  Journal of Water and Health | 06.2 | 2008

Experience in Wales (UK) of the optimisation of ortho-phosphate dosing for controlling lead in drinking water

C. R. Hayes, S. Incledion and M. Balch

ABSTRACT

Dwr Cymru Welsh Water supplies over three million people with drinking water throughout most of Wales (UK). Ortho-phosphate has increasingly been dosed at around 1 mg/L (P) to further reduce the corrosivity of supplies to the lead pipes which connect approximately 30% of houses to water mains in the company's area, additional to long-establish pH adjustment measures. The installation of new ortho-phosphate dosing schemes and the optimisation of these and existing dosing schemes, 29 schemes in total, were subject to a regulatory programme of work, agreed with the Drinking Water Inspectorate (DWI). Optimisation comprised (i) selection of appropriate ortho-phosphate doses by a procedure involving laboratory based plumbosolvency testing linked to zonal lead emission (compliance) modelling, (ii) tight dose control and (iii) extensive monitoring of lead in supply by random daytime (RDT) sampling and by the use of lead pipe test rigs. The successful outcome was confirmed by 99% of over 5,000 RDT samples complying with the future standard of 10 μg/L for lead in drinking water.

Key words | drinking-water, lead, optimisation, ortho-phosphate, Wales

C. R. Hayes (corresponding author)
Swansea University, School of Engineering,
Singleton Park,
Swansea, Wales SA2 8PP,
UK
Tel.: ++44 (0)1792 602257
Fax: ++44 (0)1792 295676
E-mail: *c.r.hayes@swansea.ac*

S. Incledion
Asset Strategy and Regulation,
Dwr Cymru Welsh Water,
Pentwyn Road, Nelson, Mid-Glamorgan,
Wales CF46 6LY,
UK

M. Balch
United Utilities Operational Services Ltd.,
Pentwyn Road, Nelson,
Mid-Glamorgan, Wales CF46 6LY,
UK

INTRODUCTION

Dwr Cymru Welsh Water supplies most of Wales with drinking water with its potable operational activities out-sourced to United Utilities Operational Services Ltd. The area supplied within Wales is shown in Figure 1. Over three million people and industry are supplied by an average of 900 Mld. The water supply system extends to 81 impounding reservoirs, 105 water treatment works, 27,000 km of water mains, 532 pumping stations and 715 service reservoirs. Most of the water abstracted is surface derived with only a small proportion of groundwater. About 75% of the surface water is low in alkalinity, being mostly derived from rural uplands, and prior to treatment is typically slightly acidic with organic colour contents as high as 30°H. The remaining surface water, mainly from the south-eastern part of Wales, has a higher alkalinity and generally less organic colour, reflecting the greater lowland characteristics of these waters. Figure 1 indicates the geographical distribution of these water types. The great majority of the surface water abstractions are treated comprehensively by multiple stage physio-chemical treatment and disinfection.

doi: 10.2166/wh.2008.044

In the United Kingdom, the extent of the problem of lead in drinking water became clearer following several national surveys (Royal Commission 1983) in the 1970s, leading to national recommendations (Department of Environment 1980) for corrective treatment:

- pH adjustment to >8.0 for low alkalinity waters (<50 mg/L $CaCO_3$) with additional dosing of ortho-phosphate (a corrosion inhibitor) if necessary (the ortho-phosphate reduces lead solubility by converting some of the lead carbonate in the corrosion scale to lead phosphate)
- ortho-phosphate dosing of high alkalinity waters (>50 mg/L $CaCO_3$).

From the late 1970s, the former Welsh Water Authority adopted a treatment policy of pH adjustment to >8.0 for all surface derived waters, achieved at most works by lime dosing. In this era, the standard for lead in drinking water was taken to be 100 μg/L from WHO guidelines

Figure 1 | Drinking water supplies in Wales from Dwr Cymru Welsh Water.

(World Health Organization 1970) and the pH adjustment policy was found to be generally successful.

In 1985, the standards of the first European "drinking water" directive (European Commission 1980) became a legal requirement, including a standard for lead of 50 μg/L as a "maximum admissible concentration" in "running water". The standards of this directive were implemented by regulations in 1989 (UK Government 1989) and the interpretation given in associated Government guidelines (Department of the Environment 1989) was that the lead standard would be assessed by random-daytime, first-draw (RDT) sampling. This guidance also required water companies to undertake RDT surveys to achieve minimum specified amounts of lead data, if it was not already available, by mid-1991, and to initiate further corrective action if appropriate. In consequence, ortho-phosphate dosing at 1 mg/L(P) was initiated in the mid-1990s at 30 works. A number of these works have since been abandoned.

The revised "drinking water" directive (European Commission 1998) set yet more stringent standards for lead in drinking water, both of which apply at the point of use:

- 25 μg/L from December 2003, and
- 10 μg/L from December 2013.

Although these new standards are defined by the directive as the weekly average concentration ingested, the UK has adopted (UK Government 2000) both standards as the maximum concentrations permitted at the point of use, with assessment based on RDT sampling.

The Drinking Water Inspectorate then issued guidance (Drinking Water Inspectorate 2000, 2001) to the water companies in England and Wales which required them to undertake further assessments of plumbosolvency, to install further corrective treatment if >5% of RDT samples exceeded 10 μg/L and to optimise that treatment, or to optimise existing treatment measures for plumbosolvency control if this same criterion was exceeded.

In consequence, Dwr Cymru Welsh Water entered into 29 formally agreed "regulatory programmes of work" with the Drinking Water Inspectorate to install and/or optimise existing ortho-phosphate dosing plants. A further 10 phosphate dosing schemes were not subject to a regulatory programme but were also optimised. The total of the 39 treatment works where ortho-phosphate is now dosed accounts for 90% of the company's supplies by volume. This paper outlines how the company optimised this ortho-phosphate dosing and the outcomes which were achieved, using the Talybont supply as an illustrative example.

METHODOLOGY AND RESULTS

The approach taken to optimisation followed the guidance issued to water companies in England and Wales (Drinking Water Inspectorate 2000, 2001) and comprised:

(i) the development of an optimisation strategy, which was submitted to the Drinking Water Inspectorate for scrutiny;
(ii) the selection of water supply specific ortho-phosphate doses, on the basis of laboratory plumbosolvency testing and zonal lead emission (compliance) modelling;
(iii) tight operational control of ortho-phosphate dosing;
(iv) a comprehensive monitoring programme involving both RDT sampling and the use of lead pipe test rigs.

On completion of optimisation, a detailed report on each scheme was then submitted to the Drinking Water Inspectorate for scrutiny. Further details of the methods used and the results obtained are presented in summary format in the following sections.

Optimisation strategy

The guidance issued by the Drinking Water Inspectorate in relation to plumbosolvency control by treatment measures (Drinking Water Inspectorate 2000, 2001) provided a generalised framework for achieving and demonstrating optimisation. It required or implied that water quality in supply needed to be of generally good quality and that appropriate doses of ortho-phosphate and a suitable pH condition needed to be maintained. Of greatest relevance to general water quality were iron discolouration and the presence of organics, particularly humic and fulvic acids. Assuming that water quality was of generally good quality, the biggest challenges were the selection of ortho-phosphate dose and its routine operational achievement.

The Inspectorate's guidance on the definition of optimisation (Drinking Water Inspectorate 2000, 2001) is mostly directional but does include the criterion that no more than 2% of RDT samples for lead should exceed 10 μg/L, for a scheme to be considered optimised. This criterion was the focus of the company's strategy, allied to correct ortho-phosphate dose selection and its regular achievement.

Ortho-phosphate dose selection

In an ideal world, a single universal dose of ortho-phosphate would be applied based on industry-wide experience. Whilst a common dose of 1.0 mg/L(P) was used by many water companies in relation to achieving compliance with the earlier standard of 50 μg/L, including Dwr Cymru Welsh Water, more recent experience of aiming for compliance with 10 μg/L has indicated (Hayes *et al.* 2006) that doses need to be more precisely tuned to individual waters. The simplest approach to dose selection would be to adjust the dose up and down operationally until the lead concentrations observed in a zone were satisfactory for the least dose possible (so as to minimise operating cost and any environmental impact). In practice, there can be a problem because of the prolonged time it may take for the lead pipes in a zone to equilibrate with the ortho-phosphate dose applied, ranging from a few months to several years (Hayes 2004). In consequence, a simple control loop for ortho-phosphate dosing may be denied.

A more sophisticated approach was adopted by Dwr Cymru Welsh Water in the selection of water-specific ortho-phosphate doses, involving laboratory based plumbosolvency testing and zonal lead emission modelling.

Laboratory plumbosolvency testing was undertaken by the standard method developed by Colling *et al.* (1987, 1992) for the major works requiring ortho-phosphate dosing and for a representative selection of the minor works requiring ortho-phosphate dosing. Testing involves pumping test water through sections of new lead piping at 25°C with a water-pipe contact time of 30 minutes and measuring the lead emissions over a four week period. At the end of the test period, the water is allowed to stagnate in the lead piping for 16 hours and then sampled, to provide an indication of the lead solubility equilibrium concentration. For the major works, testing was undertaken for a range of ortho-phosphate doses over a range in pH conditions.

Typical results are illustrated by Table 1 and show the expected benefit of increased pH without ortho-phosphate with this low alkalinity water, that pH is less important when ortho-phosphate is dosed and that the responses of the water to increasing ortho-phosphate doses follow a declining exponential curve in approximate terms. The results in Table 1 only give an indication of the ortho-phosphate dose which might be required and not a precise determination; for example, at pH 8.0 the optimum dose is most likely greater

Table 1 | Plumbosolvency test results for Talybont WTW at 25°C*

Ortho-phosphate dose mg/L(P)	Median 30MC Pb (μg/L) at pH 7.5	Median 30MC Pb (μg/L) at pH 8.0	Median 30MC Pb (μg/L) at pH 8.5
0.0	154	129	87
0.6	92	35	39
0.9	33	9	16
1.2	6	6	4
1.5	5	4	3

*The median lead results after 30 minutes contact were determined from the second and third weeks of testing when conditions have normally stabilised. The figures presented are the average of the duplicate pairs tested. These results can be extrapolated to average ambient water temperature conditions by multiplying them by 0.5, the factor determined by Croll 2001. Historically, chemical coagulation was intermittent but is now a routine feature of the treatment works; the results in Table 1 relate to treated water after chemical coagulation and filtration.

than 0.6 mg/L (P) but could be between 0.9 and 1.5 mg/L (P). However, the shape of the phosphate response curve does provide important diagnostic information.

For 20 treated waters from across Wales, the results of testing different ortho-phosphate doses at pH 7.5 are summarised in Table 2. For waters without ortho-phosphate, a wide range in plumbosolvency was observed with no conspicuous relationship to source type of extent of treatment, other than that two waters without chemical coagulation treatment and with known organic colour contents up to 30°H were among the highest plumbosolvencies observed (as indicated by the 16 hr and 30MC results). The general explanation for the variation in plumbosolvency which was observed is probably a combination of alkalinity and organic content, although cause-effect relationships were not investigated specifically. The averaged results show the expected trend of decreasing lead with increasing ortho-phosphate but even at 1.5 mg/L(P) the equilibrium lead concentration (as judged by 16 hrs contact) was as high as 86 μg/L, significantly greater than the new lead standards set by the EU directive, even allowing for the test temperature.

It is also very significant that the ratio of 16 hr to 30MC lead results vary as much as they do, as this indicates that the shape of the lead dissolution curve (ie: lead concentration through time) varies and is water specific, making the application of generalised dissolution characteristics difficult.

In order to gain a deeper insight into how zones might respond to ortho-phosphate, the supply areas of all 39 ortho-phosphate dosing schemes were modelled by the methods developed by Van der Leer and Hayes and described in detail elsewhere (Van der Leer *et al*. 2002; Hayes *et al*. 2006). In summary, a single pipe model is applied throughout a probabilistic framework created randomly from a series of statistical distributions which each describes one of the several variables determining lead emissions from lead pipes. The single pipe model calculates the lead concentration in the pipe outlet every second when the imaginary tap is open and assumes a simple exponential function to describe the dissolution of lead through time (when the water is stationary) and plug flow; both these assumptions are simplistic but exhaustive research (Hayes 2002) has shown them to equate adequately to the diffusion process (Kuch & Wagner 1983) and to turbulent flow (because of the anticipated flow rates in small diameter pipes) and to much reduce computational requirements.

The variables which make up the probabilistic framework of the zonal model are pipe length and diameter, the amount of water flowing through each pipe in a day and the pattern of the flow events, the flow rate (normally applied as a constant) and the plumbosolvency of the water as defined by the initial mass transfer rate for lead (factor M in $\mu g/m^2/s$) and the equilibrium concentration for lead (factor E in μg/L). Factors M and E can be applied as a distribution to simulate changes across a zone but were applied as a constant in the modelling of the Welsh zones as water quality is sufficiently stable within the supply networks. These variables can be applied in the zonal model to any specified size of zone (number of simulated houses) and for any assumed percentage occurrence of lead pipes in the simulated zone. Factors M and E define the shapes of the lead dissolution curves which are illustrated in Figure 2 and the concentrations of lead which will dissolve in 30 minutes, equating to both samples taken from a lead pipe after 30 minutes stagnation and samples taken after a 30 minutes contact time if the water is flowing (so slowly that it is virtually stagnant). It is therefore possible to calibrate

Table 2 | Summary of plumbosolvency testing of 20 treated waters in Wales at pH 7.5 and 25°C

	Average and range in Pb results from 20 treated waters in Wales (μg/L)		
Ortho-phosphate dose	**0.0 mg/L (P)**	**0.6 mg/L (P)**	**1.5 mg/L (P)**
Median 30MC Pb (μg/L)	142 (42 to 452)	25 (4 to 118)	6 (3 to 15)
16 hr Pb (μg/L)	735 (109 to 1555)	111 (8 to 581)	23 (5 to 86)
Ratio 16 hr Pb to 30MC Pb	5.8 (1.8 to 15.2)	3.7 (1.3 to 6.3)	3.6 (1.3 to 6.6)

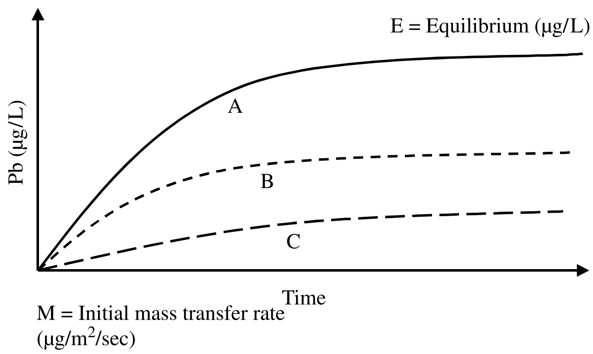

Figure 2 | Lead dissolution through time as a function of M and E.

Table 3 | Validation of the zonal model for the Talybont supply

Comparison of output from sampling model to the water company's results	% Failing > 10 μg/L	% Failing > 25 μg/L	% Failing > 50 μg/L
Results from 1990/5 surveys*	21.81	11.79	4.52
Simulated results (condition 1 in Table 4)	18.44	11.33	4.79

*A total of 509 samples were taken prior to ortho-phosphate dosing.

the zonal model using the 30MC and 16 hr stagnation results from plumbosolvency testing, albeit with adjustment to average ambient water temperature.

To validate the zonal model, a sampling model was used which simulated RDT sample results and enabled a comparison to be made to the results from actual RDT sampling by Dwr Cymru Welsh Water. The zonal model was routinely calibrated using the results from plumbosolvency testing to define factors M and E for the non-phosphated condition, from an assessment of the percentage occurrence of houses with a lead pipe by analysis of detectable lead in RDT samples over periods of up to 10 years, and applying standardised distributions of the other variables.

The validation was good to excellent in most cases as illustrated by the example for the Talybont supply in Table 3 (in a few cases the zonal model was calibrated to achieve a good match between the simulated and actual RDT data) from which it was concluded that the model could be used to investigate different percentage reductions in plumbosolvency (eg: as would result in curves A, B and C in Figure 2) and the likely result of different ortho-phosphate doses.

An example of the relationship between simulated RDT sample results and reductions in plumbosolvency is given in Table 4 for the same Talybont supply. It can be seen in Table 4 by interpolation that an 87% reduction (in between conditions 5 and 6) in plumbosolvency should equate to the DWI criterion (Drinking Water Inspectorate 2000, 2001) for optimisation of ortho-phosphate dosing which allows no more than 2% of RDT samples to exceed the lead standard of 10 μg/L. Cross referencing to the results from laboratory plumbosolvency testing (Table 1) indicated that an average ortho-phosphate dose of 0.9 mg/L (P) would be sufficient for achieving this criterion, assuming the average of the three pH conditions (a reflection of pH variation in supply) and using the established relationship (Hayes 2002) that a value of factor M of 0.1 is equivalent to a 30MC lead concentration of 49.8 μg/L at average ambient water temperature. The averaged 30MC test result for a phosphate dose of 0.9 mg/L (P) of 19.3 μg/L (Table 1) when adjusted to average ambient water temperature (by halving) therefore equates to a value for M of 0.0194, slightly lower than the value for M of 0.022 required to achieve an 87% reduction in plumbosolvency.

Based on the coupling of the methods described above, the required percentage reduction in plumbosolvency and the required average ortho-phosphate dose was established for all 39 dosing schemes. The required percentage reduction in plumbosolvency averaged 76% but ranged from 50 to 92% as shown in Figure 3, the required reduction being strongly influenced by a combination of the plumbosolvency of the water prior to ortho-phosphate dosing and the percentage of houses in the supply area with a lead pipe. In this latter respect, the percentage of houses with a lead pipe was estimated to range from 8 to 65% with an average of 28%. The average dose of ortho-phosphate needed to achieve the DWI criterion ranged from 0.6 to 1.5 mg/L (P) with an average of 0.9 mg/L (P) across the 39 dosing schemes, close to the earlier standard assumption.

Operational control

At most schemes, ortho-phosphate is dosed using orthophosphoric acid (75%) and a dosing pump which is proportional to the variable treated water flow from the

Table 4 | Results for the Talybont supply from the sampling model, based on the average of the RDT results obtained from 100 simulated surveys, each of 52 simulated samples*

Condition	% reduction in plumbosolvency	M (μg/m²/sec)	E (μg/L)	% Houses > 10 μg/L	% Houses > 25 μg/L	% Houses > 50 μg/L
1	0	0.180	300	18.44	11.33	4.79
2	70	0.054	90	8.56	1.78	0.20
3	75	0.045	75	6.69	1.12	0.05
4	80	0.036	60	5.15	0.60	0.00
5	85	0.027	45	2.78	0.19	0.00
6	90	0.018	30	0.86	0.01	0.00

*The Talybont supply was modelled assuming that 35% of houses had a lead pipe.

works. At a few works the more neutral mono-sodium di-hydrogen phosphate salt is dosed as a 32% liquor. An on-line phosphate monitor is in use, sampling after phosphate injection, results being displayed both locally and at a central control point (*via* telemetry) but the results are not used to control the dosing pump.

The phosphate set points of the dosing system have been set to achieve the average required dose but applied as a slightly higher summer dose and slightly lower winter dose in some cases. This arbitrary approach is considered to give better protection during the summer when lead concentrations are potentially at their highest. High–high, high, low and low–low alarm settings have then been set to give two levels of alarm response. Alarms are shown locally and at a central control point (*via* telemetry). Operational staff visit all dosing schemes daily (seven days a week). During each visit the working order

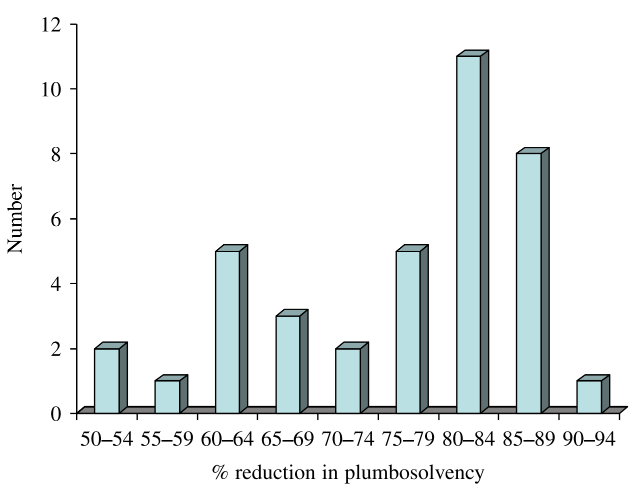

Figure 3 | Reductions in plumbosolvency to achieve DWI optimisation criterion (no more than 2% RDT samples to exceed 10 μg/L).

of the ortho-phosphate dosing plant is checked visually and the dose is checked using a portable test kit.

Alarms received at the central control point are logged and will prompt site attendance if appropriate. Response times are influenced by any known circumstances and by the severity of the alarmed condition. The way in which alarms are dealt with is specified generically by the operating company's Business Management System; in general, high and low alarms prompt attention during the next site visit, whereas high–high or low–low alarms prompt immediate attention.

The phosphate monitors in use had often experienced problems, as a result of chemical reagent quality and monitor reliability. This prompted a comprehensive review leading to site-specific improvements where necessary and the adoption of a minimum acceptable criterion for monitoring that the standard deviation (SD) of results should not exceed 0.2 mg/L (P). The range in dosing performances which were experienced is illustrated by Figure 4, the observed spiking being due to hydraulic effects; all schemes related to the regulatory programme of work now mostly comply with the tight performance imposed.

Monitoring regime for lead

RDT sampling for lead at consumers' taps was the principle means for determining the success of ortho-phosphate dosing, at frequencies which often greatly exceeded the regulatory minimum (European Commission 1998; UK Government 2000), achieved simply by taking a sample for lead whenever a bacteriological sample was taken at the higher frequencies involved. With low sample numbers,

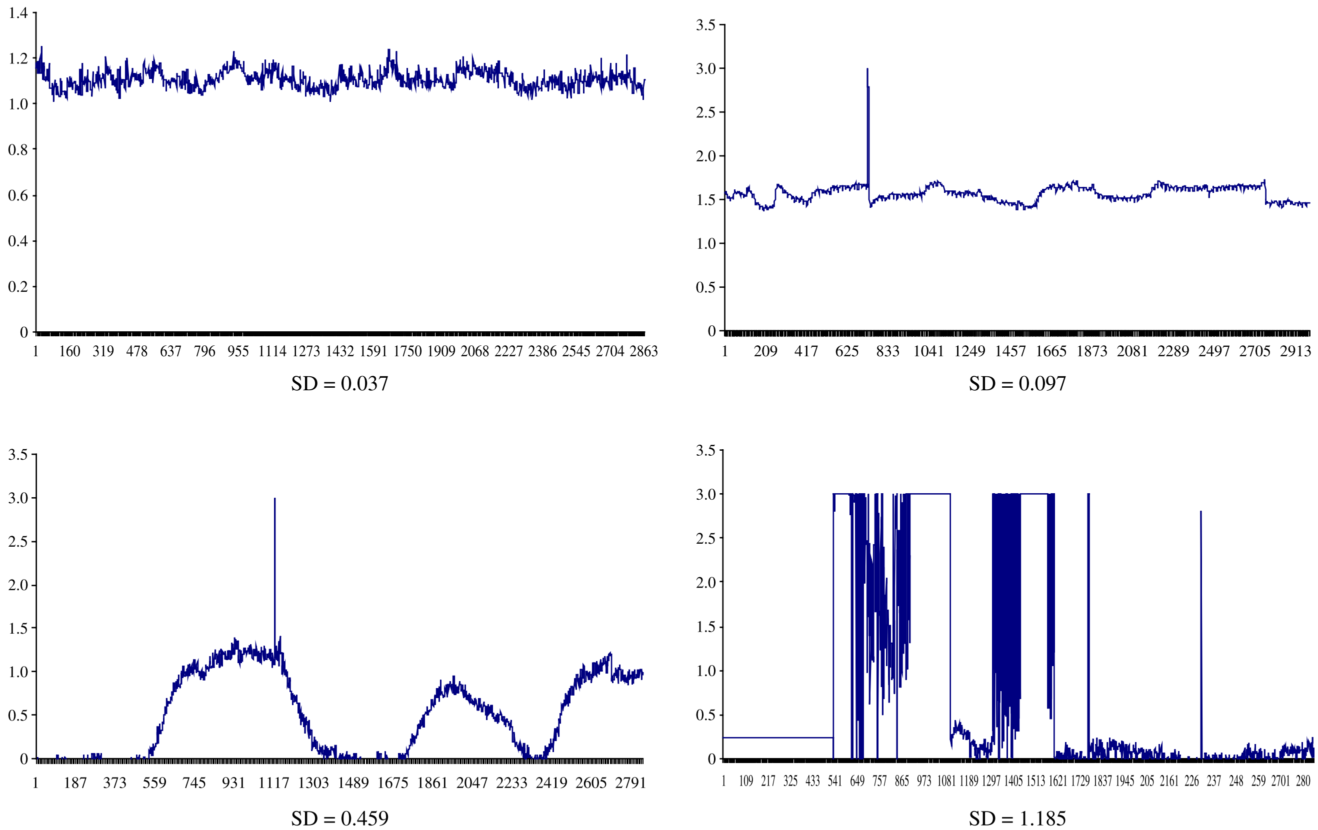

Figure 4 | Continuous phosphate monitoring at four schemes.

RDT sampling for lead is not very reproducible, particularly for waters prior to ortho-phosphate dosing, but once ortho-phosphate dosing had been established reproducibility was much better, as illustrated by Table 5 for the Talybont supply. By bulking RDT lead results for several years, these reproducibility problems can be diminished.

Figure 5 summarises the RDT results for lead, before and after the commencement of ortho-phosphate dosing, for the 29 schemes in the company's regulatory programme of work and the overall success of dosing is readily discerned. Taking all schemes together, 18.7% of 11,118 RDT samples for lead exceeded the 10 μg/L standard prior to ortho-phosphate dosing (with 8.7% exceeding 25 μg/L), reducing to 1.0% of 5,659 RDT samples for lead exceeding the 10 μg/L standard once ortho-phosphate dosing had been properly established (with 0.4% exceeding 25 μg/L). By mid-2005, compliance with the DWI criterion was clearly demonstrated for 26 of the 29 schemes, with two borderline (very slightly above 2% exceeding 10 μg/L) and one supply not complying (5.4% exceeding 10 μg/L). These three schemes are subject to further optimisation measures, including additional RDT sampling.

To supplement the RDT sampling for lead at consumers' taps, lead pipe test rigs were installed at strategic locations in each supply area. Typically, one test rig was installed prior to the point of ortho-phosphate dosing, one soon after dosing and two or more within the supply network. Two manufacturers of test rigs were used, the designs being similar in principle (Drinking Water Inspectorate 1990), as illustrated in Figure 6. The 3 m length of 12 mm internal diameter new lead pipe in the rig is automatically flushed then sampled after the water has stagnated for 30 minutes. Samples intermittently replenish a sampling container so that fresh samples are always available for collection.

The rigs supplied by ProMinent performed satisfactorily once the flushing times had been adjusted to their maximum, to minimise lead concentrations prior to the stagnation cycle. The rigs from HMS were more problematical due to their

Table 5 | Variation in RDT results for lead

Year	N samples	N > 10 μg/L	N > 25 μg/L	N > 50 μg/L
(a) Before the dosing of ortho-phosphate				
1990	132	37	23	13
1991	228	55	25	9
1992	61	8	4	0
1993	45	8	6	1
1994	29	3	2	0
(b) After the dosing of ortho-phosphate commenced in 1995				
1996	29	2	0	0
1997	28	1	0	0
1998	28	1	0	0
1999	9	0	0	0
2000	8	0	0	0
2001	26	1	1	1
2002	28	0	0	0
2003	82	0	0	0
2004	33	0	0	0
2005	14	0	0	0

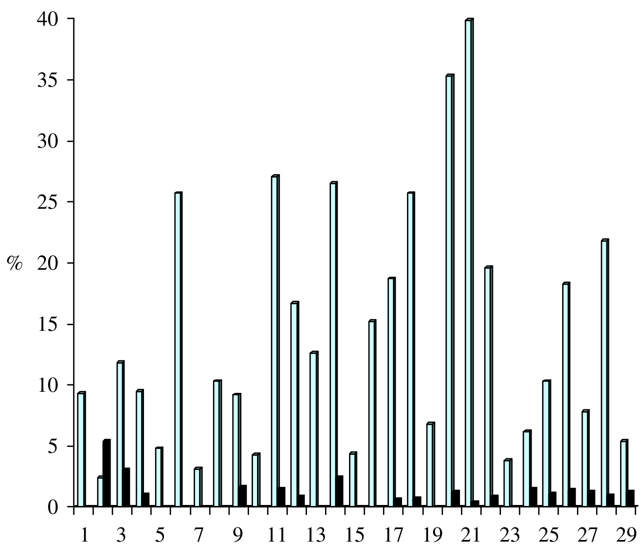

Figure 5 | Percentage of RDT samples non-compliant with the lead standard of 10 μg/L before and after ortho-phosphate dosing #. The data relates to the 29 schemes (numbered along the "x" axis) in the company's regulatory programme of work. The light columns are before ortho-phosphate dosing and the dark columns after dosing had been optimised operationally.

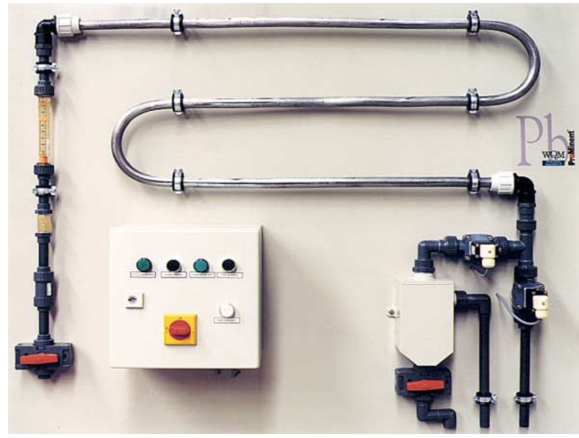

Figure 6 | Lead pipe test rig.

greater use of metal fittings in construction; consequential problems with galvanic corrosion were addressed during 2004 by the replacement of metal fittings by plastic fittings for holding the lead pipes *in situ* and by replacing the lead pipes to avoid corrosion signatures.

The averaged results from January to June 2005 are summarised for the Talybont supply in Table 6. These recent data indicate that the phosphate dose being deployed was achieving about a 95% reduction in plumbosolvency, compared to the 87% required for compliance (as indicated by zonal modelling) with DWI's 2% RDT criterion. The results also demonstrate that for ortho-phosphate dosed water the modified HMS rig gave similar results to those supplied by ProMinent.

The use of new lead piping in the test rigs provides an ultimate measure of the success of ortho-phosphate dosing, because equilibrium with the phosphate is rapid, whereas actual reductions in lead may take longer (Hayes 2004) to

Table 6 | Averaged results from lead pipe test rigs in the Talybont supply

Location	Typical lead concentration after 30 minutes stagnation (μg/L)	Manufacturer
Pre-phosphate	79	ProMinent
Final	4	ProMinent
Gwehelog	4	ProMinent
Nash	3	HMS
Valve House 4	3*	ProMinent

*Single spike ignored.

achieve due to the greater complexity of corrosion deposits in the old lead pipes *in-situ* within the supply area. Apart from providing supplementary performance information, because the test rigs respond rapidly to changes in ortho-phosphate, they provide a simple indication of the continuing sufficiency of dosing.

CONCLUSIONS

1. Ortho-phosphate dosing has been very successful, in overall terms, in greatly reducing the concentration of lead at consumers' taps, with 99% of random daytime samples complying with the standard of 10 μg/L, well within the criterion for optimisation set by the Drinking Water Inspectorate.
2. The need to consider the replacement of lead pipes in order to achieve compliance with the EU Directive and associated UK regulations has therefore been much reduced.
3. Comprehensive public health protection has been achieved at a substantially lower cost than would be incurred by the replacement of lead pipes.

REFERENCES

Colling, J. H., Whincup, P. A. E. & Hayes, C. R. 1987 The measurement of plumbosolvency propensity to guide the control of lead in tap waters. *JIWEM* **1**(3), 263–269.

Colling, J. H., Croll, B. T., Whincup, P. A. E. & Harward, C. 1992 Plumbosolvency effects and control in hard waters. *JIWEM* **6**(3), 259–268.

Croll, B.T. 2001 Personal communication.

Department of the Environment 1980 *Report of the Expert Advisory Group on Identification and Monitoring, Lead in Potable Water Technical Note No. 1*.

Department of the Environment 1989 *Guidance on Safeguarding the Quality of Public Water Supplies*. HMSO, UK.

Drinking Water Inspectorate 1990 Lead in drinking water supplies – monitoring the effectiveness of treatment to reduce plumbosolvency. *Information Letter* 2/90. Available at: www.dwi.gov.uk.

Drinking Water Inspectorate 2000 Determination of requirements to meet new lead standards. *Information Letter* 12/2000. Available at: www.dwi.gov.uk.

Drinking Water Inspectorate 2001 Further guidance on requirements to meet new lead standards. *Information Letter* 3/2001. Available at: www.dwi.gov.uk.

European Commission 1980 Council Directive (80/778/EC) of 15 July 1980 relating to the quality of water intended for human consumption. *Official J.* L229/11–29, **23**, 30 August 1980.

European Commission 1998 Council Directive (98/83/EC) of 3 November 1998 on the quality of water intended for human consumption. *Official J. L330* **32**, 23–45.

Hayes, C. R. 2002 *Simulation of Lead Emissions to Drinking Water – the Development and Application of Computational Methods for Optimising Plumbosolvency Control*. PhD Thesis University of Wales Swansea, UK.

Hayes, C. R. 2004 Lead in drinking water - have we got the balance? In: *Quality at the Tap*, Seminar, Manchester, Chartered Institution of Water and Environmental Management, 15th June 2004.

Hayes, C. R., Bates, A. J., Jones, L., Cuthill, A. D., Van der Leer, D. & Weatherill, N. P. 2006 Optimisation of plumbosolvency control using a computational model. *Wat. Environ. J.* **20**, 256–264.

Kuch, A. & Wagner, I. 1983 A mass transfer model to describe lead concentrations in drinking water. *Wat. Res.* **17**(10), 1303–1307.

Royal Commission on Environmental Pollution 1983 *Lead in the Environment*. Ninth Report, HMSO, UK.

UK Government 1989 *The Water Supply (Water Quality) Regulations 1989*. Statutory Instrument 1989 No. 1147, HMSO, UK.

UK Government 2000 *The Water Supply (Water Quality) Regulations 2000*, Statutory Instrument No. 3184, UK.

Van der Leer, D., Weatherill, N. P., Sharp, R. J. & Hayes, C. R. 2002 Modelling the diffusion of lead into drinking water. *Appl. Math. Model.* **26**(6), 681–699.

World Health Organization 1970 *European Standards for Drinking Water*. WHO, Geneva, Switzerland.

First received 4 January 2007; accepted in revised form 19 April 2007. Available online January 2008