the maximum pressure minus the minimum pressure, including all transients, experienced by the system during normal operations as shown in Figure 3. The effect of accidental conditions such as power failure may be excluded.



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 (1) 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 cycle amplitude 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.

## Effect of Temperature

Reference (1) notes that the available data indicates that there is no evidence of a change in response of PVC fatigue crack growth rates with temperature, at least in the lower temperature region where results are available. This is logically consistent with known fatigue behaviour, since the propensity to propagate a crack reduces with increasing ductility which results in yielding and blunting of the crack tip and a reduction in local stress intensity. Thus one would expect that PVC, with increasing ductility and decreasing yield strength, would not be degraded in fatigue performance at higher temperatures.

It follows that, while normal derating principles must be applied in class selection for static pressures, (ductile burst), no additional temperature derating need be applied for dynamic design.
ie. select the highest class arrived via:-

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

## Safety Factors

Equations (1) and (4) represent the lower bound of test data generated from a number of different sources over the last few years on commercially produced PVC and OPVC pipes. The mean line for this data is approximately half a log decade higher than this, and the relationship assumes no threshold stress level at low stress amplitudes and long times.

It is 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 is impossible to predict the extent of surge pressures. In such circumstances, relatively low cost surge mitigation techniques, for example the solid state soft-start motor controllers, should be considered. It is of course recommended that actual operating conditions for all systems should be checked by measurement, 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:

I. Limit the number of cycles by:
   A. Increasing well capacity for a sewer pumping station;
   B. Matching pump performance to tank size to eliminate short demand cycles for an automatic pressure unit; or
   C. Using double-acting float valves or limiting starts on the pump by the use of a time clock when filling a reservoir

II. Reduce the dynamic range by:
   A. Eliminating excessive water hammer; or
   B. Using a larger bore pipe to reduce friction losses

## Fittings

PVC fittings present a problem worthy of special consideration. Complex stress patterns in fittings can 'amplify' the apparent stress cycle. An apparently harmless pressure cycle can thus produce a damaging stress cycle leading to a relatively short fatigue life.

This factor is particularly severe in the case of branch fittings such as tees, where amplification factors up four times have been noted. The condition can be aggravated further by the existence of stress cycling from other sources, for example bending stresses induced flexing under hydraulic thrust in improperly supported systems.

Prudence therefore dictates that a suitable factor of safety be applied to fittings in assessing class requirements. It is recommended that the following factors be applied to the design dynamic pressure cycle for fittings:

| **Tees** | equal | Dx3/4D | Dx1/2D | Dx1/4D |
|---|---|---|---|---|
| Safety Factor | 4 | 3 | 2 | 1.5 |

| **Bends** | 90°short | 45°short | 90°long | 45°long |
|---|---|---|---|---|
| Safety Factor | 3 | 2 | 2 | 1.5 |

| **Reducers** | Dx3/4D | Dx1/2D | Dx1/4D |
|---|---|---|---|
| Safety Factor | 1.5 | 2 | 2.5 |

| **Adaptors & Couplings** | equal size | wyes |
|---|---|---|
| Safety Factor | 1 | 6 |

## Example:

A golf course watering scheme is designed to operate at 0.70 MPa. Balanced loading will ensure no pump cycling during routine watering. However, the system is to be maintained on standby with a jockey pump for hand watering purposes and this will cut in and out at 0.35 and 0.75 MPa. With normal usage and leakage this may occur every half hour on average for twelve hours a day. A twenty-five year life is required.

The pressure cycle is 0.4 MPa. Allow 20% for water hammer but no surging is likely in this type of system. Total dynamic cycle 0.48 MPa. The total life cycles predicted is 25 x 365 x 25 = 228,000. Referring to the chart, a class 9 pipe is satisfactory (Class 9 is required to cope with normal operational pressure). For fittings the effective dynamic cycle is

Equal Tees : 4 x 0.48 = 1.92 MPa
Elbows 90° : 3 x 0.48 = 1.44 MPa

Class 18 fittings are suitable for only 1.8 MPa effective dynamic range. Equal tees may not have an acceptable life in this system.

**Solution:** Reduce the dynamic range or reduce the frequency or the periods on standby.

## References

1. **JOSEPH, S.H.,** (University of Sheffield) "Fatigue Failure and Service Lifetime in uPVC Pressure Pipes", Plastics and Rubber Processing and Applications, Vol 4, No. 4, 1984, pp. 325-330, UK.

2. **AS 1477**, "Unplasticised PVC (UPVC) Pipes and Fittings for Pressure Applications", Standards Australia.

3. **HUCKS, R.T.,** "Designing PVC pipe for water distribution systems",J. AWWA, 7 (1972), PP. 443-7.

4. **KIRSTEIN, C.E.,** Untersuchung der Innendruck-Schwellfestigkeit von Rohren aus PVC-hart, "Publication of the Institut fur Kunstsoffprufung and Kunststoffkunde", Unversitat Stuttgart, 1972.

5. **GOTHAM, K.V. AND HITCH, M.J.,** "Design considerations for fatigue in uPVC pressure pipelines", Pipes and Pipelines Int., 20 (1975), pp. 10-17.

6. **STAPEL, J.U.,** "Fatigue properties of unplasticised PVC related to actual site conditions in water distribution systems", Pipes and Pipelines Int., 22 (1977), pp. 11-15 and 33-6.

7. **GOTHAM, K.V. AND HITCH, M.J.,** "Factors affecting fatigue resistance in rigid uPVC pipe compositions", Brit. Polym. J., 10 (1978), pp. 47-52.

8. **JOSEPH, S.H.,** "The pressure fatigue testing of plastic pipes. In: Plastics Pipes 4, PRI, London, 1979, Paper 28.

9. **MOORE, D.R., GOTHAM, K.V. AND LITTLEWOOD, M.J.,** "The long term fracture performance of uPVC pipe as influenced by processing", In: Plastics Pipes 4, PRI, London, 1979, Paper 27.

10. **BS CP312, part 2,** "Unplasticised PVC pipework for the conveyance of liquids under pressure, AMD 2377, Sept. 1977, BSI, London.

11. **DUKES, B.W.,** “The dynamic fatigue behaviour of UPVC pressure pipe”, In: Plastics Pipes VI, PRI, York, UK ,1985.

12. **DUKES, B.W.,** Private Communication, 15th July 1983.

13. **BENHAM, P.P.,** “Fatigue tests on H.S. Pipe”, Private Communication, 28th October 1977.

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# Appendix A

Design Chart for Dynamic Stresses