WHAT DO WE KNOW ABOUT PRESSURE:LEAKAGE RELATIONSHIPS IN DISTRIBUTION SYSTEMS?

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Abstract

In some countries – notably Japan and the UK – the importance of managing distribution systems to minimise excess pressures is widely recognised as a fundamental aspect of leakage management strategy. International data on pressure:leakage relationships demonstrates that leakage in distribution systems is usually much more sensitive to pressure than would be predicted by the 'square root' relationship, with different components of leakage responding differently to pressure. An understanding of pressure:leakage relationships is therefore fundamental to a systems approach to leakage control. Practical guidance is offered on appropriate equations for data analysis, and predictions in individual situations.

Introduction

Although pressure is one of the easiest parameters to measure in a distribution network, leakage statistics are almost always quoted without any reference to average pressure – except in Japan, where the link between pressure and leakage is explicitly recognised. Perhaps it is the lack of readily available pressure statistics which leads so many Utilities to effectively ignore the influence of operating pressures when monitoring leakage, setting targets, assessing performance, and formulating leakage management strategy.

This is demonstrated in Figure 1, where the central small square represents the volume of Unavoidable Annual Real Losses (1), and the larger square represents the volume of Current Annual Real Losses. As the network deteriorates, the Real Losses will tend to increase if they were are not constrained by the four Leakage Management Activities –

- Pipe materials management, Speed and Quality of Repairs, Active Leakage Control
- Pressure Management

Pressure Management can involve both increases and decreases in pressure, at different times of the day or year. In either case, there will be a significant influence on the annual volume of both Unavoidable and Current Real Losses. For example, for the last 20 years the Japanese have used the standard relationship that leakage rate varies with Pressure $^{1.15}$ (2), i.e. a 1% change in pressure will typically change average leakage rate by 1.15% .

Management of pressures is therefore one of the fundamentals of an effective leakage management policy. Utilities which use, or are considering using, pressure management as part of their leakage management strategy will need to consider the following key issues:

- The importance of maintaining consistent pressures with minimal variations
- Relationships between maximum pressure and rate at which new leaks occur
- Relationships between pressure and rates of flow from existing leaks
- Predicting the effects of pressure management on leakage rate, consumption and income
- The influence of minimum standards of service, and topography

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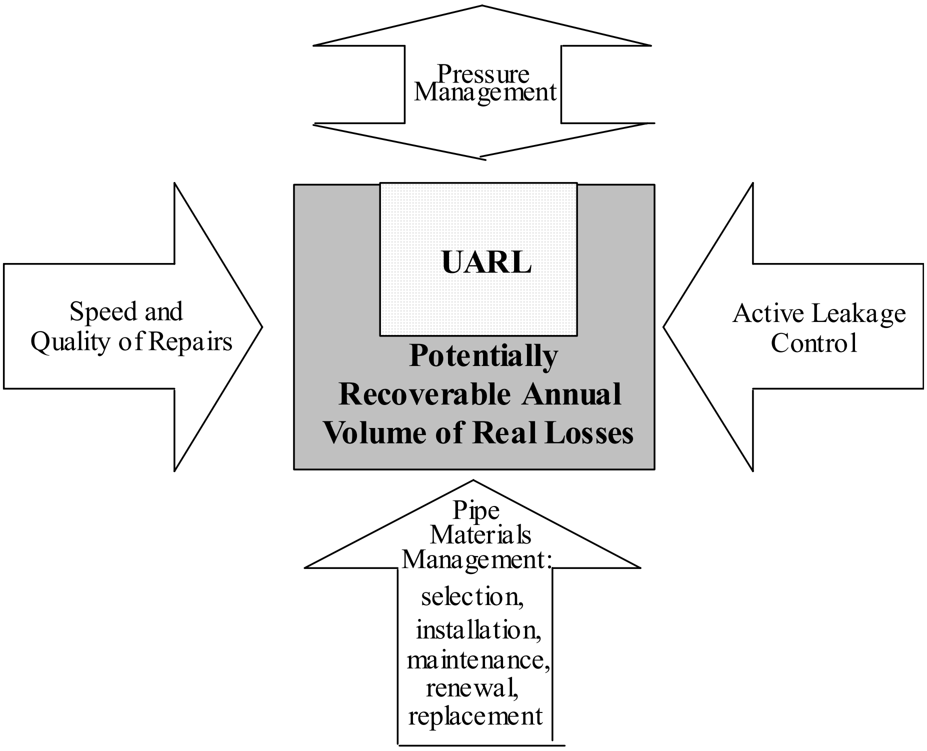

Fig.1 The four basic leakage management activities which constrain annual real losses

The paper will present information from international sources on these key issues, and draw conclusions of practical application. Much of the work described here represents the most basic application of the concept of Fixed and Variable Area Discharges, FAVAD (3). FAVAD can be used to rationally interpret a wide range of experimental test data on pressure:leakage relationships from pipe samples and sectors of distribution systems, and also to categorise relationships between pressure and components of consumption by customers.

The concepts and techniques described in this paper have been successfully applied in numerous countries over the past six years, in conjunction with BABE (Background and Bursts Estimates) concepts, to analyse the results, and predict the consequences, of pressure management on leakage rates, consumption and Utility income. The ongoing development and testing of these concepts is being progressed through the FAVAD Liaison Group based in the UK. Anyone interested in contributing data or experience is invited to contact the author.

The Key Issues

The importance of consistent pressures with minimal variations

Frequent sudden changes in pressure reduce the average life of pipes. This can be demonstrated by calculating the frequencies of new mains bursts (per 100 km of mains/year) and new service connection bursts (per 1000 services/year), and comparing these figures with data from other systems. In the extreme case of intermittent supply situations, new burst frequencies may be 10 times or more what would be expected for continuous supply at the same average pressure. The first, most important pressure management message is therefore:

Avoid frequent pressure changes; wherever possible pump into reservoirs, not direct into distribution mains

Relationships between Maximum Pressure and Frequency of New Leaks

Some UK data exists on how mains burst frequencies vary with pressure, for individual district metered areas (3) and for large supply systems (Fig. 2). Both sets of data imply that, for systems with continuous supply, mains burst frequency increases rapidly when pressure exceeds around 35 to 40 metres head.

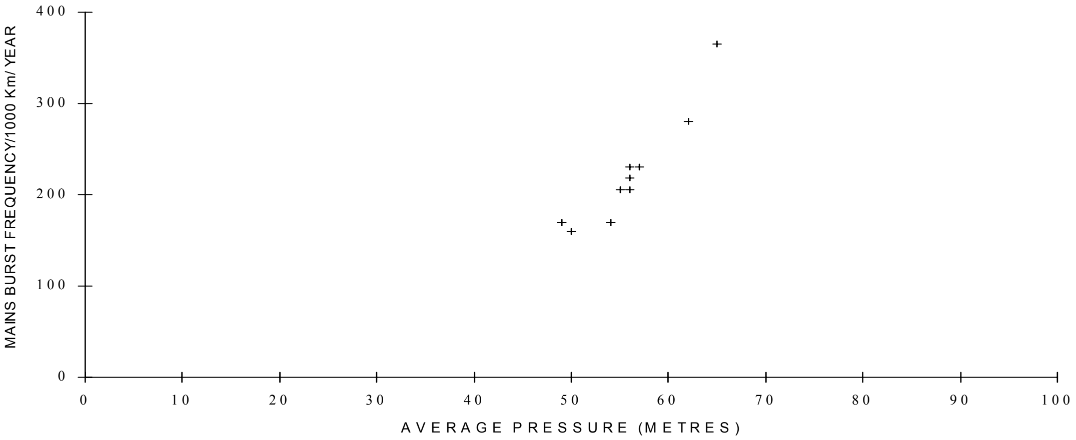

Fig. 2 Plot of Average Pressure vs. Mains Leak Frequency, Large Supply Systems in Wales

Other data notified to the author include the following:

- Australia: a_ 40% pressure reduction in one sector of a city reduced the frequencies of all new leaks on mains, services, and fittings in that sector by 55%
- Auckland, New Zealand: when average pressure in Ecowater's distribution system was reduced from 71 to 54 m., frequency of new leaks on mains fell to the lowest in 8 years
- Brazil: In 8 sectors with 140 km of mains subject to pressure management, new leak frequency on mains and services was reduced from 155 per month to 95 per month

Clearly, there is no unique relationship between maximum pressure and new leak frequency, but the above evidence shows that excess pressures in systems subject to continuous supply result in higher frequencies, and higher repair costs, than are necessary. For developed countries with high unit repair costs, this may be the dominant economic driver for introducing pressure management.

Relationships between pressure and flow rates from existing leaks

The principle of conservation of energy dictates that the velocity (V m/sec) of a jet of water passing through an orifice varies with the square root of the pressure (P metres), according to the equation:

$$\text{Velocity V m/sec} = Cd \times (2gP)^{0.5}$$

Many engineers assume – incorrectly - that leakage rates in distribution systems must therefore vary with the square root of pressure, and so will be insensitive to changes in pressure. However, the unspoken assumption that Cd is constant is not necessarily valid; for individual leaks, Cd can change depending upon whether the flow is laminar, transitional or turbulent. This depends upon the Reynolds number R (= V x Hd/KV), where Hd is the hydraulic diameter of the orifice and KV is the kinematic viscosity (which varies with temperature).

Figure 3 (courtesy of Effective Fluid Engineering) shows the relationship between Cd and Reynolds Number for discharges through a 1mm orifice drilled into the side of a 15 mm diameter copper pipe. For this particular set of test data, in the Laminar flow range ($R < 3000$, $L < 10$ l/hour), Cd rises rapidly to 0.80 as R increases, implying that discharge rates of small leaks may be very sensitive to changes in pressure because of changes in Cd.

In the Fully Turbulent flow range ($R > 8000$, $L > 30$ l/hour), Cd remains steady at around 0.75, whilst in the Transitional flow range, ($10 < L < 30$ l/hr), Cd oscillates between 0.70 and 0.85.

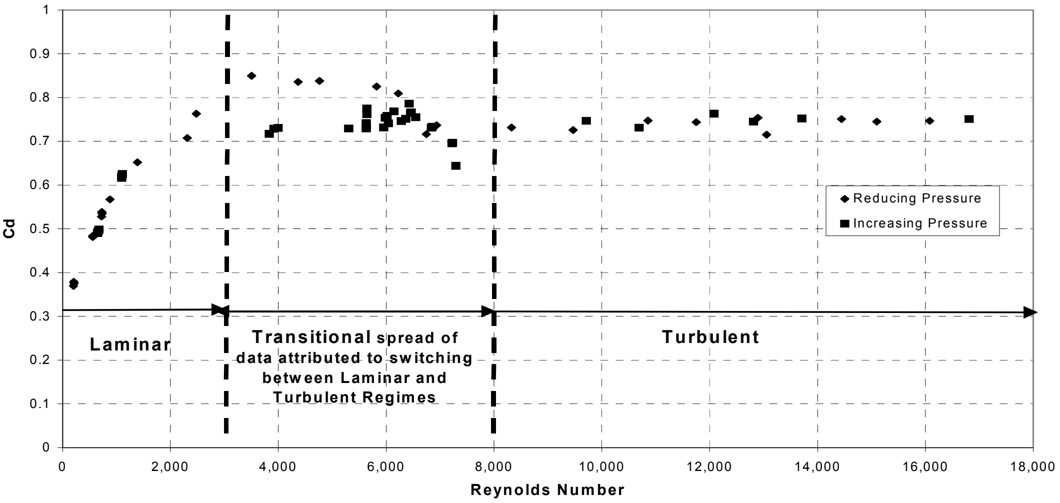

Fig.3 Discharge Coefficient of a 1mm Diameter Orifice vs. Reynolds Number

A further reason to question the general assumption of a square root relationship is that the leakage rate L (volume/unit time) also depends upon the orifice area (A), according to the equation:

$$L = V \times A = Cd\,A \times (2gP)^{0.5}$$

For longitudinal splits in plastic PE and PVC pipes, it can be rationally expected (4), and clearly observed in laboratory tests (5), that the orifice area varies with pressure. If the area varies linearly with pressure (e.g. a longitudinal split which opens in one dimension) then A will vary with $P^{1.0}$, and Leakage rate L will vary with $P^{1.5}$. If the split opens up in two dimensions – longitudinally and radially – then A will vary with $P^{2.0}$, and L with $P^{2.5}$.

Occasionally, exponential equations ($L = e^{SP}$) have been applied to experimental pressure:leakage rate data (4,6) but the approach is flawed – the exponential equation implies that effective area (CdA) <u>increases</u> as pressure decreases below 0.5/S, which is clearly unrealistic. The most appropriate general equations to use for simple analysis and prediction of pressure:leakage relationships – whether for laboratory tests on individual faults in pipes, or for aggregate leakage from sectors of distribution systems – are the equations:

$$L \text{ varies with } P^{N1} \quad \text{and} \quad L_1/L_o = (P_1/P_0)^{N1}$$

From the above considerations, it may logically be expected that the exponent N1 in the above relationship could vary between 0.50 and 2.50, depending upon the type(s) of leak present. These relationships are shown in Figure 4. In the remainder of this paper, it will be demonstrated that international test data on individual leaks and distribution system sectors supports this general theory.

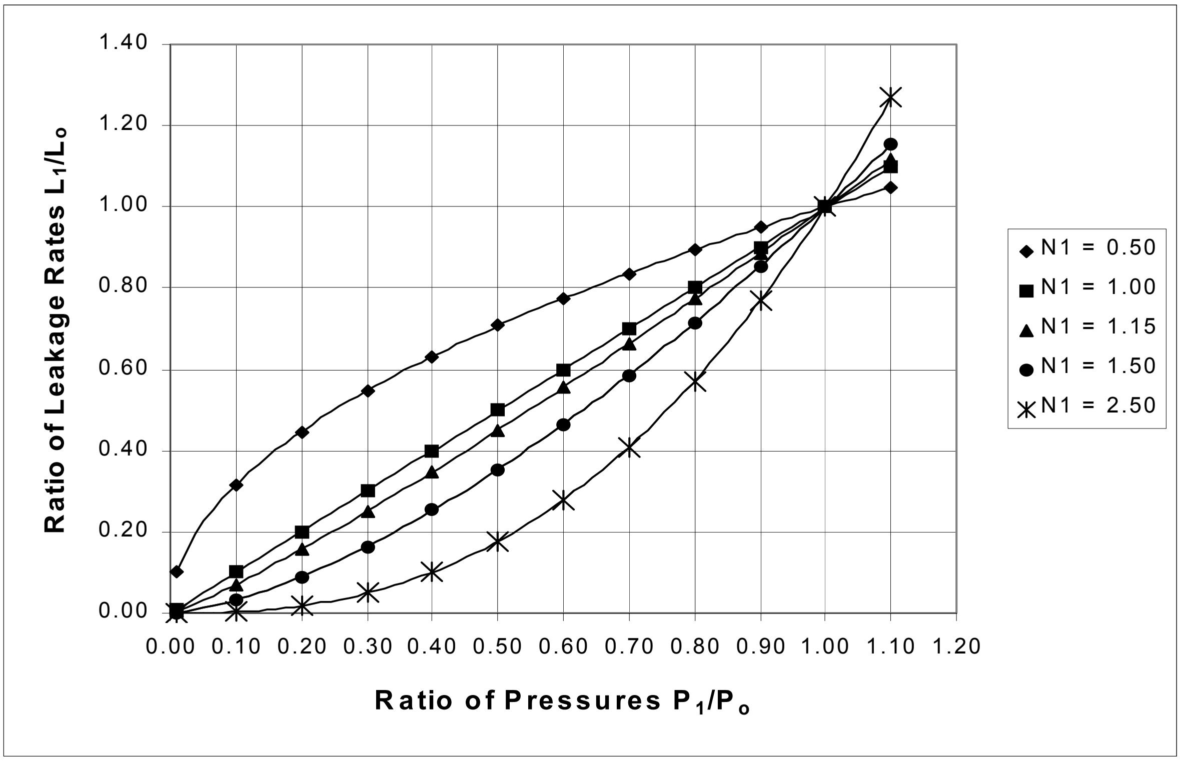

Fig 4 General Relationships between Pressure and Leakage Rate using the N1 Approach

Predicting effects of pressure management consumption and income

Management of pressures in the distribution system will influence, to a greater or lesser extent, all discharges from pipework subject to that pressure. The presence or absence of storage at customers' properties – ground level tanks, roof tanks, toilet cisterns – influences these relationships between pressure and components of consumption and leakage from customers' pipes. Components of consumption can also be readily modelled using the 'NI' exponent approach, for example:

- Volumes used by washing machines are 'fixed volume', independent of pressure (N1 = 0)
- Discharges from hosepipes are likely to vary with the square root of pressure (N1 = 0.5)

Consumption can be broken down into 'fixed volume' components, and components with particular N1 values, derived from simple pressure:flow rate tests on individual devices. The effect on consumption (and Utility income) of any proposed changes in pressure can then be predicted as part of the process of evaluating individual pressure management opportunities.

The influence of minimum standards of service, and topography

In the author's experience, when minimum standards of service for pressure are specified – whether for customers or for fire-fighting – the effect on leakage rates is rarely considered. Most systems run at excess pressures for more than 90% of the time, due to seasonal or 24-hour variations in consumption. A more flexible approach to defining standards of service for pressure can have a significant influence on the annual volume of real losses.

The layout of the distribution system in relation to the local topography will also influence the extent to which retrospective pressure management is feasible. It is noteworthy that the Japanese try to design new systems to minimise the occurrence of excess pressures, taking topography into account as part of the initial network design process.

International Data on Pressure:Leakage Rate Relationships

The international data assembled by the author fall into three groups :

- laboratory tests on holes in pipes (actual failures, or artificially created leaks)
- tests on sectors of actual distribution systems, with customers supply turned off
- night tests on sectors of actual distribution systems, including customer night use

Laboratory Tests on Holes in Pipes

In 1980, HIKI (7) described tests in Japan in which holes of 1 to 5 mm diameter holes were drilled in metal pipes of 60 to 180mm diameters, which were then buried in sand or submerged in water, and the leakage rates measured at different pressures. Leakage rates ranged from 24 to 900 litres/hour, pressures from 2 to 60 metres. Calculated N1 values varied from 0.36 to 0.70, with an average close to 0.50. Takizawa (8) states ‘similar conditioned model pipeline tests carried out by Tokyo Waterworks in 1982 supported the above conclusion and showed N1 values of 0.51 to 0.54 under the condition of relatively high leakage flow (1500 l/hr)’

Recent re-examination of the HIKI test data by the FAVAD group suggests that some of the variability of N1 values – those higher or lower than 0.50 – may be due to changes in Cd, in the laminar and transitional flow ranges (see Fig 3).

In the UK (6), pressure:flow rate data were presented for short lengths of leaking service connections, which had been removed and tested over pressure ranges from 10 to 75 metres, and flow rates of 0 to 4000 litres/hr. For the metal pipe failures (corrosion holes or splits in Galvanised Iron, Copper or Lead pipes) the N1 value was always close to 0.50. By contrast, for the plastic pipes, the N1 value was typically around 1.5, but with substantial hysteresis effects evident for rising and falling pressures.

Ashcroft & Taylor (5) reported on laboratory tests on artificially created leaks in plastic pipe - slits of 10mm and 20mm length in 22mm Class D polythene pipe. Pressures were varied from 10 to 100 metres, resulting in flow rates from 0 to 700 litres/hr for the 10mm slit, and 0 to 5000 litres/hr for the 20mm slit. The flows increased after each pressure cycle, as the slits increased in length. Calculated N1 values were 1.39 and 1.72 for the 10mm slit and 1.23 to 1.97 for the 20mm slit. The average N1 value for all 5 tests was 1.52.

Tests on Sectors of Distribution Systems

Ogura (2) presented results from 20 short tests on small sectors of actual distribution systems in a Japanese city, nineteen of which had metal mains. In each test, the service connections were turned off, to eliminate consumption and customers’ leakage. Sections of the main were isolated by closing valves, and inflow needed to maintain leakage rates at different pressures was recorded. The pressure was raised from around 5 metres to around 40 metres head, and then reduced. Each sector test lasted for approximately 45 minutes.

Ogura calculated individual values of N1 ranging from 0.65 to 2.12; the resulting weighted average of N1 = 1.15 has been used as the Japanese standard value for the last 20 years. The key feature of these results is that sectors with metal mains consistently gave N1 values significantly greater than 0.50; Takizawa (8) attributes this to several types of leakage in the system, including ‘little leakages … through gaskets of joints and others’. Yeung (9), re-analysing Ogura’s data, showed that N1 only exceeded 1.0 for the lowest values of aggregate effective area (CdA) of leaks. This is consistent with the expectation that small leaks at joints and fittings in the laminar flow range, even in metal pipes, will experience large variations in Cd with pressure, thus significantly increasing the N1 value above 0.50.

Further evidence of N1 values on leaking fittings is provided by laboratory tests on defective taps by Parry (10), over 100 years ago. His data produces N1 values of 0.61 to 1.26 (average 0.88) for 6 tests at flows between 2 and 150 litres/hr, and pressures between 6 and 30 metres.

Tests on sectors of distribution systems, with customer night use

Most of these tests have been carried out in the UK, but the technique has also been applied in Brazil, Malaysia, Australia, New Zealand, and other countries. Inlet pressure in single-feed districts is gradually reduced over a period of hours, days, or weeks, and the effect on minimum night flows and average pressure in the district is monitored. Minimum night flow includes leakage on the distribution system and customers' pipes, and customer night use.

In 1980, the results of such tests on 17 sectors of UK distribution systems were published. Prior to these particular tests, all detectable leaks had been located and repaired; the only remaining leaks should be individual small undetectable 'background' leaks at joints and fittings. Re-analysis of the data using the FAVAD approach showed N1 values for minimum night flow ranging from 0.70 to 1.68, with an average of 1.13. If estimates of customer night use could have been deducted, N1 values for leakage in these tests would have been higher. Individual tests in Australia and New Zealand in sectors after all detectable leaks have been located and repaired have produced N1 values close to 1.50 for 'background' leakage.

Numerous unpublished UK tests since 1980, on sectors both before and after leak detection surveys, have produced N1 values for leakage (after deduction of estimated customer night use) ranging from around 0.50 to 1.50, with an average N1 close to 1.0. Tests in Brazil on 7 sectors with very high leakage showed N1 values between 0.52 and 0.67 for metal pipe systems, and values close to 2.5 for two high-leakage areas with PVC splits and joint leaks.

Considering all the available data, the best guidance for predicting average N1 values for individual sectors is that N1 depends on pipe material and level of leakage, with N1 for background (undetectable) leakage being around 1.5, whatever the pipe material. In Fig. 5, the Infrastructure Leakage Index (X-axis) is the ratio of Current Annual Real Losses to Unavoidable Annual Real Losses (1), Fig. 1, and is a measure of comparative leakage level.

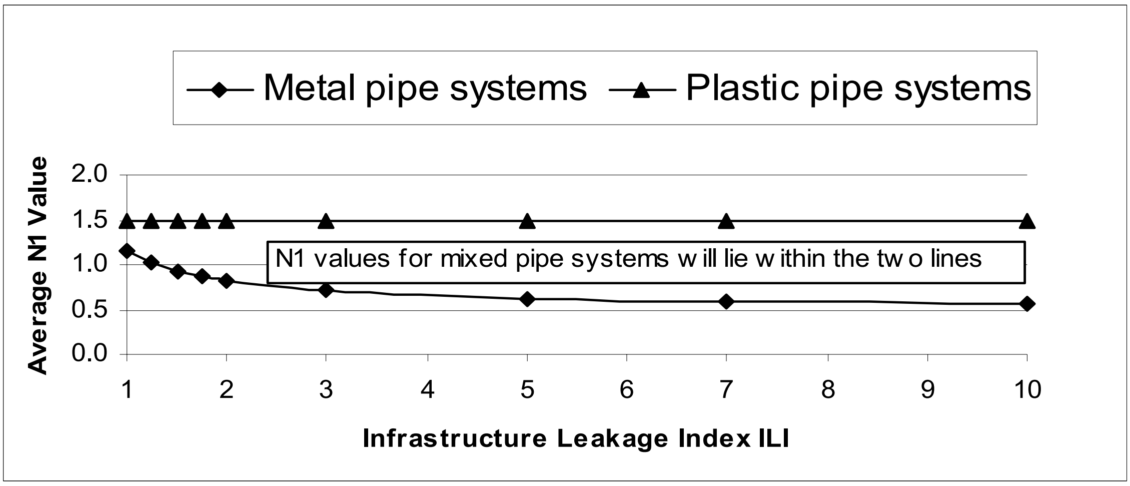

Fig. 5: Best Available Guidance on Predicting N1 values for Individual Sectors

Conclusions

- Pressure management is a fundamental consideration in any leakage management strategy
- Frequent variations in pressure are associated with higher frequencies of new leaks – intermittent supply situations typically result in very high new leak frequencies
- In continuous supply situations, permanent reduction of excess pressures can significantly reduce the frequency of new leaks and bursts
- In the equation Leakage Rate L = Cd A x $(2gP)^{0.5}$, where P is pressure, the effective area (CdA) will vary with pressure in some situations
- The most appropriate general equations for simple analysis and prediction of relationships between pressure (P) and leakage rate (L) in distribution systems are:

  L varies with P^{N1} and $L_1/L_o = (P_1/P_0)^{N1}$
- In the above equations, it is possible for the exponent N1 to range from close to 0.50 to as much as 2.50, depending upon the mixture of leaks and the dominant type of leaks
- Undetectable small 'background' leaks from joints and fittings in distribution systems are quite sensitive to pressure, with N1 values typically close to 1.5
- Larger detectable leaks from plastic pipes typically have N1 values of 1.5 or even higher
- Larger detectable leaks in metal pipes typically have N1 values close to 0.50
- N1 values for individual sectors can be predicted from Fig 5 if pipe material and leakage level (in terms of Infrastructure Leakage Index) can be assessed
- In absence of knowledge of pipe materials and leakage level, assume a linear relationship (N1 = 1.0)
- The 'N1' approach can also be used to analyse and predict relationships between pressure and individual components of customer use

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