Ten Years Experience in using the UARL Formula to calculate Infrastructure Leakage Index.

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This paper, which is now mainly of historical interest, introduces and discusses several evolutions in the application of UARL equations during the first ten years of their use.

- In Table 1, conversion of the assumptions for typical flow rate and duration of reported and unreported bursts into equivalent volume per burst at 50m pressure.
- In Table 2, the component of UARL from property line or curb stop to meter is expressed in litres/km of mains/day
- In Figure 1, a more diagnostic equation for Unavoidable Background Leakage (UBL) in which leak flowrates vary with average Zone Pressure to the power 1.5 (variable area leakage, see Figure 1)
- Table 3 shows how the upper and lower system size and pressure limits for application of UARL were relaxed between 1999 and 2009 to allow practitioners to use the equation in smaller systems. This had limited reliability but did highlight occurrences of ILIs less than 1.0 in some very small systems at low pressures.
- Figure 2 shows how pipe materials (rigid or flexible) influence pressure:leak flow relationships using a more detailed FAVAD concept approach.
- Part 2 discusses common errors in calculating UARL and other possible reasons for ILIs less than or equal to 1.0 being calculated in some international systems. The issues identified in Table 3 (small systems), Figure 2 (influence of pipe materials) and Part 2, together with the introduction of pressure:burst frequency relationships not identified until 2012, are incorporated in the UARL with SCF (System Correction Factor) concept in 2000 (see 'Low ILIs in Small Systems')

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Abstract
The formula for Unavoidable Annual Real Losses (UARL) was published by the 1st Water Loss Task Force in 1999, as a structured and auditable approach to estimating 'how low could you go?' The equation was developed using the BABE (Bursts and Background Estimates) component analysis concept, and the FAVAD (Fixed and Variable Area Discharges) concept for pressure:leak flow rate relationships.

In addition to estimating 'how low could you go' for Real Losses in any distribution system (subject to lower limits for system size and pressure), the UARL permitted the calculation of a new non-dimensional performance indicator – the Infrastructure Leakage Index (ILI). The ILI is the ratio of the Current Annual Real Losses (CARL), derived from a Water Balance, to the UARL calculated from the formula.

Since 1999, UARL and ILI have been calculated for many hundreds of systems internationally, and ILI has been adopted as a key performance indicator by national organisations in several countries. The UARL formula and ILI have been the subject of much comment (both for and against), and some misunderstandings. The paper reviews these issues, to try to assist future users of UARL and ILI, and Unavoidable Background Leakage (UBL), to better understand their advantages and limitations, and when their use is appropriate or otherwise.

Introduction
The first part of this paper briefly summarises the concepts and parameters originally used to develop:

- the equations for Unavoidable Background Leakage (UBL) and UARL
- the sensitivity of UBL and UARL to changes in these parameters.
- the gradual relaxation since 1999 of the limits for applying the UARL formula

The second part of the paper, considers the principal criticisms that have been made relating to the use of the UARL and ILI, namely:

- if the UARL formula is correct, how can a calculated ILI be less than 1.0?
- some users find it difficult to reliably assess average pressure
- the term 'Unavoidable' is inappropriate

The third part of the paper. 'Looking Ahead' considers the topics:

- is there a case for changing the coefficients in the UARL equation?
- should ILI be used for metric benchmarking, process benchmarking, or both?

Part 1: The UARL and UBL Equations

Concepts and Parameters
Leakage management practitioners recognise that it is impossible to eliminate real losses from distribution systems. There must therefore be some lower limit for real

losses – 'how low you could go' - which could be achieved at any particular operating pressure, for well managed infrastructure in good condition.

- for night flows, this is the Unavoidable Background Leakage (UBL), consisting of individual small hidden leaks that are not detectable visually or acoustically; the equation for Unavoidable Background Leakage was not highlighted in the original 1999 paper (Lambert et al, 1999) due to limitations of space.
- for annual water balance, Unavoidable Annual Real Losses (UARL) consists of UBL plus losses from detectable Reported and Unreported leaks and bursts.

Both the UBL and the UARL will vary with pressure, so the empirically derived parameters used for calculation of UARL and UBL were initially specified at a standard pressure of 50 metres. Some of the terminology (but not the values) has recently been modified for more user-friendly interpretation, as compared to the original format in the 1999 AQUA paper. Table 1 shows the modified format.

Table 1: Parameters values used to calculate UBL and UARL at 50 metres pressure

Infrastructure Component	Unavoidable Background Leakage	Detectable Reported Leaks and Bursts	Detectable Unreported Leaks and Bursts
On Mains	20 litres/km/hr	12.4 bursts/100 km/yr. at 12 m^3/hr for 3 days = 864 m^3/burst	0.6 bursts/100 km/yr. at 6 m3/hr for 50 days = 7200 m^3/burst
On Service Connections, Main to Property Line	1.25 litres/conn/hr	2.25/ 1000 conns/yr. at 1.6 m^3/hr for 8 days = 307 m^3/burst	0.75/1000 conns/yr. at 1.6 m^3/hr for 100 days = 3840 m^3/burst
On Service Conns from Property Line to meter, if customer meter is not located at the property line	0.50 litres/conn/hr*	1.5/ 1000 conns/yr.* at 1.6 m^3/hr for 9 days = 346 m^3/burst	0.50/1000 conns/yr*. at 1.6 m^3/hr for 101 days= 3878 m^3/burst

* for 15 metres average length

The parameters for Unavoidable Background Leakage were initially based on numerous tests in District Metered Areas, mainly in England and Wales during the late 1990s, after Utilities had used the latest available technology to find and fix all detectable leaks, to achieve mandatory leakage targets. The values used were acceptable to Germans and Austrians specialising in leakage control on generally good infrastructure, and were also checked with a limited number of tests in Australia and New Zealand. Tests in the UK and Brazil (1995 to 2009) show that background leakage typically varies with pressure to the power 1.5 (FAVAD N1 = 1.5). So when analysing components of night flow, the equation for calculating unavoidable background leakage on mains and service connections up to the property line is:

$$\text{UBL (litres/hour)} = (20 \times \text{Lm} + 1.25 \times \text{Ns}) \times (\text{AZNP}/50)^{1.5} \quad \text{........ (1)}$$

where Lm is mains length (km). Ns is number of service connections (main to property line) and AZNP is the Average Zone Night Pressure (metres)

When calculating UARL, in addition to the Unavoidable Background Leakage, it is also necessary to allow for the frequency, flow rate and duration of reported and unreported leaks and bursts. Frequencies in Table 1 were based on averages for international data, assuming 5% of mains bursts and 25% of service connection bursts were unreported. Mains bursts vary greatly in flow rate, but large bursts should have shorter run times, so Table 1 effectively calculates average volume lost per mains burst at 50 metres pressure. Typical service connection burst flow rates (1.6 m^3/hour) were based on published data from the UK, Brazil and Germany from 1994.

Whilst UBL varies with pressure to the power 1.5, reported and unreported bursts vary with pressure to the power 0.5 (Fixed Area leaks: ring cracks, corrosion holes etc.) or 1.5 or more (variable area leaks such as splits in flexible pipes). For large systems with mixed materials, it is usually assumed that average leak flow rates vary linearly with average pressure (FAVAD N1 = 1.0), so Table 1 data can be converted to a daily calculation of UARL, assuming a constant pressure over 24 hours.

Table 2: Components of Unavoidable Annual Real Losses

Components of Unavoidable Annual Real Losses at 50 metres pressure (metric units)					
Infrastructure Component	Unavoidable Background Leakage UBL	Reported Breaks	Unreported Breaks	Unavoidable Annual Real Losses UARL	
Mains	480 litres/km/day	290 litres/km/day	130 litres/km/day	900 litres/km/day	18 litres/km/day/ metre of pressure
Service Connections, main to curb-stop	30 litres/conn/day	2 litres/conn/day	8 litres/conn/day	40 litres/conn/day	0.80 litres/conn/day/ metre of pressure
Service Connections, curb-stop to meter	800 litres/km/day	95 litres/km/day	355 litres/km/day	1250 litres/km/day	25 litres/km/day/ metre of pressure
Typical FAVAD N1	Close to 1.5	0.5 to 2.5, depends on pipe materials and types of leaks		Assumed as average of 1.0 for UARL formula	

The format of Table 2 is presented differently from the original Table 4 in Lambert et al (1999), in order to try to avoid errors of interpretation that have been made by some users of the UARL formula. The most serious of these errors is to assume, when analysing components of night flows, that the UBL varies linearly with pressure. Figure 2 shows how UBL on mains and services (up to the property line) calculated from Eqn (1) varies with Average Zone Night Pressure and density of connections.

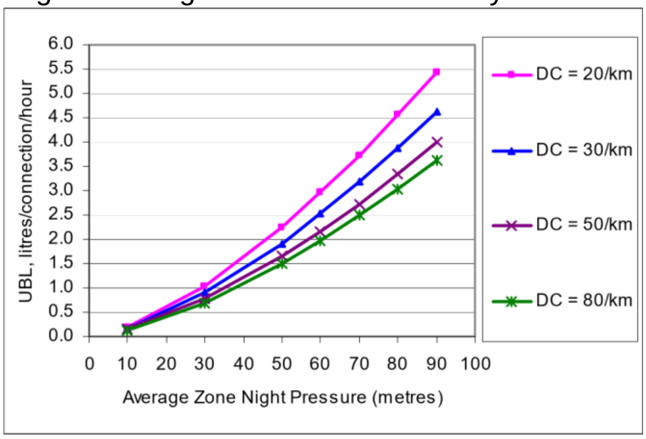


Figure 1: Variation of Components of UBL with AZNP and Density of Connections

There is no specified lower limit for using the UBL formula, but at lower pressures (less that 20 metres), or other situations when effective acoustic leak detection becomes difficult, it is unlikely the predicted UBL figure can be achieved in practice.

The basic equation for the calculation of UARL is:

$$\text{UARL (litres/day)} = (18 \times Lm + 0.8 \times Ns + 25 \times Lp) \times P \quad \text{……….(2)}$$

where Lm is mains length (km). Ns is no. of service connections (main to property line), Lp is total length of underground pipes (property line to meter) and P is the average 24-hour pressure (metres)

Regarding sensitivity of the UARL equation, Table 2 shows that at 50 metres pressure, UBL forms the largest component of UARL – 480 out of 900 l/km/hr (53%) on mains, 30 out of 40 litres/conn/day (75%) on services (main to meter) and 800 out of 1250 l/km/day (64%) on private pipes (property line to meter).

The components from reported and unreported bursts typically account for the remaining 1/3rd of the UARL. For any particular Utility and system, the parameters for this part of a ‘system-specific’ calculation will not be the same as the assumptions in Table 1 (which are indicative for frequencies and flow rates). However, if all the detectable reported and unreported leaks and bursts are located and repaired in the indicated timescales, the aggregate volume of all these components should be similar to the UARL prediction. A free software (UARLSensitivityCalcs.xls), available from the author on request, can be used to check this; for most well managed Utilities with infrastructure in good condition, the system-specific UARL will be unlikely to differ by more than +/- 15% from the ‘standard’ UARL formula.

The original paper (Lambert et al 1999) recognised that in situations where all (or almost all) leaks and bursts become rapidly visible at the ground surface, the basic UARL equation will over-estimate the UARL, as all bursts will be reported and repaired quickly. If it had been assumed (in Table 1) that 100% of all leaks and bursts were reported, the resulting UARL equation in litres/conn/day would have been

$$(15.8 \times Lm + 0.65 \times Ns + 18.5 \times Lp) \times P$$

which is around 20% less than the basic UARL formula. However, at ILI values close to 1.0, it is usually difficult to calculate Current Annual Real Losses volume to better than +/- 20% even in fully metered systems, so the % error in the calculated UARL would still be no worse than the % error in CARL calculated from the water balance.

It is now recognised that the original figure of 1.6 m^3/hour used for service pipe leak flow rates at 50 metres pressure is too high; around 0.6 m^3/hour is more appropriate for international use. However, it can also be argued that 8 days average run time for reported service pipe leaks was optimistic, if it were 21 days the volume lost per burst event at an average flow rate of 0.6 m^3/hour in Table 1 would be unchanged

Limits of Application of the UARL Equation

Table 3 shows how the limits of application for the standard UARL calculation have gradually been relaxed since the original AQUA publication in 1999. The latest lower limits for system size can be assessed using a combination of mains length (Lm in km) and number of service connections (Nc). Research into the applicability of the UARL formula to trunk mains systems continues at the time of writing this paper

Table 3: Relaxation of limits of application of UARL formula, 1999 to 2009

Parameter	Limits	Lambert et al, AQUA	Lambert & McKenzie	Liemberger & McKenzie	Lambert
		1999	2001	2005	2009
Density of Connections/km	Minimum	20	20	Removed	No lower limit
	Maximum	100	Removed		No upper limit
	Minimum	20	25	25	See Graph

Average Pressures (m)	Maximum				See Graph
System Size	Minimum	Not stated	Nc > 5000	Nc > 3000	Nc + 20 x Lm > 3000

Thornton & Lambert (2005) showed that the range of pressures over which the UARL formula is likely to be reliable depends upon the FAVAD N1 for the detectable bursts (Figure 2). For systems where all detectable bursts are fixed area (FAVAD N1 = 0.5), the standard UARL equation may be reliable to within +/- 10% for pressures between 10 and 80 metres. But for systems with all detectable bursts have a FAVAD N1 of 1.5, the true UARL is underestimated by the standard formula as pressure falls, and over-estimated as pressure rises.

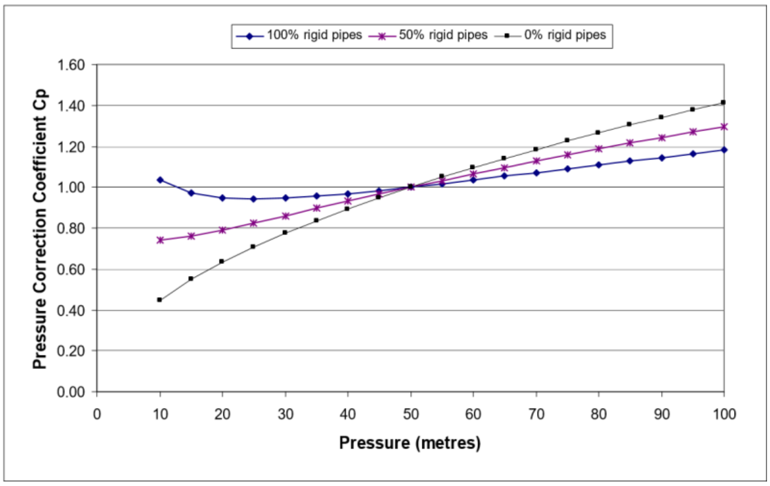


Figure 2: Influence of type of pipe materials on UARL as pressure changes

Liemberger & Mckenzie (2005) consider that this effect, identified in Figure 2, is not a problem in developing countries with low pressure, as the basic UARL equation will lead to over-estimates of the true UARL and under-estimates of the ILI. They also consider that the UARL calculation is very useful in developing countries for systems with fewer than 3000 service connections. The author agrees with both of these views for developing countries. It is only in developed countries that care is needed in situations where the basic equation may consistently over-estimate UARL and lead to ILIs less than 1.0 if assumptions used in the UARL equation are inappropriate.

Part 2: Criticisms of the UARL and ILI

How can the UARL formula be correct if an ILI less than 1.0 is calculated?

Circumstances in which a calculated ILI less than 1.0 can arise are as follows:

a) at low ILIs, the confidence limits for Current Annual Real Losses from a Water Balance are likely to be at least +/- 20%, even with fully metered systems

b) systematic errors in the water balance calculation – under-registration of bulk input meters, over-registration of bulk export meters, over-estimation of metered consumption if no meter lag correction, over-estimation of estimated customer meter under-registration, over-estimation of Unbilled Authorised consumption and Unauthorised Consumption

c) doing the calculation too quickly after the end of the Water Year, before all bulk supply meter and consumption data has been checked and validated

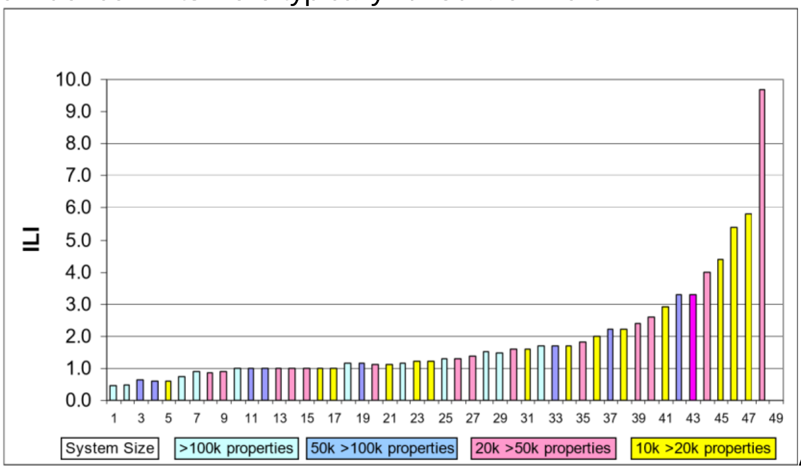
d) over-estimation of number of service connections (by assuming equality with number of billed properties); over-estimation of average pressure

e) the system falls outside the limits of size and average pressure in Table 3 of this paper and Figure 2

f) in the very few systems internationally where there are no unreported bursts, the UARL would be around 20% less than predicted by the standard formula

In an Austrian benchmarking project in 2005-06 (data from 2004), Koelbl et al (2007) reported that 11 out of 24 Austrian Utilities with more than 3000 service connections had calculated ILIs less than 1.0, with 8 in the range 0.3 to 0.8, having confidence limits of around +/- 50%. However, when the data for these low ILIs were checked, it was found that some pressures had been over-estimated, and Unbilled Authorised Consumption and Customer Meter Under-Registration had generally been over-estimated; most of the 11 'low' values were in fact close or more than 1.0. In the 2007-08 Austrian benchmarking project with 2007 data (Neunteufel et al, 2009) 5 of 16 Utiliites with more than 3000 service connections had ILIs less than 1.0 (0.39, 0.53, 0.70, 0.89, 0.95). There were 'possible large errors in system input volume' for three of these five ILI estimates, including the two lowest values; considering confidence limits, only 2 of the upper limits of these five ILI estimates are less than 1.0 (0.85 and 0.86).

In Australia, during several years of serious drought, leakage levels in many Utilities have been significantly reduced. The National Performance Report for 200607 showed many Utilities with ILIs close to 1.0, and 6 out of 43 with ILIs less than 0.9 (Figure 3), ranging from 0.4 to 0.7. Further checking showed that, in two of these, there were significant problems with bulk metering that year. In the three other cases investigated, when meter lag and other systematic errors were identified, recalculated ILIs were close to or greater than 1.0. The checks showed that data errors were being indicated not only by the low ILIs, but also Real Losses less than 50 litres/service connection/day. Confidence limits were typically +/- 30% or more.



Australian 2006-07 ILIs

Figure 3: Australian ILIs for 2006-07. Source: WSAA

The Austrian and Australian experience are not the only occasions where the ILI has identified data errors in systems with relatively low real losses. This is because the UARL formula allows for 4 key parameters – mains length, number of service connections, meter location (relative to property line) and average pressure. So when an ILI significantly less than 1.0 is reported, experience suggests that all aspects of the Real Losses volume calculation need to be checked and validated, with confidence limits, rather than only questioning the validity of the UARL equation.

Criticism: Some users find it difficult to reliably assess average pressure In most countries, it is not usual practice to assess, or report, average pressure. Given that pressure significantly influences leak flow rates, some components of consumption, burst frequencies and infrastructure life, this is a surprising omission. However, there are several standardised systematic approaches for calculating average system pressure, particularly in countries where the benefits of pressure management are known. Each Water Utility in England and Wales knows the average pressure for each DMA, Supply Zone and whole Utility, even though they are not required to report it to their regulators. Japanese Utilities regularly quote average pressures for their systems. Average pressures can be calculated, if the will to do so exists, but better guidance on best practice calculation methods is needed .

In fact, the confidence limits for the ILI calculation (and all other Real Losses PIs) are often dominated by the confidence limits for the calculated Real Losses volume; if this is +/- 30% (at an ILI close to 1) and the confidence limits for calculated average pressure are +/- 10%, the confidence limits for ILI (assuming mains length and number of service connections are known) are only +/- $(30\%^2 + 10\%^2)^{0.5}$ = +/- 31.6%

Criticism: the word 'Unavoidable' is inappropriate
At any given pressure, the UBL, which accounts for around 2/3rds of the UARL, is unavoidable, unless every joint and fitting are exposed. 'Awareness' and 'Location' components of the total duration of reported bursts used in the UARL are also unavoidable. Active leakage control interventions to locate unreported leaks require a sufficient aggregation of such leaks to make the costs of an intervention economic.

Chesneau et al (2007) agreed that background leakage is 'unavoidable' but prefer to consider some part of the volume lost from reported and unreported bursts as 'retrievable'. This would mean using 'Unavoidable' for background leakage (UBL) and 'Unavoidable plus Retrievable' (U+RARL) instead of UARL. This is more precise, but potentially confusing. 'Minimum Achievable' replaces 'Unavoidable' in World Bank Institute definitions (Minimum Achievable Annual Physical Losses MAAPL) but this seems to have similar shortcomings to 'Unavoidable'. The author agrees that 'Unavoidable' is not a precisely accurate term when applied to Annual Real Losses (UARL) but it has the merits of simplicity and (after 10 years of use) familiarity.

PART 3: Looking Ahead

Is there a Case for changing the Coefficients in the UARL formula?

The original paper (Lambert et al, 1999) created an audit trail to allow the 15 parameters in Table 1 used in the derivation of the UARL to be modified at a later date if appropriate. The following comments on the parameters are relevant

- further tests in the UK (UKWIR, 2005) have not found anything to contradict the UBL components on mains and service connections up to the property line
- UBL on private pipes after the property line is likely to vary and to be lowest where customer meters are located at the property line
- Research into the applicability of the UARL formula to trunk mains systems continues at the time of writing this paper.
- Renaud et al (2007) suggest that UARL predictions may be too high for small rural systems with low connection densities; this is consistent with all mains bursts being reported, but insufficient to justify change without additional data.
- average flow rate for service pipe bursts should be 0.6 m^3/hour rather than 1.6 m^3/hour, but the original assumed average durations were probably optimistic.
- experience in Australia suggests that in serious droughts, average run times of mains bursts can be shortened to less than the figures assumed in Table 1

- in the very few Utilities in which all detectable leaks and bursts are reported, the UARL could be up to 30% less than predicted from the basic formula

In three cases where the use of the UARL formula has been independently reviewed (Liemberger & McKenzie, 2005; Koelbl et al 2007; WSAA 2008), the conclusions were that there was no case for modifying the coefficients of the basic UARL equation; that the ILI was a very useful performance indicator, and the UARL equation was acceptable in its present form. Any minor benefits from making small changes in the coefficients would be more than offset by the disruption and confusion caused to users around the world by having two or more UARL equations.

Should the ILI be used for Metric or Process Benchmarking, or both?
The two key objectives of the first IWA Water Loss Task Force (Lambert et al, 1999) were to recommend a standard international water balance terminology, and to review performance indicators *for* <u>*international comparisons of losses in water supply systems*</u>, for inclusion in the 1st Edition of 'Performance Indicators for Water Supply Services' (Alegre et al, 2000). At that time, some ten years ago, no distinction was made, in either of these two IWA publications, as to the difference (Cabrera, 2008) between Metric benchmarking and Process benchmarking.

- *Metric benchmarking* compares numerical performance indicators of different Utilities, with very different characteristics; comparing 'apples' with 'pears'
- *Process benchmarking* identifies and adapts best practices to improve performance within an individual utility, for measuring progress towards targets

The last 10 years experience shows that ILI is the most useful PI currently available for Metric benchmarking at Utility, State, National and International Level. However, for process benchmarking, if pressure management is part of a Real Losses reduction strategy, the ILI is not an appropriate PI (Fanner et al, 2007); litres/service connection/day should be used for systems > 20 conns/km., or m^3/km/day if < 20/km.

Conclusions

- parameters used to calculate UARL and UBL have been specified in Table 1 and Table 2 in alternative formats, to assist users in their interpretation
- the equation for Unavoidable Background Leakage, for use in night flow component analysis, with a FAVAD N1 of 1.5, has been clearly specified
- updated limits for application of the UARL equation are provided in Table 3
- where ILIs less than 1.0 have been calculated, all aspects of the calculations of Real Losses volume should be checked and validated, with confidence limits
- in systems where there are no unreported leaks, ILIs down to 0.7 are possible
- minor aspects of the UARL parameters could now be modified, but possible benefits would be outweighed by confusion caused to existing users
- the ILI is the best available performance indicators for metric benchmarking of real losses, but is not suitable as a process benchmarking PI if pressure management is part of the Real Losses reduction strategy

Acknowledgements
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