nyrstar
Resources for a changing world

Appendix L:

Environment and health feasibility study - Port Pirie Smelter Transformation

Environment and Health Working Party – Nyrstar Port Pirie Transformation Project

Environment and Health Feasibility Study – Port Pirie Smelter Transformation

Prepared by:
Rob Thomas (SA Government)
Mark Hibberd (CSIRO)
Andrew Gilbert (Nyrstar)
Kevin Buckett (SA Health)

5 July 2013

Contributors:
David Simon (SA Health)
Matt Howell (Nyrstar)
Michael R Moore (ACTRA)

TABLE OF CONTENTS

GLOSSARY

ACTRA	Australasian College of Toxicology and Risk Assessment
ADHD	Attention deficit hyperactivity disorder
APb	Air lead (concentration, i.e. the concentration of lead particulates in the air, units – micrograms per cubic metre (µg/m^3)
BPb	Blood lead level, units – micrograms per decilitre (µg/dL)
BAT	Best available technology
BATEA	Best available technology economically achievable
BLL	Blood lead level, units – micrograms per decilitre (µg/dL)
CAPEX	Capital expenditure
CDC	Centers for Disease Control and Prevention (USA)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Cu	Copper
EBS	Enclosed Bath Smelting
EHWP	Environment and Health Working Party (of the Nyrstar Port Pirie Transformation Project)
EIP	Environmental Improvement Program
ESP	Electrostatic precipitator
IQ	Intelligent quotient
ISASMELT	a bath smelting process with a submerged combustion lance, developed jointly by Mount Isa Mines and CSIRO
KIVCET	a type of flash-smelting furnace developed in the former USSR. The name is a Russian acronym for ‘flash-cyclone-oxygen-electric-smelting’
NEPM	National Environmental Protection Measure
NHANES	National Health and Nutrition Examination Survey

NHMRC	National Health and Medical Research Council
NTP	National Toxicology Program (USA)
ODTF	Olympic Dam Task Force
Pb	Lead
$Pb_{24\text{-hr}}$	Air lead average concentrations averaged over 24 hours
PM_{10}	Particulate matter in the atmosphere that has an aerodynamic diameter of 10 µm (micrometres) or less
QSL	a direct smelting technology. The name is an acronym for the developers Queneau, Schuhmann, and the company Lurgi
SES	Socio-economic status
SKM	Sinclair Knight Merz, an engineering consulting company
SKS	an enclosed bath smelting technology, an acronym for the Shuikoushan company that developed the process
TEOM	Tapered Element Oscillating Microbalance (instrument for measuring particulate mass)
THEC	Trail Health and Environment Committee
TSL	Top submerged lance
TSP	Total suspended particles
WHB	Waste heat boiler
WHO	World Health Organisation
Zn	Zinc

1. INTRODUCTION

Nyrstar Port Pirie has been directed by the EPA to reduce lead emissions from its smelter. EPA requires Nyrstar to submit an Investigative Environment Improvement Program (EIP). The program requires Nyrstar to conduct a number of investigations, the most important of which (due 31 March 2013) is to provide a report on lead reduction options, including identification, feasibility assessment, technical assessment, economic assessment and determination of best available technology economically achievable (BATEA).

Nyrstar recognised that it does not have the capacity to undertake this program with its own resources and approached the State Government to provide assistance. A Joint Steering Committee was formed and a number of subcommittees, including the Environment & Health Working Party (EHWP), were established to provide specialist advice.

The EHWP is led by A/Prof Rob Thomas (ODTF) and Matt Howell (Nyrstar) and includes Dr Mark Hibberd (CSIRO), Andrew Gilbert (Internal Nyrstar Environmental Consultant) and Dr Kevin Buckett (SA Health). Professor Michael R. Moore (Australasian College of Toxicology and Risk Assessment) was contracted by the Working Party, and Dr David Simon (SA Health) has contributed to the report.

The Steering Committee requested that the EHWP provided advice on:

- Evaluation of the likely sources of smelter emissions;
- The capability of alternative smelting technologies to reduce the emissions;
- The likely outcomes for air lead and blood lead;
- Evaluation of the adequacy of these outcomes for protection of children of Port Pirie; and
- Recommendations on the best strategy for future protection of children.

While most of this advice will also be required for the Investigative EIP, the Steering Committee requested that it be provided, at least in preliminary form, by October/November 2012. This would enable the Steering Committee parties to determine whether the project was technically and environmentally viable and whether they should go ahead with in-principle support for investment and move to the next stage of feasibility investigation.

This request was made by the Steering Committee in August 2012 leaving the EHWP only three months to prepare its report. Obviously with such a short time-frame it was not possible to conduct detailed investigations. Normally an investigation of this complexity would take 12 to 18 months and so an alternative approach had to be developed. Fortunately some relevant investigations (commissioned by Nyrstar) were already underway and the EHWP has been able to make use of these. This includes the investigation of the major lead sources by CSIRO using pollution backtracking (Hibberd 2012).

However, in the absence of a comprehensive emission inventory and the complexity of the relationship between air lead and blood lead, this report by the EHWP relies largely on analysis of available data, observations of experience from overseas smelters, and expert judgement to develop its findings and recommendations.

Consequently, while the EHWP considers that the information is accurate enough for the Steering Committee to make its in-principle decision, it is envisaged that the analysis and predictions presented in this report will be refined during the feasibility study following the in-principle decision.

2. LEAD SOURCES

This section starts with a brief background of the smelter at Port Pirie, before giving an overview of the main smelter sources, and then summarising key findings from a backtracking study that identified the main smelter sources of Port Pirie's air lead using air quality and meteorological data.

2.1 SITE HISTORY

Located on the eastern shore of Spencer Gulf in South Australia, approximately 230 km north of Adelaide, the Port Pirie smelter has been in constant operation for more than 120 years. There is an adjacent dedicated port facility where concentrates are received, with final products dispatched by road and rail.

The Nyrstar Port Pirie site is one of the world's largest primary lead smelting facilities and the third largest silver producer. The plant is an integrated multi-metals recovery facility with the flexibility to process a wide range of lead rich concentrates and smelting industry by-products. The Port Pirie operation incorporates a lead smelter and refinery, a precious metals refinery, a copper plant and a zinc plant. It produces a range of metals including 195,000 tonnes of lead, 30,000 tonnes of zinc, 4,000 tonnes of copper, 18,500,000 troy ounces of silver and 36,000 troy ounces of gold per annum.

The Port Pirie site has a number of current challenges as it is a very old site that has been in constant operation for over 120 years. It utilises largely old sintering technology which generates airborne emissions. There is a constant focus on reducing emissions and raising environmental awareness through training and changed work practices to help create greater ownership by employees. Elevated blood lead levels in children in the Port Pirie community have been a long standing issue. The most recent action on the issue commenced in 2005, when Nyrstar (at that time Zinifex) approached several key stakeholders – the SA Department of Health, the Port Pirie Regional Council, and the Environment Protection Authority to propose a unique way of addressing the issue. The idea involved key partners joining together to work collectively to achieve the required reduction in lead levels in children under 4 years of age, the age group most at risk of lead exposure. The 'Ten by 10' program commenced in 2005. From 2011 the name changed to 'Ten for Them', with a focus on reducing blood lead levels in children to as low as possible.

2.2 OVERVIEW OF SMELTER SOURCES

In 1999, a basic fugitive particulate emissions study was carried out by Sinclair Knight Merz (SKM 1999). This study consisted of a quantitative assessment of the emissions from the Sinter Plant, Blast Furnace, Slag Fumer, and KDR area. Air dispersion modelling was then used to determine offsite impacts and estimate the contribution from the various sources. The results of this study were used to determine the actual tonnages of lead and other metals emitted by source from the smelter and also the relative contributions to concentrations at particular receptors. The combined effects of the meteorology, the source characteristics, and their locations relative to the receptor affect their relative contributions at the receptor compared with the relative source emission strengths.

Since this time, significant emissions reduction work has been carried out to reduce emissions from the Blast Furnace. The basis of this has been the installation of a Blast Furnace Top Enclosure and associated fume capture system. It is estimated that this improvement has reduced the Blast Furnace Top emissions by about 75%. Based on this improvement since the SKM study and NPI estimates showing that other point and area sources contribute about 20% of the total lead emissions, it is estimated that the contributions to Port Pirie air lead are currently approximately 50% from the Sinter Plant and Blast Furnace and approximately 30% from the Slag Fumer.

Since 2005, Nyrstar has made a significant commitment to the community through the ‘Ten by 10’ and ‘Ten for Them’ programs. Approximately $50 M has been spent on site and in the community on emission reduction and exposure reduction initiatives, as part of these programs.

It is important to note that with the replacement of the Sinter Plant planned as the major capital expenditure of the Transformation Project, the Blast Furnace feed quality will improve significantly, and the demands on the smelting draughting/baghouse system will be significantly reduced. As a result, it is expected that the Blast Furnace will operate with fewer plant-upset conditions (and hence reduce the potential for emissions) and will make use of the improved availability of the draughting system. It is also important to note that the Sinter Plant throughput of materials is of the order of one million tonnes per annum, and of that, approximately 50% is in constant recycle being transported to and from the pit. This means that much of the intermediates material handling and storage on the Port Pirie smelting site (and thus sources of lead dust) is as a direct consequence of this single unit metallurgical process.

For these reasons, it is considered that the Sinter Plant and the associated activities account for the main proportion of lead emissions from the site and that the Transformation Project will lead to reductions of more than 50% in lead dust emissions from the smelter site.

2.3 MAIN SMELTER SOURCES OF AIR LEAD

A study by CSIRO (Hibberd 2012) used pollution roses and backtracking analysis to identify the region of the smelter most likely to contain the sources responsible for the majority of days with high air lead concentrations in Port Pirie. As shown below, the region identified was that occupied by the sinter plant and blast furnace.

Figure 1 shows the Port Pirie wind rose[1] from the well-sited Boat Ramp wind sensor for the four years from 1 November 2007 to 31 October 2011. Most of the winds are from the south-south-east and north-north-west, with less frequent winds from the south-south-west, and very few winds from the north-east sector. There was little year-to-year variation in the wind roses during this four year period.

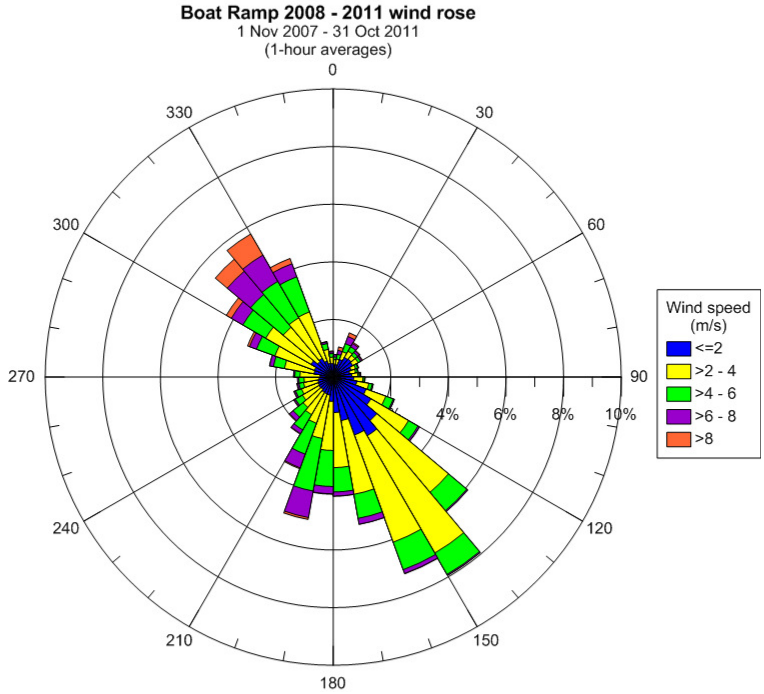

Figure 1. Port Pirie wind rose as measured at the Boat Ramp site for the four years from 2007 – 2011. Note that a recent check (Dec 2012) of the alignment of the wind sensor indicated that a correction of +3° needs to be applied to these wind directions.

---

[1] A wind rose shows the frequency of winds plotted by wind direction, with colour bands showing wind ranges. The length of each band is proportional to the frequency of wind from that direction.

Figure 2 shows the locations of the high volume air samplers in Port Pirie, which measure 24-hour average air lead concentrations each day. Continuous 10-minute average PM_{10} measurements[2] using a TEOM instrument[3] are also made at several sites – Dental Clinic, Boat Ramp, and the Terrace.

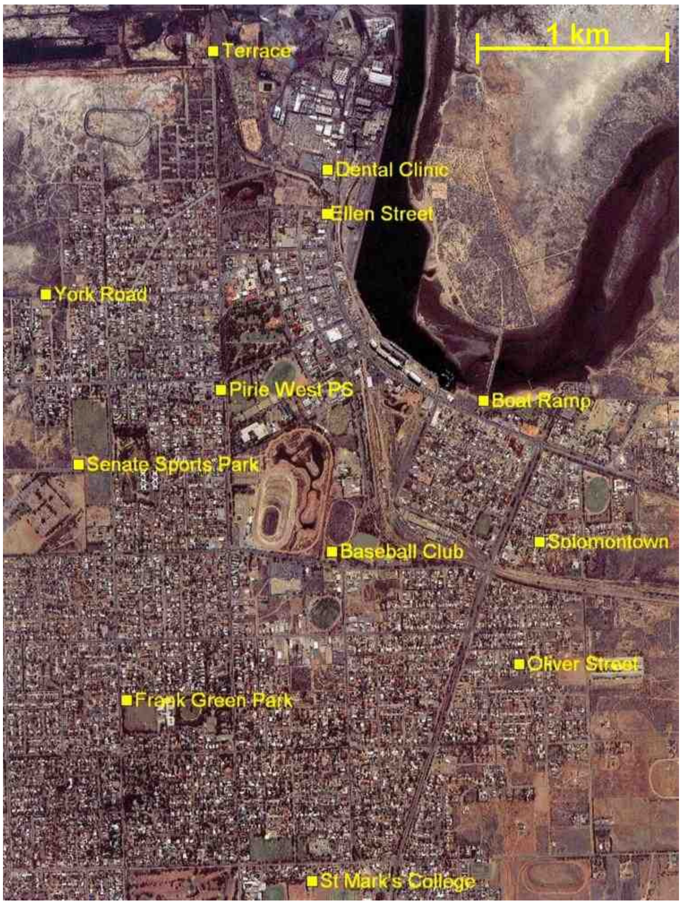

Figure 2. Location of the high volume air samplers in Port Pirie. The Nyrstar smelter is located north of the Dental Clinic site.

---

[2] PM10 is particulate matter in the atmosphere that has an aerodynamic diameter of 10 µm (micrometres) or less. It is one of the six criteria pollutants for which there are national standards in Australia (see www.environment.gov.au/atmosphere/airquality/publications/standards.html

[3] A Tapered Element Oscillating Microbalance, an instrument for measuring particulate mass.

In the same way that a wind rose depicts the distribution of wind speeds at each wind direction, a pollution rose depicts the distribution of pollution concentrations at each wind direction. It is an easily understood means of showing which wind directions are associated with the highest pollution concentrations. Pollution roses were generated from data at the Dental Clinic and Boat Ramp sites because lead, wind and PM_{10} data were available from these sites and the lead concentrations were well above detection thresholds. These two sites also provided the best opportunity for triangulation to pinpoint the lead sources.

The pollution roses were generated from data on high air lead days (defined here as 24-hour average lead concentrations $Pb_{24\text{-hr}} > 10$ µg/m^3 at the Dental Clinic and $Pb_{24\text{-hr}} > 2$ µg/m^3 at the Boat Ramp) using 1-hour average PM_{10} data as a surrogate for relative lead concentrations (see (Hibberd 2012) for more details). The pollution roses include data from approximately 10% of days over the four year period 2008-2011. The Dental Clinic pollution rose (Figure 3) shows that on high lead days, almost two-thirds of the high PM_{10} concentrations (yellow and red, >50 µg/m^3) occur for wind directions between north and north-easterly, pointing to the main sources being in this octant.

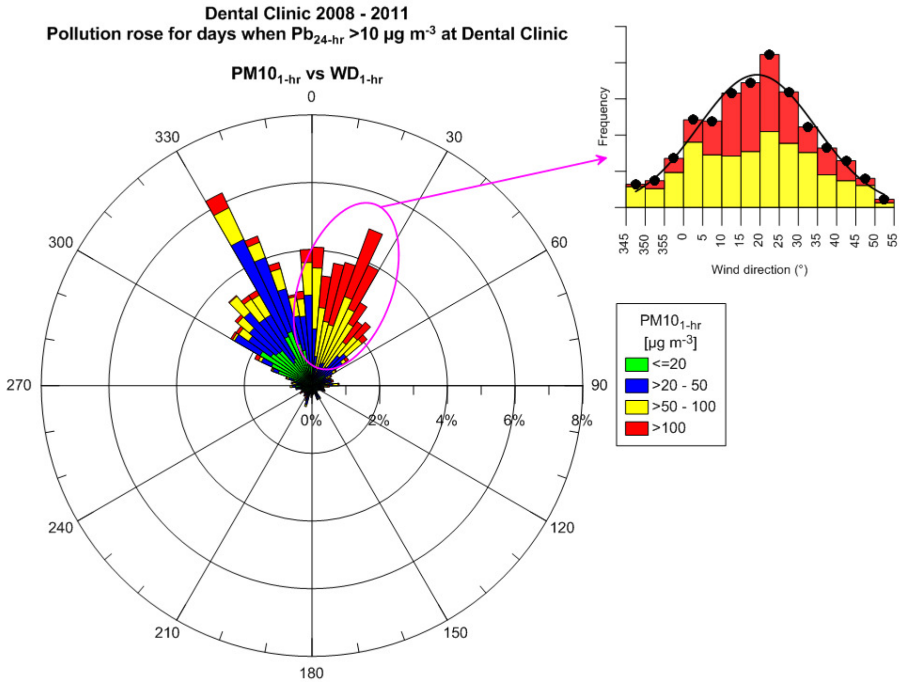

Figure 3. Pollution rose at Dental Clinic of 1-hour average Pb concentrations versus 1-hour average wind direction for days when $Pb_{24\text{-hr}} > 10$ µg/m^3. Note that a recent check (Dec 2012) of the alignment of the Dental Clinic wind sensor shows that a correction of +8° needs to be applied to these wind directions.

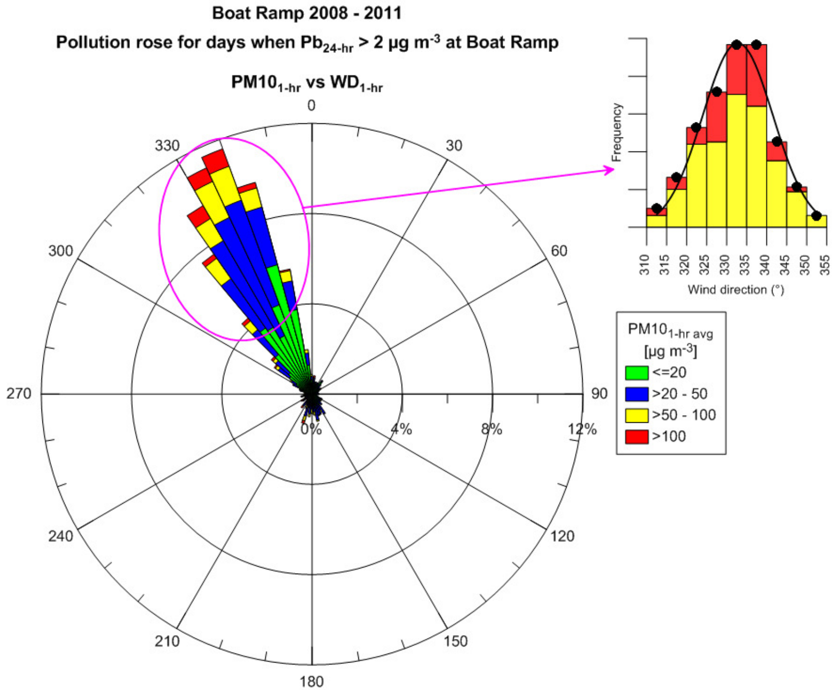

Figure 4. Pollution rose at Boat Ramp of 1-hour average Pb concentrations versus 1-hour average wind direction for days when $Pb_{24\text{-hr}}$ > 2 µg/m^3. Note that a recent check (Dec 2012) of the alignment of the Boat Ramp wind sensor show, shows that a correction of +3° needs to be applied to these wind directions.

An extract of these data plotted at the top right-hand side of the figure shows the peak at 22.5 ° and with the other data well fitted by a Gaussian distribution with the highest values between 10 ° and 30 °**.** By comparison, at the Boat Ramp site, Figure 4 shows a strong clustering of the data on high lead days at wind directions around the wind direction of 335° with the highest values between 330° and 340°.

The main wind directions corresponding to high PM_{10} concentrations on high air lead days are shown overlaid on a map of Port Pirie in Figure 5. (Note that the wind direction corrections noted in the captions to Figure 3 and Figure 4 have been applied in Figure 5.) The intersection of the lines pinpoints the main emission sources as being in the immediate vicinity of the Sinter Plant. This result confirms the conclusion of Section 2.2 that the Sinter Plant (and associated activities) is the dominant source compared to the Slag Fumer and Pit areas.

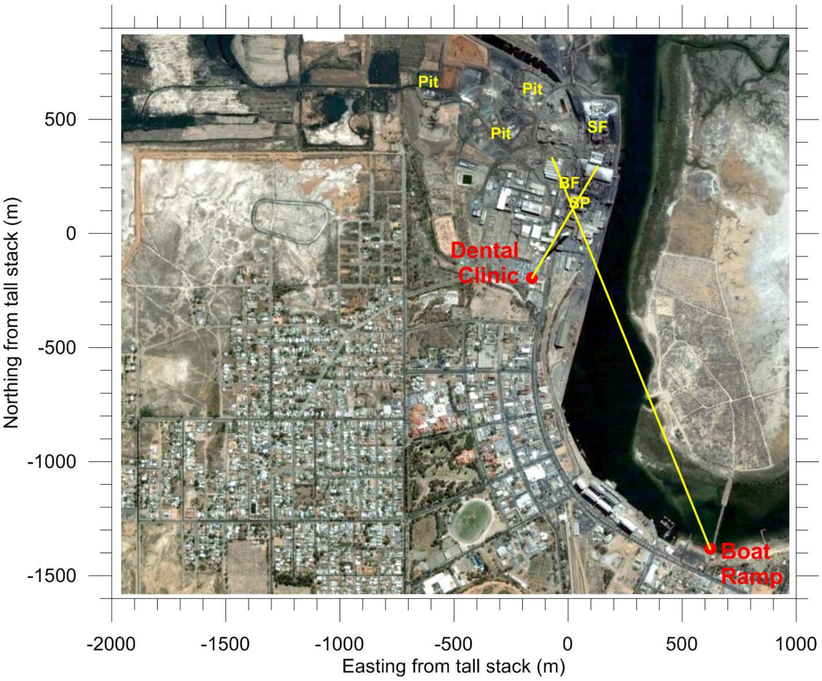

Figure 5. Map of Port Pirie and the smelter showing the principal wind directions identified in pollution roses from Dental Clinic and Boat Ramp (previous figures) as being associated with high PM_{10} concentrations on high air lead days. The intersection of the yellow lines pinpoints the main sources as being in the vicinity of the Sinter Plant (SP) and Blast Furnace (BF). This analysis shows that these are the dominant sources compared to the Slag Fumer (SF) and the Pit areas. Note that the wind direction corrections described in the captions for Figure 3 and Figure 4 have been applied here.

3. SOLUTION FOR REDUCING EMISSIONS

3.1 TECHNOLOGY TRANSFORMATION

The key premise of the Port Pirie redevelopment project is to replace the aged sinter plant with modern enclosed bath smelting technology, thereby eliminating the major source of fine oxide and other Pb-based emissions to air. The updraught sinter machine was commissioned in 1956 and although considered best available technology at that time, this no longer the case. Updraught sintering involves a high temperature, pressure forced process, coupled with a suction of Pb laden off gasses to gas cleaning and sulphur capture. The plant consists of numerous open conveyors and dry crushing rolls that give rise to substantial fugitive dust sources due to the physical inability to draft all process stages. The process itself uses approximately 50% recycled materials (predominately sinter), which is comprised chiefly of Pb oxides. As a consequence, the numerous dry handled materials over a geographically large footprint, combined with a high temperature process that is inherently difficult to control, lead to it being the largest source of Pb in air emissions from the site. Section 2.3 summarises the key findings of a separate report by CSIRO (Hibberd 2012), which confirms the source apportionment conclusions summarised above.

A secondary but important source of emissions arises from the blast furnace when treating off-grade or cold sinter. As sinter physically degrades with time and loses its mechanical properties, the blast furnace performance also erodes, leading to characteristic emission events ('furnace blowholes'). These events result in localised high intensity gas eruptions from the main furnace charge and are difficult to fully capture, despite the ventilation hood fitted over the furnace structure. A move away from sinter to a uniform slag, consistent in physical and chemical properties is expected to translate into consistent blast furnace operating performance, thereby reducing or eliminating the blowhole characteristics. Finally, replacement of the aged sinter plant with modern enclosed bath smelting technology (EBS) will reduce the volume of blast furnace feed, since a proportion of the EBS output is lead bullion, which bypasses the blast furnace. As a result, the blast furnace operational intensity will be moderated, further improving process stability and fume capture.

Other sources of Pb materials that contribute to the Pb in air profile include the secondary materials handling area 'the pit', the slag fuming plant and concentrate handling system. It must be noted that the bioavailability of each material is heavily dependent on chemical composition and particle size, with very fine oxides being most bioavailable and coarse sulphide concentrates being least bioavailable.

3.2 ENCLOSED BATH SMELTING – PROCESS REVIEW AND COMPARISON

The essential feature of enclosed bath smelting (EBS) processes is that the smelting reactions are performed in the molten state within an enclosed vessel. The input and output ports of the vessel, required to enable addition of raw materials and reagents and removal of molten and gaseous products, are sealed and/or 'protected' in a manner such that emissions are small in quantity and are controlled. This is achieved by maintaining negative pressure in the vessel with the gas offtake treated to remove pollutants. Similarly, changes of injection devices (lances or tuyeres) during operation must be able to be performed in such a manner that emissions are minimised and controlled during the change-over period.

Globally, most lead is smelted using the well established sintering – blast furnace route. Enclosed bath smelting technologies that have been applied on a commercial scale to primary lead smelting are KIVCET, QSL, Top Submerged Lance smelting (TSL), both Outotec® Ausmelt and ISASMELT variants, and SKS. SKS is the most recent development (early 2000s). Globally, at present there is one smelter using the Kaldo[4] process (Boliden in Sweden), two smelters using KIVCET technology (Canada and China), two using QSL technology (Germany and Korea), one using ISASMELT (Belgium) and one using Ausmelt technology (both in China), and fifteen using SKS technologies (1 in Mongolia, 14 in China), with a further fifteen under construction (1 in Mongolia, 1 in India, 13 in China).

The QSL and KIVCET processes combine the oxidation and reduction stages in the one vessel. The TSL and SKS processes require two vessels with a transfer of molten or solid slag between them. In the QSL process, premixed charge is fed from conveyor belts through feed ports into the horizontal, cylindrical reactor. Oxygen is blown through tuyeres at the bottom of the reactor. Due to the slight inclination, the lead bullion flows to the front end of the oxidation zone and primary slag, containing residual lead oxide, flows counter-currently into the reduction zone where pulverised coal is added to reduce the lead oxide in the slag to metallic lead which then flows back to the oxidation zone. The vessel can be rotated through about 90° to lift the tuyers clear of the slag for tuyere maintenance or replacement.

In the KIVCET process, lead sulphide in the concentrate is converted to lead oxide in the flash smelting shaft and a mixture of lead-zinc-iron oxides and flux agents form a semi-fused slag which collects under a layer of coarse coke below the smelting shaft. As this coke sinks through the slag, the lead oxide is reduced to lead bullion. This mixture of bullion and slag then flows under a separation wall from the first compartment into the second compartment where heat is applied by means of carbon electrodes. With additional retention time, the slag separates from the bullion to

---

[4] The Kaldo process is a batch process, and is mainly used for treating secondary lead materials.

form two layers. From this compartment, slag is tapped to the slag furnace and bullion is tapped for transfer to the Pb refinery.

In the Outotec® Ausmelt and ISASMELT processes, air, oxygen and fuel/reductant (typically pulverised coal) are injected into the molten slag bath contained in a vertically mounted, cylindrical reactor, by means of a vertically suspended lance. Oxygen enrichment may be used to reduce off-gas volumes and minimise fuel requirements. The Outotec® Ausmelt lead process may include smelting, slag reduction and fuming stages; however, the fuming stage is only necessary if zinc recovery is required. For smaller scale projects each stage (smelt, slag reduction and fuming if necessary) can be conducted as a batch process in a single furnace. To increase production, two furnaces, one performing oxidation and the other reduction, can be employed. Where it has been employed on a large scale, the ISASMELT process has been configured with a single vessel oxidation process operating continuously to produce a molten high lead slag which is tapped, cast and fed as lump to a blast furnace as a replacement for lead sinter.

The SKS process has some similarities to the QSL process in that the reactor is a horizontal, cylindrical vessel with bottom tuyeres. However, as with the Outotec® Ausmelt and ISASMELT processes, the oxidation and a reduction stages are performed in separate reactors. The reduction stage can be performed in a blast furnace, using solidified, lumpy the slag from the oxidation stage, or it can be performed in second bottom-blown reactor (with electrical heating by electrodes) by directly transferring the molten slag from the first stage.

Like the other processes, the SKS reactor is a closed vessel, except for the ports provided for feeding raw materials and the gas offtake for removing gaseous products. It is a bath smelting process which involves injection of gases (and solid particles) into a molten bath to produce conditions that result in rapid reaction through the high heat and mass transfer rates induced by the turbulent conditions in the bath. Like the other processes (to varying degrees), there is a quiescent zone in the reactor to allow lead bullion and slag to separate into layers so they can be removed separately.

In all the technologies (except KIVCET), the lance or tuyeres need to be replaced periodically. This may range from once every several weeks (e.g., Outotec® Ausmelt and ISASMELT processes) to several months, according to the technology (30 - 60 days has been quoted for the SKS process). In all the technologies, this is possible to perform ‘on-the-run’ by temporarily taking the reactor offline. This involves stopping air/oxygen blowing and feeding of raw materials while the lance/tuyere is replaced without having to empty the reactor of the molten bath. The process can then easily be restarted by recommencing air/oxygen injection and feeding of the raw materials. In the case of the QSL and SKS reactors, the reaction vessel is rotated along its axis to expose the lance/tuyeres above the molten bath to enable them to be replaced while the molten bath is in place while for the Outotec® Ausmelt and ISASMELT processes, the lance is simply raised vertically to remove it from the fixed reaction vessel.

3.3 SEQUENCE OF PROCESS IMPROVEMENTS

The process transformation at Port Pirie involves replacement of the sinter plant and improvements in other sources of Pb-based emissions in a staged process. The general sequence of continuous improvements at Port Pirie is thus:

- Sinter plant replacement with enclosed bath smelting furnace
- Recovery of pit materials, followed by closure and remediation of pit footprint.
- Concentrate handling improvements
- Hygiene air improvements
- Slag fuming improvements - based on pinpointing sources using air lead data

3.3.1 SINTER PLANT REPLACEMENT WITH ENCLOSED BATH SMELTING

The general sequence of improvements commences with replacing the plant with a modern EBS furnace system, complete with BAT (Best Available Technology) fume handling and hygiene ventilation. A mix of concentrates and zinc plant residues (mainly paragoethite from Hobart and lead sulphates from Nyrstar zinc smelters) will be processed in the first stage EBS to produce a Pb bullion and a slag phase. The bullion will be tapped into ladles under controlled conditions and transferred to the existing Pb refinery for purification and casting into finished products. The slag phase will be cast on a conventional straight line casting machine into 'bricks' for charging to the existing blast furnace, where it will be reduced to Pb bullion and a zinc rich slag phase as is currently the case. Slag casting from the EBS furnace will be performed under a ventilation hood to capture any Pb fume that is released while the slag is molten.

The change to EBS eliminates the sinter plant emissions, but also substantially reduces blast furnace emissions through improved process performance and control. Engineering options will be assessed to consider automating the blast furnace feed system, since the slag from the first stage EBS furnace will present a physically lower charge volume than the present sinter feed. Automated blast furnace feed systems are well known in a variety of base and ferrous metals and allow complete enclosure, similar to the EBS system.

3.3.2 RECOVERY OF PIT MATERIALS

The sinter process requires new concentrates and other residues to be thinly coated over particles of existing sinter, before being thermally fused into a solid mass (‘sintered’) in the sinter machine. Consequently, sinter machine feed consists of approximately 50% recycled materials and results in a high circulating load of intermediates. Since there is a physical limit to the proportion of intermediates that can be sintered (non-sulphur bearing feeds have no fuel value), the site requires surge capacity for the range of Pb, Zn and Cu based plant residues that arise in the normal course of operations. Storage is presently in a 30 hectare open area, with materials segregated by origin and generally wetted with sprays or proprietary dust suppressants. Despite these limited controls, wind mobilisation of dusts is an everyday problem. Slurried materials are also tracked via vehicle tyres around roadways and when dried, represent a physically large and persistent source for dust emissions.

The application of EBS technology allows all pit materials to be substantially eliminated. EBS is a 'single pass' system that does not require recycled feed components to carry the new concentrates (unlike the sinter process). As a consequence, it is expected the approximately 20,000 tonnes of intermediate residues currently stored in the pit, including all of the Pb oxide bearing sinter material will be completely consumed within the first full operating year. The closure of the pit will allow for land remediation that will not only eliminate this as a source of wind borne Pb, but also eliminate the source of the slurry material that is carried on vehicle tyres and deposited on the site roadways.

3.3.3 CONCENTRATE AND OTHER FEED HANDLING IMPROVEMENTS

While concentrates are known to be a minor source of Pb emissions on high wind days, the simplified plant layout of an EBS facility will allow a smaller number of conveyor belts used for feed transportation. This lends itself then to simple but effective designs for full enclosure with appropriate hygiene ventilation. Such designs are standard practice in many industries and were observed specifically at the Umicore (Hoboken) and Teck Resources (Trail) multi-metal smelters.

Feed blending is allowed for in the modernised plant design, such that all feed materials are either stored in covered bunkers or metered feed bins with appropriate dust capture.

3.3.4 VENTILATION IMPROVEMENTS

Implementation of EBS relieves a significant load from the existing Pb plant bag house system, since the sinter plant is no longer required to be serviced from this facility. Volume and flow calculations indicate approximately 40% of the existing baghouse capacity will be freed up by decommissioning the sinter plant. This figure includes the volume necessary to fully draught the EBS furnace charge ports, bullion tap and slag tap / casting conveyor. The EBS furnace does not require the large volume draughting required for the sinter plant, since sulphur rich off-gasses are treated via the gas cleaning and acid plant. The smaller volume of hygiene drafting air around the furnace feed ports, slag tap and bullion hearth are minor considerations in terms of overall volume and well within the capabilities of the existing system. Surplus baghouse capacity will be available to reduce and treat fume emissions from other parts of the plant.

3.3.5 SLAG FUMING PROCESS AND EMISSION IMPROVEMENTS

Source apportionment studies using vector determined sampling stations for exclusively capturing slag fuming plant emissions will enable a considered determination of slag fuming emissions on ambient community air lead levels. At present the Boat Ramp and Ellen St sampling stations capture a variety of potential sources. In 2011 a major upgrade of the slag fuming baghouse stack fan and motor was conducted, enabling the baghouse to be operated continuously under negative pressure. Whilst plant data supports the view that this has dramatically reduced emissions from this section of the plant, it is recommended the locations of ambient monitoring stations be reviewed with a view to ensuring specific process plant performance (EBS furnace, blast furnace and slag fuming plant) can be readily and separately identified, such as with a site on the 'island'.

3.4 EMISSIONS CONTROL

In all cases of enclosed bath smelting, there are two distinct gas streams – process off-gases and hygiene air – that are fully captured and cleaned, prior to atmospheric discharge. Systems for gas capture and handling are long established and technically advanced; they pose little technical risk to the upgrade project.

3.4.1 PROCESS OFF-GAS

The primary gas stream is the sulphur rich off-gases produced by the reaction vessel. Comprised of approximately 12-14% sulphur dioxide, this hot gas is first taken through a waste heat boiler (WHB) to produce steam for electricity cogeneration or process heating in hydrometallurgical circuits. The WHB is a fully enclosed system that is occasionally accessed through ports to allow inspection and cleaning whilst on line. Because the WHB is under negative pressure (off-gas is suction drafted through the boiler), fume cannot escape the inspection ports owing to external air ingress. Coarse dust from the WHB falls to the bottom of the boiler chamber and exits via a sealed rotary valve into a sealed screw or other hot conveyer, preventing fugitive discharge.

Following the WHB, off-gas is passed through a cyclone and an electrostatic precipitator (ESP) to remove the last fractions of particulate dust, before being cooled via a quench tower and ducted to a mercury removal circuit and sulphuric acid plant. The tail gas from the sulphuric acid plant is essentially free of Pb particulates, these having been removed well upstream of the catalytic converters. It is not proposed to discuss the operation of the gas cleaning and acid plant as these are industry standard systems with a long established record of acceptable emissions performance with respect to metals.

3.4.2 HYGIENE VENTILATION

The second and larger gas stream is broadly referred to as hygiene ventilation and covers point source draughting to control dust and fume emissions. The mode of action is high volume air suction through an appropriately sized baghouse. The baghouse contains purpose designed microfiltration bags designed to remove sub-micron particle matter from the gas stream, before ventilating the cleaned air to atmosphere. Continuous, real-time gas and particle analysers are used to constantly verify compliance with relevant licence conditions. Such an example is the all stack emission monitoring system at Port Pirie which monitors sulphur dioxide and TSP (total suspended particulates), enabling changes to be detected and responded to. Use of baghouse style air filtration is a well established and technically advanced discipline in common use throughout the industrialised world. Recent advances include the use of Gore-Tex and ceramic filters to enable high temperature filtration and reduce the infrastructure requirements (and hence capital and maintenance costs) upstream of the baghouse.

High volume draughting hoods are designed and fitted at all process interfaces where fume or process gas can escape. Primary point sources are the furnace off-gas interface where this cannot be hard-ducted, together with all raw materials feed ports and slag/bullion offtakes. Secondary sources are molten material handling systems (crucibles, transfer launders, casting systems) and dry raw material transfer points. In general, all conveyers used to transport dry materials are enclosed within a conveyer gallery, such that external weather events have no bearing on material containment.

High volume draughting points create a substantial, but localised negative pressure environment such that abnormal emission events can be fully captured. Perhaps the best illustration of this was the observation by the EHWP of the feeding and lance port of the ISASMELT furnace at Umicore Hoboken. The violent nature of the furnace reactions occasionally leads to ejections of fume and small particles from the top of the furnace. The large volume suction hood fitted around this port enabled visibly rapid and complete fume capture; there was no evidence of fume or dust escaping the system.

4. OBSERVATIONS OF BEST AVAILABLE TECHNOLOGY

In order to understand the likely effects of technology transformation, the EHWP formed a delegation to visit lead smelters that have been upgraded. The delegation included Rob Thomas, Mark Hibberd and Andrew Gilbert. Matt Howell joined the delegation in Europe and Canada.

Ideally the delegation would have arranged to visit smelters operating SKS technology in China. However we were advised that it was unlikely that we would obtain visas and useful environmental data. We therefore made arrangements to visit lead smelters operating in the West – Umicore at Hoboken in Belgium and Teck Resources at Trail in Canada.

Much of the environmental data for both smelters is publicly available however useful interrogation and understanding of the data could only be achieved by face to face discussions. Furthermore, by holding detailed discussions, the environment managers at both smelters were willing to provide the delegation with other information that is not publicly available. The smelter operators were also willing to provide the delegation with some practical verbal advice that they would not normally put in writing.

One of the complications for the EHWP is the comparison of air quality and blood lead data for different smelters. Each smelter has a different climate - Hoboken has a cool and wet climate, Teck has dry summers and snow-bound winters, and Port Pirie has a dry and hot climate. This has an impact on the data and makes direct comparison problematic, in particular if any quantitative analysis is required. Nevertheless, there are common trends that can be observed for each smelter and useful qualitative judgements can be made.

The following observations from the two smelters summarises the data and key observations. These provide critical insight for the EHWP on the likely performance of the Port Pirie smelter, post-transformation.

4.1 UMICORE (HOBOKEN, BELGIUM)

Umicore and its predecessors have been operating in Hoboken since 1887. It is a polymetallic metals smelter and produces a range of metals including lead, nickel, copper, silver, gold, platinum, palladium, rhodium, iridium, ruthenium, indium, selenium, tellurium, bismuth, antimony, tin and germanium. Their products have a broad range of uses including batteries, fuel cells, automotive catalysts, photovoltaic cells, cables, wires, stainless steel, glass industry, flat screens, electronics, and various alloys.

They process around 350,000 tonnes of more than 200 different types of raw materials including both mine concentrates and recycled materials. Recycling is an important part of their business and they recover up to 17 different metals from recycled materials. They have a significant research group and its programs are largely focussed on transforming metals into hi-tech materials. Their business model fits strongly with environmental trends – resource scarcity, electrification of the automobile, more stringent emission control and renewable energy.

The company has a strong focus on closing the loop by securing supply and recycling materials and with the aim of also minimizing environmental impact of their operations.

Figure 6 shows the location of the Umicore smelter in Hoboken, a suburb of Antwerp, Belgium. In 1996 the company made a strategic decision to clean up the pollution from the plant and undertake an ‘extreme makeover’. As part of this investment, they commissioned a new enclosed bath smelting technology, ISASMELT, in 1997.

Figure 6. Location of the Umicore smelter in Hoboken, a suburb of Antwerp. The image shows that there is housing and monitoring sites located immediately adjacent to the smelter. Monitoring site locations from **(VMM 2009)**.

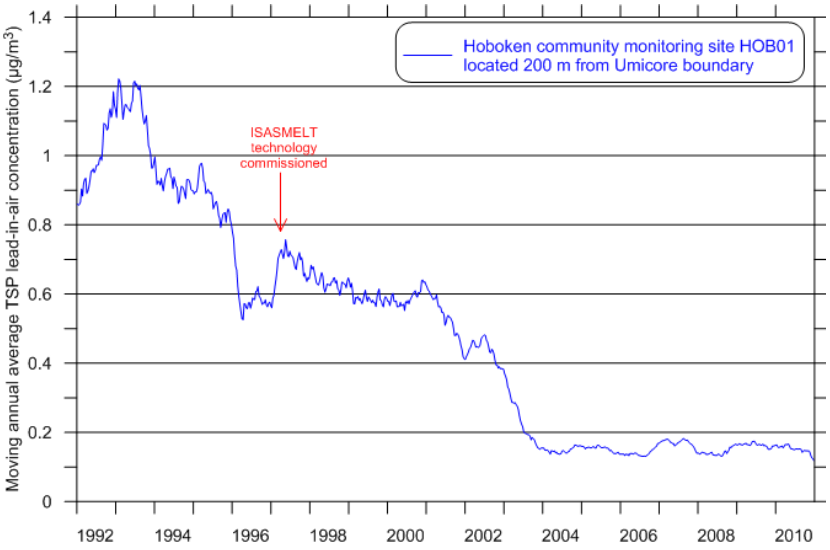

Figure 7. Air lead concentrations at community monitoring site adjacent to Umicore smelter shown as moving annual averages. The ISASMELT technology was commissioned in 1997. Data from **(AirBase 2012)**.

Following the introduction of this plant, air lead quality improved dramatically with a reduction from an annual average of about 1 µg/m^3 before the transformation to about 0.6 µg/m^3 after four years and then with further improvements to a plateau with a range of 0.15 – 0.2 µg/m^3 (Figure 7). This led to a concomitant reduction in the geometric mean[5] of blood lead levels in the surrounding community from an average of 20 µg/dL (for 2-6 year old children) in 1997 to a range of 7 - 10 µg/dL for the period 2007 to 2012 (Figure 8). These data are for the suburb of Moretusburg (in Hoboken), where all houses are between 10 and 650 m from the smelter boundary (Figure 6).

The geometric mean of blood lead level is an important measure of overall population performance, however the blood lead distribution is significantly skewed. This requires another measure, the percentage of children below the health guideline (10 µg/dL) to also be used to assess performance. From Figure 9 it can be seen that this percentage has also increased substantially from 60% (in 2003) to 90-95% in 2011; earlier data was not available.

---

[5] The geometric mean (or geomean) is a measure of the median of data that has a log-normal distribution, which is typically the case for blood lead levels.

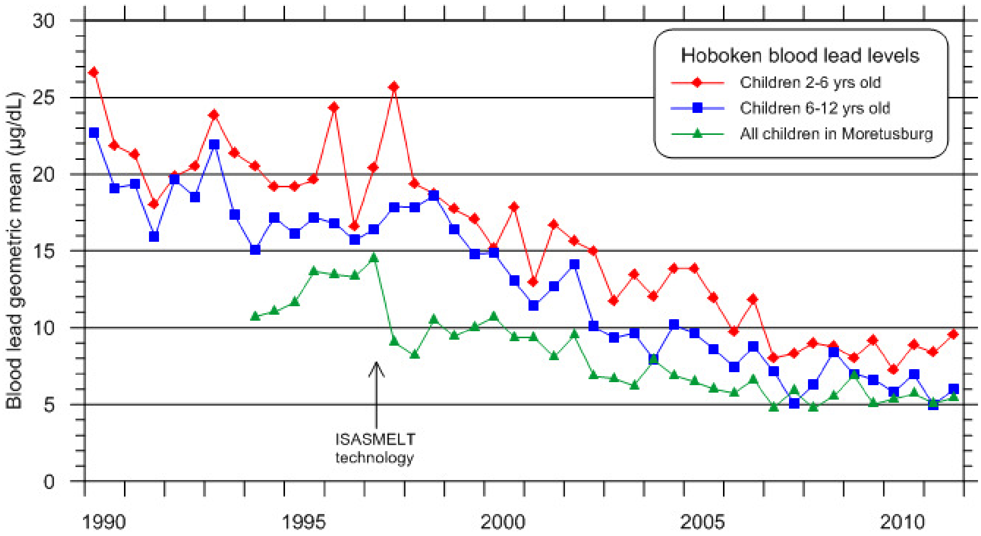

Figure 8. Reduction in geometric mean blood lead levels for age groups of children in Hoboken since the introduction of the new technology at the Umicore smelter. From **(Nelen and Thys 2011)**.

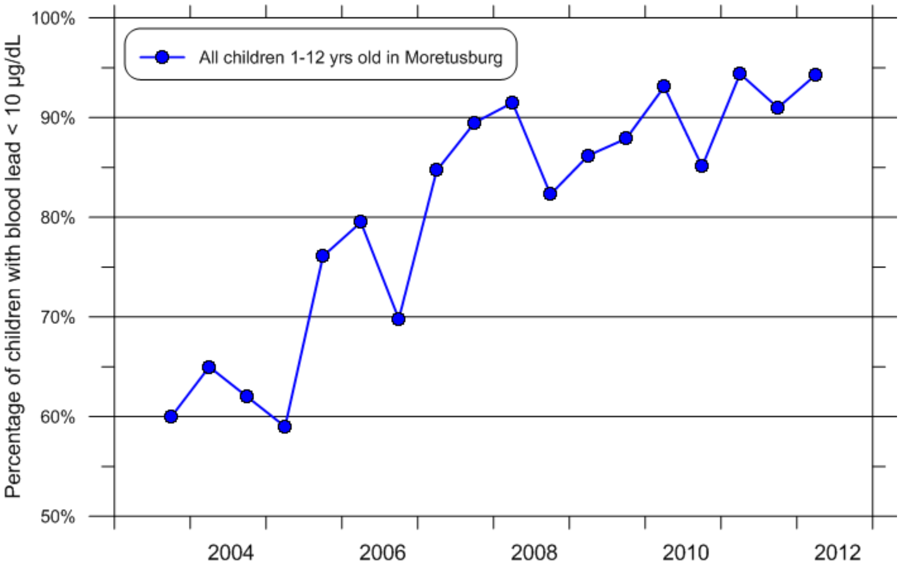

Figure 9. Increase in percentage of all children in Hoboken with blood lead levels below 10 µg/dL since the second half of 2003. Data from **(Nelen 2005-2012)**.

It is important to note that blood lead reduction occurs at a slower pace than air lead reduction. This is because air lead reduction is an immediate process. Blood lead reduction, on the other hand, depends on transfers or losses from tissues like bone into blood before excretion in urine, all of which are time limited.

Another important observation is that similarly to Port Pirie, there is housing close to the smelter, only 10 metres from the boundary. (The nearest housing at Port Pirie is about 200 metres from the boundary of the smelter). The main air monitoring stations in Hoboken are located within the adjacent housing estate (see Figure 6), which is much closer than licence monitoring sites in Port Pirie (Oliver St and Pirie West Primary).

The air lead standard in Europe[6] was set at 0.5 µg/m^3 in January 2005. A transitionary value of 1.0 µg/m^3 was applied in the immediate vicinity of specific, notified industrial sources from January 2005 until January 2010, after which time the 0.5 µg/m^3 limit was also applied to these sources.

The blood lead recommendation, following (US CDC 2005), is 10 µg/dL.

4.2 TECK RESOURCES (TRAIL, CANADA)

Teck has been operating since the 1890s in the town of Trail, British Columbia (Figure 10). Like Umicore, it is a polymetallic smelter producing 18 metal and chemical products but with an emphasis on zinc and lead. Their products have a broad range of uses including galvanizing, batteries, LCD screens, fibre optic cables, pulp and paper production, fertilisers and bleaching agents.

Similar to Umicore and Port Pirie, there is housing close to the smelter, in fact it can be seen from Figure 10 that the smelter has housing nearby in three different directions (see particularly the shaded West Trail, East Trail and Tadanac areas in the right-hand part of Figure 15). Because of the significant population areas along the river (principal wind directions along the valley), there is an extensive monitoring network in the region (Figure 11).

---

[6] http://ec.europa.eu/environment/air/quality/standards.htm

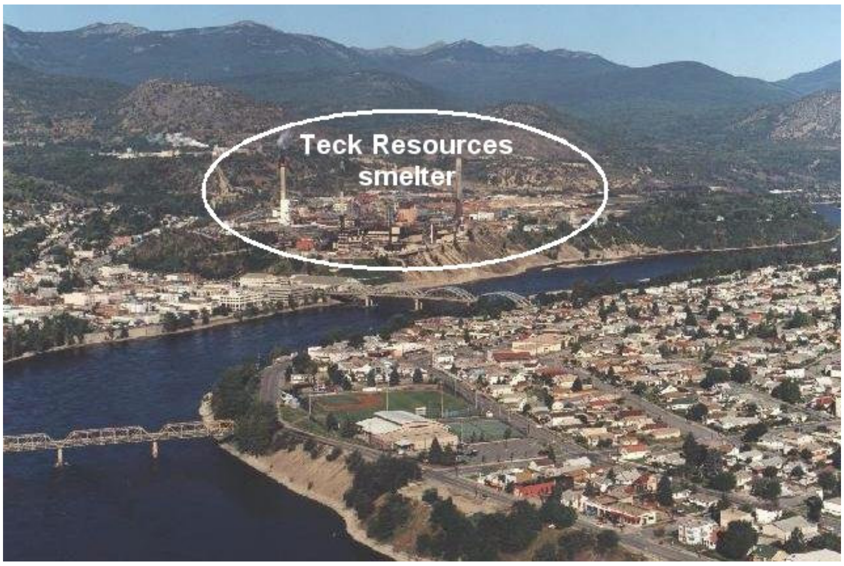

Figure 10. Location of the Teck Resources smelter on the Columbia river in Trail, Canada showing the location of some of the housing in relation to the smelter.

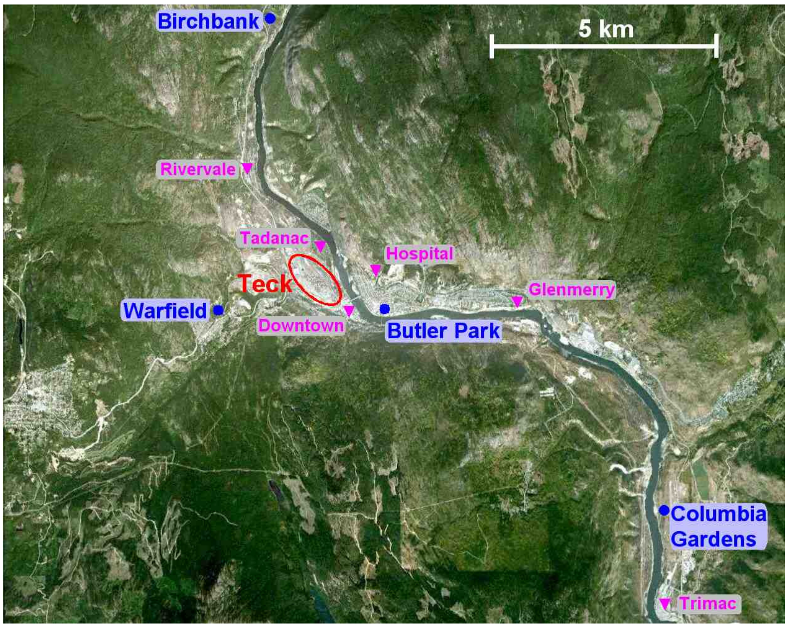

Figure 11. Locations of the four main air quality stations (Birchbank, Butler Park, Warfield and Columbia Gardens) and some of the dustfall monitoring sites (▼) around the Teck Resources smelter in Trail. The main air quality monitoring site at Butler Park is about 2 km from the smelter boundary.

In 1997, in order to clean up the lead pollution and improve metal processing efficiency, they installed a Kivcet lead smelter, which resulted in reduction of total air lead emissions by about 80%, and a reduction in fine, mobile dust lead loadings by about 50% (British Columbia Ministry of Environnment 2009). Following commissioning, they experienced a dramatic reduction in air lead concentrations from 1.6 µg/m^3 annual average (1997) to around 0.5 µg/m^3 which plateaued over the period 1998 to 2011 (Figure 12). This led to a concomitant reduction in blood lead in the surrounding community from an average of 12 µg/dL (for children aged 6 months to 3 years) in 1997 to an average of 5 µg/dL from 2001 to 2011 (Figure 12).

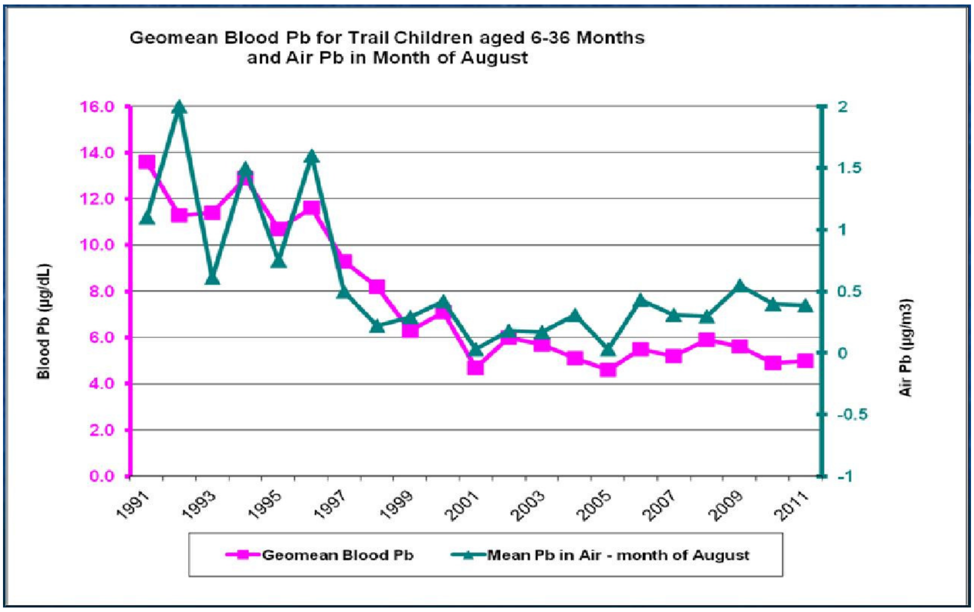

Figure 12. Time series of air lead and blood lead concentrations in Trail in August (month with highest values of blood lead) from 1991 – 2011. Note different scales and different locations of zero for blood lead and air lead. **(THEP 2011)**

As with Umicore, blood lead reduction occurred at a slower pace than air lead reduction. Interestingly the blood lead reduction at Teck has been a little better than Umicore – average of 5 µg/dL compared with 7 to 10 µg/dL. The reasons for this are that the monitored population all lives much closer to the Umicore smelter than at Teck and because of the snow cover in winter at Trail which holds the fine particles and then washes them away with the snow melt thus providing better protection for the community.

Although the British Columbia objective for annual average lead in TSP is 1.0 µg/m^3, the current air quality ‘target’ for Teck is the THEC (Trail Health and Environment Committee) goal of 0.2 µg/m^3 at their community monitoring sites at Butler Park and Birchbank. Their blood lead health guideline is 10 µg/dL.

Figure 13 shows a longer history back to 1975 of the geometric mean of blood lead levels in Trail and a comparison with the US average, which was 15 µg/dL in 1975. Figure 14 shows the corresponding percentage of 6-36 month aged children with blood lead levels below 10 µg/dL. This has increased from 30-40% before the technology upgrade to values above 90% post KIVCET.

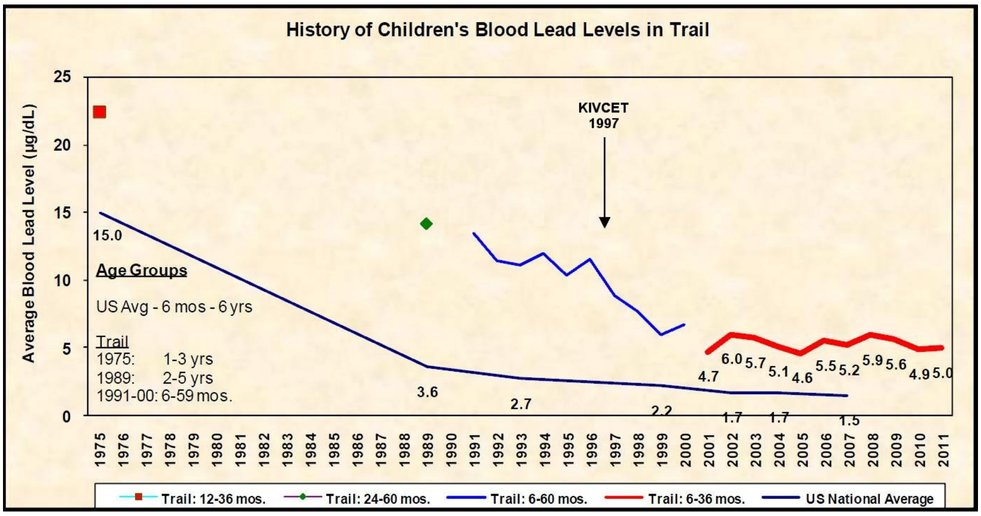

Figure 13. History of geometric mean of blood lead levels in children in Trail since 1975 compared to US averages. **(THEP 2011)**

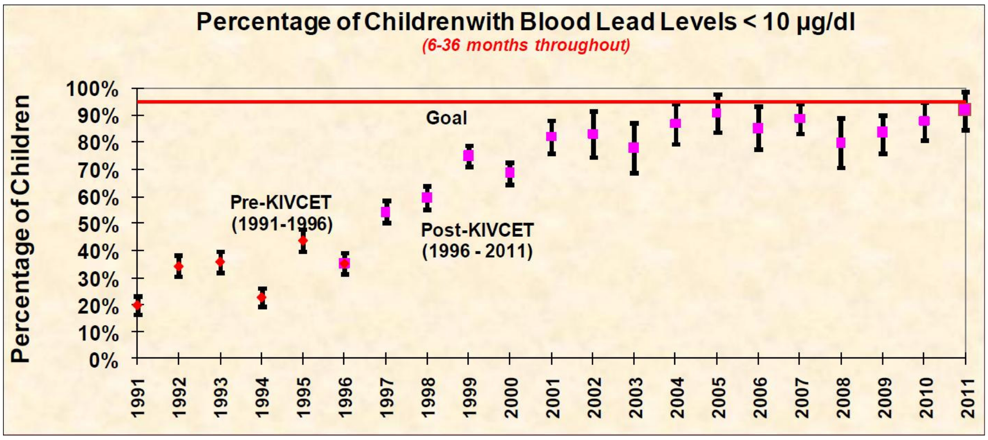

Figure 14. History of percentage of 6-36 month aged children with blood lead levels below 10 µg/dL since 1991. **(THEP 2011)**

Both the geometric mean and the percentage of children above or below 10 µg/dL are metrics derived from the full distribution of blood lead levels in the population (Figure 15), which shows the proportion of the population at each blood lead level. The figure shows the dramatic shift to the left of the distributions since the 1997 transformation at Trail, but also the continued presence of a fraction of children with higher blood lead levels.

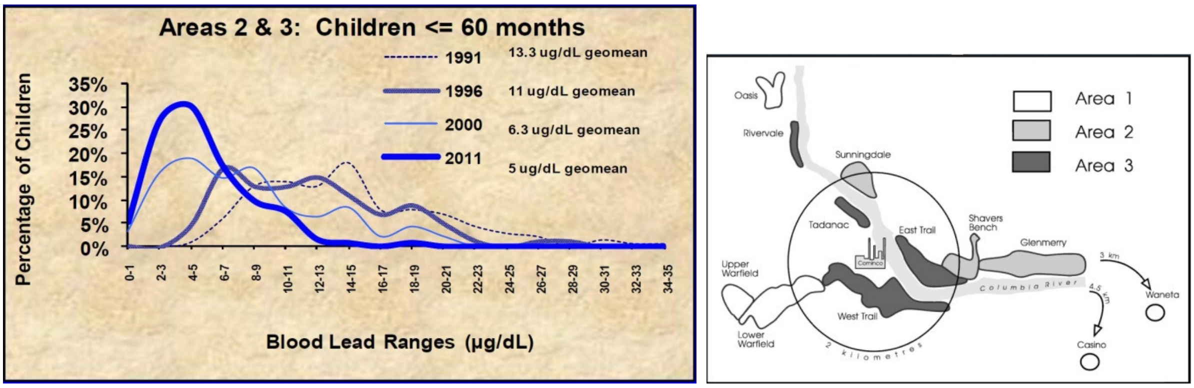

Figure 15. Change in distribution of blood lead levels in Trail children over two decades spanning the installation of the KIVCET technology. The geometric mean of 13 µg/dL in 1991 decreased to 5 µg/dL in 2011. The locations of Areas 2 & 3 are shown in the right-hand part of the figure. **(THEP 2011)**

4.3 CONCLUSION RE LIKLEY POST-TRANSFORMATION PERFORMANCE AT PORT PIRIE

Despite the differences between the Umicore and Teck smelters, both sites recorded major reductions in air lead and blood lead levels following the introduction of new smelter technology. To assist with estimating the likely changes that would occur at Port Pirie following the proposed Transformation, the data on air lead and blood lead reductions at Hoboken and Trail have been combined in Figure 16 and Figure 17. The data show significant scatter because of year-to-year variations in climate and production levels as well as the impact of ongoing improvements. Indicative trend lines (drawn by eye) show that halving of air lead levels occurred after 1–4 years, whereas halving of blood lead levels took about 7-9 years. However, blood lead levels in Port Pirie (Figure 29) are already significantly lower than pre-transformation levels at Trail and Hoboken; the results in Section 7 provide a better understanding of the relationship between reductions in air lead and blood lead. Legacy lead (Section 6.3.3) can also make a significant contribution to blood lead levels.

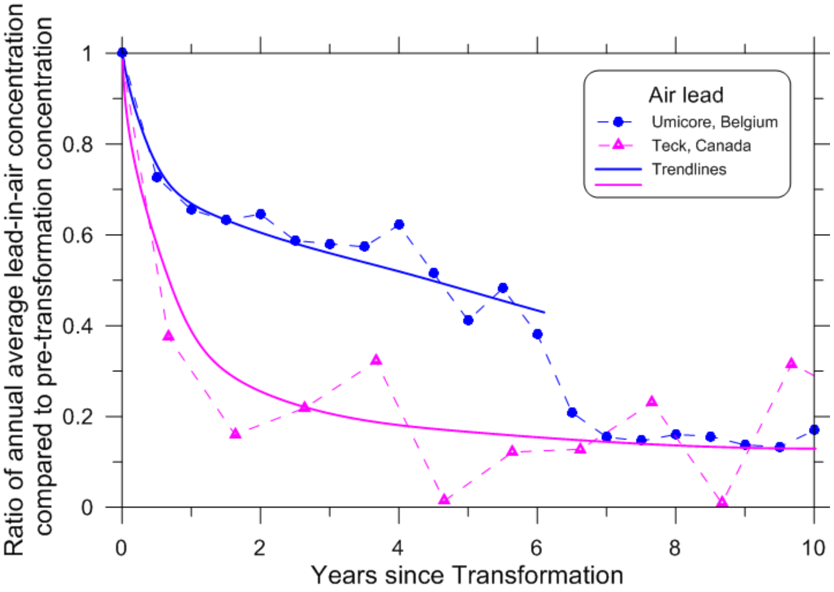

Figure 16. Comparison of the rate of reduction of air lead concentrations following technology transformations at Umicore and Teck (data replotted from Figure 7 and Figure 12).

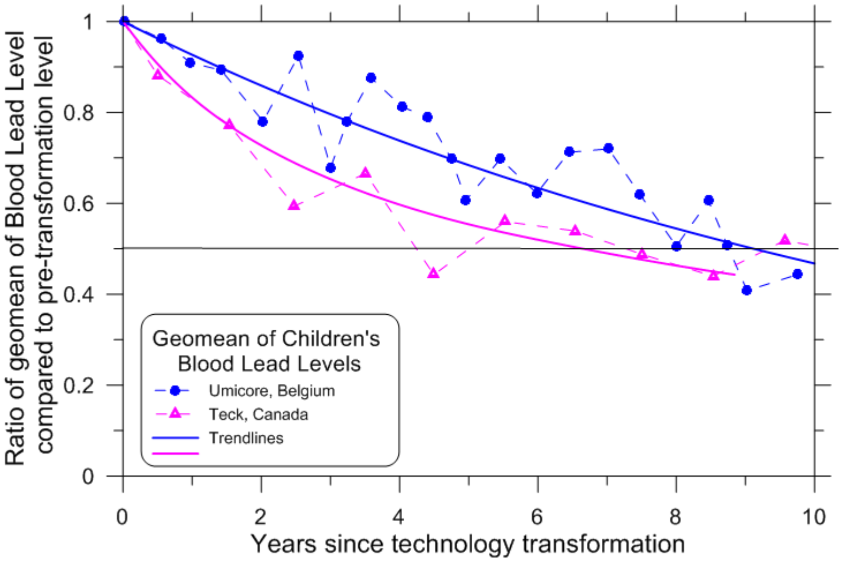

Figure 17. Comparison of the rate of reduction of blood lead levels following technology transformations at Umicore and Teck (data replotted from Figure 8 and Figure 12).

5. AIR QUALITY DATA FOR PORT PIRIE

5.1 SPATIAL VARIATION IN AIR LEAD CONCENTRATIONS

Nyrstar currently operates a dozen monitoring sites across Port Pirie with high-volume samplers collecting 24-hour TSP (total suspended particle) samples, which are analysed for a range of metals including lead. Figure 18 shows the distribution of annual average concentrations across the city from the last five years (2008-2012) with fitted smoothed contours shown in yellow.

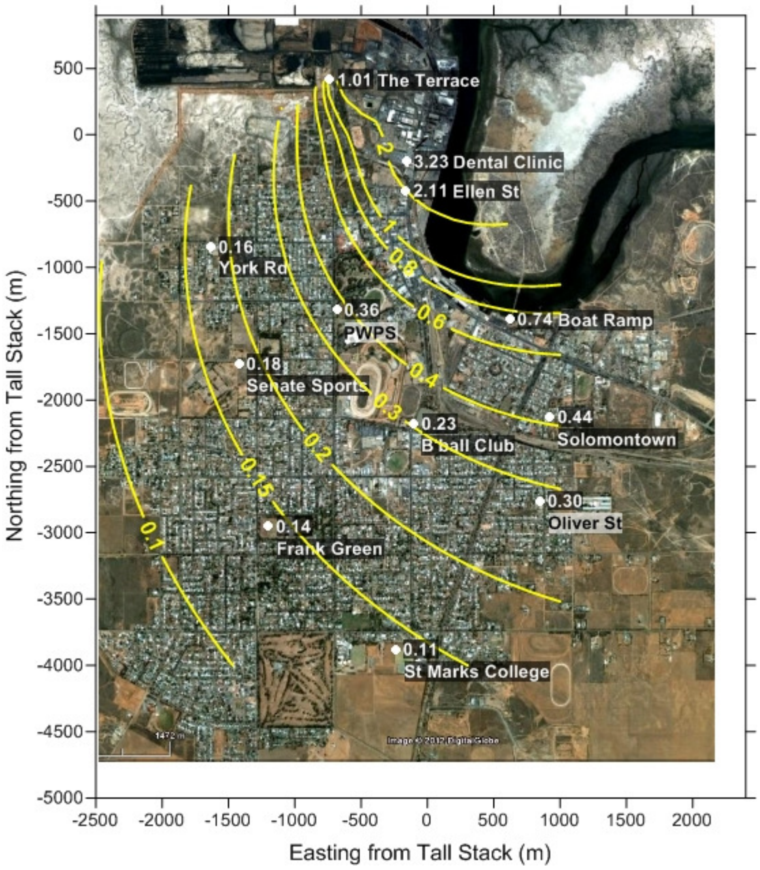

Figure 18. Five-year (2008–2012) average air lead concentrations (units of µg/m^3) at the Port Pirie monitoring sites with fitted smoothed contours shown in yellow.

The shape of the contours is strongly influenced by the dominant wind directions (see Figure 1) with the highest concentrations at a given distance to the southeast of the smelter and lower concentrations to the south and southwest. The five-year average concentrations were used to minimise scatter due to year-to-year variations.

Analysis reported in the latest fugitive emissions study of the Nyrstar smelter (PAE Holmes 2012) showed that in 2010/2011 background air lead concentrations at the licence monitoring sites[7] (determined from days when the wind directions were not from the smelter sector) were less than 0.005 µg/m^3. This confirms that current smelter sources are the dominant source of air lead in Port Pirie.

5.2 HISTORICAL AIR LEAD TRENDS

The longest running site of the Nyrstar network is at Pirie West Primary School. The 30-year record of running annual averages is given in Figure 19 (with each value plotted at the end of the averaging period on the time axis). A few gaps in the record have been filled using surrogate data from other monitoring sites with a scaling factor applied equal to the ratio of the annual averages in Figure 18 at Pirie West Primary to that at the site with the surrogate data. Note that the vertical axis is a log scale to show proportional changes more clearly. Focussing on the most recent decade, an exponential fit to the data shows that there has been an average decrease of 11% p.a. in annual average concentrations with lead levels since 2008 being consistently lower than at any time in the previous 25 years. The lower concentrations in 2011 are most likely due to higher than average rainfall – the 12 months from July 2010 to June 2011 had 30% above average rainfall and 60% more rain days than average. The reductions over the last ten years are the result of a wide range of tenby10 projects to reduce the environmental impact of the smelter.

---

[7] The licence monitoring sites are Pirie West Primary School and Oliver Street.

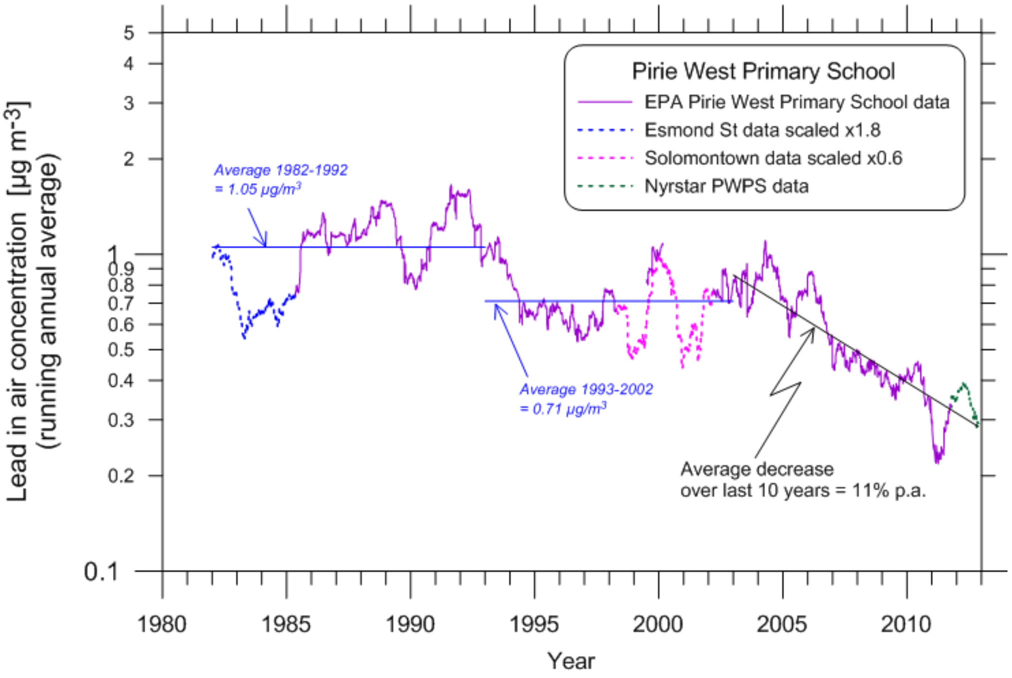

Figure 19. Running annual average lead concentrations at Pirie West Primary School over the last 30 years. Some gaps in the record at this monitoring site have been filled using data from other monitoring sites in Port Pirie. See text for details.

The monitoring sites used for assessing EPA compliance are the Pirie West Primary School and Oliver Street sites. Figure 20 shows the 14-year record of annual average air lead concentrations from the Oliver Street monitoring site, again with some surrogate data adjusted as described for Figure 19. As at Pirie West Primary School, an exponential fit shows that there has been an average decrease of 11 % p.a. over the last decade and with a similar rainfall-induced dip in 2011. Indeed analysis of data from each of the monitoring sites show average reductions of 8–12 % p.a. over the last decade, with the decrease at the Terrace averaging 17% p.a., probably because of its closer proximity to the pit, which was the target of significant improvements as part of the tenby10 projects.

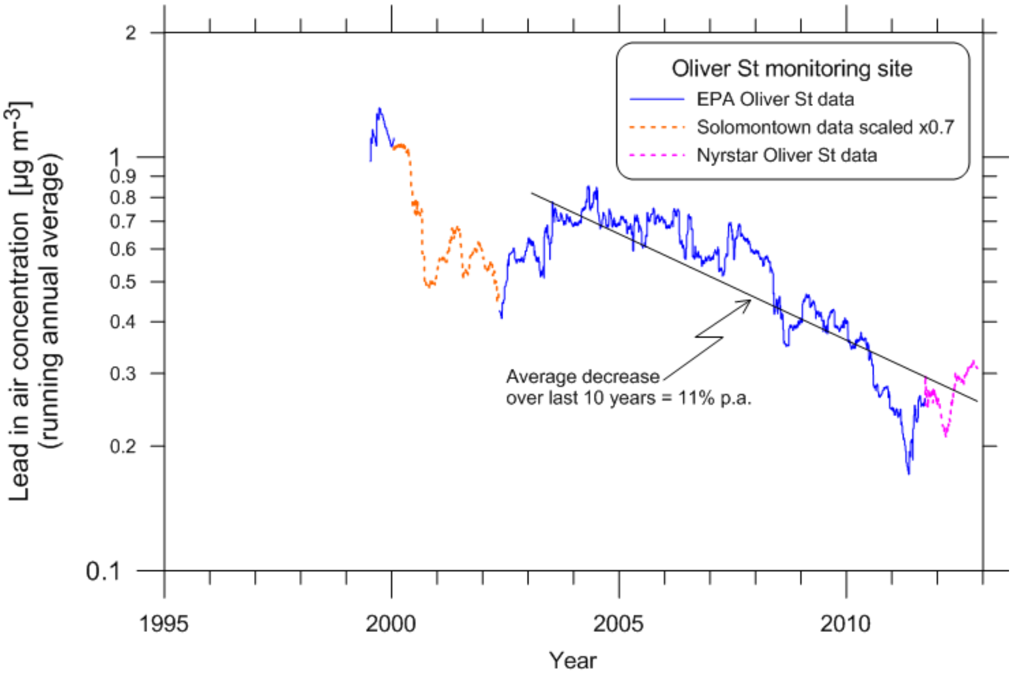

Figure 20. Running annual average lead concentrations at Oliver Street monitoring site over the last 14 years. Some gaps in the record at this monitoring site have been filled using data from other monitoring sites in Port Pirie, which have been scaled by the ratios of the annual averages at these sites in Figure 18**.**

5.3 LEAD DEPOSITION RATES

As the primary route for entry of lead into the body is via ingestion rather than by inhalation, it is important to understand the relationship between air lead and deposited lead dust. Figure 21 shows the strong linear correlation between air lead and lead deposition rates across the Port Pirie monitoring sites. This indicates that air lead concentration is a useful measure of the amount of lead dust deposited due to emissions from the smelter, which contribute to the lead reservoirs discussed in Section 6.3.4. The various sources of lead dust are considered in more detail in Section 6.3.3.

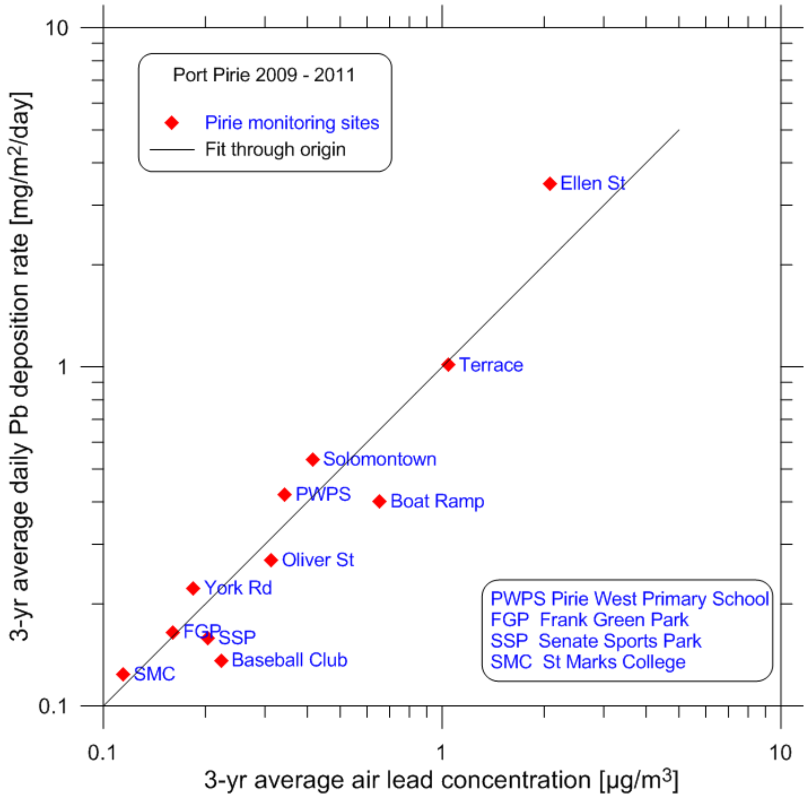

Figure 21. Relationship between average lead deposition and average air lead concentrations at the Nyrstar monitoring sites across Port Pirie.

The ratio of lead deposition rate to air lead concentrations in Figure 21 is 1.0 ± 0.3 (mg/m^2/day) per (µg/m^3). This compares with a slightly higher ratio of 1.8 for the Butler Park site in Trail[8], although data are only available for the month of August, and a much larger ratio of about 8 at Hoboken[9]. The reasons for the differences have not been investigated but it is postulated that there is a higher proportion of coarse dust (with deposits more quickly) at Hoboken than at Trail or Port Pirie.

---

[8] Butler Park is in Area 3 (Figure 15), so the average August dustfall in Areas 2/3 from 2008-2010 of 0.85 mg/m^2/day can be compared with the average August TSP air lead concentration at Butler Park for these years of 0.48 ug/m^3 (THEP 2011).

[9] The lead deposition rate at site HB01 (Figure 6) was 1.3 mg/m^2/day in 2009 and the annual average air lead concentration in PM10 was 0.17 µg/m^3 (VMM 2009). Note that this air lead concentration is in PM10, whereas the results for Trail and Port Pirie are in TSP. Comparisons of Port Pirie data from Oliver St and Ellen St monitors show that TSP air lead concentrations are on average 2.3 times larger than PM10 air lead concentrations, but this TSP/PM10 ratio depends on the relative proportions of the various dust sources and is expected to vary from smelter to smelter.

6. LEAD EXPOSURE IN PORT PIRIE

6.1 INTRODUCTION

This section discusses sources of lead in Port Pirie, lead exposure pathways, and contributors to lead exposure. The discussion is limited to children aged 0-4 years because this is the population that is most sensitive to the health effects of lead and subsequently is the data that has been collected for an extended period of time.

The aim of smelter *technology transformation* in Port Pirie is to ensure that residents, particularly children, have blood lead levels that meet the current NHMRC recommendation: that all Australians should have blood lead levels below 10 micrograms per decilitre (µg/dL) and that children's lead exposure should be minimised. As discussed elsewhere in this report, the aim is for continual improvement. This aim aligns with one of the South Australian Premier's seven strategic priorities — 'every chance for every child'. This strategic priority is intended to concentrate efforts and drive the work of government to improve health outcomes for children, particularly in the first five years of life. It is clear that reducing blood lead levels will provide better health outcomes for Port Pirie children.

6.2 HISTORICAL PERSPECTIVE

In cities where an active lead smelter has either closed or significantly reduced its lead emissions, children's blood lead levels in nearby residential areas have subsequently reduced. Three cities have recorded data that is comparable to data that SA Health collects about Port Pirie children's blood lead levels – the reductions at Hoboken and Trail have been discussed in Section 4; the smelter at Cockle Creek, Boolaroo, New South Wales, Australia closed in 2003-4.

In all three cities, some young children remained with blood lead levels above 10 µg/dL after emission reduction or smelter closure. In 2011, 14 years after the 1997 smelter technology transformation in Hoboken, about 10% of all children had blood lead levels above 10 µg/dL (Figure 9), and at Trail, 9% of the 106 children tested under the age of 3 years had blood lead levels above 10 µg/dL (Figure 14). In 2005-6, the last time that blood lead levels were reported from Cockle Creek and three years after the lead smelter closed, 7% of the 130 children aged 0-4 years had blood lead levels above 10 µg/dL (Figure 22). Comparison is difficult as child-activity patterns may be different as is the extent to which bare soil contributes to the child's exposure – the dry climate in Port Pirie is conducive to bare soil.

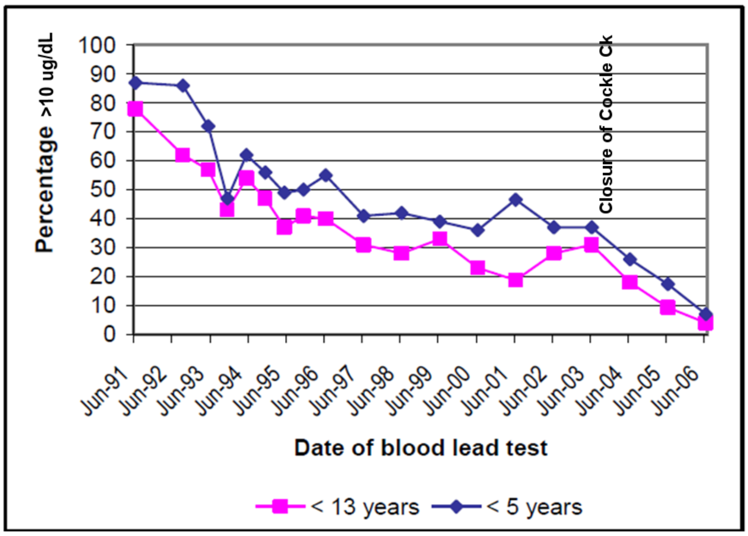

Figure 22. Changes in percentage of children with blood lead levels above 10 µg/dL in Cockle Creek following smelter closure in 2003.

6.3 LEAD EXPOSURE FOR CHILDREN

6.3.1 BLOOD LEAD RECOMMENDATIONS

The National Health and Medical Research Council (NHMRC, 2009a) states:

'Based on the research evidence on the effects of low-level exposure to lead, it is not possible to make a definitive statement on what constitutes a 'safe level' or 'level of concern' for blood lead concentrations.'

Therefore the Council published a recommendation in 2009:

- *All Australians should have a blood lead level below 10 µg/dL.*
- *All children's exposure to lead should be minimised.*
- *All women are advised to minimise their exposure to lead both before and during pregnancy and also while breastfeeding.*

The World Health Organisation (WHO) also maintains a guideline of 10 µg/dL.

In 1999-2000 the geometric mean blood lead level in the US was 2.4 µg/dL for 12-14 month old children. In 2012, the US CDC (CDC, 2012) replaced its 'level of concern' with a childhood blood lead reference value based on the 97.5th percentile of population blood lead levels in children aged 1-5 years. This is currently 5 µg/dL, and will be updated every 4 years based on the most recent population surveys. Its rationale is based on evidence that lead has effects at very low levels. It is estimated that there are currently 450,000 US children aged 1-5 years who have blood lead levels above 5 µg/dL.

In Germany a reference value of 95th percentile provides the values of 3.5 µg/dL for children aged 3-14 years, 7 µg/dL for women and 9 µg/dL for men.

Occupational health standards are generally higher than those for the general population. These standards are not relevant for the general population and particularly not for children, but the numbers are listed here for completeness. The current Australian standard (NOHSC 1994) is that workers shall be removed from lead-risk jobs if they have a blood lead level of 50 µg/dL (all men and women not of reproductive age), 20 µg/dL (women of reproductive age), and 15 µg/dL (women who are pregnant or breastfeeding).

6.3.2 FACTORS INFLUENCING CHILDREN’S BLOOD LEAD LEVELS

Figure 23 shows the complexity of the relationship between smelter lead emissions and children’s blood lead levels with multiple variables —the lead sources (blue) and the contributing factors (orange). That is, there are many factors influencing a child’s blood lead level, not just the air lead concentration.

A plot of each individual child’s blood lead levels versus the annual average air lead concentration at their residence shows a wide scatter (Figure 24), reflecting the complexity of the relationship. For an individual, the variations in air lead concentration explain less than 30% of the variation in their blood lead levels, leaving 70% of the variation due to other factors. These include individual variations in lead exposure pathways, shown in Figure 23 and in more detail in Figure 27, as well as variations in legacy lead contamination (lead contaminated dust and soil) in the child’s living environment and uncertainty surrounding air lead concentrations in the child’s environs (i.e. at the child receptor). However, on a population-wide basis, Figure 25 shows the strong impact of reducing air lead concentrations on increasing the number of children with blood lead levels below 10 µg/dL.

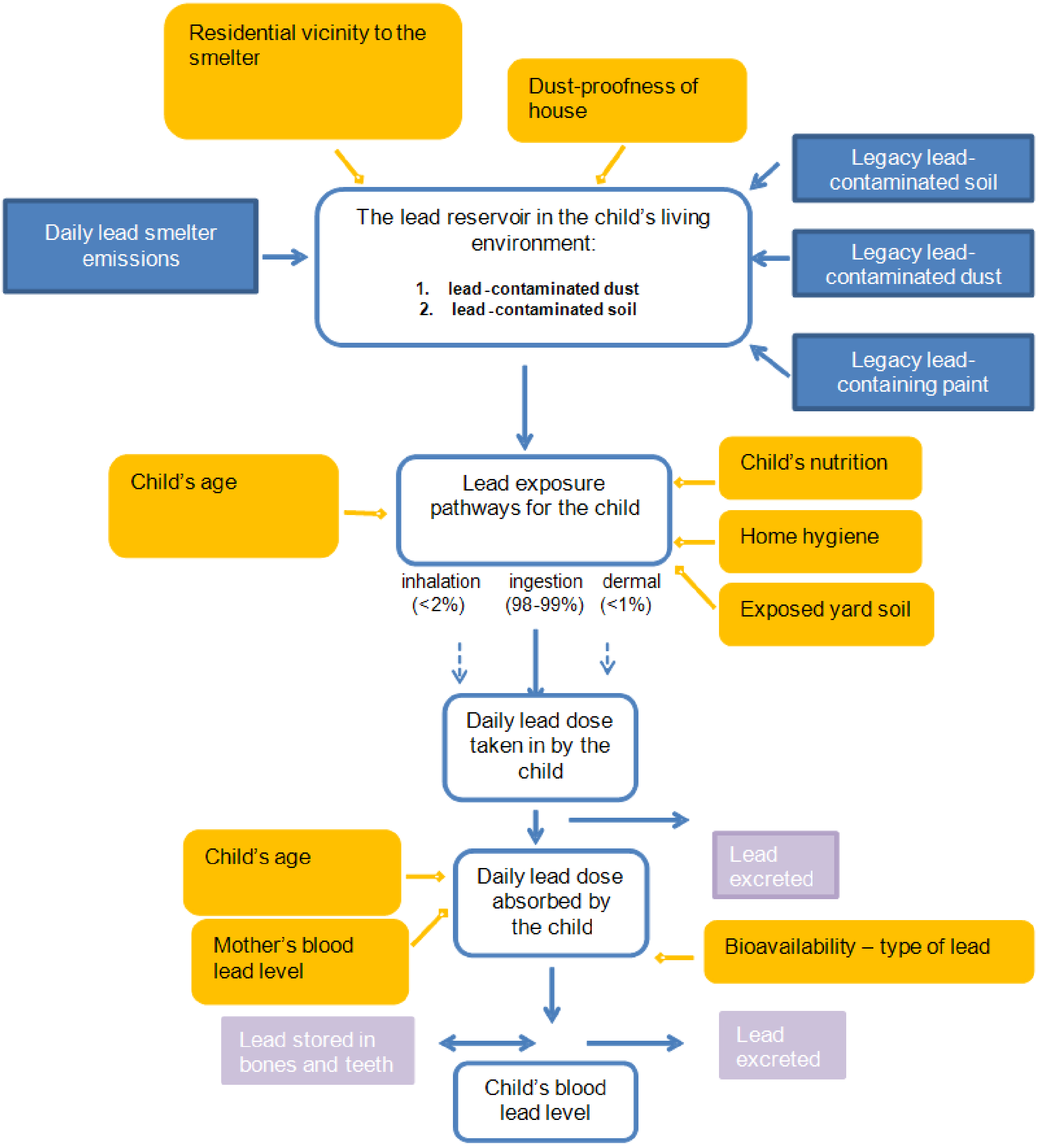

Figure 23. Schematic diagram of lead exposure for children showing lead sources (blue) and contributing factors (orange) that influence the child's exposure level.

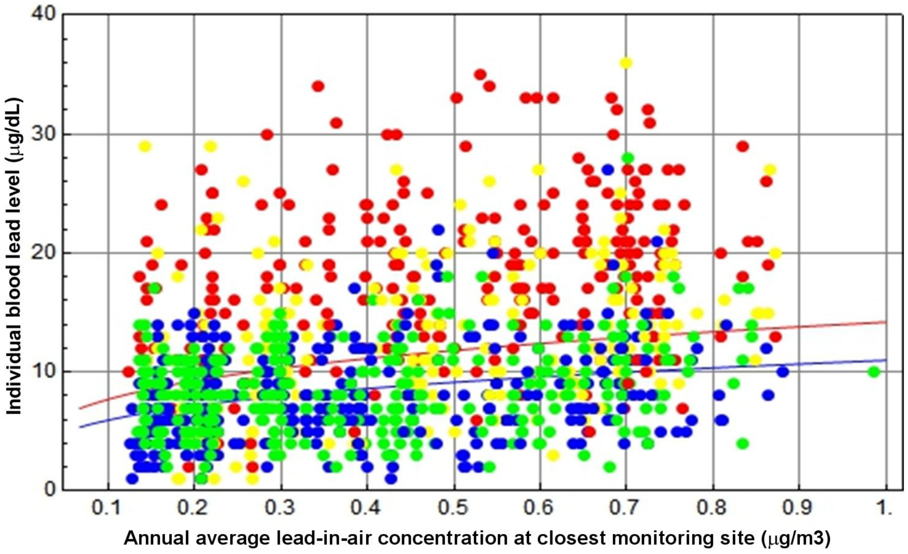

Figure 24. Scatter plot of individual blood lead levels and the 12-month average air lead concentrations measured by the monitoring site closest to the child's place of residence (in 2005). The colours denote the exposure index, where red indicates the greatest difficulty in reducing exposure and green the least, with yellow and blue have a level of difficulty between these. The two lines denote regression models for children in high risk (red) and low risk (blue) areas. See discussion in text.

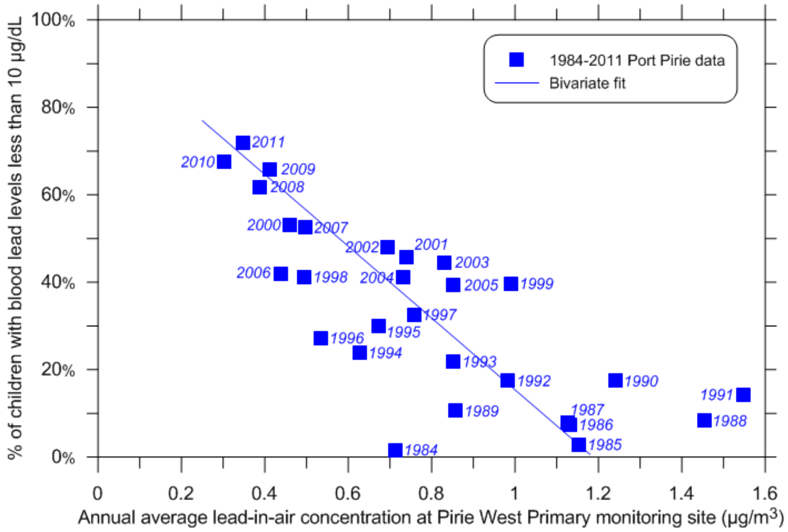

Figure 25. Regression of percentage of 1–4 year old children in Port Pirie with blood lead levels below 10µg/dL against the annual average air lead concentrations at Pirie West Primary monitoring site, one of the EPA licence sites. The bivariate fit accounts for uncertainty in both variables **(Cantrell 2008)**.

6.3.3 LEAD SOURCES

The source of lead that Port Pirie children are ultimately exposed to is principally smelter derived with rare contributions from other sources, occasionally lead paint. Smelter lead emissions can directly deposit into home reservoirs (*contemporary* contamination) or feed into home reservoirs via a number of steps (*legacy,* also called *historic,* contamination of dust and soil in Port Pirie environs by smelter emissions and motor vehicle emissions over previous years).

Contemporary lead exposure arises principally from fugitive emissions from the smelter site rather than stack emissions, the latter of which are estimated to make up about 10% of smelter lead emissions and a smaller proportion of air lead concentrations measured in Port Pirie due to the better dispersion from elevated sources. These fugitive emissions originate from smelting processes and on-site lead deposits (e.g. stock piles of raw materials and deposits on roads, roofs, tarmacs, bare soil, etc.). The time that elapses between emission of a lead particle from the smelter and ingestion of the particle by a child is unknown. Both *contemporary* lead exposure and *legacy* lead exposure are smelter sourced, but separated temporarily by some unknown period of time.

Lead dust particles travel downwind at a distance dependent upon particle size and wind strength and other complex meteorological parameters. Particles may land on other surfaces and be *re-*entrained into the air. This latter process is energy intensive requiring high wind gusts such as those observed on hot windy days prior to a synoptic front. Houses are readily penetrated by airborne lead particles and are very effective in retaining them—the age of housing stock is a key feature that determines dust particle entry.

Lead dust particles can also be mechanically transported, where lead particles lodge onto objects such as clothes (an important direct source from the smelter if workers wear their on-site clothes home), shoes, animal fur, wheels of children's prams and strollers, etc. These contaminated objects may then be directly handled and mouthed by the child, e.g. pets or wheels of stroller. Alternatively, as these objects pass across the floors of homes, lead can be transferred onto other surfaces, particularly adding to the carpet lead reservoir.

6.3.4 LEAD RESERVOIRS

Lead that is emitted from the smelter, or entrained by wind, or mechanically transported, adds to lead reservoirs that feed, to varying extents, into exposure pathways of the child. Lead reservoirs in a child's living environment consist of lead-contaminated dust or soil inside or outside the child's house or a building or facility where the child spends significant time such as child or day-care centre, kindergarten, grandparent's house or playgrounds. Lead reaches home reservoirs in the vicinity of the child over days, months or years.

Inside the home, carpet, soft furnishings and ceiling spaces are the primary lead reservoirs of the home reservoir. Outside the home, an undeveloped yard with exposed soil is the primary lead reservoir. The CSIRO has demonstrated that most carpet dust is located in the lower quarter of the carpet pile. This makes removal extremely difficult, even for the most fastidious cleaner and powerful vacuum cleaner. Walking on contaminated carpet moves lead particles in the vertical direction with some particles reaching the surface. This is the most accessible lead in the home for children, and for this reason, children who are crawling are at most risk of lead exposure.

Dust containing lead is in constant motion within residential premises and is readily and constantly re-mobilised from lead reservoirs and deposited on the myriad of surfaces that comprise children's exposure pathways (depicted in Figure 27). Because of the exposure risk posed by contaminated surfaces, much attention is directed towards ensuring that children are placed on impermeable clean surfaces, their hands are washed and dried and objects that leave the house, either remain outside, or are thoroughly washed before re-entering the home. Wet-dusting and HEPA-filtered vacuum cleaning is encouraged, but since reservoirs are constantly being re-supplied, even vigilant cleaning cannot eliminate them. Replacement of carpets and yard soil is an option but re-contamination, especially of carpets, reduces the effectiveness of these options under current emission conditions.

6.3.4.1 INFLUENCE OF HOUSE LOCATION AND ITS DUST-PROOFNESS

The primary factors influencing the amount of lead in the lead reservoirs are the child's residential location and the dust-proofness of the house. Lead emitted from the smelter deposits to the ground at rates relative to distance from the smelter, reducing with downwind distance from the smelter (Figure 18 and Figure 21) such that environmental lead contamination is lower in more southerly parts of the city. Therefore, residential location controls to some extent the lead reservoirs in the child's environs and subsequently the child's lead exposure.

Furthermore, the ease of entry of lead particles into a home is determined, in part, by the leakiness of the house envelope – old weather-board homes are the leakiest. Homes in close proximity to the smelter are impinged with the highest concentrations of air-borne lead and are, in general, older leakier homes. The relationship between wind-speed and dust ingress also needs to be considered along with house related behaviours on hot or windy days. In general, the condition of houses in Port Pirie follows a gradient of poor to best, travelling in a southerly direction from the smelter. The socio-economic gradient found in Port Pirie inevitably matches the age of the homes – with poorer families living in the highest lead impinged areas, which compounds the issue of residential proximity to the smelter.

To summarise, the high lead-exposure risk areas are Pirie West, Solomontown and the CBD (Figure 26). These suburbs are subject to greater lead-contaminated dust concentrations and greater lead load per unit surface area because they are in close proximity to the smelter and downwind from it and contain aged and poorer housing. Distance from the smelter and the south-west sector of Port Pirie in general provides the most protection, along with good quality homes (brick veneer has proven to be effective), and limited surrounding exposed soil, including yards, parks and footpaths.

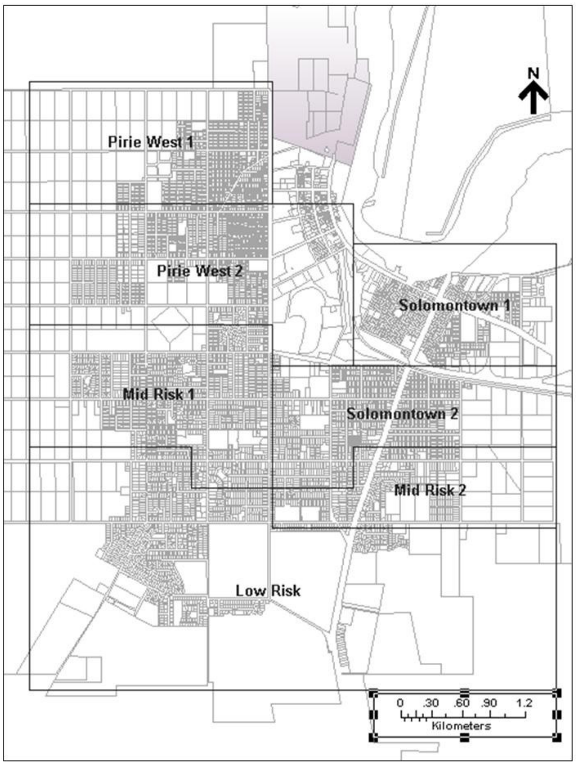

Figure 26. Map showing the zones used by SA Health to specify risk of lead exposure.

6.3.5 LEAD EXPOSURE PATHWAYS

Children live within a complex web of lead exposure pathways. Each pathway has two distinct stages:

1. The passage of lead particles from the lead source, whether direct from smelter or indirectly via the environmental lead reservoir (e.g. lead-contaminated soil and dust) to the lead reservoirs in the vicinity of the child (home reservoirs).
2. The passage of lead particles from the lead reservoirs in the child's environment into the child's body.

Both stages are complex but the penultimate destination of lead particles is to contaminate an object that the child will mouth such as a hand, a toy, a dummy or food. When the object is mouthed, lead enters the mouth, and if swallowed, some particles will be absorbed. Ingestion is the primary route for entry of lead into the body; while the respiratory route of exposure for a child makes an extremely small contribution to total exposure. Simon et al (2007) estimated that inhalation contributes less than 2% whereas the US EPA (USEPA 2007) estimated its contribution to be 1%.

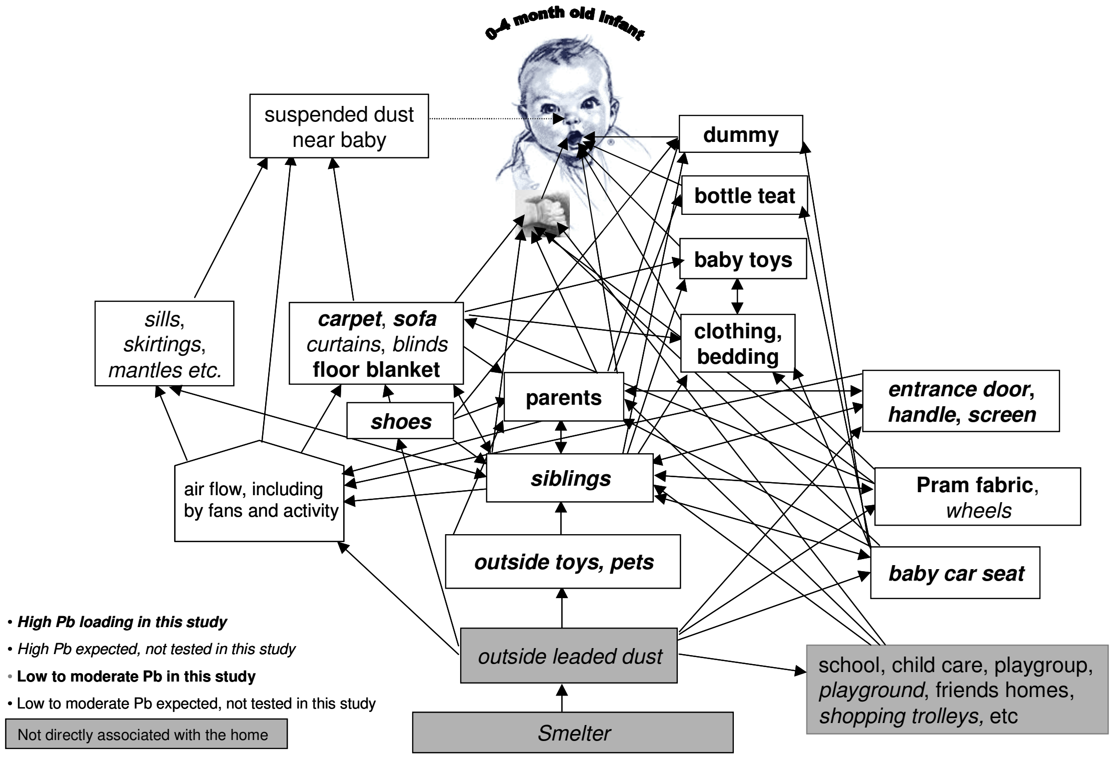

Figure 27. Schematic of the lead exposure pathways in the child's environment **(Kranz B. 2004)**

6.3.5.1 INFLUENCE OF CHILD'S AGE

As explained above, the most important as well as the most efficient and effective exposure pathway is from the lead reservoir, such as carpet, lounge or hard surface to an object that is mouthed—most commonly the hand or fingers. Mouthing of surfaces is a natural behaviour and is highly age-related, beginning at 5 weeks old. That is, the child's age is a primary factor in the lead exposure pathway.

Prior to mouthing, the lead load of the newborn is derived from its mother. Since lead is chemically similar to calcium, it is absorbed by the mother and therefore the foetus is exposed, achieving the same blood lead level as the mother. Furthermore, pregnancy mobilises the mother's calcium stores to ensure that the growing foetus is not deprived of calcium, which also releases lead into the blood because lead is stored in the same bone-stores as calcium. The mother's body burden of lead together with her blood lead level determines the blood lead level and body burden starting point of a newborn.

On birth, the child's exposure is limited to incidental lead contamination, such as re-entrained lead and lead on clothing or bed linen. However, once motor control begins to develop, the natural exploratory behaviours of the child increases its range and the potential for lead exposure increases rapidly from this period onward. The most critical stage is when the child begins to crawl because it is almost certain that the child will not be protected from contaminated surfaces without severely curtailing natural behaviours (e.g. placing the child into a 'playpen'). It has been found that as a child transitions from crawling to standing he or she will have reduced hand-lead contamination at each behavioural milestone. A toddler is likely to have a lower exposure indoors than when he or she was crawling. However, if the toddler is allowed to explore the contaminated outdoor environment he or she can quickly become highly exposed. In exceptional circumstances some children exhibit a pattern of behaviour called 'pica', that is eating of non-food objects. These children are at particular risk of excessive exposure to lead. The decrease in blood lead levels with age is also seen in the data from Umicore in Figure 8.

6.3.5.2 INFLUENCE OF SOCIO-ECONOMIC STATUS (SES)

In addition to the impact of social economic status (SES) on housing condition and the lead reservoir (section 6.3.4), SES also impacts on other aspects of lead exposure within the caring environment of the child. For example, lower SES is associated with poorer nutrition, reduced focus on hand and house hygiene, less resources available for cleaning and barriers against lead reservoirs e.g. mattresses, high chairs and educational disadvantage (especially care-givers) reduces the effectiveness of exposure-reduction education, which all contribute to a higher risk of lead exposure.

6.3.6 LEAD METABOLISM

Lead enters the body via the mouth and the particles are solubilised (or digested) prior to absorption from the gut. Lead is best solubilised in highly acidic media (low pH) such as the fasting stomach environment. Lead absorption is reduced by preventing children from fasting because non-fasting stomachs have higher pH that is less conducive to absorption. All children are therefore encouraged to have breakfast and to snack between meals.

Lead solubilisation takes time. The extent to which a dose of lead becomes available for gut absorption depends on particle size (large particles take longer), lead type (oxides of lead solubilise much faster than lead ore–galena), stomach pH, and gut motility. Some of the solubilised lead is absorbed in the upper small intestine and the remainder is excreted in faeces. The extent to which lead is made available to be absorbed is called its *bio-accessibility* and the extent to which a dose of lead is transferred into the blood is called its *bio-availability.*

Lead absorbed from the gut is transferred into the blood and then rapidly transferred inside red blood cells. This location markedly reduces further lead excretion, unlike chemicals that stay in the serum (liquid part of the blood), and therefore can be readily excreted. Lead is then slowly *partitioned* into various organs – firstly into soft tissue such as muscle and brain, and then into teeth and bones. It is difficult to extract lead once it is stored in bone – it is nearly impossible in adults (except during bone remodelling and osteoporosis), but easier in children. Lead chemically resembles calcium, which is why the body absorbs it and stores it in bone. Absorbed lead is excreted by the kidney, making the kidney a target organ for lead toxicity.

7. RELATING AIR LEAD AND BLOOD LEAD IN PORT PIRIE

This section presents an analysis of blood lead and air lead data from Port Pirie and by including data from Teck and Umicore establishes a number of robust correlations.

A principal aim of the technology transformation is the reduction of lead emissions from the smelter and hence reductions in air lead concentrations in Port Pirie, which are regulated through Nyrstar's environmental licence. All else being equal, there is a linear relationship between the annual lead emissions and annual average air lead concentrations. For example, halving lead emissions (from a fixed set of sources) will lead to a halving of air lead concentrations due to these sources. However, the relationship between blood lead levels and air lead concentration is somewhat more complicated.

The trend in blood lead levels in 1-4 year old children over the last 28 years in Port Pirie (Figure 28) shows a dramatic improvement since 1984 with an overall upward trend in the number of children with blood lead levels below 10 µg/dL, except for the period 2003-2005. However, currently there are still approximately 25% of children above 10 µg/dL.

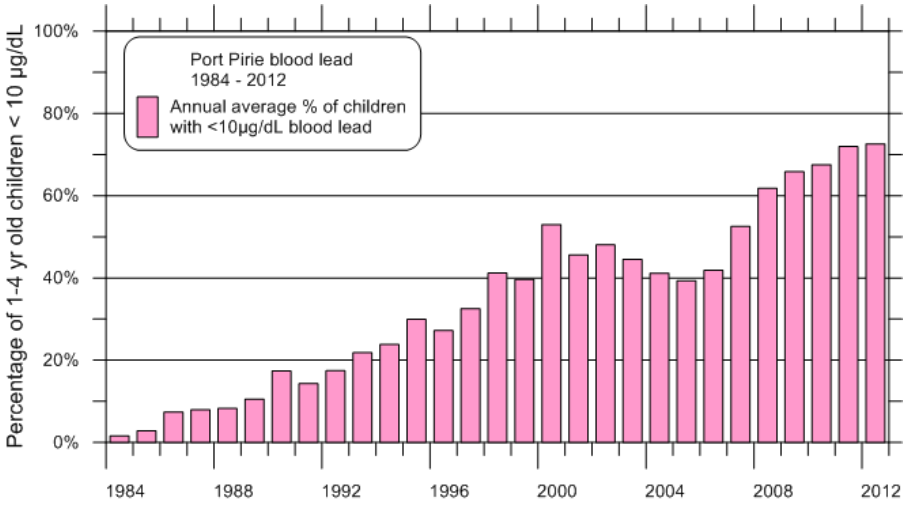

Figure 28 Historical trend in Port Pirie blood lead levels represented by the proportion (percent) of 1–4 year old children <10 µg/dL.

Figure 29 shows the relationship between blood lead levels and air lead concentrations using data from Port Pirie (for 1-4 year old children) with air lead data from each of the licence monitoring sites, Trail (children aged 6-36 months) and Hoboken (2-6 year old children). There is very close agreement between the Port Pirie and Trail data with the best fit showing a slope of about 9 µg/dL per µg/m^3 and an intercept of BPb = 3–4 µg/dL when APb = 0. The Umicore data also shows a good correlation between BPb and APb, but with almost double the slope and double the intercept. The reasons for this are unclear but are possibly related to the higher dust deposition for a given APb at Hoboken (as noted in Section 5.3) and the closer proximity of the Hoboken population to the smelter than at the other two sites.

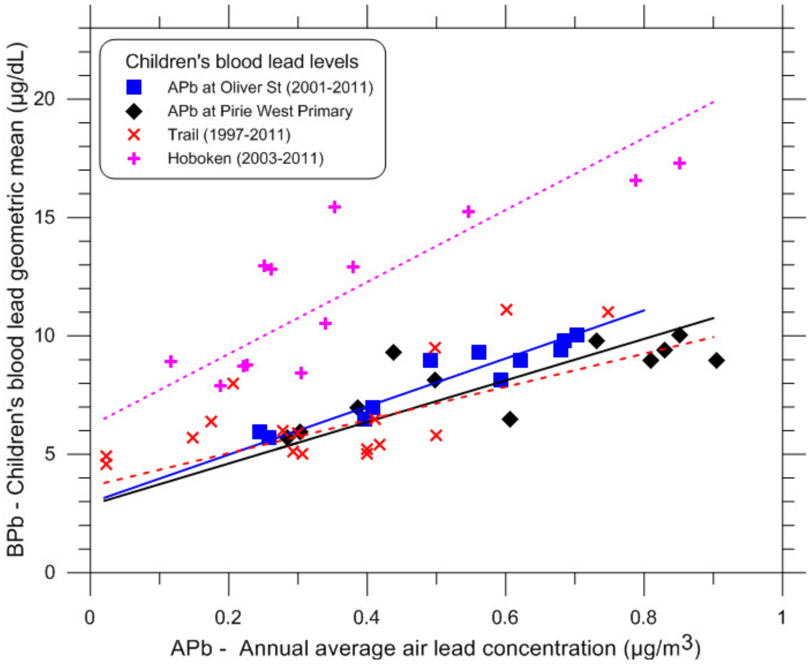

Figure 29. Relation between geometric mean of blood lead levels and annual average air lead concentrations based on historical data from Port Pirie (1–4 year olds), Trail (½–3 years) and Hoboken (2–6 years). The lines are bivariate fits **(Cantrell 2008)** to the respective data.

As mentioned in Section 4 and discussed more fully in Sections 6 and 8, it is not only the mean blood lead levels but also the number of children below the guideline value of 10 µg/dL that is important from a health perspective. Figure 30 shows the dependence on air lead concentrations of the percentage of children with blood lead levels below 10 µg/dL. The data is from the same sources as in Figure 29 except that the Hoboken data is for all children (this was the only data available), rather than just younger 1–4 year old children, so those have not been included in determining the overall trends because older children generally have lower blood lead levels. There is greater scatter than in

Figure 29 but the trends are quite robust. The trend lines were determined using bivariate fits (Cantrell 2008), which allow for uncertainties in both variables. Extrapolating the Port Pirie and Trail curves to APb = 0 indicates that in these two towns adjacent to primary lead smelters we would still only expect about 95% of children to have blood lead levels below 10 µg/dL even if air lead concentrations were reduced to zero. The remaining 5% above 10 µg/dL probably reflects the residual background exposure due to legacy sources (see Section 6.3.3).

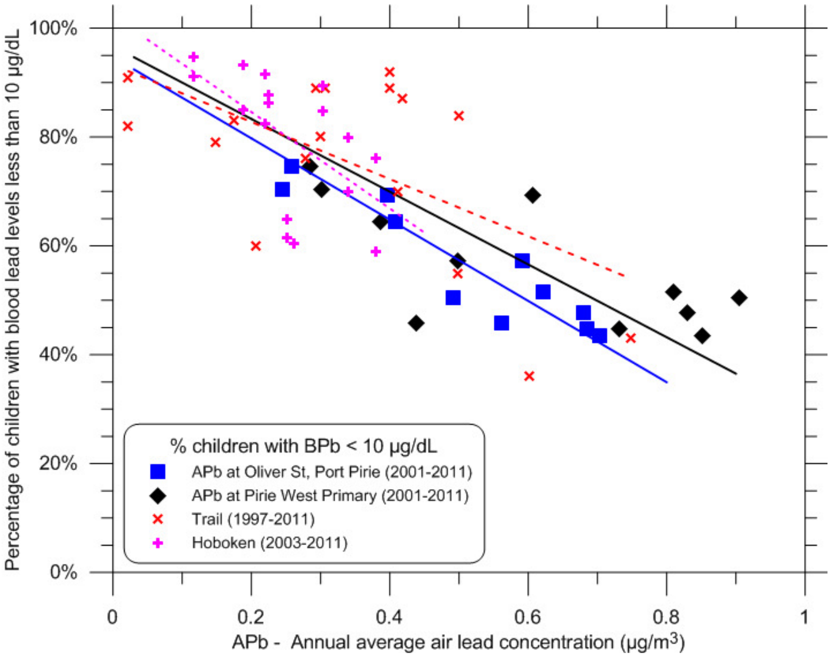

Figure 30. Relation between percentage of children with blood lead levels below 10 µg/dL and air lead concentrations based on historical data from Port Pirie (1–4 year olds), Trail (½–3 years) and Hoboken (all children).

The skewed nature of the blood lead distributions was shown for Trail data in Figure 15 and is shown more clearly for 2011 Port Pirie data in Figure 31. This figure also includes a log-normal fit, which is seen to fit the data extremely well. The geometric mean of 5.7 µg/dL is close to the peak in the distribution and the long tail to the right indicates that there is a small but non-zero probability of blood lead levels that are several times higher than the geometric mean.

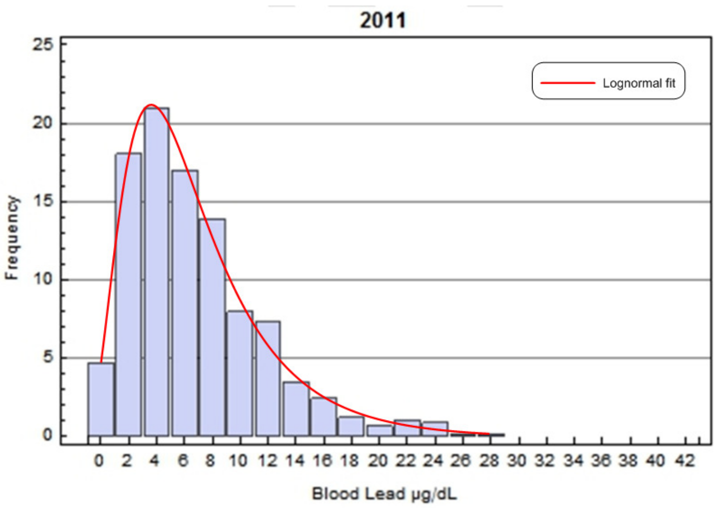

Figure 31. Frequency distribution histogram of blood lead data from Port Pirie children tested in 2011. Also shown is a lognormal fit, which fits the data very well and emphasises the skewed nature of the distribution.

For log-normal distributions there is a linear relationship between fraction of the population below a given value and the geometric mean. This is also evident in the very high correlation in the data from the each of the three sites shown in Figure 32. (This combines the data on geometric means and percentage of children below 10 µg/dL from Figure 29 and Figure 30.) Extrapolating the fits to the top axis indicates that there would be very few exceedances of 10 µg/dL if the geometric mean was about 3 µg/dL in Port Pirie, 4 µg/dL in Trail and 5 µg/dL in Hoboken. The strong correlation between these two parameters demonstrates the link between air lead concentrations and the fraction of the population below 10 µg/dL, which gives confidence to predictions in Section 9 about the likely impact of the reduced emissions from the smelter transformation on blood lead levels.

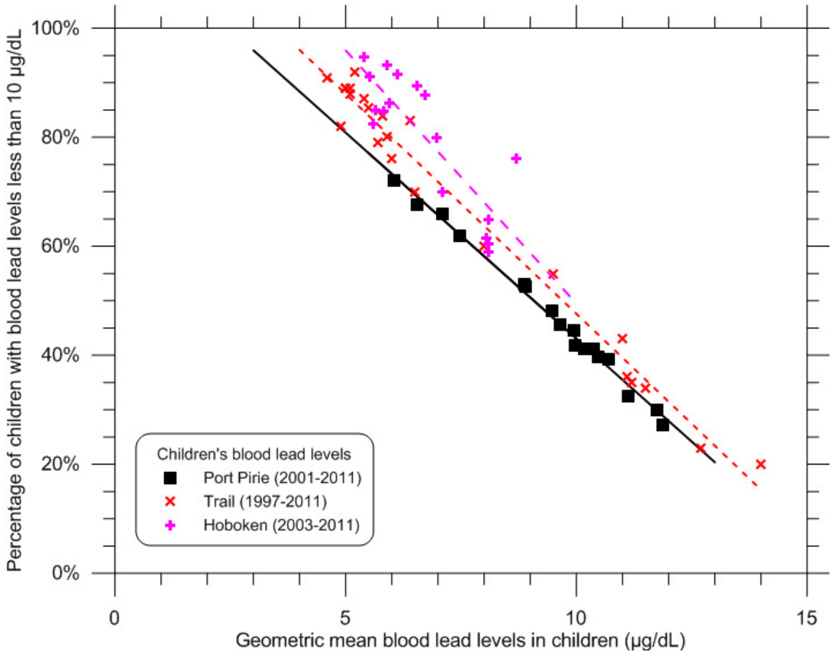

Figure 32. Relation between percentage of children with blood lead levels below 10 µg/dL and geometric mean of blood lead levels based on historical data from Port Pirie (1–4 year olds), Trail (½–3 years) and Hoboken (all children).

8. FRAMEWORK FOR MANAGING LEAD EXPOSURE

8.1 HEALTH OUTCOMES ASSOCIATED WITH LEAD EXPOSURE

This section is a narrative to do with health outcomes associated with lead exposure and with the associated language. An issue at present is that the presentation of information on health outcomes of lead exposure has used language calculated to cause anxiety among the recipients of this information. The term ’lead poisoning’ is frequently used when there is no evidence of any health outcome or any form of clinical syndrome or illness. This emotive, pejorative language is unhelpful in trying to deal with the real needs of those who have experienced increased exposure to lead. The National Health and Medical Research Council in Australia has taken a balanced and measured position on evaluation of the outcomes of lead exposure and on the basis of that developed guidelines on the possible health outcomes of certain levels of lead exposure. The guidelines are provided as recommendations to the states and territories. These are in line with the recommendations of the World Health Organization and with other jurisdictions. Guidelines for blood lead concentrations in Australia have changed over the years. In 1981 the value was 30 µg/dL, which was lowered to 25 µg/dL in 1987. By 1993 the value was decreased to 10 µg/dL. The guidelines are just that - recommendations to the states and territories that then remain to be adopted by the states and territories into their regulations and legislation.

Lead is an element, present in the Earth's crust and ubiquitously present in our environment. For that reason it would be impossible to have no lead in our bodies or to have a blood lead concentration of zero. Actions taken over the past 30 years have diminished general urban and suburban environmental exposure to lead in the developed world. Mitigation programs such as the removal of lead in petrol and paint have succeeded in lowering general population blood lead levels in various parts of the world. One can assume that the same will apply to Australia although no measures of change have been made in the general population since 1995. In these mitigation programs the low-lying fruit has been plucked and matters have moved to the need for control and regulation of other less evident sources of exposure. Inevitable attention has focused on lead producing areas and on geological sources of lead.

Fortuitously most lead-containing ores are relatively insoluble and consequentially of limited bioavailability. However, lead hazard is all around us. We use lead in many ways, especially for lead-acid storage batteries. The majority of motor vehicles and other forms of transport contain one or more batteries. As long as the containment is sound the hazard does not translate into risk. Since our society has decided to use lead we have created a need for its extraction. This is not a new phenomenon. Lead has been produced since antiquity and is likely to continue to be produced. This means that in places where lead-bearing ores are being mined and in those places where lead is extracted, refined and recycled there will be a lead hazard to those carrying out the mining and extraction and to those in close proximity to these operations. The hazard translates into risk when exposure is not managed adequately.

8.2 ENVIRONMENTAL JUSTICE

In the United States the EPA defines Environmental Justice thus:

'Environmental Justice is the fair treatment and meaningful involvement of all people regardless of race, color, nationality, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. It will be achieved when everyone enjoys the same degree of protection from environmental and health hazards and equal access to the decision-making process to have a healthy environment in which to live, learn, and work.'

If a decision were made to transfer lead production to a developing nation from Australia a profound ethical issue would arise. As a developed nation we need lead as a commodity for our industrial base. We currently produce lead subject to increasingly rigorous regulation aimed at protection of the general population and the workers producing the metal. If production were transferred to a developing nation with less effective environmental regulation, either as part of legislation or through enforcement, we would carry the ethical responsibility for the populations involved as part of environmental justice. Advocates of environmental justice make the argument that socially disadvantaged populations often undertake environmentally hazardous activities because they have few economic alternatives and/or are not fully aware of the risks involved. Environmental issues have lesser importance in socially disadvantaged groups faced with pressing socio-economic issues such as income, education, nutrition and employment. Their voice is seldom heard on matters relating to the environment, as an extension of their lack of awareness of environmental justice. A combination of this lack of awareness and lack of political and economic power makes poor minority communities a frequent target for environmentally hazardous activities, which are also hazardous to their health.

Respect of equality of opportunity and protection of both humans and the environment in which they live enhances the environment's ability to sustain human well-being. The nexus between health and wealth means that those who are relatively wealthy gain disproportionate benefits from the economic activities that degrade the environment, while those who are relatively powerless and poor typically bear disproportionate costs.

8.3 OUTCOMES, MANAGEMENT & TREATMENT OF LEAD EXPOSURE

Management and treatment of lead exposure it is a matter currently being evaluated by NHMRC (NHMRC 2009). It would be inappropriate to provide any detailed recommendations on this until such time as their review is completed. In the interim we note the following. Assessment of lead status in individuals is best carried out by measurement of blood lead. Hair lead measurement is of no value. Lead exposure should not be treated by chelation. A hierarchical treatment and management program for overexposure to lead is available in which chelation therapy is only implemented in extreme circumstances where there are defined clinical outcomes. Before blood lead measurements are undertaken there has to be some reasonable expectation of exposure. Diagnoses of low IQ or ADHD are not indicators for blood lead measurement. In any circumstances where individual adverse health outcomes are established in an individual, all potential aetiological factors should be considered.

It is unnecessary in this section to describe the health outcomes of lead exposure. Numerous articles in past years have done just that in great detail. The most recent are publications this year (2012) from the Centres for Disease Control (CDC, 2012) and the National Toxicology Program (NTP 2012) in USA (2012). The measurement of health outcomes from lead exposure below 10 µg/dL is difficult. Changes such as development of renal disease and anaemia can only start to be seen at relatively high blood lead concentrations – greater than 15 µg/dL. The review carried out by the National Toxicology Program in USA is helpful in understanding the level of reliable epidemiological evidence associated with these outcomes. In the summarial tables the assessment of outcomes is categorised as being ‘sufficient’, ‘limited’ or ‘inadequate’ for blood lead ranges of <5 and <10 µg/dL, in adults and children. Without exception all the studies were carried out in populations as epidemiological investigations. None were associated with change in individuals.

8.4 A DISTRIBUTIONAL APPROACH

It is notable that in the publications from CDC and NTP there has been a shift away from the concept of absolute numerical guidelines to description of lead exposure on the basis of population norms. These population norms or population distributions of blood lead are derived from the various National Health and Nutrition Examination Survey (NHANES) studies in USA. This approach remains to be evaluated for use in Australia. This population-based approach, which has also been taken in Germany, relies on identifying that subset of the population, which lies above a discrimination limit. In Germany the discrimination limit has been set at the 95th percentile of the population distribution of blood lead levels. In the USA the limit is the 97.5th percentile of the population. The most important aspect that has to be taken into account in any of these descriptors of outcomes from lead exposure is that all are derived from the epidemiological studies of very large populations. Information derived in this way gives guidance on acceptable levels in populations but cannot and should not be used in understanding of outcomes of lead exposure of individuals.

In pursuing a distributional approach of the nature described above, decisions have to be made at a political level on the proportion of the population that will be protected. As indicated above, the United States of America has adopted protection for 97.5% of the population. The distributions generated this way are always skewed (for example see Figure 15 and Figure 33), which means that arithmetic means of the blood lead concentrations in the population are inappropriate. For this reason geometric means, which more properly describe the peak of the distribution, have generally been adopted.

8.5 RELIABILITY OF MEASURES OF EXPOSURE AND OUTCOMES OF EXPOSURE

A key issue in understanding the relationships between exposure, outcomes and blood lead concentrations is that all of these measures have a substantial level of variance. Blood lead conventionally measured is likely to have a 10% or more variance on the laboratory results and probably more at the lowest levels of measurement. This would be combined with variance associated with sampling and personal physiology. IQ is a very imprecise measure and is normally broken down into different components all of which have substantial levels of variance. Exposure is a combination of a large number of different inputs, measurements of which has always been fraught with difficulty.

This tells us that we should not ascribe excessive levels of accuracy to relatively imprecise measures. More pertinently we should seek to make the action on exceedance of guidelines or other regulatory limits match the degree of over-exposure.

8.6 LEAD KINETICS

In describing the relationship between lead exposure and the body burden of lead, the assumption that the relationship is linear is incorrect. Blood lead concentrations are taken as a surrogate measure of body burden. Most studies have shown that the relationship is non-linear, with the greatest rate of change in blood lead being observed at the lowest levels of exposure. This is true for both gastrointestinal exposure and pulmonary exposure. There is a complex relationship between vectors of lead exposure and the bioavailability of the different lead species in the source.

For airborne exposure to lead, particle size is critical. Lead species are not gaseous or liquid (excepting some alkyl lead compounds) which means that all lead in the air will exist as particles of various sizes. Only the smallest particles can pass through the upper respiratory tract to the deep space of the lung alveoli for potential absorption. Such particles have a relatively high bio-availability because of their high surface area to volume ratio. Larger particles are likely to be swept by muco-ciliary action into the oesophagus and there follow the same gastrointestinal absorption route as lead-bearing materials in diet. The rate of absorption of gastrointestinal lead is very variable, from less than 1% to 20+%, and highly contingent on the satiety state of the individual. Gender and age are also drivers of the bioavailability of lead with children and women in their childbearing years more likely to absorb more lead because of mineral insufficiency, especially iron deficiency (see section 6.3.5).

On an international basis the relationship between lead exposure from the air and blood lead is similar at a number of different sites all proximal to lead smelters. This relationship would suggest that there is an intercept on the blood lead axis around 3 µg/dL as shown in Figure 29 for Port Pirie. The graph of the relationship is fairly shallow with a gradient of around 9 µg/dL per µg/m^3 but would suggest that even if air lead concentrations could be reduced to near 0 there will still be a residual background of exposure from other sources - both natural and anthropogenic (see section 6.3.3).

8.7 LEAD IMPACTS ON BIOCHEMISTRY & INTELLIGENCE

The relationship between the presence of lead in organisms and various biochemical outcomes is also curvilinear. These effects can often be observed at very low levels of lead exposure but in general are not associated with any specific clinical outcome. For example the enzyme 5-aminolaevulinate dehydratase is highly sensitive to the presence of lead. Its activity decreases curvilinearly as lead concentrations rise. At environmental levels of exposure the inhibition is not associated with any clinical outcome. It is also possible to measure changes in long nerve conduction velocities, which are slowed as lead concentrations rise but are not tied to any clinical changes at environmental exposure levels. These too would seem to follow non-linear relationships. It is thus unsurprising that measures of lead-related IQ change also follow non-linear relationships. The normative value for IQ for any population is 100 and graphs of log/linear relationships which place the intercept greater than 100 are inappropriate. It is also inappropriate to use these epidemiological relationships, which have been developed for a large population to describe outcomes in any individual.

The relationship between lead exposure and IQ is a particularly fraught association. Increased lead exposure does contribute to diminution in IQ. However there are multifactorial drivers of intelligence. At current levels of lead exposure in the general population other factors are probably more important in development of intelligence. In particular environment, genetic background, education, nutrition, gestation and birth weight are all material factors in development of IQ pre-and post-natally. The same applies to exposed populations in whom lead is another factor in development of intelligence.

8.8 THE HISTORICAL BACKGROUND IN PORT PIRIE

In the particular circumstances of Port Pirie, examination of lead exposure and blood lead concentrations has been pursued over many years. The record from 1984 onwards shows a continuous downward trend in mean blood lead concentrations. This is consistent with the continued attention to minimisation of exposure and mitigation of effects of exposure. The various curves in Figure 33 describe the distribution of blood lead concentrations in Port Pirie in

- 1984,
- 2011,
- post-introduction of new technologies for lead smelting, and
- distribution in a population of infants in NSW described by (Gulson, et al. 2008).

The distributions demonstrate that in 1984 most subjects exceeded 10 µg/dL but at that time the guidance value was higher (30 µg/dL). The situation now shows that about 25% of the population have blood leads greater than 10 µg/dL. This is consistent with the process of continuous improvement over the past 27 years. The projected situation post-transformation suggests that there would still be some subjects with blood lead concentrations greater than 10 µg/dL. This takes into account residual non-airborne exposure resulting in mean blood leads of about 3 µg/dL (see Figure 29). If further actions are taken to minimise these parallel routes of exposure there could be further diminution in the percentage of subjects with blood lead greater than 10 µg/dL.

In a continuous distribution it is obvious that in the ‘tail’ of values, even for a suburban population in NSW (far removed from a lead smelter), some will have BPb > 10 µg/dL. A corollary to this is that the discrimination limits of 30 µg/dL in 1984 and 10 µg/dL presently are not descriptors of health outcomes. A shift from 9 µg/dL to 11 µg/dL does not imply a sudden shift of health outcomes, merely a 2 µg/dL change in BPb in a continuum of change.

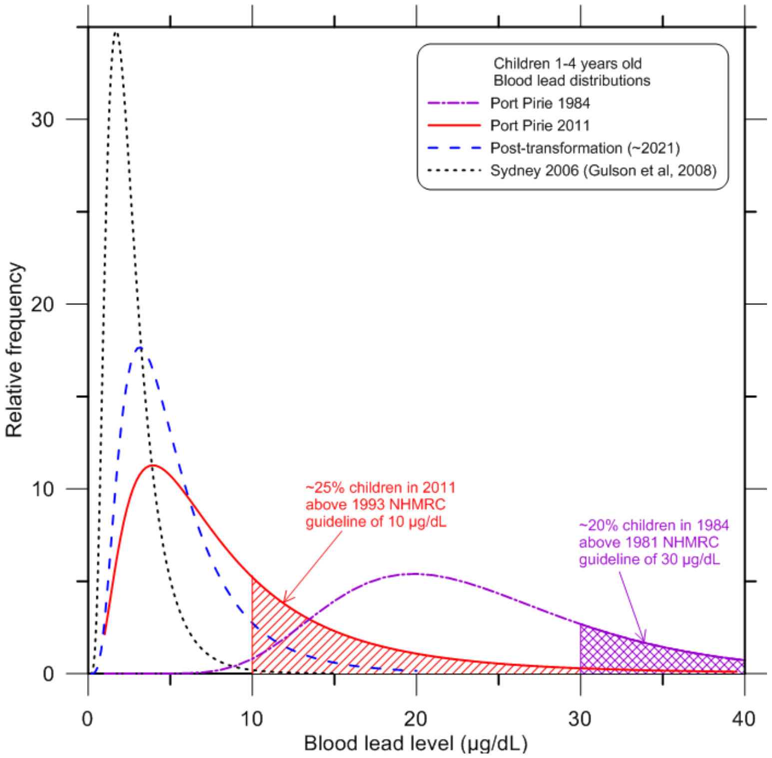

Figure 33 Schematic representation of blood lead distributions for Port Pirie in 1984, now (2011), and projected Post-transformation, compared with a urban Sydney population.

8.9 A DISTRIBUTIONAL APPROACH AND SUBSEQUENT MANAGEMENT

To evaluate change and to put in place a rational scheme of management of exposure, a shift from arbitrary guidelines to population distributions has merit. The data for Port Pirie occupational exposures and general population exposure is already being collected. The need now is to define the % point in the distribution above which a scheme of action to mitigate lead exposure should be implemented. For consistency with the approach taken by USA the 97.5th percentile might be used.

There is then a need for action to deal with the subgroup of the population whose blood lead lies outside the desired 97.5% population envelope. The reasons for individual excess exposure and absorption need to be sought and managed by appropriate education and training given on matters relating to hygiene, exposure to dust and exposure to other vectors. These are not the only potential reasons for increased blood lead concentrations. As indicated previously, gender and age are drivers of absorption. Mineral balance and nutrition are particularly important and in some circumstances altered physiology may contribute to hyper-absorption of metals. Such factors need to be actively sought and managed in the individual to minimise their uptake of lead. Experience has shown that the outcome of lead mitigation measures takes some time to become evident. It is important both politically and publicly to make this clear since impatient demands for instant outcomes are unlikely to be realised.

9. POST-TRANSFORMATION PERFORMANCE

9.1 INTRODUCTION

Before describing the likely environmental and health performance post-transformation, it is useful to note the outcomes from continuing as-is (status quo) or smelter closure.

Status quo. The improvements in blood lead levels achieved since 2005 with the 'Ten by 10' and 'Ten for Them' programs have started to level off – approximately 25% of children still have blood lead levels above 10 µg/dL (Figure 28). These programs have seen action on both exposure reduction in the community and emission reductions from the plant. The latter have approximately halved air lead concentrations since 2005 (Figure 19) but the current dominance of sinter plant emissions highlighted in Section 2 points to only marginal further improvements in air lead and blood lead levels being possible until the aged sinter plant is replaced with modern technology.

Smelter closure. Results on blood lead reductions following the closure of the Cockle Creek smelter (Figure 22) show that even after three years there were still 7% of young children above 10 µg/dL. This is because lead from soil and house reservoirs continues to contribute to children's exposure. Thus, even with smelter closure, remediation of the environment would be required to reduce all children's exposure to an acceptable level. Furthermore, although not considered in this report, smelter closure would be likely to have extreme negative impacts on the socio-economic and hence health outcomes of Port Pirie residents.

9.2 LIKELY PERFORMANCE POST-TRANSFORMATION

The primary source of lead emissions at the Port Pirie smelter is the sinter plant. Nyrstar proposes to replace the existing sinter plant with modern encapsulated bath smelting technology. EHWP commissioned CSIRO to review the newest of these technologies (SKS) and they advised that it is 'bona fide' example of best practice in the general class of enclosed bath smelting technologies.

Based on the work described in Section 2 it is estimated that the transformational upgrade of the sinter plant will reduce the amount of lead dust emissions from the smelter site by more than 50%. Based on standard dispersion modelling principles and an understanding of the other sources, it follows that air lead concentrations will also reduce by more than 50%. In the following, we assume an initial 50% reduction due to the technology transformation of the sinter plant with further reductions occurring as a result of ongoing continuous improvements described in Section 3.3 (e.g. pit remediation, improved concentrate handling and fume reduction using surplus baghouse capacity). It is estimated that over the next 10 years this is likely to produce total reductions of 75% of current values.

Observations by the EHWP of best practice smelters (in Belgium and Canada) summarised in Section 4.3 show that a halving of air lead concentrations took from 1–4 years (Figure 16) so we have assumed an average of these figures for the Port Pirie transformation. These estimates have been used to show the projected reductions schematically in Figure 34. Current annual average air lead concentrations of about 0.4 µg/m^3 at licensed EPA monitoring sites will drop to 0.2 µg/m^3 over a couple of years with further reductions during the decade to possibly produce values as good as 0.1 µg/m^3. The EHWP believes that an annual average of 0.2 µg/m^3 could be achieved consistently while 0.1 µg/m^3 could be achieved much of the time but not consistently.

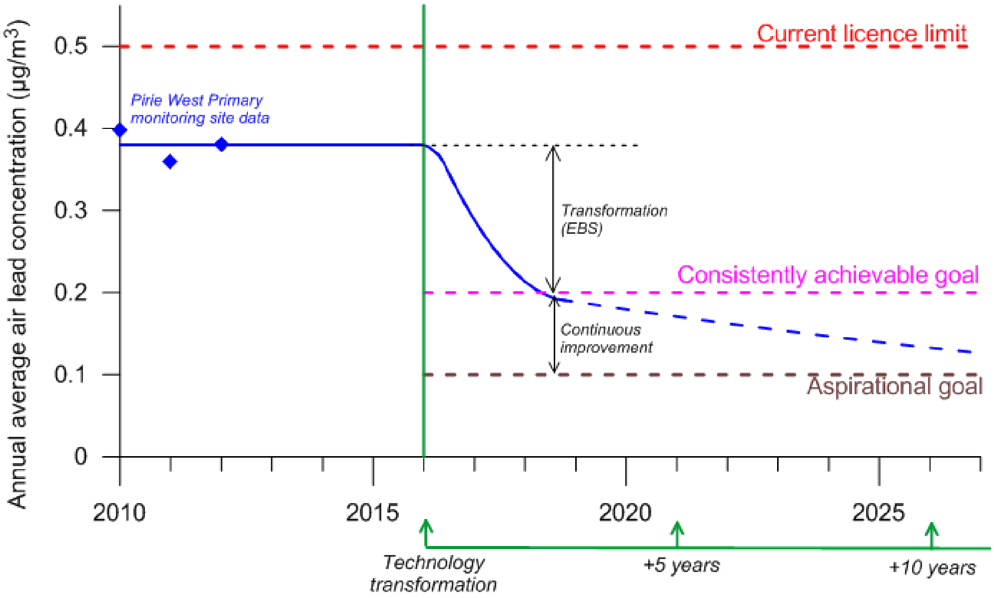

Figure 34 Schematic diagram of projected reductions in air lead concentrations at EPA licensed monitoring sites (Oliver Street and Pirie West Primary School) following the introduction of EBS (encapsulated bath smelting) technology in 2016 and implementation of a continuous improvement program.

Using the results presented in Figure 30, we can estimate that a reduction of annual average air lead concentrations to 0.2 µg/m^3 will increase the percentage of children with blood lead levels below 10 µg/dL from the current value of about 70-75% to about 85%. However, as shown in Figure 17 for other best practice smelters, the timescale for blood lead reductions is longer, typically 7-9 years.

These numbers were used to produce the schematic illustration in Figure 35 of the projected increase in the percentage of children with blood led levels below 10 µg/dL.

Further targeted projects to reduce emissions to meet the aspirational goal of 0.1 µg/m^3 for air lead, together with the targeted community lead abatement program described in Section 9.3 are projected to see the percentage of children below 10 µg/dL reach 85-90% about 8 years after the transformation with further increases to 95% about a decade after the transformation. This equates to a decrease from around 200 children currently above the NHMRC recommendation to around 40 children a decade after the transformation.

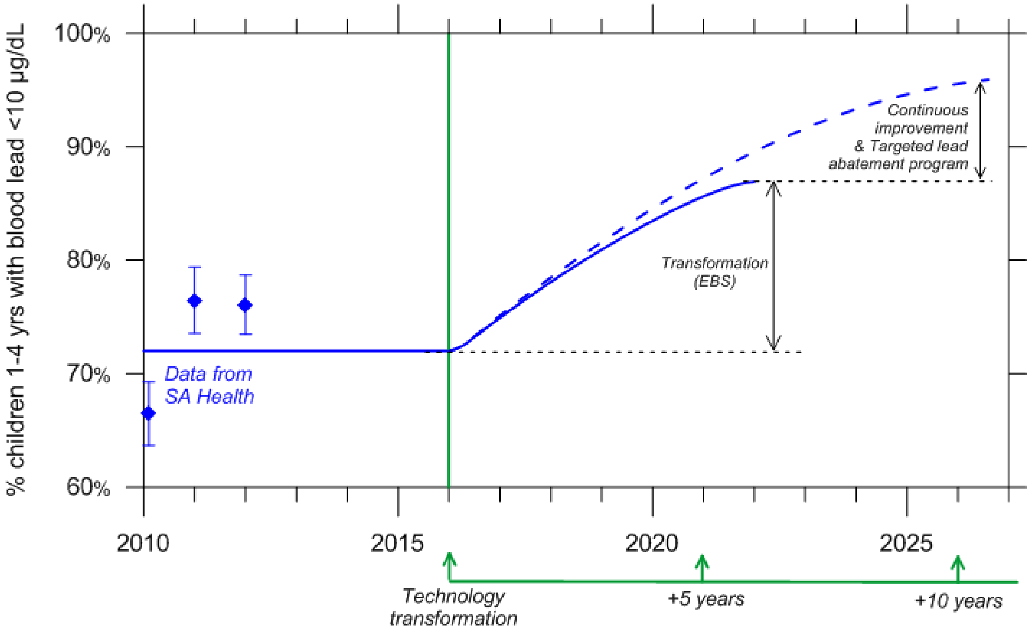

Figure 35 Schematic diagram of projected increase in percentage of children with blood lead levels below 10 µg/dL following the introduction of EBS (encapsulated bath smelting) technology in 2016 and implementation of the targeted lead abatement program.

In order to provide a better understanding of the impact of the transformation on blood lead levels within the community, Figure 36 shows the projected changes in the blood lead distributions using the results of the analyses presented in Section 7. These projections show that with the transformation and the targeted lead abatement program, a large percentage of the population would have blood lead levels that are no different from those reported from urban Sydney in 2006.

Following the transformation, there will still be some contamination from other smelting site sources, such as the Slag Fumer, and therefore ongoing smaller-scale upgrades will be required. However as air quality improves (post-transformation) it is unlikely that further CAPEX will bring about another step-change in blood lead levels as the contamination from historical sources of lead will become a relatively larger part of the 'residual exposure'.

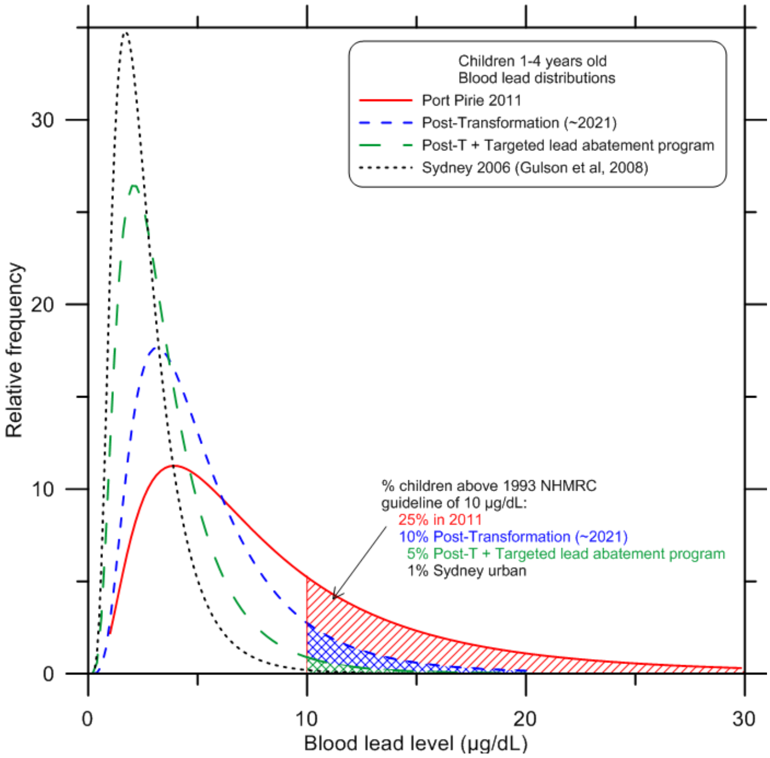

Figure 36 Schematic of current and projected blood lead distributions in Port Pirie compared with distribution among children in Sydney in 2006 **(Gulson, et al. 2008)**.

9.3 TARGETED LEAD ABATEMENT PROGRAM

In order to manage this 'residual exposure' risk, Nyrstar and the South Australian Government have established a working group to develop objectives and recommendations for the implementation of a new Targeted Lead Abatement Program (TLAP) in Port Pirie.

The TLAP working group will identify current and potential future community lead exposure reduction strategies and assess which are likely to have the greatest impact in reducing children's blood lead levels. A first milestone for the TLAP working group is to provide details of the proposed program and its implementation for consideration for implementation by the Port Pirie Transformation Steering Committee, the group overseeing the numerous work streams that need to be delivered by the end of 2013 to enable the project to proceed. Leading up to this milestone, numerous key stakeholders from a range of areas will be engaged to provide input into the development of TLAP. In this process, ongoing communication and community engagement regarding the TLAP process and implementation will be vital.

Nyrstar and the State have made a commitment to pursue the TLAP for a period of 10 years in order to achieve the long term objectives of the program. During this time the program will need to be constantly evaluated and modified to respond to changing environmental conditions in the community during and post-transformation.

Community engagement and ownership of the Port Pirie blood lead reduction program has been the cornerstone of its success since 1984. Since 2006 there have been three community blood lead awareness campaigns, ’Ten by 10’, ‘Ten For Them’ and the most recent ‘Thumbs up for low levels’. The Port Pirie Targeted Lead Abatement Program is considered a natural progression of these previous programs and critical to the success of the transformation project and the subsequent reduction in community blood lead levels.

TLAP is expected to commence in 2014 in the lead up to the proposed construction and commissioning of the new technology in 2016. Strategies will continue post commissioning to minimise exposure to historical lead disposition and ensure the transformation objectives are met.

9.4 LIKELY PERFORMANCE COMPARED WITH INTERNATIONAL STANDARDS

The current Australian air quality standard (NEPM) for air lead is 0.5 µg/m^3 (12 month average) and the current NHMRC recommendation (NHMRC 2009) is that all Australians should have blood lead levels below 10 µg/dL and that all children’s exposure to lead should be minimised. NHMRC is currently undertaking a review of its guidelines which it expects to complete by late 2013 or early 2014.

The air lead standard (annual average) in Europe was reduced to 0.5 µg/m^3 in January 2005. A transitionary value of 1.0 µg/m^3 was applied in the immediate vicinity of specific, notified industrial sources from January 2005 until January 2010, after which time the 0.5 µg/m^3 limit was also applied to these sources. The blood lead intervention level in most of Europe (but see below for Germany) follows the 2005 US Centers for Disease Control and Prevention recommendation of 10 µg/dL (US CDC 2005).

The US EPA introduced a new air quality lead standard in 2008 of 0.15 µg/m^3 (rolling 3-month average). This replaced the 1978 lead standard of 1.5 µg/m^3 (quarterly average) (USEPA 2008), although there was a transitionary arrangement for areas designated nonattainment for the 1978 standard, that the 1978 standard remained in effect until implementation plans to attain or maintain the 2008 standard were approved. However, this new standard drove the closure (slated for the end of 2013) of the last lead smelter in the US (Herculaneum).

The US Centers for Disease Control and Prevention (CDC 2012) recommended in 2012 that its previous recommendation of 10 µg/dL be replaced by a reference value based on the 97.5th percentile of the blood lead levels of children 1-5 years old (currently 5 µg/dL), which should be used to identify children with elevated blood lead levels for whom public health actions should be initiated. They noted that there are currently approximately 450,000 US children above this reference level.

In Germany a reference value of the 95th percentile has been set, which is currently 3.5 µg/dL for children aged 3-14 years, 7 µg/dL for women and 9 µg/dL for men. There are currently approximately 400,000 German children aged 3-14 years above this reference value.

In summary, the worldwide trend is to continue to drive blood lead levels down further. However, as discussed in Section 8, at blood lead levels below 10 µg/dL, the health outcomes from lead exposure are all derived from epidemiological studies of very large populations, and cannot be used in understanding the outcomes of lead exposure of individuals. Certainly the term ‘lead poisoning’ is inappropriate when there is no evidence of any clinical syndrome or illness; there is need to try and move the media away from this term to one of ‘acceptable levels’ with ‘minimal effects’.

10. CONCLUSION

There is a requirement to transform the smelter at Port Pirie in order to reduce emissions of lead to air and hence reduce blood lead levels in young children in the community.

Based on the work described in Section 2, it has been demonstrated that the sinter plant (and associated activities) is responsible for at least 50% of air lead emissions from the smelter – the evidence comes from both fugitive emissions studies and backtracking analysis from Port Pirie monitoring sites.

Therefore the key premise of the transformation is to replace the sinter plant with modern best practice encapsulated bath smelting (EBS) technology, thereby eliminating the major source of fugitive lead emissions. A range of best practice technologies are used worldwide including KIVCET, QSL, Outotec, ISASMELT, and SKS. All of these technologies will perform to a high environmental standard as long as best practice gas handling facilities are properly retro-fitted.

Historic air quality data at Port Pirie shows that a series of improvements (mainly as part of the 'Ten by 10' program) has reduced annual average air lead concentrations in Port Pirie by an average of 11% p.a. over the last decade, from around 0.8 ug/m^3 to 0.3-0.4 ug/m^3 at the licensed monitoring sites at Pirie West Primary and Oliver Street. However, with more than 50% of current lead dust emissions coming from the sinter plant, it is expected that there would only be marginal further improvements until the proposed technology transformation occurs.

A review of best practice technologies at smelters in Belgium and Canada showed that their technology transformations at least halved average air lead concentrations within 1-4 years following commissioning. Following transformation at Port Pirie, we can expect air quality to improve to an annual average air lead concentration of 0.2 ug/m^3 (consistently) and there will be periods when 0.1 ug/m^3 will be achieved (but not consistently over a full 12 months).

Analysis of data from Trail (Canada) and Port Pirie show that we can expect that reducing air lead concentrations to 0.2 ug/m^3 will reduce the geometric mean of blood lead in children of Port Pirie from 6 ug/dL to 4 ug/dL over about the next 8 years. While the mean blood lead level is indicative of overall performance, the distribution in the population is significantly skewed such that there may still be a significant number of children outside of the health guideline (the 'tail'). We expect that over the next 8 years or so the percentage of children with blood lead levels below 10 µg/dL will increase from the current value of about 70-75% to about 85-90%.

As air lead concentrations are reduced further (below 0.2 ug/m^3), factors other than the reduced emissions from the transformed smelter, such as historic lead contamination, play a more significant role. Thus a targeted lead abatement program is recommended to manage this ‘residual exposure’ risk.

With ongoing improvements to the plant to reduce emissions to meet the aspirational air lead goal of 0.1 µg/m^3, the targeted community lead abatement program described in Section 9.3 is projected to see the percentage of children below 10 µg/dL reach 95% about a decade after the transformation. This equates to a decrease from around 200 children currently above the NHMRC recommendation to around 40 children a decade after the transformation.

While the objective of the targeted lead abatement program should be to ensure that all children are below the guideline, the reality is that even in a suburban population (such as Sydney) a small number of children will still be above the guideline. At this stage there is a need to shift the management of blood lead levels from guideline values to a ‘distributional approach’ such as that recently adopted in the US and Germany. In the meantime, a focus on mean blood lead improvements and a targeted program for the children who continue to have higher blood lead levels (post-transformation) is the way forward for Port Pirie.

The next steps require preparation of the Engineering Feasibility Study, Environment Improvement Program, Targeted Lead Abatement Program and Development Assessment reports. They all rely on the concepts and principles outlined in this document – the Environment and Health Feasibility Study – and further work should ensure that they build on these concepts. In some cases further work will lead to increased confidence around the concepts put forward however it is unlikely that this will lead to substantial changes in the projections for air quality and blood lead levels.

11. REFERENCES

AirBase. "AirBase 6 - the European Air quality dataBase." 2012. http://acm.eionet.europa.eu/databases/airbase/index_html; www.eea.europa.eu/data-and-maps/data/airbase-the-european-air-quality-database-6.

British Columbia Ministry of Environnment. *Profiles on remediation projects - Teck Cominco Lead-Zinc Smelter, Trail,BC.* www.env.gov.bc.ca/epd/remediation/project-profiles/pdf/teck-cominco.pdf, 2009.

Cantrell, CA. "Review of methods for linear least-squares fitting of data and application to atmospheric chemistry problems." *Atmos. Chem. Phys.* 8 (2008): 5477–5487.

CDC. *Low Level Lead Exposure Harms Children: A Renewed Call for Primary Prevention. Report of the Advisory Committee on Childhood Lead Poisoning Prevention.* www.cdc.gov/nceh/lead/ACCLPP/Final_Document_030712.pdf, 2012, 65.

CDC,. "Update on Blood Lead Levels in Children." 2012. www.cdc.gov/nceh/lead/ACCLPP/blood_lead_levels.htm.

Gulson, B, et al. "Longitudinal monitoring of selected elements in blood of healthy young children." *J. Trace Elements in Medicine and Biology* 22 (2008): 206-214.

Hibberd, MF. *Preliminary Analysis of meteorological and Lead Data from Port Pirie Monitoring Sites.* CSIRO, 2012.

Kranz B., Simon D.L., and Leonardi B.. " The behavior and routes of lead exposure in pregrasping infants." *J Exp Anal Environ Epidemiol* 14, no. 4 (2004): 14: 300-311.

Maynard, EJ, LJ Franks, and MS Malcolm. *The Port Pirie Lead Implementation Program: Future Focus and Directions.* www.health.sa.gov.au/pehs/PDF-files/ptpirie-future-focus-06.pdf, 2005.

Nelen, V. *Loodgehalten bij kinderen uit Hoboken (Lead levels in children from Hoboken).* www.provant.be/leefomgeving/onderzoek/milieu_en_gezondheid/zware_metalen/, 2005-2012.

Nelen, V, and G Thys. *Bevolkingsonderzoek lood in blood. Antwerpen District Hoboken, Wijk Moretusburg-Hertogvelden. Verslag najaar 2011.* Provinciaal Instituut voor Hygiëne, www.provant.be/binaries/HobokenNJ11_tg_tcm7-145267.pdf, 2011.

NHMRC. 2009. www.nhmrc.gov.au/guidelines/publications/new36new37.

NHMRC,. “Blood lead levels for Australians - Information Paper.” 2009a. www.nhmrc.gov.au/_files_nhmrc/publications/attachments/gp2-lead-info-paper.pdf.

NOHSC. *National Standard for the Control of Inorganic Lead at Work; NOHSC:1012.* National Occupational Health and Safety Commission, ww.safeworkaustralia.gov.au/sites/swa, 1994.

NTP. “NTP Monograph on health effects of low-level lead.” 2012. http://ntp.niehs.nih.gov/NTP/ohat/Lead/Final/MonographHealthEffectsLowLevelLead_prepublication_508.pdf.

Ohmsen, G. *Bio-accessibility of Pb, AS and Cd in smelter materials and indoor air-fall dusts.* SA Department of Health, 2006.

PAE Holmes. “Nyrstar Port Pire - Fugitive metals emissions study.” 2012.

Simon, D L, E J Maynard, and K D Thomas. “Living in a Sea of Lead - Changes in Blood and Hand Lead of Infants Living Near a Smelter.” *J Exp Sci Environ Epi* 17 (2007): 248-259.

SKM. “Fugitive Particulate Emission Study, Pasminco Port Pirie Smelter.” 1999.

THEP. “Fall 2011 Blood Lead Report.” 2011. www.thep.ca/upload/resources/13/fall11bloodlead_original.pdf.

US CDC. *Preventing lead poisoning in young children.* www.cdc.gov/nceh/lead/publications/prevleadpoisoning.pdf, 2005.

USEPA. *Lead air quality standards.* 2008. www.epa.gov/air/lead/standards.html.

USEPA. “Review of the NAAQ standard for lead: policy assessment of scientific and technical information OAQPS Staff Paper: EPA-542/R-07-013.” 2007, 5-16.

VMM. *Studie van de luchtverontreiniging in de omgeving van de Umicore vestiging in Hoboken; Jaarrapport 2009.* http://publicaties.vlaanderen.be/docfolder/21170/rapport_Hoboken_2009.pdf, 2009.

Resources for a changing world