EXPERT REPORT

PREPARED BY

PROFESSOR JOSEPH HUN-WEI LEE

Expert Witness appointed by the Commission of Inquiry into Excess Lead Found in Drinking Water

5 February 2016

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Specialist Field	:	Water environment engineering: Environmental hydraulics/fluid mechanics; water quality modelling
Appointed on behalf of	:	The Commission of Inquiry into Excess Lead Found in Drinking Water (the "**Commission**")
Prepared for	:	The Commission
On instructions of	:	Messrs. Lo & Lo, Solicitors for the Commission ("**Lo & Lo**")
Subject matter / Scope of engagement:	:	To assist the Commission in discharging its duties under the Terms of Reference and by acting as an expert witness in the inquiry hearings
Documents reviewed	:	Selected documents from the Hearing Bundles
Documents referred to in this Report	:	See **Appendix I**
Sketches, Photographs and Diagrams integral to this Report by the Author	:	See **Appendix II**
Tables and Summaries	:	See **Appendix III**

Sampling Protocol (affected and unaffected estates) :	See **Appendix IV**
Sampling Protocol (3 vacant flats) :	See **Appendix V**
Summary on Computational Fluid Dynamics (CFD) modelling :	See **Appendix VI**
Date of Inspection of some of the involved estates (*name of the estates*) :	1) **10 November 2015** (Kwai Luen Estate Phase I - Luen Yat House; Kai Ching Estate - Hong Ching House; Tak Long Estate - Tak Long House) 2) **27 November 2015** (Vacant flat in Un Chau Estate) 3) **12 December 2015** (Vacant flats in Un Chau Estate; Kwai Luen Estate) 4) Field sampling visits to all "affected estates" and selected "unaffected estates" (see **Appendix III, Table 2**)
Site visits :	1) **9 November 2015** Shatin Water Treatment Works Government Laboratory 2) **12 November 2015** Ngau Tam Water Treatment Works 3) **7 December 2015** Training Centre of the Construction Industry Council

The Terms of Reference of the Commission are as follows:

(a) to ascertain the causes of excess lead found in drinking water in public rental housing developments;

(b) to review and evaluate the adequacy of the present regulatory and monitoring system in respect of drinking water in Hong Kong;

(c) make recommendations with regard to the safety of drinking water in Hong Kong

Instructions

I have been instructed to give my opinion on the matters under paragraph (a) of the Terms of Reference. In providing my opinion, I have also been instructed to consider the following areas and undertake the following tasks:

(a) to ascertain the factual source(s) of excess lead found in drinking water in public rental housing and to advise on what work and tests are to be performed;

(b) to evaluate the methodologies and to review and verify the findings of the WSD Task Force's Interim and Final Reports in respect of the Waterworks system and the Inside Service system in public rental housing developments, from the perspective of a civil engineer; and

(c) to conduct, if necessary, independent investigation on behalf of the Commission into the above systems in order to ascertain the factual source(s) of excess lead found in drinking water.

Introduction

1. I, Professor Joseph Hun-wei Lee of the Hong Kong Special Administrative Region of China, have been appointed as the Commission's expert to assist the Commission in determining the matters under the Terms of Reference. The opinions and conclusions in this Report are based on: (i) a review of key documents and information supplied to me by **Lo & Lo**; (ii) analysis of lead concentration data collected by the Water Supplies Department (WSD) and Housing Department (HD) prior to the end of November 2015; (iii) independent sampling of all buildings in the "affected estates" and selected buildings in the "unaffected estates"; and (iv) analysis and interpretation of lead concentration data using a computational fluid dynamics (CFD) model of a representative household water supply system. Site visits were made to selected housing estates and the chemical laboratories in the water treatment works in Shatin and Nga Tam Mei. Discussions with WSD and HD were also held during the site visits.

Background of the Incident

2. During July – September 2015, following queries from the public, the Water Supplies Department and the Housing Department collected a number of drinking water samples in the Public Rental Housing (PRH) Estates of Hong Kong. The lead concentrations of 106 samples in 11 estates were found to exceed the WHO provisional guideline value of 10 micrograms per liter (μg/L). The WSD "Task Force on Investigation of Excessive Lead Content in Drinking Water" also conducted an investigation on the causes of excess lead. The Task Force Report (October 2015) concluded that the main cause of the excess lead was due to the use of lead solder in the construction of the fresh water supply plumbing system **[A1/19/689, §3.1.7(a)]**. While the main cause of the lead contamination was being reviewed independently, WSD also provided interim alternative drinking water supply to selected estates and recommended precautionary measures of water usage at the consumer tap (e.g. flushing for one to two minutes each morning before taking any water for drinking or cooking **[A1/21/815]**) to reduce possible health risks.

3. Hong Kong has traditionally not monitored lead concentrations in residential flats. There were no drinking water quality standards with respect to lead prior to this excess lead incident, although new parameters for testing of water samples with

respect to lead, cadmium, chromium and nickel were introduced as a result of WSD Circular Letter No. 1/2015 since 13 July 2015 **[C5/60/4066-4067]**.

4. According to the test results of water samples provided by the WSD and the Government Laboratory **[A3/43/2382-2390** and **A3/44/2409-2440]**, lead concentration was measured on 1,325 samples in the 11 "affected estates" (36 buildings; a typical building has around 40 floors and 800 flats). Excess lead (≥ 10 μg/L) is found in 8.0 percent of the samples with 14.6 percent in the range of 5-9 μg/L **[Appendix III, Table 1]**. In addition to the "affected estates", lead measurements were also made for 3,806 samples in 45 estates (163 buildings) completed in or after 2005 (the "unaffected estates")**[A3/43/2391-2401]**. Based on the data, it seems the measurements were made at different times during office hours, with no apparent planned schedule.

5. There has been great concern among the residents and the public on the safety of drinking water in PRH estates since the incident broke out in July 2015. Effective corrective measures must be based on an adequate understanding of the causes of the lead contamination in the "affected estates".

6. The lead concentration of drinking water at the consumer tap in a PRH estate building depends on a complex myriad of factors including: the time of consumption and prior use, the sources of lead in the water supply system, the pipe material and chemical properties of the water, detailed plumbing arrangements, and the age of the building. Different methods of sampling the same household supply will also give different results. There is currently no universal accepted method for sampling lead in drinking water; the appropriate method depends on the particular purpose for which sampling is carried out.

7. As this review progressed, it became clear that an independent field sampling of drinking water at the affected PRH estates would be necessary. The lead concentration measured on the 1,325 drinking water samples in the 11 "affected estates" are all based on "fully flushed samples" (i.e. for each flat a 250 mL sample was taken after flushing the tap for 2-5 minutes). While this sampling method provides a measure of water quality of the bulk water supply, it does not reflect the actual and sometimes high lead concentrations to which the residents are exposed. Such data does not provide an estimate of the mean lead concentration used for

drinking and cooking, nor an adequate basis for assessment of health risks. This concern on the inadequacy of the sampling method adopted by the Water Supplies Department was expressed in the Joint Expert Report (Preliminary) by Fawell and Lee **[V1/1/1-44]**.

8. Unlike other countries where lead contamination has been investigated, lead pipes are not used in the water supply system of Hong Kong. On the other hand, the deposition, release and transport of any lead introduced into the highly compact labyrinth of water supply system in a PRH estate building is a unique feature that has previously not been studied. In view of the enormous scale of the problem and the paucity of data, resort has also to be made to the use of a computational fluid dynamics (CFD) model to assist with the data interpretation. Great effort has also been made by **Lo & Lo** to examine, retrieve, collate and analyse all the lead concentration data collected, measured and tracked by different parties (WSD, HD, and the Government Laboratory)**[A3/43-45/2382-2505]**.

Technical Investigation

Sampling of drinking water at PRH estates

9. A field sampling program was designed and implemented during 2 – 22 December 2015. The aim was to provide an independent data set for identification of the causes of lead contamination and to provide a basis for health risk assessment. The sampling covered 36 buildings in the 11 "affected estates" and 7 buildings in 6 selected "unaffected estates". In each building, 3 flats at upper, middle and lower levels were randomly selected by the Housing Department. In total, 129 flats were sampled [see **Appendix III, Table 2**].

10. The field sampling was carried out by trained researchers (six teams, each of two members) from the Hong Kong University of Science and Technology (HKUST). For each flat, a total of 5 samples were taken from the kitchen tap with the water continuously flowing: a "first draw" sample and 4 subsequent samples at 20 second intervals. The sampling was carried out in the early morning (between 6:30-9:00 am); the resident was informed by HD staff to flush the kitchen and wash basin taps the night before the sampling for 5 minutes before going to bed, and not to use the

kitchen tap afterwards before the sampling. The tap flow rate was also measured. The sampling protocol is illustrated in **Figure 1 in Appendix II**.

11. The samples were preserved and logged in by the Health, Safety & Environment Office (HSEO) Laboratory of HKUST and sent to the Government Laboratory (GL) for analysis of lead concentrations. HSEO also carried out lead concentration measurements as a cross-reference and supplement, and for targeted purposes. The HSEO of HKUST is an accredited laboratory under the HOKLAS scheme. In total 645 samples were collected; 290 and 269 samples were analysed by GL and HSEO respectively; cross-checking confirmed the reliability of the measurements. Details of the sampling protocol can be found in **Appendix IV**.

12. More detailed sampling was also carried out in 3 vacant flats of 3 estates (Un Chau Estate, Kwai Luen Estate and Kai Ching Estate)[see **Appendix III, Table 7**]. The aim was to study how lead concentration at the kitchen tap varied with time in relation to water stagnation (out of use) in the water supply chain of the individual flat. This provided a systematic data set for comparison of different sampling methods, for assessment of health risks, and for calibration and validation of the CFD model. For these flats, two additional sampling taps were installed with the assistance of WSD and HD: one at the water meter position for the flat (in the meter room), and one at the entry location to the flat (which may be the kitchen or washroom depending on the design of the flat). The kitchen and wash basin taps were flushed by HD staff the night before; samples were taken at the kitchen tap as well as the two special sampling taps. A longer sampling period of 5 minutes was used. The configuration of the water supply chain pipe of each flat (location and arrangement of meter room; number, type and location of pipe joints, pipe lengths) of each flat was also measured on site. Details of the sampling protocol can be found in **Appendix V**.

    A total of 80 samples were collected for the vacant flats; 40 samples were analysed by GL and HSEO respectively.

Computational fluid dynamics modelling of water supply chain

13. Any sources of lead introduced into the drinking water supply system will affect the lead concentration at the consumer tap. As the WSD measurements indicate absence of lead contamination in the supply line to each building, roof tank, and down pipe

(the central water supply line from the roof tank to the individual households), the focus is on the release, accumulation, and transport of the lead in the branch water supply chain from the down pipe to the individual flats on each floor.

14. Lead can accumulate in the water supply chain and be transported to the consumer tap of a particular flat as follows. An individual parcel of water flows from the down pipe to the meter room and passes a labyrinth of piping to a pipe along the ceiling of the corridor before entry into the flat (either the kitchen or wash room). The water parcel passes through a number of fixtures and joints along the flow path – Tee joints, elbows, water meters and valves. **Figures 2 and 3** in **Appendix II** depict a typical arrangement of a water supply chain for a PRH estate flat.

15. When the water tap is not in use, say overnight, the water in the supply chain of a particular flat is stagnant. Any lead deposits will be released into the water through chemical reaction and molecular diffusion; the lead concentration in the system will increase with time. When the water tap is turned on, say the next morning, the accumulated lead in the system will be transported in the turbulent pipe flow and the lead concentration at the consumer tap depends on the accumulated lead during the stagnation period and the mixing and transport in the system. The distribution of the dissolved lead along the supply chain both during stagnation and after opening the tap can be obtained through computational fluid dynamics (CFD) modelling.

16. CFD modelling is a tool to determine the changes in lead concentration along the supply chain and with time. The supply system is discretized or divided into a large number of cells (finite volumes), and the lead distribution is determined by numerical solution of governing equations based on mass and momentum conservation. The input to the model is the pipe configuration, the pipe flow rate, and the assumed stagnation equilibrium lead concentrations and lead leaching rates at the joints and pipes based on the WSD laboratory data. The output of the model is the lead concentration in each grid cell. Details of the CFD modelling are given in **Appendix VI**. **Figure 4** in **Appendix II** shows the computational grid for a representative vacant flat. **Figure 5** in **Appendix II** shows a typical lead distribution in a pipe joint at different times after stagnation. The model has been calibrated and validated against data obtained from the vacant flat tests by both WSD and the independent experiments of this study. The aim of the computer modelling is to provide an indirect check on the measured lead leaching rates, and to gain more insights into

the causes and possible mitigation measures against risks of drinking lead-contaminated water in PRH estate flats in Hong Kong.

OPINION & FINDINGS

(i) Analysis of Lead Concentration Data

17. The WSD data for the "unaffected estates" provided guidance for the targeted field sampling in December 2015 **[Table 3, Appendix III]**. For these 45 estates (163 buildings) completed in or after 2005 excess lead was found in 11 samples (out of 3806 samples taken). It is notable that 86.3% of the samples had lead concentrations below 1 μg/L (below detection), and 98.1% below 5 μg/L. Lead contamination risks for these estates appear to be very low. The 11 excess lead samples were derived from 5 estates (namely, Shui Chuen O Estate, Yee Ming Estate, Tin Ching Estate, Choi Tak Estate and Kwai Chung Estate) that were labelled "unaffected" probably due to different methods of interpretation. For the purpose of independent lead sampling, a total of 6 "unaffected" estates (Shui Chuen O Estate, Yee Ming Estate, Choi Tak Estate, Kwai Chung Estate, Un Chau Estate (Phase 5) and Sau Mau Ping (South) Estate) were selected **[Table 2, Appendix III]**.

18. Lead concentrations were also measured on a total of 2,639 samples collected from 138 estates (308 buildings) completed before 2005 **[Table 4, Appendix III]**. No excess lead is found in any of the samples. It seems that any lead introduced into the water supply system would have been substantially leached over the 10 year period.

19. The independent and planned sampling of every building with suspected lead contamination (in the "11 + 6" estates) provides independent data for general risk assessment and as a basis for assessment of health risk and sampling protocol, and possible advice to residents.

20. Different sampling methods lead to different lead concentrations. The independent sampling reveals that 47.2% of the "first draw" samples have excess lead – as compared with 8.0% of the fully flushed samples **[Table 5, Appendix III]**. The independent sampling data is also consistent with the information from the Coalition of the Victims of Contaminated Drinking Water **[AC1/1-22]**, although details of the sampling protocol for this set of data are unknown.

21. The complex variation of lead concentration with time is captured by our sampling. Two characteristic patterns of lead concentration variation with time were observed. In about 37% of the cases in which lead was detected, the maximum concentration is observed in the first draw sample, followed by a monotonic decrease in the subsequent samples (at t=20, 40, 60, 80 sec). In other cases (around 63%), the maximum concentration is detected in the second sample at t=20 sec, followed by a sharp decrease **[Figure 6, Appendix II]**. This second pattern is mostly found in flats completed in or after 2010. The delayed peak concentration is usually found in flats with higher lead contamination, and probably reflects the relative location of the lead sources from the kitchen tap (whether the significant lead sources are in the meter room, corridor, or inside the flat).

22. While general patterns can be discerned, the sampling also indicates occasional samples that would not follow any general trend. For example, the lead concentration of four samples (t=0, 20, 40, 80 sec) can be below detection, with the sample (t=60 sec) giving unexpectedly high concentration that may reveal the picking up of a lead particle in the system. Such outliers are rare but reflect the complexity of the problem once lead sources are introduced into the water supply chain.

23. Since multiple samples were taken in each flat, a measure of the lead contamination risk can be given by a mass integrated average lead concentration of the 5 samples taken – the "flat concentration" is the concentration measured by the total mass divided by the total volume collected (450 mL). Based on the flat concentration, 53.2% and 58.2% of the samples have excess lead (depending on 2 or 5 samples respectively) as compared to the 8.0% for the individual flushed sample **[Table 5, Appendix III]**.

24. The average of the flat concentrations of the randomly selected upper, middle, and lower floors gives a "building concentration". The lead contamination of a building can be classified as follows: (i) Class 1 – the building concentration and all sample concentrations are less than 10 μg/L; (ii) Class 2 – the building concentration is less than 10 μg/L but with at least one sample greater than 10 μg/L; (iii) Class 3 – the building concentration is greater than 10 μg/L **[Table 6, Appendix III]**. Out of the 43 buildings sampled, 18 buildings are of Class 2 or above, while 9 buildings are

considered Class 1. The remaining 25 buildings are considered significantly lead contaminated.

(ii) Causes of Excess Lead

25. The detailed data for the three representative vacant flats point to the sources of lead in the water supply chain of the flats. The sampling shows significant lead concentrations measured at the water meter position as well as at the location of first entry to the flat. This means most of the lead contamination comes in the pipe network in the meter room, and along the corridor leading to the flat **[Table 7, Appendix III]**. This is consistent with the significant measured lead deposits and leaching rates found in the meters, valves, elbows (90 degree bend) and pipe joints reported by the WSD task force. **Figure 7** in **Appendix II** shows the measured lead deposits in the water supply chain of Luen Yat House, Kwai Luen Estate. While it is difficult to extrapolate the lead deposits measured on pipe sections of 0.2 m length, it is clear that the elbows and joints contribute significantly to the lead contamination. Flow recirculation patterns around a 90 degree pipe bend will also favour lead accumulation in isolated pockets.

26. Based on the measured leaching rates and maximum stagnation concentrations reported (WSD task force report)**[A1/19/685-686 and C19.6/140/14205-14209]**, the lead concentration at the kitchen tap both during stagnation and after the tap is turned on can be estimated by the CFD model. Considering the limited data and the complexity of the problem, the predictions of the calibrated model are in reasonable agreement with the WSD data **[Figure 8, Appendix II]**. This provides an indirect confirmation of the detailed stagnation lead concentration and leaching rate measurements made by WSD.

27. By adopting lead source strengths within the range of the WSD measurements, the CFD simulation of lead concentrations at the kitchen tap are consistent with our own measurements **[Figure 9, Appendix II]**. For the vacant flats it seems that for both 4-hr and 18-hr stagnation periods the lead concentration drops to below 10 μg/L levels in about 30 seconds. As noted above, in lead contaminated flats, occasional outliers of lead concentration are still possible.

28. Based on a holistic assessment of the collective WSD and HKUST data, and the CFD modelling, it seems that the main cause of the excess lead found in drinking water of PRH estates is due to the leaching of significant lead deposits in the pipe joints and fittings (e.g. elbows, valves, meters). From the soldering demonstration by a plumbing expert of the Construction Industry Council (7 December 2015) and the WSD data, it is clear that lead soldering material can be introduced into the pipe joints due to over use of lead solder and/or poor workmanship. Whether the lead deposits are greater along the pipe length (due to shearing off and sedimentation of lead solder deposits and/or electro-chemical reactions of copper alloys with the water) or at the pipe joints is of secondary importance. In any case, the measured leaching rates are consistent with the lead concentration measured at the tap.

(iii) Review of Findings of the WSD Task Force Reports

29. Overall the Water Supplies Department and the Government Laboratory have carried out a thorough and substantial investigation within the time and other constraints. In particular, the dismantling and chemical analysis of the key components of the water supply chains of three representative flats was a sensible and practical step. Although only three representative flats were selected, the examination of the 134 pipe components and fittings yielded very useful information.

30. The direct measurements on the lead content and leaching rates of pipe sections, joints (elbows, sockets, tees) and fittings (meters, valves, taps) provided valuable data to unravel the causes of excess lead (Annex 2.3 – 2.5 of WSD Report)**[A1/19/744-756]**. There is great variability (one to two orders of magnitude) in the measured leached lead mass from the pipe and joints (elbows and sockets) and fittings (one order of magnitude). The total leached mass from the fittings are similar for the three locations. Given the mass of lead deposited in the components of the water supply chain it can be roughly estimated that it could take as long as 5-10 years for most of the lead mass to be leached into the water, especially for the pipe joints. This is consistent with the present finding that the estates completed in or before 2010 have generally a lower lead concentration.

31. Based on my visit to the Ngau Tam Mei treatment works to see the dismantled "components" and the chemical tests employed, it is clear that the dismantling and

transport of the pipe components and the chemical analysis have been carefully conducted. As the CFD model calculations are based on the measured leaching rates, the credibility of the WSD measurements is also supported by the congruence of the predictions of lead concentrations with data. In view of the variability and randomness of the lead sources within a branch water supply system leading to a flat, it was judged that independent laboratory tests of the lead content of pipe joints and fittings would not have added much value. Rather the effort was directed towards the development of the CFD model.

32. The independent sampling and measurements by two accredited laboratories demonstrated the robustness and accuracy of the lead concentration measurements by the Government Laboratory. Based on the average kitchen tap flow rate of 0.26 L/s, turning on the tap for 2-5 minutes (say 3 min) would cover a supply chain pipe length of over 100 m. Assuming a typical pipe length of around 20 m, this would translate to more than "5 plumbing volumes". Hence the government sampling method was essentially a "fully flushed" sample according to generally accepted definitions (time taken to flush 3-5 plumbing volumes). The WSD sampling would not give the maximum or average lead exposure levels of the consumer. Nevertheless, the collective WSD data was very useful in guiding the independent sampling, and also as a basis for assessing the general lead contamination risk among the PRH estates.

33. The tap-water concentrations measured in this study are consistent with the significant lead contents of the solder measured (between 27% and 42%, p.21 of Task Force Report)**[A1/19/672]**. The use of the isotopic analysis to ascertain the correlation between lead in water and the lead in the solder joints is judged to be reasonable and valid.

34. Measurements on pipe joints in the flat in Hung Hei House of Hung Fuk Estate (HFE) – where stainless steel pipes with mechanical joints and copper pipes with lead-free solder joints are used – show the absence of lead (Annex 2.7 of WSD Report)**[A1/19/772]**. The pipe joints and fittings in these flats are otherwise similar to flats in the affected estates. This control experiment provides solid evidence that the leaded solder joints should be the main cause of excess lead in drinking water and the relative insignificant lead contribution of copper alloy fittings. Tak Long House of Tak Long Estate that we visited is a similar building that uses stainless steel pipes

and mechanical joints. The tap-water lead concentration in one flat of Tak Long House (not included in this report) also indicated below detection levels.

35. The mathematical model adopted in the WSD report is essentially a mass balance assuming fully mixed conditions. Consistent with the present review, the results generally indicate the significance of the contributions of the lead solders (or the lead deposits along the pipes derived from the lead solder). However, it is highly questionable whether the lead sources in the copper pipes (e.g. p.30 of WSD Report) **[A1/19/681]** can be estimated by linear extrapolation of the measurements on short lengths (0.2 m) of copper pipes containing lead deposits. There is also no data to test the scenarios depicted. The estimates of lead mass leached from the pipes for the Kai Ching Estate are hence prone to significant uncertainties. This uncertainty will affect the relative contribution of lead deposits on pipes, joints, and fittings to the water tap lead contamination. Additional tests similar to the vacant flat experiments will help to further resolve this issue.

Summary and Conclusions

36. Independent planned sampling and analysis of lead contamination of 43 buildings in 17 PRH estates have confirmed the main WSD findings. Regardless of the method of sampling, the "affected estates" and the "unaffected estates" are largely confirmed. The more detailed sampling results in a more accurate assessment of the extent of lead contamination in the different estates and buildings. The average lead concentration of about 50% of the samples in the "affected estates" exceeded the WHO provisional guideline value of 10 μg/L.

37. Lead contamination in the densely populated PRH estates seems to be dominated by lead solder deposits in the numerous joints of the water supply chain from the down pipe to the individual flats. The lead concentration at the kitchen tap varies with time in a complex manner possibly due to the random nature of the lead deposits in the system. First draw samples may or may not contain the highest concentration. In general, more sporadic variations and higher concentrations are found in the estates completed in or after 2010.

38. The detailed sampling provides data for health risk assessment. Both the data and CFD results indicate that lead concentration in most cases drop rapidly within 30-60

seconds. A flushing time in the order of 0.5-1 minute appears to be adequate for guarding against risks of lead contamination.

Expert's Declaration

I, PROFESSOR JOSEPH HUN-WEI LEE DECLARE THAT:

1. I declare and confirm that I have read the Code of Conduct for Expert Witnesses as set out in Appendix D to the Rules of High Court, Cap. 4A and agree to be bound by it. I understand that my duty in providing this written report and giving evidence is to assist the Commission. I confirm that I have complied and will continue to comply with my duty.

2. I know of no conflict of interests of any kind, other than any which I have disclosed in my report.

3. I do not consider that any interest which I have disclosed affects my suitability as an expert witness on any issues on which I have given evidence.

4. I will advise the Commission if, between the date of my report and the hearing of the Commission, there is any change in circumstances which affect my opinion above.

5. I have exercised reasonable care and skill in order to be accurate and complete in preparing this report.

6. I have endeavoured to include in my report those matters, of which I have knowledge or of which I have been made aware, that might adversely affect the validity of my opinion. I have clearly stated any qualifications to my opinion.

7. I have not, without forming an independent view, included or excluded anything which has been suggested to me by others, including my instructing solicitors.

8. I will notify those instructing me immediately and confirm in writing if, for any reason, my existing report requires any correction or qualification.

9. I understand that:

(a) my report will form the evidence to be given under oath or affirmation;

(b) questions may be put to me in writing for the purposes of clarifying my report and that my answers shall be treated as part of my report and covered by my statement of truth;

(c) the Commission may at any stage direct a discussion to take place between the experts for the purpose of identifying and discussing the issues to be investigated under the Terms of Reference, where possible reaching an agreed opinion on those issues and identifying what action, if any, may be taken to resolve any of the outstanding issues between the parties;

(d) the Commission may direct that following a discussion between the experts that a statement should be prepared showing those issues which are agreed, and those issues which are not agreed, together with a summary of the reasons for disagreeing;

(e) I may be required to attend the hearing of the Commission to be cross-examined on my report by Counsel of other party/parties;

(f) I am likely to be the subject of public adverse criticism by the Chairman and Commissioners of the Commission if the Commission concludes that I have not taken reasonable care in trying to meet the standards set out above.

Statement of Truth

I confirm that I have made clear which facts and matters referred to in this report are within my own knowledge and which are not. Those that are within my own knowledge I confirm to be true. I believe that the opinions expressed in this report are honestly held.

Professor Joseph Hun-wei Lee
5 February 2016

APPENDIX I

Documents referred to in this Report

Government documents and Witness Statements

1. "Excessive Lead in Fresh Water Supply in Public Housing Estates", LC paper No.: CB(1)1133/14-15(01), Legislative Council Panel on Housing meeting on 22 July 2015. **[A1/2/2-23]**
2. "Lead in Drinking Water Incidents", LC Paper No. CB(2)2195/14-15(01), Legislative Council Special House Committee meeting on 8 October 2015.
3. "Updated background brief on lead in drinking water incidents", LC Paper No. CB(2)2195/14-15(02), Legislative Council Special House Committee meeting on 8 October 2015.
4. Witness Statement of Anthony Cheung Bing Leung, Chairman of the Housing Authority on 29 October 2015. **[B15.1/336/37419-37502]**
5. Witness Statement of Ada Fung Yin Suen JP, Deputy Director of Housing (Development and Construction) of the Housing Department on 29 October 2015. **[B15.1/337/37503-37641]**
6. Water Services Department, "Final Report of the Task Force on Investigation of Excessive Lead Content in Drinking Water", 30 October 2015. **[A1/19/650-801]**
7. Witness Statement of Lam Tin Sing Enoch, Director of Water Supplies on 6 November 2015. **[C19.7/114/10279-10299]**
8. Fourth Witness Statement of Chan Kin Man, Chief Waterworks Chemist, Water Supplies Department, on 4 December 2015. **[C19.6/145/14517-14621]**

Technical References/International standards

1. Bailey, RJ, Holmes, D, Jolly, PK and Lacey, RF, "Lead concentration and stagnation time in water drawn through lead domestic pipes", WRc Environment TR 243, Water Research Centre, UK, October 1986.

2. Drinking Water Inspectorate, UK, "Guidance on the Implementation of the Water Supply (Water Quality) Regulations 2000 (as amended) in England", Version 1.1, March 2012. **[C19.6/145/14569-14573]**

3. Kuch, A and Wagner I, "A mass transfer model to describe lead concentrations in drinking water", Water Research, Vol. 17, No. 10, 1983, pp. 1303-1307.

4. Lacey, RF and Jolly, PK, "Sampling for household water-lead", WRc Environment TR 244, Water Research Centre, UK, October 1986.

5. Ministry of Health, Labour and Welfare, Japan, "the Waterworks Law, Drinking Water Quality Standards", 2004.

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7. Oliphant, RJ, "Summary report on the contamination of potable water by lead", External Report No. 125E, Water Research Centre, UK, November 1983.

8. Scottish Centre for Infection and Environmental Health," Scottish New Homes Lead Survey Stage 1", October 2000. **[A1/14/198-243]**

9. Scottish Centre for Infection and Environmental Health, "Scottish New Homes Lead Survey Stage 2", 2003. **[A1/15/244-398]**

10. The Hong Kong Institution of Engineers, "Report on the Study of Lead in Drinking Water in Public Housing Estates", 2 November 2015. **[U1/3/3-127]**

11. The International Organization for Standardization, "ISO 5667-5:2006 Water quality - Sampling - Part 5: Guidance on sampling of drinking water from treatment works and piped distribution systems", 2006. **[C2/19/1526-1549]**

12. Van der Leer, D, Weatherill, NP, Sharp, RJ and Hayes, CR, "Modelling the diffusion of lead into drinking water", Applied Mathematical Modelling, Vol. 26, 2002, pp. 681-699.

13. World Health Organization, "Guidelines for drinking-water quality", fourth edition, 2011. **[C2/18/1244-1525]**

Photographs, Sketches and Diagrams

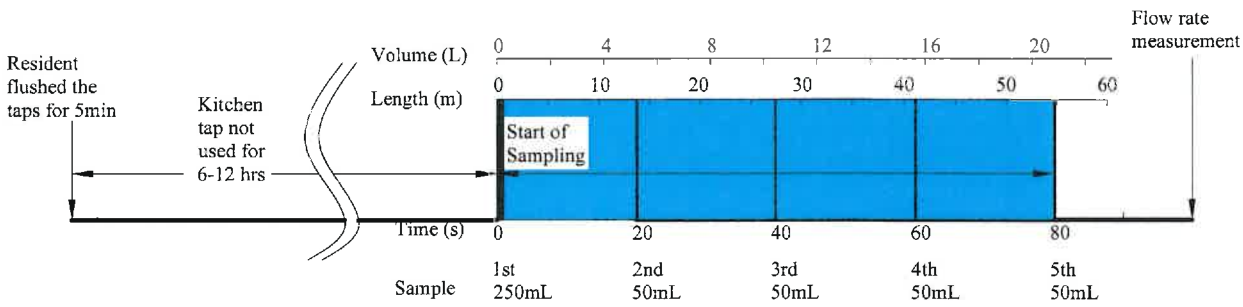


Figure 1 Lead sampling protocol of PRH estates in December 2015. The sampling time and corresponding pipe length and water volume shown is based on the measured average flow of 0.26 L/s and typical pipe diameter of 22 mm

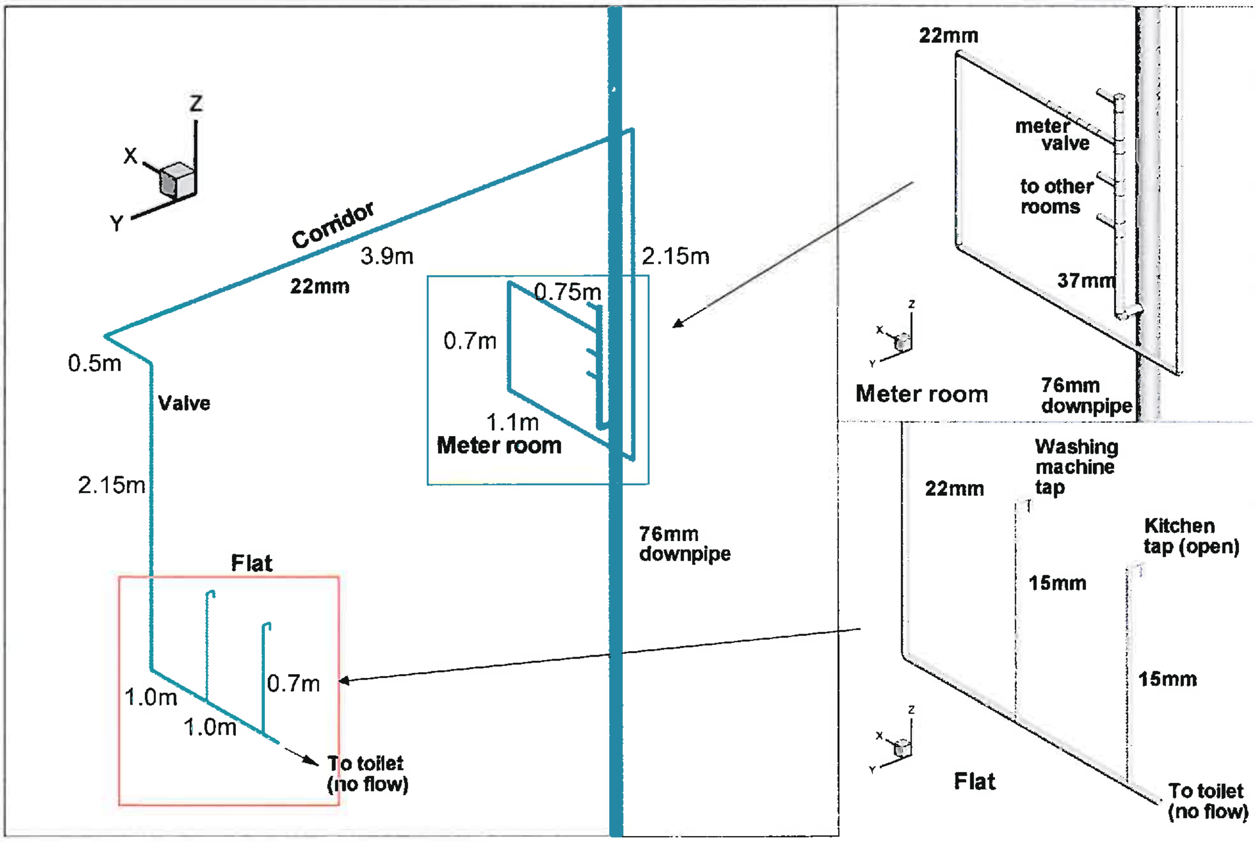


Figure 2 Typical arrangement of water supply chain for a PRH estate flat (Room 1813, Un Nga House, Un Chau Estate). This example shows a flat with 22 mm diameter supply pipe; total pipe length is 14 m, with 8 right angle bends/elbows), and 5 Tee-joints

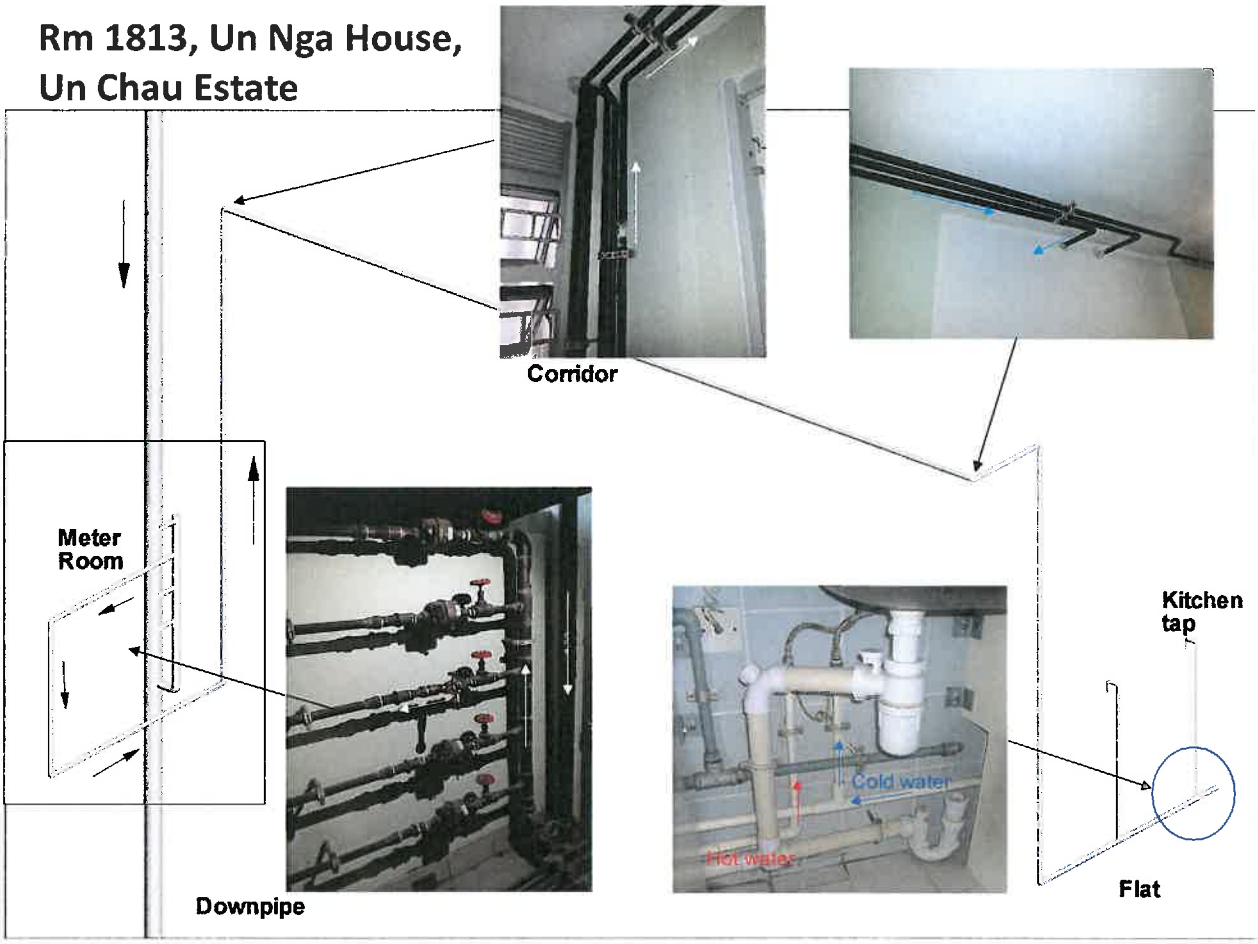


Figure 3 Photos of typical arrangement of water supply chain for a PRH estate flat (Room 1813, Un Nga House, Un Chau Estate)

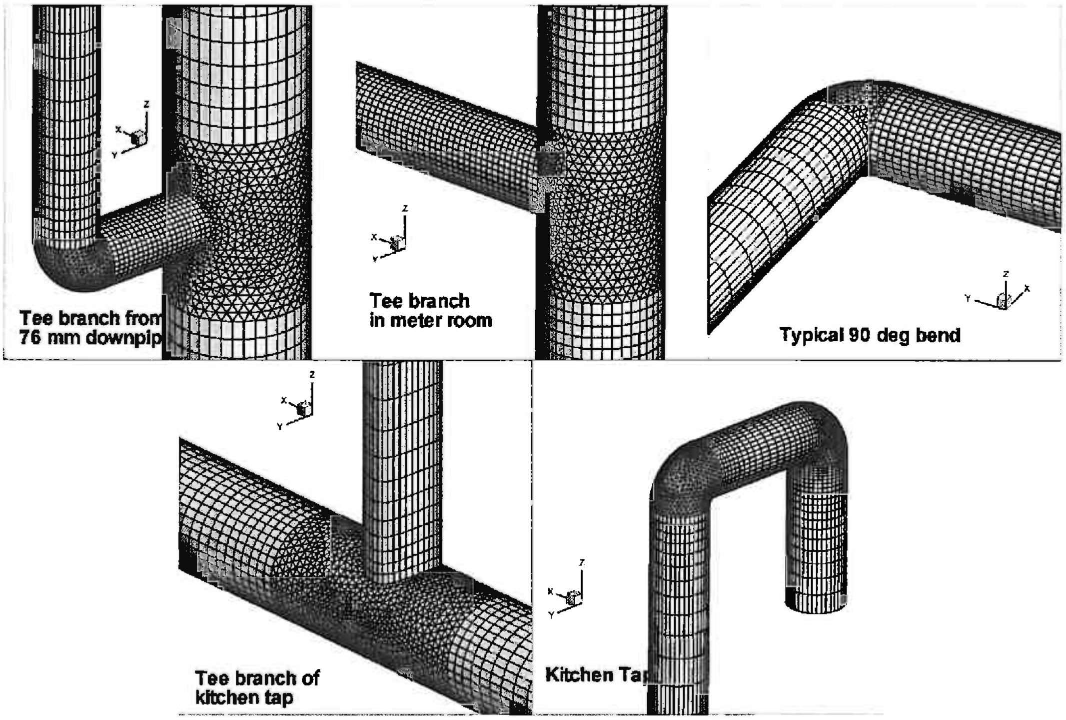


Figure 4 Typical configuration of computational grid at pipe connections in the water supply chain

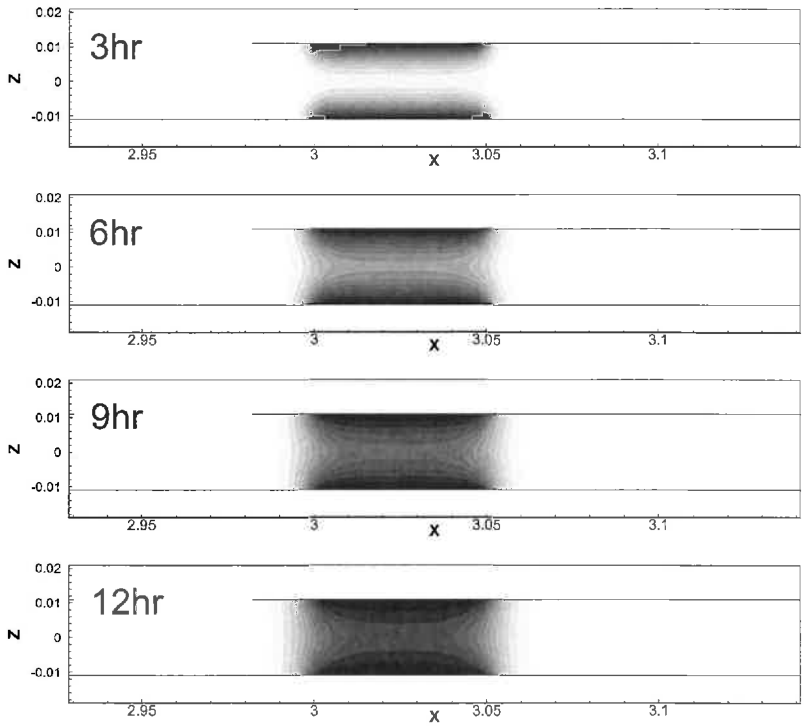


Figure 5 Typical lead distribution in a pipe joint at different times after stagnation

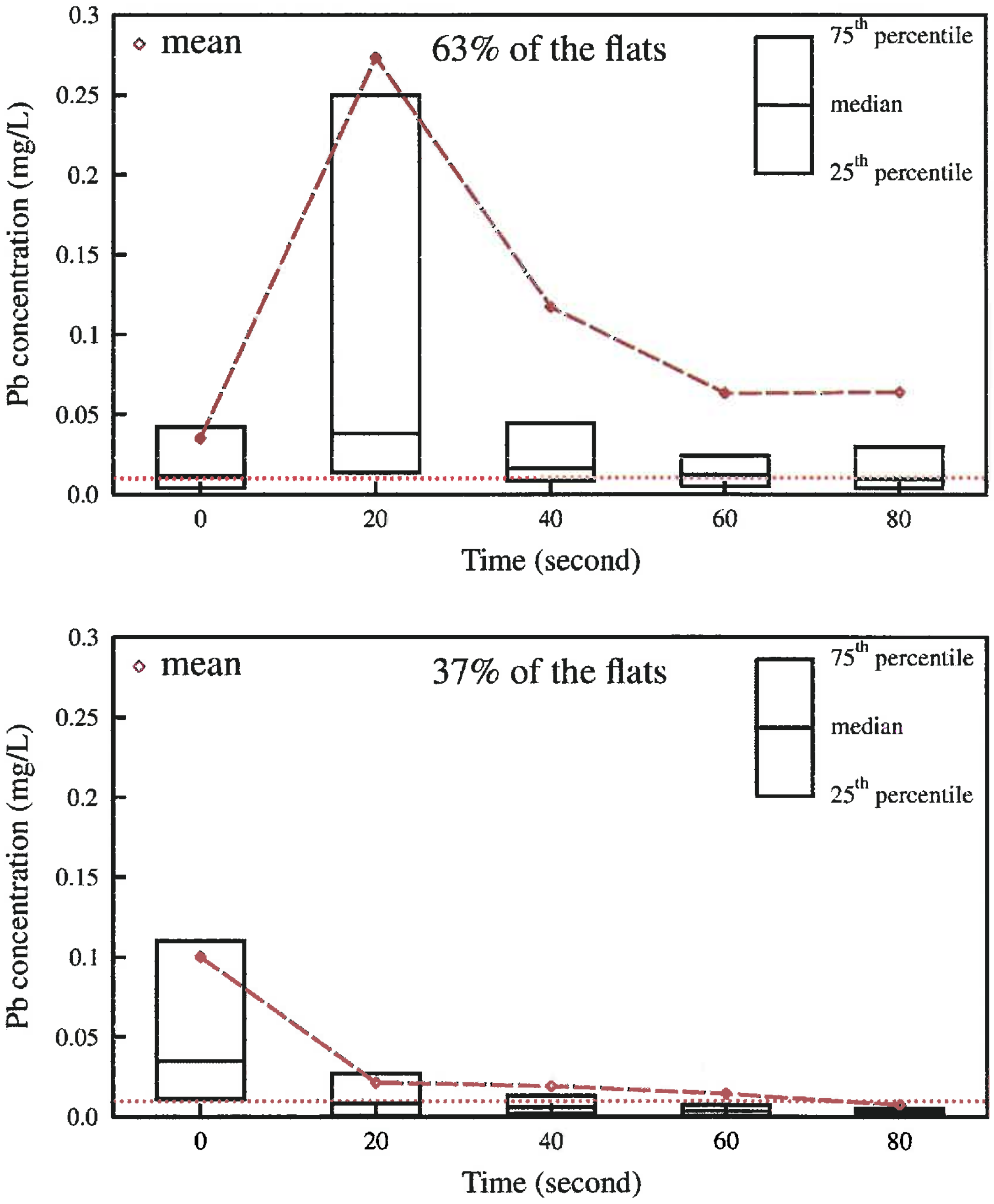


Figure 6 Typical patterns of tap-water lead concentration variation with time

Item No.	Type	Mass of lead deposit in components (mg)	Mass of lead leached per components in 24 hr (µg)	No. of components	Total mass of lead leached in 24 hr (µg)**
Meter Room					
L15	pipe	0.68	4.2	26*	110
L15A	elbow	9.32	28.8	2	57.6
L11	valve	1.20	10.7	1	10.7
L12	stopcock	0.05	25.8	1	25.8
L13	meter	11.46	65.9	1	65.9
L21	pipe	0.37	1.3	5.5*	7.3
L14	elbow	32.00	44.6	2	89.2
L18	elbow	8.36	23.0	4	92
L16	socket		4.0	1	4
Corridor					
L18	elbow	8.36	23.0	4	92
L21	pipe	0.37	1.3	103*	133
L16	socket		4.0	6	24
L17	socket		2.0	1	2.0
L19	socket		1.3	1	1.3
Flat					
L35	valve	0.06	14.9	1	14.9
L36	elbow		3.6	8	28.8
L16	socket		4.0	6	24
L37	pipe		0.7	58*	40
L31	tap		3.5	1	3.5
L31A	tap		5.8	1	5.8

*No. of component in pipe = length of pipe/sample length (~0.2m)
**Total mass of lead leached = Mass of lead leached per components x No. of components

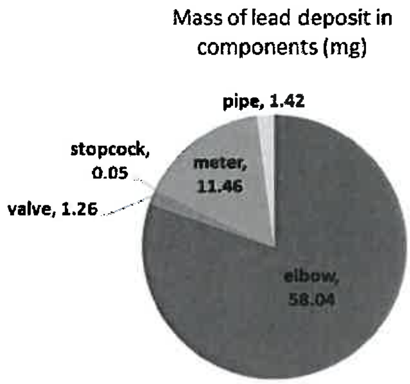
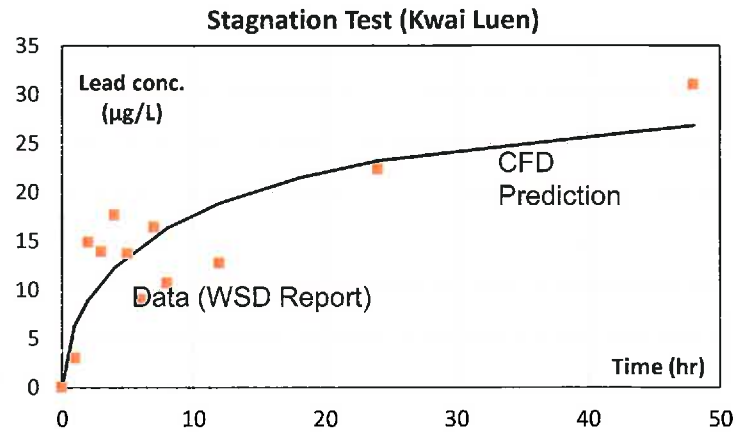
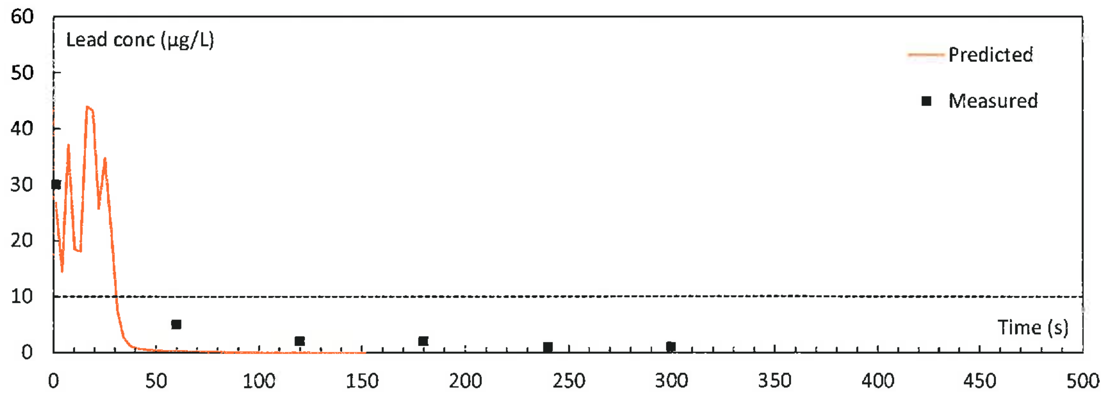


Figure 7 Measured lead deposits (mg) and estimated leached mass in 24 hours (µg) inside the different components of the water supply chain (Luen Yat House, Kwai Luen Estate) – from WSD Task Force Report.

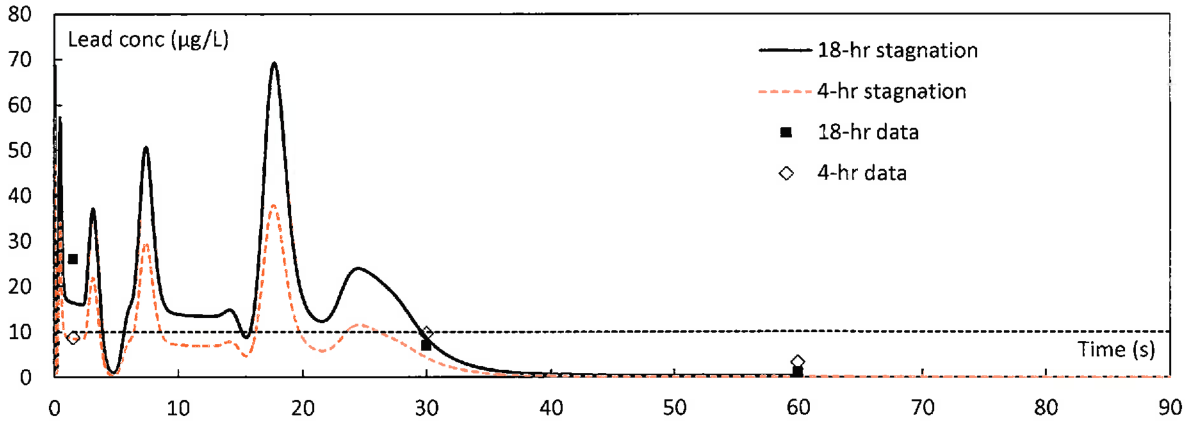


(a) Stagnation Test

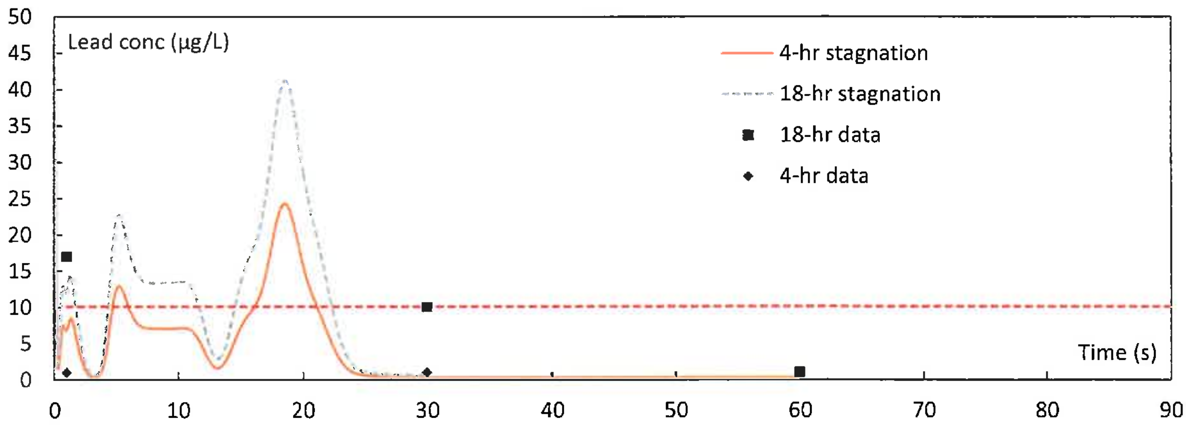


(b) Flushing Test

Figure 8 Comparison of predicted lead concentration at kitchen tap with WSD data (Luen Yat House, Kwai Luen Estate)



(a) Room 3607, Luen Yat House, Kwai Luen Estate



(b) Room 1813, Un Nga House, Un Chau Estate

Figure 9 Comparison of predicted lead concentration at kitchen tap with HKUST data (Kwai Luen and Un Chau Estates)

APPENDIX III

Tables and Summaries

Table	Description
1	List of "affected estates" sampled by Water Supplies Department during July – September 2015: (a) number of samples with excess lead; (b) distribution of lead concentration (total number of samples = 1325)
2	List of PRH estates and houses covered by independent sampling (2-22 December 2015
3	Distribution of measured lead concentrations for 3,806 samples in "unaffected estates" completed in or after 2005
4	Distribution of measured lead concentrations for 2,639 samples in "unaffected estates" completed before 2005
5	Comparison of excess lead data of WSD and HKUST – "fully flushed" vs first draw samples
6	Classification of buildings based on the HKUST sampling results
7	Measured lead concentrations (mg/L) in meter room, entry to flat, and kitchen tap for vacant flats

Table 1 List of "affected estates" sampled by Water Supplies Department during July – September 2015: (a) number of samples with excess lead; (b) distribution of lead concentration (total number of samples = 1325)

(a)

Estate	Year of completion	No. of buildings	No. of samples	No. of samples with excess lead
Kwai Luen Estate Phase 2	2014	2	122	5 (4.1%)
Kai Ching Estate	2013	6	327	8 (2.4%)
Wing Cheong Estate	2013	2	64	2 (3.1%)
Lower Ngau Tau Kok Estate Phase 1	2012	5	163	7 (4.3%)
Shek Kip Mei Estate Phase 2	2012	2	79	8 (10.1%)
Tung Wui Estate	2012	2	52	4 (7.7%)
Hung Hom Estate	2011	3	74	18 (24.3%)
Yan On Estate	2011	3	69	6 (8.7%)
Choi Fook Estate	2010	3	92	13 (14.1%)
Un Chau Estate Phase 2 and 4	2008	5	138	23 (16.7%)
Ching Ho Estate	2008	3	145	12 (8.3%)
Total		36	1325	106 (8.0%)

(b)

Lead concentration (μg/L)	Number of samples	Percentage
< 1	403	30.4%
1-4	623	47.0%
5-9	193	14.6%
10-19	70	5.3%
20-29	14	1.1%
≥ 30	22	1.7%
Total	1325	

Table 2 List of PRH estates and houses covered by independent sampling (2-22 December 2015)

Date of Survey (2015)	Estate	House	Flat
2-Dec	Hung Hom (A)	Hung Yan	910, 1715, 3905
		Hung Yat	107, 3207*, 3811
		Hung Yiu	317, 1917, 3610
	Yan On (A)	Yan Chung	408, 2403, 3702
		Yan Hei	206, 1906, 3512
		Yan Yuet	920, 2508, 3405
3-Dec	Kwai Luen (A)	Luen Yat	303, 2506, 3804
		Luen Yuet	310, 2205, 3201
	Shek Kip Mei (A)	Mei Leong	803, 1510, 4004
		Mei Wui	310, 2308, 3007
	Wing Cheong (A)	Wing Chun	213, 1718, 3405
		Wing Kit	1305, 2610, 3815
4-Dec	Ching Ho (A)	Ching Chung	108, 1209, 3815
		Ching Hin	114, 2202, 2908
		Ching Yu	1612, 2107, 3513
	Choi Fook (A)	Choi Hay	518, 2124, 4006
		Choi Lok	615, 1920, 4010
		Choi Sin	620, 3010, 4005
7-Dec	Lower Ngau Tau Kok (A)	Kwai Fai	106, 1810, 3715
		Kwai Hin	210, 2309, 4115
		Kwai Leung	209, 2213, 3609
		Kwai Sun	214, 2720, 4411
		Kwai Yuet	406, 1718, 4506
	Sau Mau Ping (South) (U)	Sau Sin	304, 2304, 3414
8-Dec	Choi Tak (U)	Choi Shing	211, 2106, 3914
	Kwai Chung (U)	Hop Kwai	1009, 2419, 3501
		Pak Kwai	919, 2413, 3916
	Tung Wui (A)	Wui Sum	103, 1220, 2807
		Wui Yan	916, 1603, 3303
9 Dec	Kai Ching (A)	Hong Ching	605, 2402, 3113
		Lok Ching	421, 1806, 3212
		Mun Ching	221, 1916, 3410
		Sheung Ching	116, 1022, 4022
		Yan Ching	219, 1913, 3605
		Yuet Ching	508, 1908, 3107
10-Dec	Un Chau Phase 2 & 4 (A)	Un Chi	217, 1906, 3902
		Un Hei	205, 1501, 3406
		Un Kin	403, 1003, 1802
		Un Lok	1004, 1805, 3402
		Un Nga	513, 2112, 3703
	Un Chau Phase 5 (U)	Un Wai	416, 2204, 3503
17-Dec	Yee Ming (U)	Yee Yan	1124, 2315, 3015
22-Dec	Shui Chuen O (U)	Hei Chuen	316, 1303, 2108

(A) Affected Estates, (U) Unaffected Estates

*A vacant flat

Table 3 Distribution of measured lead concentrations for 3,806 samples in "unaffected estates" completed in or after 2005

	No. of estates	No. of buildings	No. of samples	No. of samples with Pb concentrations			
				< 1 μg/L	1–4 μg/L	5-9 μg/L	≥ 10 μg/L
All samples with Pb < 1 μg/L	5	9	128	128 (100%)			
All samples with Pb < 5 μg/L	17	42	926	872 (94.2%)	54 (5.8%)		
All samples with Pb < 10 μg/L	18	73	1801	1544 (85.7%)	221 (12.3%)	36 (2.0%)	
At least one sample with Pb ≥ 10 μg/L	5	39	951	740 (77.8%)	175 (18.4%)	25 (2.6%)	11 (1.2%)
Total	45	163	3806	3284 (86.3%)	450 (11.8%)	61 (1.6%)	11 (0.3%)

Table 4 Distribution of measured lead concentrations for 2,639 samples in "unaffected estates" completed before 2005

	No. of estates	No. of buildings	No. of samples	No. of samples with Pb concentrations			
				< 1 μg/L	1–4 μg/L	5-9 μg/L	≥ 10 μg/L
All samples with Pb < 1 μg/L	109	225	2009	2009 (100%)			
All samples with Pb < 5 μg/L	20	56	440	412 (93.6%)	28 (6.4%)		
All samples with Pb < 10 μg/L	9	27	190	178 (93.7%)	3 (1.6%)	9 (4.7%)	
Total	138	308	2639	2599 (98.5%)	31 (1.2%)	9 (0.3%)	

* A total of 2,656 sample results is available; 17 of them are obtained from 9 schools and have been excluded.

Table 5 Comparison of excess lead data of WSD and HKUST – "fully flushed" vs first draw samples

Estate	No. of buildings	WSD/HD		HKUST	
		No. of samples	No. of samples with excess lead	No. of samples (flats)	No. of first draw samples with excess lead
Kwai Luen Estate Phase 2	2	122	5 (4.1%)	6	5 (83.3%)
Tung Wui Estate	2	52	4 (7.7%)	6	5 (83.3%)
Shek Kip Mei Estate Phase 2	2	79	8 (10.1%)	6	6 (100.0%)
Wing Cheong Estate	2	64	2 (3.1%)	6	3 (50.0%)
Kai Ching Estate	6	327	8 (2.4%)	18	14 (77.8%)
Un Chau Estate Phase 2 and 4	5	138	23 (16.7%)	15	5 (33.3%)
Hung Hom Estate	3	74	18 (24.3%)	9	6 (66.7%)
Lower Ngau Tau Kok Estate Phase 1	5	163	7 (4.3%)	15	5 (33.3%)
Yan On Estate	3	69	6 (8.7%)	9	1 (11.1%)
Ching Ho Estate	3	145	12 (8.3%)	9	1 (11.1%)
Choi Fook Estate	3	92	13 (14.1%)	9	0 (0.0%)
Total	36	1325	106 (8.0%)	108	51 (47.2%)

Table 6 Classification of buildings based on the HKUST sampling results

Estate	No. of class 1 buildings	No. of class 2 buildings	No. of class 3 buildings	Total no. of buildings
Choi Tak	1	0	0	1
Sau Mau Ping	1	0	0	1
Shui Chuen O	1	0	0	1
Un Chau Phase 5	1	0	0	1
Choi Fook	2	1	0	3
Ching Ho	1	2	0	3
Kwai Chung	1	1	0	2
Yan On	1	2	0	3
Hung Hom	0	1	2	3
Lower Ngau Tau Kok	0	2	3	5
Yee Ming	0	0	1	1
Kwai Luen	0	0	2	2
Shek Kip Mei	0	0	2	2
Tung Wui	0	0	2	2
Wing Cheong	0	0	2	2
Un Chau Phase 2 & 4	0	0	5	5
Kai Ching	0	0	6	6
Total	9	9	25	43

Table 7 Measured lead concentrations (mg/L) in meter room, entry to flat, and kitchen tap for vacant flats

Estate	House	Flat	Date	Meter	Entry	t = 0s	t = 30s	t = 60s	t = 120s	t = 180s	t = 300s
Un Chau	Un Nga	1813	12/12/15 10:30	0.007	0.017	0.017	0.010	<0.0025	<0.0025	<0.0025	<0.0025
				0.004*	0.008*						
			12/12/15 14:00	0.011	0.008	<0.0025	<0.0025	<0.0025	<0.0025	<0.0025	<0.0025
				0.005*	0.004*						
			12/17/15 11:05	0.008	0.008	0.002	<0.002	0.004	<0.002	<0.002	<0.002
				0.005*	0.006*						
Kwai Luen	Luen Yat	3607	12/12/15 11:53	0.017	0.033	0.026	0.007	<0.0025	<0.0025	<0.0025	0.011
				0.004*	0.003*						
			12/12/15 14:45	0.013	0.019	0.009	0.010	0.003	<0.0025	<0.0025	<0.0025
				0.005*	0.010*						
			12/17/15 11:45	0.014	0.022	0.012	0.011	<0.002	<0.002	<0.002	<0.002
				0.009*	0.002*						
Kai Ching	Mun Ching	2221	12/17/15 10:15	0.010	0.031	0.018	0.003	0.004	<0.002	<0.002	<0.002
				<0.002*	<0.002*						
			12/17/15 13:00	0.006	0.013	0.008	<0.002	<0.002	<0.002	<0.002	<0.002
				<0.002*	0.002*						

* samples were collected again at the meter room and the pipe entry to the flat about 5 minutes after the "t = 300s" sample was taken.

Sampling Protocol
(affected and unaffected estates)

Introduction

In view of the inadequacy of the sampling by the Water Supplies Department and Housing Department, independent and planned sampling was carried out by the Hong Kong University of Science and Technology (HKUST). The purpose of the field sampling was to provide (i) an independent dataset for identification of the sources and causes of excess lead in drinking water, and (ii) a basis for general health risk assessment. The sampling activity covered 36 buildings in the 11 "affected estates" and 7 buildings in 6 selected "unaffected estates". In each building, 3 flats at upper, middle and lower levels were randomly selected by the Housing Department (HD). In total, 129 flats were sampled. **Table 2 of Appendix III** shows the details of all flats sampled.

Sampling protocol

The field sampling activities were all conducted by trained HKUST researchers. Coordinator of the field sampling was Dr. NT Lau of the Division of Environment of HKUST. There were 6 sampling teams. Each team consisted of two members; at least one member could speak and understand Cantonese well enough to communicate with the HD staff and the residents. Each team was responsible for sampling one building (three flats) each day. All team members were briefed and received training before the commencement of the survey on 30 November, 2015. The training was provided by Dr. Samuel Yu of HKUST Health, Safety & Environment Office (HSEO) Laboratory, which is accredited under the Hong Kong Laboratory Accreditation Scheme (HOKLAS).

The field sampling activity was conducted during 2-22 December 2015. The schedule of sampling is shown in Figure IV-1.

Preparation work by Housing Department (HD)

The resident was informed by HD staff to flush the kitchen and wash basin taps the night before sampling for 5 minutes before going to bed, and not to use the kitchen tap afterwards before the sampling. In case a filter was installed, the filter was removed by a contractor appointed by HD the day before sampling.

Briefing

A briefing session was conducted at 4pm the day before every sampling day. Sampling teams obtained the sampling bottles (provided by HSEO Lab) together with sampling forms and other apparatus (one 1 litre bottle and one 250 mL measuring cylinder for flow rate measurement), and the contact points and details of the next-day sampling from the field program coordinator Dr. Lau.

Sampling

Field samplings were conducted between 6:30 am – 9:00 am. The teams would meet with the Housing Department staff for briefing before commencement of the sampling.

Sampling procedure:

1. The sampling team briefed the residents the sampling exercise. The residents were asked two questions - (i) if kitchen and wash basin taps have been flushed for 5 minutes the day before; and (ii) if kitchen and wash basin taps have been used again after the flushing.

2. The kitchen tap was turned fully open to the cold water side with the first sample (250 mL) collected immediately at time zero. The tap remained open throughout the sampling.

3. The second, third, fourth and fifth samples (50 mL each, except the fifth sample of the third flat of each building, which was a 250 mL sample for quality control purpose) were collected at 20, 40, 60 and 80 seconds after the tap was turned on.

4. The sample identification number was recorded on the sampling form. Any potential contamination and other relevant information were also recorded.

5. A photo of the kitchen tap was taken using smartphone or camera.

6. Flow rate measurement: Water was collected using the 1 litre bottle provided; the time required to collect approx. 1 L of water was recorded. The exact volume of the water collected was measured using the 250 mL measuring cylinder provided.

An illustration of the sampling survey is shown in **Figure 1 of Appendix II**.

Post-Sampling and analysis of samples

After the sampling, the samples were transported back to HKUST. All apparatus and log sheets were returned. The teams reported any unusual circumstances to the coordinator and clarified the information on sampling forms in debriefing sessions held every morning on sampling days. All samples were preserved and logged in by HSEO Lab, and then selected samples were sent to the Government Laboratory (GL) around noon time by HSEO staff. The water samples were analyzed for lead, copper and nickel.

A total of 645 samples (excluding vacant flat and control flat samples) were collected; 290 samples were analyzed by GL and 269 samples by HSEO Lab. The unanalyzed samples were stored in HSEO Lab's calibrated refrigerator for future analysis. Results of analyses by GL were sent back to HKUST once available. Eighteen samples analyzed by both GL and HSEO Lab of HKUST were used for cross checking. For samples with lead concentration less than or equal to around 0.01 mg/L, the differences were typically less than 0.001 mg/L (1 μg/L); the mean difference of lead concentration over the range of 0.05 mg/L is 0.0022 mg/L (Figure IV-2).

Sun	Mon	Tue	Wed	Thu	Fri	Sat
29 Nov	30 Nov Training at HSEO	01 Dec	02 Hung Hom Estate Yan On Estate	03 Kwai Luen Estate Wing Cheong Est. Shek Kip Mei Estate	04 Ching Ho Estate Choi Fook Estate	05
06	07 Lower Ngau Tau Kok Estate Sau Mau Ping South Estate	08 Tung Wui Estate Kwai Chung Estate Choi Tak Estate	09 Kai Ching Estate	10 Un Chau Estate	11	12 Un Chau Estate* Kwai Luen Estate* * Vacant flat
13	14	15	16	17 Yee Ming Estate Kai Ching Estate* Un Chau Estate* Kwai Luen Estate*	18	19
20	21	22 Shui Chuen O Est.	23	24	25	26

Figure IV-1 Calendar for HKUST field sampling program.

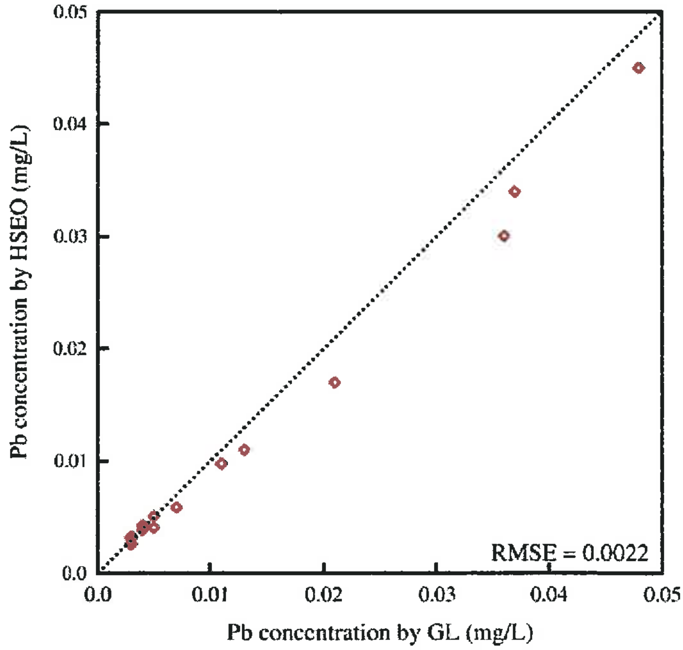


Figure IV-2 Cross checking of lead concentration analyzed by Government Laboratory (GL) and HKUST HSEO Lab.

APPENDIX V

Sampling Protocol
(3 Vacant Flats)

Special sampling surveys were also conducted in 3 vacant flats of three estates. Two sampling taps were installed: (i) at the water meter position inside the meter room; and (ii) at the location of pipe entry inside the flat. The kitchen and wash basin taps were flushed by HD staff for 5 min the day before. Samples were taken at the sampling and kitchen taps (Figure V-1). The vacant flat sampling was carried out by one sampling team. The pipe configuration of each flat was also measured on site for further analysis.

Vacant flats:

- Room 1813, Un Nga House, Un Chau Estate
- Room 3607, Luen Yat House, Kwai Luen Estate
- Room 2221, Mun Ching House, Kai Ching Estate

Sampling dates and estates sampled:

- 12 Dec 2015 (Sat), 10:00-15:00, Un Chau, Kwai Luen
- 17 Dec 2015 (Thu), 9:30-13:30, Kai Ching, Un Chau, Kwai Luen

Sampling procedure:

1. One 250 mL sample was collected at the meter room tap.
2. One 250 mL sample was collected at the tap at the entry of the water supply pipe to the flat.
3. The first sample (250 mL) at the kitchen tap was collected when the tap was opened. The tap remained fully open throughout the sampling.
4. The second, third, fourth, fifth and sixth samples (50 mL each) were collected at t = 30, 60, 120, 180 and 300 seconds at the kitchen tap.
5. The kitchen tap flow rate was measured using 1 L bottle and measuring cylinder.

6. After the flow rate measurement (which took around 5 minutes), one 250 mL sample was collected again at the meter room tap.

7. One 250 mL sample was again collected at the tap at the pipe entry to the flat.

8. After around 3 hours, the vacant flat was revisited and steps 1-7 were carried out again to collect one more set of samples (except for the second day of sampling for Un Chau Estate and Kwai Luen Estate vacant flats).

After the sampling, the samples were transported back to HKUST. All apparatus and log sheets were returned. All samples were preserved and logged in by HSEO Lab and then selected samples sent to the GL for analysis. A total of 80 samples were collected for vacant flats; 40 samples were analyzed by HSEO Lab and 40 by GL.

(a) (b) (c)

Figure V-1 Sampling at (a) installed tap in meter position; (b) tap at the water supply pipe entry to flat; and (c) kitchen tap.

APPENDIX VI

Summary on Computational Fluid Dynamics (CFD) Modelling

A three-dimensional (3D) unsteady computational fluid dynamics (CFD) model is used for investigating the accumulation of dissolved lead in stagnation and its mixing and transport in flowing condition.

Stagnant condition

In stagnant condition, the leaching of lead from the pipe wall and fixture surface into the water is governed by molecular diffusion. It is assumed that immediately adjacent to the pipe wall, the dissolved lead concentration is in the maximum equilibrium condition (Kuch and Wagner, 1983; Van der Leer et al, 2002). The three-dimensional diffusion process in the water supply chain can be described by a Fickian diffusion equation:

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

where $C(x,y,z,t)$ is the lead concentration in water; (x,y,z) are the spatial coordinates; t is the time; D is the molecular diffusivity of lead in water, taken as 10^{-9} m2/s (Kuch and Wagner, 1983; Van der Leer et al, 2002). At the location immediately adjacent to the pipe surface, a fixed lead concentration C_{eq} is prescribed as the equilibrium concentration. In this formulation, the leaching rate of lead is not a constant but decreasing with time as the water becomes more saturated with lead. In the absence of any better information, the equilibrium lead concentration for a given pipe joint or component is taken to be the measured maximum lead concentration determined in the 24-hour leaching test for a corresponding component for the vacant flat on 33/F, Luen Yat House, Kwai Luen Estate (WSD Task Force Report).

Flowing condition

With the water tap turned on, it is assumed that the flow in the relatively short water supply chain (in the order of 15-30 m) attains steady state condition immediately after the tap is open. The dissolved lead accumulated during the stagnation period will then be transported by the turbulent pipe flow to the open tap. Besides being transported by the flow, the lead will be mixed over the cross-section by the turbulence in the flow; the lead cloud will also disperse longitudinally due to transverse velocity shear. The mixing and transport of dissolved lead in the steady pipe flow is governed by the advective-diffusion equation:

$$\frac{\partial C}{\partial t}+\frac{\partial(uC)}{\partial x}+\frac{\partial(vC)}{\partial y}+\frac{\partial(wC)}{\partial z}=\frac{\partial}{\partial x}\left(E_T\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(E_T\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(E_T\frac{\partial C}{\partial z}\right)+S$$

where $C(x,y,z,t)$ is the lead concentration in water; $[u,v,w]$ (x,y,z) is the velocity field and E_T is the turbulent diffusivity determined by a two-equation turbulence model (k-ε model). E_T is typically in the order of 10^{-2}-10^{-3} m^2/s. Lead leaching rates at different locations along the water supply chain (corresponding to different pipe joints and sections) are prescribed as mass sources S - defined as the leaching rate of lead per unit pipe wall surface area. S is taken as the measured lead leaching rate from 24-hour leaching tests for the flat on 33/F, Luen Yat House, Kwai Luen Estate (WSD Task Force Report). This modelling methodology for predicting lead distribution in the stagnant fluid and moving flow is similar to the approaches of Kuch and Wagner (1983) and Van der Leer et al (2002). The present method represents however a significant advance over the 1D modelling adopted in the earlier works, as 3D modelling allows a more accurate depiction of the complex flow and solute transport in the water supply chain pipe network.

Numerical solution

The solution of the above governing equations was obtained numerically using the FLUENT 3D CFD code. Key information of the water supply chain of the three vacant flats studied is given in Table VI-1. The model grid is generated based on the actual pipe system geometry directly measured on-site. The pipe section between the downpipe and the kitchen tap for a typical flat is studied, excluding less important details such as the branches to other flats, and branches to washroom, and heaters (see **Figure 2 of Appendix II** for the vacant flat in Un Chau Estate). Mixed tetrahedral and hexagonal grid cells are used to fit the boundary of various components (elbow, tees) in the system, with minimum grid cell size of about 1 mm (**Figure 4, Appendix II**). Meters, valves are modelled similar to a short pipe section of 5 cm; the lead leaching rate/equilibrium concentration (based on WSD measurements) is prescribed at the pipe wall. For a typical water supply chain of a Public Rental Housing (PRH) estate flat, 800,000 to 1,000,000 grid cells are used.

For stagnant condition, zero velocity is prescribed in the whole pipe system. For flowing condition, a steady-state solution of the velocity field is first predicted with the total flow rate prescribed at the inflow boundary and zero-pressure at the open kitchen tap. The computed 3D velocity field in the pipe system is then used for predicting the lead transport. The time step for the molecular diffusion computation is 20 s, while that for transport in flowing water is 0.02 s.

Stagnation Test

The data from stagnation test by WSD Task Force is used for calibration of the leaching rate and equilibrium concentration of the components in the water supply chain. Three vacant flats and one management office in Kai Ching Estate and Kwai Luen Estate were used for the test on stagnation and flushing. The stagnation test was conducted by first thoroughly flushing the water supply chain for 15 hours. Water then remained stagnant in the water supply chain and water samples were taken at 0, 1, 2, 3, 4, 6, 8, 24 and 48 hours for determining the lead contents. The numerical prediction is carried out in a similar way for the vacant flat at Room 3607, Luen Yat House, Kwai Luen Estate. **Figure 5 of Appendix II** shows the molecular diffusion of lead at a pipe socket at different times after stagnation. It can be seen that the dissolved lead concentration gradually builds up by molecular diffusion, and fills up the cross-section. Considering the limited available data and the complexity of the problem, the predicted lead concentration is in good agreement with data – the increasing concentration with stagnation time is well predicted (**Figure 8(a) of Appendix II**).

Flushing test

Flushing test is carried out after a certain period of stagnation to determine the variation pattern of lead concentration at the consumer tap after the tap is opened. In the investigation carried out by the WSD Task Force, flushing test was carried out immediately after 48 hours of stagnation test and samples were taken at 1, 2, 3, 4, 5, 10 and 30 minutes to determine the lead content. In this numerical study, the flushing test was carried out after around 4 and 18 hours of stagnation. Samples were taken at the time when the tap was opened, and after 30 s, 60 s, 120 s, 180 s and 300 s. The flushing tests were simulated numerically; the predicted lead concentration variation with time is compared with the measured data for Kwai Luen Estate vacant flat. The result shows that during the course of flushing, the lead concentration can vary greatly due to local accumulation of dissolved lead at the elbows, joints and pipe fixtures. However, the lead concentration in general drops to a very low level after 30 – 60 seconds; this is supported by both data of this study and the WSD Task Force Report (**Figure 8(b) and Figure 9 of Appendix II**).

References

Kuch, A. and Wagner, I. (1983). A mass transfer model to describe lead concentrations in drinking water. *Water Research*, 17(10), 1303-1307.

Van der Leer, D., Weatherill, N.P., Sharp, R.J. and Hayes, C.R. (2002) Modelling the diffusion of lead into drinking water. *Applied Mathematical Modelling*, 26, 681-699.

Table VI-1 General Information about the drinking water supply chain from the downpipe in meter room to the kitchen tap in the vacant flats for this study

	Room 1813, Un Chau Estate, Un Nga House	**Room 3607, Kwai Luen Estate, Luen Yat House**	**Room 2221, Kai Ching Estate, Mun Ching House**
Total length of pipe (m)	14	17	29
No. of bends	8	10	19
No. of tees	5	6	6
Measured flow rate (L/s)	0.25	0.35	0.27

* The pipe from the corridor first enters the kitchen for Un Chau Estate vacant flat. The pipe first enters the toilet for vacant flats in Kwai Luen and Kai Ching Estates.
** Meter room located at end of corridor for Un Chau and Kwai Luen Estate vacant flats. Meter room located at lift lobby for Kai Ching Estate vacant flat.