UK experience in the monitoring and control of lead in drinking water

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ABSTRACT

At the zonal scale (e.g. a city or town), random daytime (RDT) sampling succeeded in demonstrating both the need for corrective action and the benefits of optimised orthophosphate dosing for plumbosolvency control, despite initial concerns about sampling reproducibility. Stagnation sampling techniques were found to be less successful. Optimised treatment measures to minimise lead in drinking water, comprising orthophosphate at an optimum dose and at an appropriate pH, have succeeded in raising compliance with the future European Union (EU) lead standard of 10 μg/L from 80.4% in 1989–94 to 99.0% in 2010 across England and Wales, with compliance greater than 99.5% in some regions. There may be scope to achieve 99.8% compliance with 10 μg/L by further optimisation coupled to selective lead pipe removal, without widespread lead pipe removal. It is unlikely that optimised corrosion control, that includes the dosing of orthophosphate, will be capable of achieving a standard much lower than 10 μg/L for lead in drinking water. The experience gained in the UK provides an important reference for any other country or region that is considering its options for minimising lead in their drinking water supplies.

Key words | lead in drinking water, plumbosolvency control, regulatory compliance, sampling

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INTRODUCTION

As reviewed by Troesken (2006), episodes of lead poisoning linked to drinking water were frequently recorded in medical journals during the nineteenth and early twentieth centuries. The issue then faded into history until the early 1970s, when health studies demonstrated a link between elevated concentrations of lead in drinking water and elevated blood lead levels in the Glasgow area (Beattie *et al.* 1972). At the time, water supplies to Glasgow were drawn from a loch in the nearby mountains with no treatment other than chlorination. The water was slightly acidic, had very little alkalinity and was slightly coloured from humic substances (organic acids that leach from peaty land) and in consequence was highly corrosive. Much of the housing at the time comprised apartment blocks with extensive internal lead piping and also lead-lined storage tanks. These extreme circumstances were perceived as being atypical and problems with lead in drinking water were not recognised elsewhere in the UK.

However, the UK Government prompted surveys in 1975 and 1977, which demonstrated that problems were being experience throughout the country in relation to the World Health Organization (WHO) guidelines at the time (100 μg/L not to be exceeded in any sample, 300 μg/L not to be exceeded after more than 16 hrs stagnation). As an example, a survey in the Eastern region of England in 1977 (Greene 1984), based on 1,500 random daytime (RDT) samples (selected from all properties, regardless of pipe materials), found that 1% exceeded 300 μg/L and 10% exceeded 100 μg/L. All the water supplies in this region have a high alkalinity (typically, 200–300 mg/L as $CaCO_3$). Further more extensive surveys were then carried out over the period 1979–1981. The greater realisation of the extent of problems from lead in drinking water coincided with wider concerns about lead in the environment, culminating in recommendations (Royal Commission on Environmental Pollution 1983) for corrective action in water supply areas

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where warranted, banning the use of solder containing lead for jointing copper pipes and food cans, and banning the use of lead additives in paint and petrol. Since this era, standards for lead in drinking water in the UK have tightened from 100 to 50 μg/L then 25 μg/L and will tighten further to 10 μg/L in December 2013.

This paper outlines the experience gained in the UK since the 1970s as problems with lead in drinking water have been steadily reduced, including the success or failure of sampling procedures, the optimisation of corrective water treatment and strategies for lead pipe replacement. The lessons that can be learnt from this national case study have much relevance elsewhere, particularly in those parts of Europe which have also extensively used lead piping and where only limited corrective actions have so far been taken (Hayes & Skubala 2009).

ESTABLISHING THE NEED FOR ACTION, BASED ON RANDOM DAYTIME SAMPLING

Sources of lead in drinking water and options for control

Most commonly, lead is absent from treated waters at source and is absent within the water suppliers' distribution networks, which normally do not use pipes or other components containing lead. The principal sources of lead in drinking water are the domestic pipe-work systems and the pipes that connect a dwelling to the water main in the street, where lead pipes and components containing lead are in use. Lead piping was in common use in the UK until the early 1980s and about 40% of houses have lead pipes. The lead pipes that remain are mostly the lead connection pipes that are buried between the water main and the house. Part of this pipe from the water main to the external stop tap belongs to the water supplier, being 20–25% of total length on average (Drinking Water Inspectorate 2010), and part from the external stop tap to the house belongs to the owner of the house, being 75–80% of total length on average (Drinking Water Inspectorate 2010). Most internal lead pipes have been removed when kitchens have been modernised. As an example, whereas 52% of houses are estimated to have a lead service pipe in Cambridge, only 5% of houses in this city have internal lead pipes still in use (Hayes *et al.* 2006).

Lead pipes are considered to be the major source of lead in drinking water in the UK (although lead from other sources is possible, notably lead leaching from brass and solder containing lead) and lead pipes have been the focus of corrective action. This contrasts with the view of the WHO in their recent booklet (World Health Organization 2010) on Childhood Lead Poisoning which states that solder containing lead is the principal source of lead in drinking water; this view was subsequently challenged by an international panel of experts (International Water Association 2011).

Whilst the removal of all lead pipes is the ultimate goal, the very high cost (about £10 billion in the UK), problems with split ownership, likely long timescales and the scale of disruption involved prompted a national strategy for corrective action by water treatment measures as the logical first step to take. However, corrective water treatment is specific to individual water supply systems, as a function of water quality and housing circumstances, and it was therefore necessary to establish needs at this local level by surveying lead concentrations at the point of use, that is, at the consumers' taps. Surveys were undertaken across the UK at different times, linked to the step changes in the standard for lead in drinking water that were being implemented, and were not without problems.

Surveys based on random daytime sampling

In the UK, the preferred survey method has been RDT sampling. A RDT sample is the first litre drawn from the consumer's tap (normally, the cold water tap in the kitchen) without prior flushing, from a property selected at random, taken at a random time during the working day (normally defined as 0900–1700 hrs). RDT sampling has been the basis for assessing compliance with lead standards in the UK since 1989 (Department of the Environment 1989).

The first extensive surveys were undertaken over the period 1979–1981, following the recommendations of a Department of the Environment Expert Advisory Group. RDT sampling was undertaken in water supply systems or sub-divisions thereof containing a maximum of 10,000 properties (equivalent to a population of approximately 25,000).

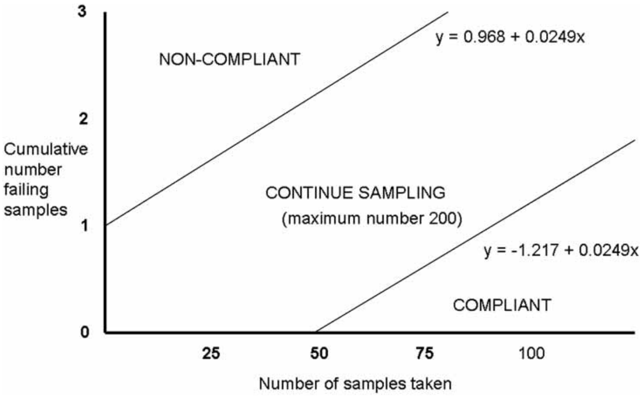

Figure 1 | Cumulative chart for judging the results of RDT monitoring.

Results were plotted on a cumulative basis (see Figure 1) to determine if more than 2.5% samples exceeded 100 μg/L with at least 95% confidence, in which case corrective action was warranted. The use of statistical tools to interpret survey data of this type was certainly 'ground-breaking' and ahead of its time but has since only been used in Scotland to determine compliance (Scottish Executive 2007). However, the survey protocol was flawed as it did not specify the period over which samples should be obtained. Most water authorities and companies carried out their surveys over the winter months because staffing logistics were easier (more go on holiday during the summer). As is now known (International Water Association 2010), samples taken in the summer were twice as likely to fail than samples taken in the winter because of the influence of temperature on lead solubility. Many supply systems were not actually surveyed because it was considered at the time (erroneously) that a few representative systems could provide the wider picture. The surveys therefore underestimated the extent of problems in the UK and corrective actions were limited to pH elevation in some areas and the commencement of orthophosphate dosing trials in a few locations.

Almost a decade later, guidance to the regulations (Department of the Environment 1989) that implemented the first European Drinking Water Directive (80/778/EC) required compliance with the quality standards to be assessed for water supply systems, or zones within a system, with a population of no more than 50,000. Compliance with the then new lead standard of 50 μg/L (50 μg/L not to be exceeded in 'running water', 100 μg/L was the maximum permitted) had to be demonstrated in the UK by RDT sampling in each system/zone (in the UK, the 50 μg/L standard was adopted without qualification as a simple maximum value). Some water companies interpreted the method of assessing compliance to mean RDT sampling only from houses believed to have a lead pipe, whereas others interpreted this to mean RDT sampling from any house in a system/zone, with or without a lead pipe. Those water companies sampling only from houses with a lead pipe tended to fail the Department of the Environment's compliance criterion (98% compliance with 50 μg/L) and consequently installed orthophosphate dosing in order to secure compliance. Those water companies sampling from any house tended to comply and took no further action.

With further new standards for lead in mind (25 μg/L from December 2003, 10 μg/L from December 2013), the Drinking Water Inspectorate (DWI) issued Information Letters (Drinking Water Inspectorate 2000 and 2001) that required the water companies in England and Wales to optimise treatment measures to reduce plumbosolvency, including the dosing of orthophosphate. Optimisation had to be demonstrated and was subject to a legal undertaking with the Secretary of State. Scotland and Northern Ireland implemented similar requirements and in consequence 95% of public water supplies in the UK are now dosed with orthophosphate for plumbosolvency control. The DWI's Information Letters gave preference to fixed point stagnation sampling to demonstrate that optimisation had been achieved but the water companies preferred RDT sampling as this was already being undertaken for bacteriological monitoring. Ten years on, RDT sampling has been shown to provide a much more effective monitoring basis than had been anticipated.

OPTIMISATION OF PLUMBOSOLVENCY CONTROL

The Drinking Water Inspectorate's requirements

DWI Information Letters 12/2000 and 3/2001 (the latter was a slightly revised version) required plumbosolvency control treatment in England and Wales to be optimised if >5% of at least 100 RDT samples had exceeded 10 μg/L in the water supply zone(s) supplied by the treatment works. Optimisation was defined as the best practical reduction in lead concentrations and was taken to mean maintaining an optimum orthophosphate dose throughout a water supply system, within an optimum pH range. If pH and alkalinity control were proposed as the only treatment measures, water companies had to demonstrate that an optimum dose of orthophosphate could not achieve a further significant reduction in lead concentrations; in practice, none did so. References were made to increasing ortho-phosphate doses to overcome organic colour and the need to minimise corrosion of iron distribution systems.

The Information Letters implemented an optimisation framework and the precise definition of an optimum orthophosphate dose was necessarily vague. It was indicated that the optimum dose of orthophosphate could be determined from laboratory tests, from full scale or pilot scale trials, by practical experience, from solubility or computational models, or if an increase in orthophosphate dose produced no further worthwhile improvement. It was also stated that a water supply system could be considered optimised if a sufficient number of RDT samples had been taken and less than 2% samples exceeded 10 μg/L. This numeric criterion was adopted by most water companies as their target for optimisation, despite the DWI's initial preference for optimisation to be demonstrated by fixed point stagnation sampling. In practice, stagnation sampling from houses was found to be difficult to sustain, similar to experience in the USA (International Water Association 2010), and the use of lead pipe test rigs was only partially successful. Importantly, the DWI followed up the progress being made by water companies with technical audits. Once concluded, optimisation schemes were reported formally. All optimisation schemes were subject to legally binding agreements with the Secretary of State. Northern Ireland and Scotland have separate administrative arrangements but these are closely aligned to England and Wales and broadly similar requirements for the optimisation of plumbosolvency control were applied.

The concentration of orthophosphate used in the UK varies from 0.5 to 2.0 mg/L (P), most typically between 1.0 and 1.5 mg/L (P), and is generally two or even three times higher than dosed in the USA (International Water Association 2010). Doses are water supply system specific, and are determined by both water quality and the extent of occurrence of houses with lead pipes. Higher doses have been used in supplies that have an elevated organic content, particularly where humic substances are involved (Cardew 2009). No problems have been reported in relation to bacterial growths within distribution networks and the impact on sewage effluent is considered slight (International Water Association 2010).

Initial concerns about RDT sampling

Table 1 provides a summary of RDT results, both before and after the introduction of orthophosphate dosing, for a water supply system in the UK, taken as an example from the optimisation schemes reported by Hayes *et al*. (2008). Prior to orthophosphate dosing, the percentage of samples exceeding 10 μg/L varied in each year by ±50% of the mean over the period shown, typical of the variation that

Table 1 | RDT results from a water supply system in the UK

Year	Number of samples	% >10 μg/L	% >25 μg/L	% >50 μg/L
(a) Before the introduction of orthophosphate dosing				
1990	132	28.0	17.4	9.9
1991	228	24.1	11.0	4.0
1992	61	13.1	6.6	0.0
1993	45	17.8	13.3	2.2
1994	29	10.3	6.9	0.0
1990–1994	495	22.4	12.1	4.4
Predicted[a]		18.4	11.3	4.8
(b) After the introduction of orthophosphate dosing				
1995	11	9.1	0.0	0.0
1996	29	6.9	0.0	0.0
1997	28	3.6	0.0	0.0
1998	28	3.6	0.0	0.0
1999	9	0.0	0.0	0.0
2000	8	0.0	0.0	0.0
2001	26	3.8	3.8	3.8
2002	28	0.0	0.0	0.0
2003	85	0.0	0.0	0.0
1995–2003	252	2.4	0.4	0.4
Predicted[a]		2.8	0.2	0.0

[a] Predictions from computational modelling (Hayes *et al*. 2008).

was observed more generally. Although this year by year variation was significant numerically, the levels of failure were much higher than the DWI's criterion for optimisation action (5%) and was therefore of limited significance operationally.

The extent of variation that is possible between surveys can be further investigated by computational modelling (Hayes & Croft 2012). In Figure 2, the percentage of surveys that were predicted to fail at a particular level (% samples exceeding 10 μg/L) are shown for a water supply with moderate plumbosolvency (i.e. not orthophosphate dosed), based on 100 simulated surveys each of 100 simulated RDT samples. The extent of variation in the predicted level of failure, that can be seen to follow a normal distribution, ranged from 11 to 32% with an average of 20.7% (approximately ±50%) being similar to that observed by actual RDT sampling in the example given in Table 1.

After the introduction of orthophosphate dosing to the water supply system concerned (Table 1), the levels of failure observed were much lower and once the orthophosphate dose and its effect had stabilised throughout the distribution system, failure levels became consistently very low. The averaged results, both before and after the introduction of dosing, closely matched the predicted results (also averaged) from computational modelling (Table 1). In a recent modelling study (Hayes & Croft 2012) the extent of variation between simulated RDT surveys was found to reduce for higher numbers of samples, from which it can be concluded that by aggregating data from several years the year by year variation will become less important. Aggregating RDT sampling data over five or more years (when available), both before and after the commencement of orthophosphate dosing, was undertaken for all treatment schemes that were optimised in Wales, in order to determine the most representative positions (Hayes *et al*. 2008).

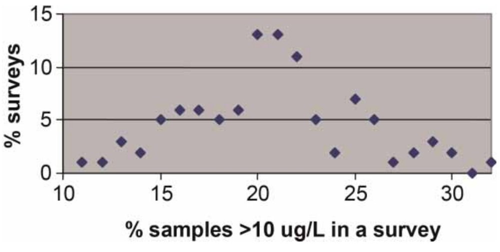

Figure 2 | Variation in simulated RDT sampling results. For a simulated zone in which 50% houses have a lead pipe and for moderately plumbosolvent water, from Hayes & Croft (2012).

What has been achieved, based on RDT sampling

The numbers of RDT samples taken for lead in England and Wales over the period 2005–2010 are shown in Table 2. The regional variation is a reflection of the populations involved and progress with the optimisation of orthophosphate dosing. The period 2005–2007 is when many dosing schemes had fairly recently been optimised. During this period, the average sampling frequency was about 24 samples per annum per water supply zone, compared to about 50 samples per annum per zone during 1989–1994, when the extent of plumbosolvency problems were being assessed to determine whether or not further corrective actions would be necessary. The routine sampling frequency during 2008–2010, following the optimisation of orthophosphate dosing, reduced to about 12 samples per annum per zone. The trend of reducing sampling frequency is consistent with less variability in the RDT results after the commencement of orthophosphate dosing (as illustrated in Table 1). Although the zonal sampling frequencies were generally fairly low on an annual basis, regional aggregation results in substantially more data from which conclusions can be drawn. The numbers of samples identified in Table 2 help put the monitoring workload in England and Wales into perspective.

The summary results from this monitoring are given in Tables 3 and 4 for non-compliance with the 10 and 25 μg/L lead standards, respectively (Drinking Water Inspectorate 2006–2011). The recent (2009 and 2010) compliance position for lead based on 25,641 samples, 99.0% with 10 μg/L and 99.8% with 25 μg/L, is generally regarded as highly satisfactory. This compares to 80.4% compliance with 10 μg/L and 91.6% compliance with 25 μg/L over the period 1989–1994, before orthophosphate dosing became widespread, based on a total of 326,554 RDT samples (Drinking Water Inspectorate 1992, 1995). These reductions in non-compliance have been about 20-fold with respect to 10 μg/L and about 40-fold with respect to 25 μg/L. In Northern Ireland, on the basis of data from 2009 (Drinking Water Inspectorate (Northern Ireland) 2010), 99.1% RDT samples complied

Table 2 | RDT sample numbers for lead in England and Wales[a]

Region	2005	2006	2007	2008	2009	2010
Central	1,739	1,727	1,677	1,699	1,748	1,753
Eastern	1,788	1,818	1,868	2,104	1,900	1,810
Northern	4,177	6,102	3,816	3,367	3,296	3,072
Southern	1,393	1,424	1,408	1,427	1,417	1,423
Thames	11,819	13,279	12,409	2,490	2,488	2,498
Western	1,510	1,430	1,339	1,396	1,466	1,461
Wales	702	670	664	670	660	649
Total	23,128	26,450	23,181	13,153	12,975	12,666

[a] Drinking Water Inspectorate (2006–2011).

Table 3 | Percentage of RDT samples exceeding 10 μg/L lead[a]

Region	2005	2006	2007	2008	2009	2010
Central	1.78	1.74	1.01	1.00	1.14	1.31
Eastern	0.78	1.05	1.34	0.57	0.42	0.61
Northern	1.60	1.28	1.23	1.34	1.21	1.01
Southern	0.72	0.98	0.71	1.19	0.49	0.91
Thames	2.54	3.07	2.28	1.20	1.53	1.48
Western	0.73	0.98	0.45	1.22	0.55	0.62
Wales	0.85	0.75	1.05	0.75	1.06	0.46
Average	1.29	1.41	1.15	1.09	0.99	1.00

[a] Drinking Water Inspectorate (2006–2011). *Note*: DWI optimisation target was 2%.

Table 4 | Percentage of RDT samples exceeding 25 μg/L lead[a]

Region	2005	2006	2007	2008	2009	2010
Central	0.29	0.17	0.18	0.24	0.17	0.11
Eastern	0.17	0.22	0.27	0.00	0.00	0.06
Northern	0.29	0.28	0.34	0.56	0.39	0.23
Southern	0.00	0.35	0.28	0.21	0.14	0.21
Thames	0.37	0.44	0.23	0.12	0.32	0.20
Western	0.13	0.07	0.07	0.07	0.13	0.14
Wales	0.28	0.15	0.15	0.00	0.15	0.31
Average	0.22	0.24	0.22	0.23	0.22	0.17

[a] Drinking Water Inspectorate (2006–2011).

with 25 μg/L and 97.4% RDT samples complied with 10 μg/L, slightly less than in England and Wales. In Scotland, on the basis of data from 2010 (Drinking Water Quality Regulator for Scotland 2011a), 99.7% RDT samples complied with 25 μg/L and 98.4% RDT samples complied with 10 μg/L, broadly similar to England and Wales.

The summary results for England and Wales shown in Tables 3 and 4 provide several further insights:

- Optimisation of orthophosphate dosing in the Thames region took several years more than in the other regions to achieve the DWI's target of <2% RDT samples exceeding 10 μg/L.
- Better than 99.5% compliance with 10 μg/L has been achieved intermittently in four out of seven regions, implying that 99.5% compliance could be considered as a national target.
- Across England and Wales, 99.8% compliance has been achieved with 25 μg/L (the current standard) fairly consistently over the period 2005–2010.
- Better than 99.9% compliance has been achieved with 25 μg/L intermittently in four out of seven regions, implying that 99.9% compliance could be considered as a national target.

These very high levels of regional and national compliance demonstrate what can be achieved by orthophosphate dosing and exceeded initial expectations.

Based on the standard of 10 μg/L, which is also the current WHO guideline value (World Health Organization 2011), the risk to children from lead in drinking water has been reduced in England and Wales from about one in five to 1 in 100. As four out of the seven regions in England and Wales have already achieved 99.5% compliance in at least one year (Table 3), it is reasonable to conclude that this higher level of compliance could be achieved by further optimisation of orthophosphate dosing in all regions and on a more consistent basis. In case studies that used computational modelling (Hayes *et al.* 2006), the predicted failure to achieve 10 μg/L was found to be due to long lead pipes greater than 40 or 50 m, depending on the zone. This suggests that additional selective lead pipe replacement that focused on long lead pipes could achieve even higher compliance, perhaps 99.8%, which would reduce the risk level even further to 1 in 500. Recent guidance from the Drinking Water Inspectorate (2010) requires water companies to maintain the optimisation of corrosion control treatment measures and to work with local authorities in the identification of any 'hot-spots' where lead pipe replacement could be warranted. It is considered likely that 'hot-spots' will equate to very long lead service pipes in many cases.

Other reasons for failure can be:

1. Home owners making changes to internal plumbing just before sampling. This explained around 50% of a small number of failures that were investigated by one water company (Hayes *et al.* 2006).
2. Particulate lead arising from loose iron corrosion deposits. This was perceived as a major barrier to achieving the EU lead standards by treatment measures. However, it is no longer the case (Cardew 2009). Part of the explanation is the major clean up of distribution systems over the last 20 years (replacement or rehabilitation of cast iron water mains). In 2010 for England and Wales, also based on RDT sampling, compliance with the iron standard of 200 μg/L was 99.7% (Drinking Water Inspectorate 2006–2011).
3. Vibration effects where lead service pipes pass under a road-way. Cardew (2009) also comments that orthophosphate may have hardened the internal corrosion film within the lead pipes, so this effect may now be less significant (although it has not been quantified at any time).
4. Leaching from brass and legacy leaded solder. In contrast to the USA (International Water Association 2010), such sources are not regarded as an issue in the UK, other than specific exceptions such as lead leaching from brass manifolds (International Water Association 2010) and the illegal use of leaded solder (Scottish Centre for Infection and Environmental Health 2000). It is possible that optimised orthophosphate has also suppressed lead dissolution from these sources (research is required to confirm this) or these sources are only trivial.

Related compliance issues

In 2009 and 2010 for England and Wales, also based on RDT sampling, compliance with the copper standard of 2,000 μg/L was greater than 99.9% (Drinking Water Inspectorate 2006–2011) and explains why cuprosolvency is not regarded as a problem in the UK, other than for very localised exceptions. Episodes of copper pitting corrosion have occurred due to low pH, excessive levels of bleach used in disinfecting newly installed copper pipes, and debris left in newly installed copper pipe-work (International Water Association 2010). Unlike in the USA, corrosion control systems in the UK are not specifically targeted to cuprosolvency control. It is possible that the measures taken to reduce plumbosolvency are also keeping cuprosolvency in check, assuming that cuprosolvency might otherwise be more of a problem.

Compliance with the nickel standard of 20 μg/L was 99.8% in 2009 and 2010 in England and Wales, again based on RDT sampling (Drinking Water Inspectorate 2006–2011). This contrasts with lower compliance levels reported in other European countries: 98.8% in the Netherlands (Slaats *et al.* 2008) and as low as 93% in Germany (Ruebel & Becker 2008). It is possible that the significantly higher level of compliance in England and Wales is due to the suppression of nickel leaching from nickel-chrome plated plumbing components by orthophosphate.

HOW REPRESENTATIVE IS RDT SAMPLING?

The question arises: how representative is RDT sampling during 'normal office hours' of the full period of water use in a day (Slaats *et al.* 2008)? This question cannot be answered experimentally because of the year-by-year variation that is inherent in the RDT sampling results from a water supply zone and because all zones are different in relation to the circumstances that will effect RDT sampling results. However, the question has been explored by computational modelling in a recent study by Hayes & Croft (2012).

Table 5 | Simulated RDT sampling as a function of sampling period[a]

Time ranges	% Daily flow	Hours when flow occurs	%RDT samples >10 μg/L	%RDT samples >25 μg/L	%RDT samples >50 μg/L
0900–1700 (UK sampling practice)	42	8	20.19	8.32	1.92
0800–1800	60	10	19.81	8.36	2.06
0700–1900	80	12	18.95	7.70	2.00
0600–2000	90	14	18.73	7.29	2.12
0600–2100	94	15	18.89	7.67	2.48
0600–2400 (total period of flow)	100	18	20.87	9.51	2.97
1000–1600	30	6	19.64	7.55	1.78
1100–1500	23	4	18.47	6.52	1.44

[a] Simulated results for a zone with 50% houses with a lead pipe and moderate plumbosolvency water, selected from Hayes & Croft (2012) to demonstrate the dependency of RDT results on sampling period using an assumed pattern of water use over a 24-hrs period.

Table 5 provides a small number of selected simulated results from this study for a zone with moderate plumbosolvency in which 50% of houses have been assumed to have a lead pipe. The simulations indicated that the notional period of normal office hours, 0900–1700 hrs, is adequately representative of the assumed total use period 0600–2400 hrs and that extended or truncated periods of sampling provide very slightly lower results.

EXPERIENCE WITH STAGNATION SAMPLING METHODS

Thirty minutes stagnation (30MS) sampling has been used successfully in some circumstances. The sampling protocol involves flushing the domestic pipe-work for at least 2 minutes, allowing the water to then stagnate for 30 minutes, and then taking the first litre drawn from the cold water tap in the kitchen. 30MS sampling can be used to benchmark treatment changes using selected houses which have a lead service pipe. The advantage is that *in situ* lead pipes can provide a direct measure of the success or otherwise of any treatment condition, such as a particular orthophosphate dose. As an example, 30MS results at one house in Eastern England (International Water Association 2010) varied seasonally between 20 and 55 μg/L prior to orthophosphate dosing and between 3 and 10 μg/L after the commencement of orthophosphate dosing. In the subsequent optimisation of orthophosphate dosing in this area, 30MS sampling was less successful because most houses investigated had such low lead concentrations and were too insensitive to further change.

In a water supply system in Western England (International Water Association 2010) routine 30MS from four reference houses over an eight-year period was able to differentiate between two orthophosphate doses (1.0 and 1.4 mg/L as P) and revealed that it took 2–3 years for the lead pipes to fully respond to each dose, much longer than had been anticipated. In Eastern England this lag in responding to an orthophosphate dose was between 6 and 12 months for supplies fed by high quality chalk groundwater (International Water Association 2010). These observations have considerable relevance to the optimisation of corrosion control systems generally, regardless of monitoring method. Benchmark 30MS sampling was difficult to sustain at many houses as home-owners' co-operation waned.

Most water companies opted to install lead pipe test rigs that were designed to provide automatically a 30MS sample from a 3 m length of new lead piping. New lead pipe was favoured because exhumed old lead pipes had been found to give erratic results, due to physical disturbance of the corrosion film. When deployed in positions before and after orthophosphate dosing, test rigs were able to demonstrate the extent of reduction in plumbosolvency achieved by orthophosphate dosing. As an example a 95% reduction in lead concentrations was observed in the Talybont supply in Wales (Hayes *et al*. 2008). In systems where test rigs were only deployed after the point of orthophosphate dosing, the results were limited to confirming the general success of dosing, but without quantification. Some test rigs were problematical due to poor construction (Hayes *et al*. 2008).

PRIVATE WATER SUPPLIES

There are about 75,000 privately owned water supplies across the UK, serving 1.3 million people which is 2% of the UK population. From available reports (Drinking Water Inspectorate 2011a, 2011b; Drinking Water Quality Regulator for Scotland 2011b; Drinking Water Inspectorate (Northern Ireland) 2010) it can be estimated for the period 2009–2010 that 2.6% of these supplies exceeded the current 25 μg/L standard for lead and 6.4% exceeded the future 10 μg/L standard for lead. The situation was worse in Scotland with 6.4 and 12.4% exceeding these standards, respectively, and is likely explained by about half of Scotland's private supplies having a pH below 7. With the possible exception of the largest supplies, compliance will best be achieved by lead pipe removal.

DISCUSSION

Looking to the future

In the UK, optimisation of treatment measures for plumbosolvency control of public water supplies has been highly successful. With continued efforts by water companies and by looking for any remaining 'hot-spots', such as houses with very long lead service pipes, it seems possible that 99.8% compliance might be achieved with the future lead standard of 10 μg/L without removing all the lead pipes that are still in service. Public awareness campaigns and keeping the health authorities alert to lead in drinking water as a possible source of ingestion by children may diminish risks even further.

However, the recent publication by the WHO (2010) of a booklet on Childhood Lead Poisoning and the withdrawal by the Food and Agricultural Organisation (FAO) and WHO of the guideline value for tolerable lead intake could herald a reduction, in the future, of the current WHO guideline value for lead in drinking water. For the time being, the WHO's guideline value of 10 μg/L for lead in drinking water (World Health Organization 2011) has been retained but as a provisional guideline on the grounds of achievability.

Computational modelling predicts non-compliance with a potential standard of 1 μg/L for supplies with optimised orthophosphate to be no better than around 25% in a zone where 50% houses have a lead pipe and suggests that high levels of compliance with such a low standard would not be feasible by water treatment measures alone. This is illustrated in Table 6 for a range in circumstances.

Table 6 | Predicted non-compliance with standards for lead lower than 10 μg/L[a]

Plumbosolvency	% Houses with Pb	% RDT samples >1 μg/L	% RDT samples >5 μg/L	% RDT samples >10 μg/L
Moderate	50	38.50	27.26	19.76
Optimised *o*-PO_4	50	24.30	4.91	0.99
Moderate	10	7.31	5.37	3.89
Optimised *o*-PO_4	10	5.17	0.86	0.10
Moderate	2	1.64	1.26	0.89
Optimised *o*-PO_4	2	1.13	0.24	0.01

[a] Simulated results for a zone with different percentages of houses with a lead pipe and moderate plumbosolvency or reduced plumbosolvency from optimised orthophosphate treatment (in this case, an 80% reduction in plumbosolvency compared to the moderate condition), based on computational modelling methods described elsewhere (van der Leer *et al.* 2002; IWA 2010).

High levels of compliance with a lead standard much lower than 10 μg/L would only be feasible by the total replacement of lead service pipes, including the portions owned by the house-holder. As observed in several case studies (Drinking Water Inspectorate 2010; International Water Association 2010), house-holders are mostly reluctant to co-operate because of the costs and inconvenience involved. It would seem that legislation will be required that forces house-holders to co-operate. One way would be to insist that houses are certified as lead-pipe free at the time of sale or letting (Chartered Institution of Water and Environmental Management 2011) but this would take many years to become fully effective.

Even once all lead pipes have been removed, the legacy of using brass fittings containing lead and the legacy of using leaded solder to join copper pipe-work could require the continuation of optimised plumbosolvency control treatment in order to continue to minimise concentrations of lead in drinking water.

The European dimension

Elsewhere in Europe, the position appears less satisfactory (Hayes & Skubala 2009) due to widespread sampling inadequacies and the failure of the EU directive to be properly implemented in relation to the lead parameter. Limited data on the occurrence of lead pipes suggests that up to one in four children could be at risk from lead in their drinking water.

Sampling inadequacies have been recognised (Cortvriand & Hulsman 2006) and a panel of regulators has made a number of important recommendations to the European Commission (Hoekstra *et al.* 2008) that include: (i) highlighting the leaching of lead from domestic pipe-work systems in risk assessment; (ii) operational monitoring to supplement compliance monitoring, to properly underpin risk assessment; and (iii) adopting RDT sampling as the harmonised monitoring method. Recommendations to the Parties, that have ratified the Protocol on Water and Health, have been made on the monitoring of lead in drinking water and are also based on RDT sampling (Hoekstra *et al.* 2009).

The UK's experience in using RDT sampling reinforces these recommendations and should encourage other EU countries to develop their lead in drinking water control strategies on the basis of this monitoring approach.

Orthophosphate dosing perspectives

To address the widespread problem of lead in drinking water, the ultimate goal must be the total removal of all lead pipes. In a few cities, such as Brussels, The Hague and Vienna, the water companies have removed all or most of the sections of the lead connection pipes that are their responsibility and have encouraged home-owners to replace their sections of the lead connection pipes at the same time (International Water Association 2010). However, home-owners have been reluctant to do so because of the costs and disruption involved. There are no known examples of any city in which all lead pipes have been removed. Partial lead pipe replacement does not solve the problem and can even make matters worse in the short term due to the physical disturbance of lead corrosion deposits.

The latest guidance to water companies in England and Wales now includes a greater emphasis on the identification of any remaining high lead concentration 'hot-spots' as part of an annual risk assessment process, with selective lead pipe replacement the likely outcome. However, the replacement of home-owners' lead pipes at domestic premises will continue to be voluntary and require the home-owners' co-operation. In the absence of further legislation to force home-owners to replace their sections of lead connection pipes, the only comprehensive way to provide public health protection will be to continue to reduce the plumbosolvency of the water supplies by the use of corrosion inhibitors. Orthophosphate is the most effective for this purpose but dosing must be optimised if lead concentrations are to be minimised sufficiently.

The UK is not alone in using orthophosphate for plumbosolvency control, but is unique in relation to the extent to which orthophosphate has been used and its level of optimisation. Optimisation requires not only the application of the correct amount of orthophosphate, which has been found to be water supply specific, but for other water quality conditions to be appropriate, particularly pH, and organics and iron particulates which have been found to be important and may need to be controlled by supplementary measures.

There are relatively few published case studies on the use of orthophosphate for plumbosolvency control, particularly ones that address dose optimisation in such a comprehensive manner, and for these reasons the experience gained in the UK should provide a good reference point for similar treatment elsewhere in the future.

CONCLUSIONS

On the basis of the extensive experience gained over many years in the UK, it can be concluded that:

1. RDT sampling has succeeded in demonstrating the need for corrective action and the benefits of optimising orthophosphate dosing.
2. Public health protection depends closely on the survey protocol used. Slight differences in protocol or its interpretation can significantly affect conclusions.
3. Optimised orthophosphate doses are system specific and will benefit from natural organics and iron discolouration control. Following the clean-up of the UK's distribution networks, particulate lead is no longer considered to be a problem.
4. There is scope for the UK to improve the current 99% compliance with 10 μg/L by further optimisation of orthophosphate dosing and by selective lead pipe removal, possibly to 99.8%; residual non-compliance

might then be followed up by specific investigations, possibly including blood lead surveillance.

5. RDT sampling as practised in the UK is adequately representative and the aggregation of RDT results over several years or over regional areas strengthens the conclusions that can be drawn from such sampling, enabling the success of orthophosphate dosing to be reliably demonstrated.
6. It is unlikely that optimised corrosion control, that includes the dosing of orthophosphate, will be capable of achieving a standard much lower than 10 μg/L for lead in drinking water.

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