



Evaluation of exposure controls used in electrolytic nickel plating

Prepared by researchers at the
Health and Safety Executive

RR1184 (2022)
Research Report

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Prepared 2019

First published 2022

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Workers in the electroplating industry are potentially exposed to a range of hazardous substances including nickel compounds. Exposure can cause serious health effects including cancer, asthma and dermatitis. Exposure can occur via inhalation, dermal and ingestion routes.

This report describes an evaluation of six engineering control measures that can potentially reduce exposure to nickel compounds at nickel plating plants. The evaluation considered airborne emissions of soluble nickel compounds and surface contamination of the front lip of the plating tank. The research used laboratory tests on a commercially available small scale plating plant. The control measures considered are: (i) eductors - a pumped circulation system used for solution mixing; (ii) the rate of air agitation used for solution mixing; (iii) local exhaust ventilation (LEV); (iv) freeboard height - the distance between the liquid surface and the tank lip; (v) chroffles - plastic balls used to insulate the liquid surface; and (vi) surfactant concentration – process additives for the surface tension of the plating solution.

The research found that the most effective engineering control was to use eductors or add LEV to an air agitated tank. Using basic principles of occupational hygiene, the researchers identified that use of eductors was best because this eliminates emissions at source and is the most reliable option.

This report and the work it describes were funded by the Health and Safety Executive. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

Evaluation of exposure controls used in electrolytic nickel plating

Matt Coldwell¹, John Saunders¹, Steve Bennett¹, Paul Smith²

1. Health and Safety Executive,
Harpur Hill, Buxton, Derbyshire, SK17 9JN

2. Health and Safety Executive,
19 Ridgeway, 9 Quinton Business Park, Quinton,
Birmingham, B32 1AL

Acknowledgements

The authors would like to thank all those involved in this project. Particular thanks go to Paul Lansdell (Management Board, Institute of Metal Finishing,) and Dave Elliott (Chief Executive, Surface Engineering Association).

KEY MESSAGES

There are approximately 3000 workers employed at around 450 companies in the Great Britain (GB) surface treatment industry who are potentially exposed to a range of carcinogens, asthmagens and skin sensitisers including nickel (Ni) compounds. Exposure occurs by inhalation, absorption through the skin, by ingestion or any combination of these three routes.

HSE researchers undertook a series of laboratory tests to evaluate the effect of different control measures on the emissions generated from an electrolytic nickel plating tank. An assessment of how they affect the surface contamination deposited on the front lip of the plating tank was also carried out. The different controls measures assessed were:

- eductors (a pumped circulation system used for solution mixing which utilises the venturi effect)
- air agitation rate (where air agitation is the method used for solution mixing)
- local exhaust ventilation (LEV)
- freeboard height (the distance between the top of the liquid surface and the top of the tank lip)
- chroffles (plastic balls used to cover the liquid surface)
- surfactant concentration (a chemical additive required for the process, which alters the surface tension of the plating solution)

Emission of airborne soluble nickel from the plating tank was reduced by:

- use of eductors
- use of LEV
- reducing the air agitation rate
- increasing the freeboard measurement
- use of chroffles
- increasing plating solution surfactant concentration

All of the above also reduced surface contamination, except LEV. In this case the relationship was not clearly defined, however, use of higher LEV flow rates were generally associated with increased surface contamination.

Reductions of more than 98 % in the airborne emission rate measured above the tank were found when adding LEV to a system using air agitation as the solution mixing method. Comparable reductions were achieved without the need for LEV when using eductors as the solution mixing method.

Using basic principles of occupational hygiene and applying the hierarchy of control specified in the Control of Substances Hazardous to Health (COSHH) Regulations, we consider eductors to be a more suitable exposure control as they eliminate emissions at source and the process cannot be operated when they are not working. LEV captures the emissions before they can present an exposure risk, so in the event that LEV fails then exposure will occur if the process is not stopped.

EXECUTIVE SUMMARY

Introduction

Previous HSE research¹ estimated that there are approximately 3000 workers employed at around 450 companies in the Great Britain (GB) surface treatment industry who are potentially exposed to a range of carcinogens, asthmagens and skin sensitisers including nickel (Ni) compounds. Many of these workers are employed in small to medium sized enterprises. The work showed that exposure occurs by inhalation, absorption through the skin, by ingestion or any combination of these three routes.

There are a range of measures that can be used to reduce airborne emissions from electroplating tanks and these are also likely to affect the dermal and ingestion exposure potential. These measures vary in efficacy, cost, complexity, and ease of use. There is no clear guidance for the industry on the most appropriate and cost effective techniques. One of the main recommendations of the previous research was that *“A systematic evaluation of these (control) measures should be carried out to allow the provision of evidence based guidance aimed at reducing exposures to carcinogens and asthmagens in the electroplating industry.”*

Aims and objectives

Phase 1.

- To set up a test electrolytic nickel plating facility at the HSE Science and Research Centre Buxton, in consultation with industry experts.
- To establish the emission rate reproducibility from an electrolytic air agitated nickel plating tank.
- If emission rates are reproducible ($\pm 10\%$) then phase 2 would be carried out.

Phase 2.

Determine the effect on emission rates and tank lip surface contamination of a range of electroplating control measures.

Methods

For phase 1 a small scale electrolytic manually operated nickel plating process was set up with the ability to evaluate different control measures.

The metric used to assess the efficacy of different agitation/exposure control techniques was the emission rate; this being the amount of nickel becoming airborne per unit time (μg nickel per second).

Emission rate reproducibility was less than 10 %, however greater variation in results was observed with tests carried out several weeks apart. To allow comparison of all test results, a reference point was established by carrying out a “base condition check” when switching from one control to the next.

Statistical modelling was used to verify the findings for the emission rate data.

¹ HSE 2013. *Exposure to hexavalent chromium, nickel and cadmium compounds in the electroplating industry.* HSE research report RR963. <http://www.hse.gov.uk/research/rrpdf/rr963.pdf>

For phase 2, the original scope of work was expanded to consider the effect the different control measures had on the dermal exposure potential. This was assessed by measuring the contamination on the front lip of the plating tank ($\mu\text{g Ni cm}^{-2}$) using surface wipe sampling. The control measures assessed during phase 2 were;

- use of eductors (a pumped circulation system used for solution mixing which utilises the venturi effect)
- varying the air agitation rate (air agitation is the method used for solution mixing)
- use of local exhaust ventilation (LEV)
- differing freeboard height (this is the height from the liquid surface to the top of the tank)
- the use of chroffles (plastic balls used to cover the liquid surface)
- differing surfactant concentration levels (a chemical additive required for the process, which alters the surface tension of the plating solution)

Findings

The efficacy of electroplating controls is now much better understood and supported by quantitative scientific evidence. The results are summarised in the table overleaf.

Eductors and LEV offer the biggest reductions in emission rate with both being similarly effective. Eductors also significantly reduced surface contamination whereas use of LEV tended to increase it. Eductor agitated systems are likely to be cheaper to install than LEV, whether for new installations or for retro fitment onto existing plant. Running cost implications were not fully explored however ongoing running and maintenance costs of eductor plant are likely to be lower than air agitated systems. LEV captures the nickel aerosol emitted and moves it elsewhere to prevent worker exposure, which means there could be a loss of control should the LEV system deteriorate or fail. An LEV system should be designed to cut the power in such an event, so that the plating process stops and does not fail to danger. As the eductors are required by the process to achieve adequate mixing, then more robust emission control is more likely to be achieved on a consistent and sustained basis because they virtually eliminate the nickel aerosol emitted from the plating tank. This is preferable when considering the hierarchy of control specified in the Control of Substances Hazardous to Health (COSHH) Regulations.

Air agitation rate was found to have an effect on both emission rate and surface contamination, with a bigger effect observed on the surface contamination but in a less consistent relationship. Freeboard measurement had a limited effect on the emission rate but a significant effect on surface contamination, particularly at 50 mm. Use of chroffles had a significant effect on both emission rate and surface contamination. However, the surface contamination measurement does not fully assess the dermal exposure potential and so the real world impact on the dermal exposure potential may not be as significant as the experimental data suggests. This means reductions may not be as great as indicated and potentially could even result in an overall increase in dermal exposure, particularly so with chroffles given the handling of them required. Surface tension control does appear to show potentially significant reductions in both emission rate and surface contamination, however, the effect on properties of the coating were not formally evaluated, this would be an important consideration for dutyholders considering this approach.

The data obtained, for air agitated tanks, supports the use of a minimum freeboard height of 150 mm as specified in industry guidance.

Summary of the effect of different exposure control scenarios.

Exposure control scenario	Effect on nickel emission rate	Effect on nickel surface contamination
Eductors	Use of eductors reduced emission rate by more than 98 % compared to air agitation at a high rate with no LEV across a range of surface tension concentrations.	Use of eductors reduced surface contamination compared to air agitation with no LEV.
Air agitation rate	Emission rate increased as air agitation rate increased. Depending on the freeboard height, emission rate reductions of between 44 and 57 % were observed at the lowest air agitation at which acceptable plating quality was achieved (16 l.min ⁻¹) when compared to the highest air agitation rate studied (24 l.min ⁻¹).	In general as air agitation rate increased so did the surface contamination but the relationship was not consistent. Depending on the conditions, surface contamination increased between 50 % and more than 200 % at the highest air agitation rate studied (24 l.min ⁻¹) compared to lowest rate at which acceptable plating quality was achieved (16 l.min ⁻¹).
Freeboard height	Emission rate increased as freeboard height measurement decreased albeit with limited effect. Compared to 50 mm, emission rate reductions of 12 and 18 % were noted at freeboard height measurements of 150 mm and 300 mm respectively.	Increasing the freeboard height reduced the surface contamination. Surface contamination at 150 mm was twice that measured at 300 mm and that at 50 mm was 22 times more than at 300 mm.
LEV flow rate	Emission rate decreased as LEV flow rate increased. With the highest air agitation rate and the LEV set to the manufacturer's recommended flow rate, emissions were reduced by more than 98% irrespective of the freeboard height measurement.	In general as LEV flow rate increased so did the surface contamination but the relationship was not consistent.
Chroffles	Use of chroffles decreased the emission rate. The higher the level of chroffle coverage, the greater the emission rate reduction. A notional 100 % chroffle coverage reduced the emission rate by around 70% over a range of different air agitation rates.	Use of chroffles reduced the surface contamination between 50 and 80 % depending on the air agitation rate.
Surfactant concentration (surface tension control)	As tank surfactant concentration was increased, the emission rate decreased. There would appear to be exposure control benefits in running the surface tension lower than manufacturer's recommendations i.e. with high surfactant concentrations. The effect on coating properties was not considered. Compared to the upper end of the manufacturer's specification, running below the specification reduced emissions by 57 %.	As tank surfactant concentration was increased, surface contamination decreased. There would appear to be exposure control benefits in running the surface tension lower than manufacturer's recommendations i.e. with high surfactant concentrations. The effect on coating properties was not considered. Compared to the upper end of the manufacturer's specification, running below the specification more than halved the surface contamination.

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1 INTRODUCTION

1.1 BACKGROUND

Over the period 2008-2011 the Health and Safety Executive (HSE) undertook the largest known occupational hygiene survey in the Great Britain (GB) surface engineering industry, visiting over 50 companies and collecting over 6000 exposure data points. The work is described in HSE reports RR963 (HSE, 2013a), RR1042 (HSE, 2015) and peer reviewed literature (Beattie *et al*, 2017). The survey looked at current exposures and exposure control practice for hexavalent chromium (CrVI), nickel (Ni) salts and cadmium (Cd) compounds, all category 1 carcinogens.

The 2008-2011 survey estimated that there are approximately 3000 workers employed in around 450 companies in the surface treatment industry who are potentially exposed to a range of carcinogens, asthmagens and skin sensitisers during the treatment process. Many of these workers are employed in small to medium sized enterprises.

The work showed that exposure occurs by inhalation, absorption through the skin, by ingestion or any combination of these three routes. Report RR963 comments that HSE and industry agree that, currently, substitution of the hazardous agents is not practical in all circumstances. There are a range of measures that can be used to reduce airborne emissions from electroplating tanks and these are also likely to affect the dermal and ingestion exposure potential. Possible control measures include local exhaust ventilation (LEV) systems, eductors (an alternative to air agitation for mixing of the plating solution), chroffles (small plastic balls that are placed on the liquid surface to reduce the open surface area of plating solution) and surfactant. These measures vary in cost, complexity, ease of use and efficacy. There is no clear guidance for the industry on the most appropriate and cost effective techniques. One of the main recommendations in report RR963 was that “*A systematic evaluation of these (control) measures should be carried out to allow the provision of evidence based guidance aimed at reducing exposures to carcinogens and asthmagens in the electroplating industry.*”

In general the previous survey highlighted more elevated exposures and exposure control failings for nickel plating than for chrome plating. It was found that companies commonly operated air agitated nickel electroplating baths without LEV. This is contrary to the HSE/trade association guidance (SEA, 1). This guidance is based on expert opinion, but without supporting robust scientific evidence.

HSE Inspectors had highlighted the use of eductors being used as an alternative mixing technique to air agitation with some exposure control benefits reported, but with limited information available on their efficacy. Adequate mixing of the plating solution is required so that a constant supply of fresh nickel ions is available at the workpiece surface, otherwise the plating process could stall and a plating deposit of poor quality would be produced. The main mode by which eductors are considered to reduce emissions and the surface contamination potential is by eliminating the need to bubble air constantly through a warm solution. The air will rise through the plating solution through thermal effects, then burst through the surface aerosolising the solution and creating an exposure risk.

1.2 LITERATURE REVIEW

An unpublished literature review carried out by HSE Science Division (HSE SD) around 2010 indicated that there was little information available on the efficacy of the range of possible controls. Of that

found, most originated from equipment suppliers or used semi-quantitative measurement techniques to assess control efficacy. Porter and Gabe (2005) reported on the use of eductors for nickel plating. They assessed airborne concentrations when using either air agitation or eductor agitation using colourimetric nickel indicator tubes. Air agitation was reported to give airborne nickel emissions of 0.5 – 1.0 mg.m⁻³. Emissions for eductor agitation were reported to be zero. They also report other sources claiming emission reductions of over 90 % with the use of eductors. Gabe (2006) reported on the different types of agitation that are used in surface treatment processes. This included eductors, with “*little or no fume from the tank*” reported.

During preparation of this report (May 2019), a literature search was repeated using Web of Science Core Collection database. The search is summarised in Appendix 3. In summary no additional references were found.

1.3 AIM AND OBJECTIVES

The overall aim of the study was to investigate the parameters that affect the generation rate of nickel aerosol from an electrolytic nickel plating tank and quantitatively measure the efficacy of engineering controls currently available to industry. The generation of nickel aerosol is directly linked with the inhalation exposure potential from operation of nickel plating tanks. However, before the efficacy of controls could be assessed it was essential that nickel emissions measured from the plating tank were shown to be reproducible. This was to ensure that differences between data sets obtained from the application of different control measures could be seen to be statistically significant, rather than as a result of experimental variation. This would enable the effect of different controls to be determined with confidence. Therefore this work was divided into two phases. The aim of Phase 1 was to install and commission an electroplating facility at HSE’s Science and Research Centre (HSE SRC) Buxton and then determine the experimental reproducibility of emission measurements. Phase 2 focused on measuring the efficacy of a range of engineering and process controls.

The objectives of each phase were:

Phase 1

- to set up a test electrolytic nickel plating facility at the HSE SRC in consultation with industry experts
- to establish the nickel emission rate reproducibility from an electrolytic air agitated nickel plating tank
- if emission rates are suitably reproducible ($\pm 10\%$) then Phase 2 will be carried out

Phase 2

Determine the effect of the following on emission rates and tank lip surface contamination:

- use of eductors (a pumped circulation system used for solution mixing which utilises the venturi effect)
- varying the air agitation rate (air agitation is the method used for solution mixing)
- use of local exhaust ventilation (LEV)
- differing freeboard height (this is the height from the liquid surface to the top of the tank)
- the use of chroffles (plastic balls used to cover the liquid surface)

- differing surfactant concentration levels (a chemical additive required for the process, which alters the surface tension of the plating solution)

Cathode rod movement, (where oscillation of the cathode rod is used to mix the plating solution), was not included in this work as its use is not commonplace in GB. The use of lids was also not considered as the plating times are typically no more than 25 minutes in decorative nickel plating and so constant lifting of lids could introduce significant dermal exposure potential.

1.4 REGULATORY POSITION

Electrolytic nickel plating typically uses nickel chloride, nickel sulphate and metallic nickel as some of the primary chemical components in the plating tank make up. Potential health effects associated with exposure to these agents include skin and respiratory sensitisation and the International Agency for Research on Cancer (IARC) have classified various nickel compounds as group 1 human carcinogens (IARC, 2012).

Nickel compounds are considered hazardous to health and therefore the requirements of the COSHH regulations apply. COSHH regulation 7 (1) requires that *“exposure to substances hazardous to health is either prevented, or where this is not reasonably practicable, adequately controlled”*. Under COSHH regulation 7 (7) exposure control is considered adequate when:

- the principles of good practice as specified in COSHH Schedule 2A (see Appendix 1) are applied;
- any workplace exposure limit (WEL) for the substance is not exceeded; and
- for carcinogens, asthmagens and mutagens (as defined in regulation 2 of COSHH) that exposure is controlled to a level as low as is reasonably practicable (ALARP)

COSHH regulation 7 (5) also lists additional requirements for carcinogens (or mutagens) where exposure cannot be prevented.

As listed in EH40 (HSE, 2018), the relevant WEL for the purposes of anyone working in the nickel plating industry is 0.1 mg.m⁻³ (inhalable fraction) for water soluble nickel compounds as an 8-hour time weighted average (8-hr TWA).

The HSE research highlighted the use of biological monitoring (BM) as an exposure assessment tool by taking urine samples from potentially exposed workers to help draw conclusions on the adequacy of exposure controls and working practices (HSE, 2013a). For certain substances HSE has set biological monitoring guidance values (BMGV), which do not have the same legal status as WELs and, as suggested by the name, they are for guidance, these are shown in Table 2 of EH40. Where they are exceeded it should be taken as an indication that a review of controls and working practices should be carried out. There is no BMGV for nickel. However, the HSE SD BM database contains approximately 2000 recent results for urinary nickel, including workers from the electroplating sector. The 90th percentile of this data is 22 µmol/mol creatinine and this has been adopted as a guidance value for the purposes of current HSE project work. This guidance value is not health based, and includes all samples in the database so there is no “good control” element to this value, unlike that for most BMGVs. There are environmental and dietary sources of nickel. Typically, using data from the HSE SD BM database, urinary nickel levels in individuals with no occupational exposure will not exceed 10.7 µmol/mol creatinine.

A number of guidance sheets on controlling the risk of exposure to substances hazardous to health during electroplating processes were jointly written by the Surface Engineering Association (SEA) and the HSE. These include nickel based processes and guidance sheets for controlling both the risk of inhalation and skin exposure (SEA 1, 2).

2 METHODS

2.1 PHASE 1

2.1.1 Initial approach

During the early planning discussions surrounding this research, the possibility of carrying out the work in the industrial environment was considered. This approach was quickly discounted for practical reasons around the logistics of carrying out the operations away from the SD laboratory. More importantly, the lack of control over the environmental factors such as cross draughts, temperature and humidity was considered unacceptable given the level of scientific rigour required for these tests.

These early discussions included various HSE staff as well as industry experts including trade association representation and industry technical experts. There was also significant internal discussion regarding how best to control the risk to health of the researchers carrying out the experimental programme of work.

2.1.2 Experimental set up

The plating facility was housed inside a test room with internal dimensions 4 m x 4 m by 2.92 m high, high, located within a climate-controlled laboratory. A schematic of the experimental set up is shown in Figure 1, a technical drawing is in Appendix 2 and an overview of the set up is shown in Photographs 1 and 2. The set up was designed and installed by a contractor with significance industry experience and all chemicals were provided by one of the main chemical suppliers for the GB electroplating sector . The plating line was designed to mimic a manually operated small scale decorative nickel plating line used in industry. The set up comprised:

1. 500 litre Caustic degreaser tank. This was operated at 50 °C by circulation of water through a stainless steel heating panel. It was fitted with LEV to the rear to of the tank, with HEPA H14 filtration before the air was discharged externally.
2. 225 litre ambient rinse tank (post degrease).
3. 225 litre ambient acid etch tank.
4. 225 litre ambient rinse tank (post etch).
5. 500 litre electrolytic nickel plating tank (see Photograph 3). Dimensions 900 mm x 600 mm x 900 mm, working volume 405 litres. This tank was operated at 55 °C by circulation of water through a titanium heating panel. The plating solution in this tank was circulated during the plating process, either by air or eductor agitation. Both circulation systems were fitted although they were not used simultaneously. There was a rear mounted lip extract fitted across the full width of the tank (see Photograph 3), this was not used in all tests and was blanked off when not in use. The plating solution used contained nickel sulphate, nickel chloride and boric acid as the main chemical constituents.
6. A sampling hood measuring 1180 mm by 1480 mm was positioned over the tank with its lower edge 500 mm above the tank lip (see Photograph 2) and operated at a flow rate of 1270 m³.h⁻¹. The hood collected emissions and ducted them outside of the room where isokinetic sampling took place before the air was HEPA H14 filtered and discharged externally. See Figure 1 which shows a schematic of the experimental setup. Note the sampling hood was designed according to ACGIH guidance (ACGIH, 2016). This was to ensure

that it did not actively draw air off the plating tank, but rather that it received the rising thermal plume generated by the operation of the tank.

7. 225 litre ambient rinse tank (post nickel plate).

Only the plating tank was fitted with equipment to circulate the tanks contents. The two heated tanks (degreasing and plating) were served by a domestic hot water boiler which passed the hot water through the two heating panels mentioned above.

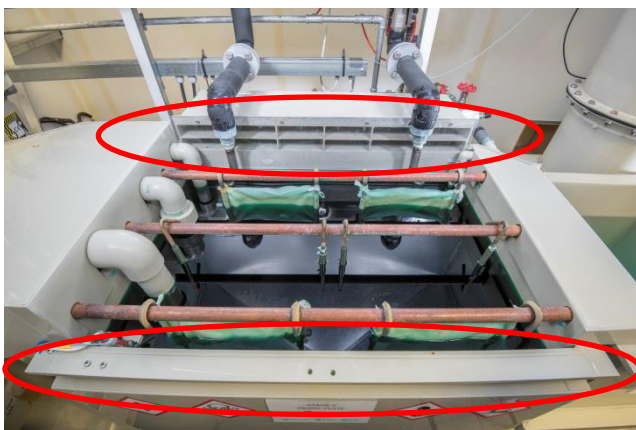
The six tanks were located in two bunds which held 110 % of the total volume of the largest tank. All tanks and bunds were made from polypropylene and were suitable for use with the material each contained. The manufacturer verified the integrity of each tank.



Photograph 1. Overview of plating line, view 1.



Photograph 2. Overview of plating line, view 2.



Photograph 3. Plan view of plating tank. Note LEV extract to rear and front lip where surface wiping carried out are both circled.



Photograph 4. Arrangement of eductors (circled). Note there are a total of six, three each side all angled upwards (two obscured by anode baskets).

As air was continually extracted from the test room during testing via the sampling hood and the LEV(s) extraction, replacement air needed to be planned. Replacement air entered the room via four 0.4 m by 0.4 m openings, which were arranged such that two were installed in two opposite walls diagonally opposed to each other. With this arrangement, the room was maintained at a slight negative pressure relative to the surrounding laboratory, which ensured there was no leakage into

the wider work area when the test room door was closed. For increased safety, a manometer was mounted adjacent to the test room entrance door so that room negative pressure could be monitored and checked prior to entering the room.

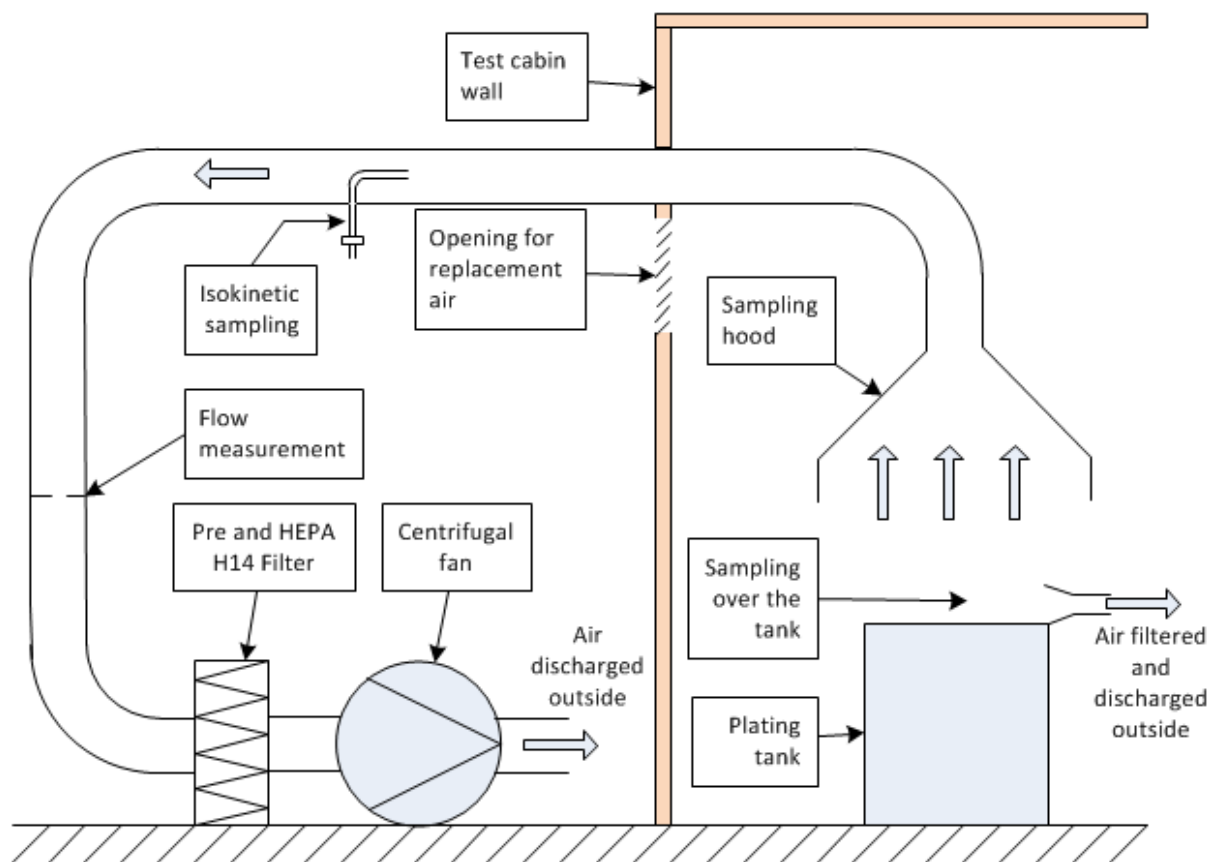


Figure 1. Schematic of the experimental set up

2.1.3 Test room commissioning

Test room commissioning tests were carried out with the plating tank filled with water to 300 mm from the top of the tank (i.e. a 300 mm freeboard) and heated to operating temperature (55 °C)

In order to visualise air movement within the test room and to ensure that the incoming air did not unduly disturb the rising plume of air from the plating tank, smoke tests were carried out and observations made by the operator. Smoke was released using both smoke pencils and a smoke machine. The smoke releases were focused around the perimeter of the tank and the sampling hood with the ventilation running. The smoke pencil tests indicated that, visually, the hood was successfully receiving and extracting the entire rising plume, however, the smoke machine tests indicated that a very small amount of the rising hot air could be escaping the sampling hood.

To determine where the air could be escaping, tracer gas tests were carried out using 10 % sulphur hexafluoride (SF_6) in nitrogen, with SF_6 being the detectable component of the tracer gas. Tracer gas was released at a number of positions across the top of the tank with the water heated to the operating temperature. This highlighted that there was a very small amount of the rising air that did not enter the rear side of the hood. To mitigate this, a 100 mm panel was added along the length of

the rear edge of the sampling hood (see photograph 5). Further testing showed that this resolved the issue (i.e. total capture was achieved) and therefore the additional panel was left in place.



Photograph 5. Close up of sampling hood. Note panel to rear highlighted.

2.1.4 Sampling methodology and analysis

To determine the emission rate of nickel arising from the plating bath, isokinetic sampling was carried out in the measuring duct (see Figure 1). Initially the use of real-time particle monitors was investigated. However, as the instruments fundamentally operate on light scattering, any particle that passes through the sensing volume will produce a signal. Initial tests highlighted that the optics were responding to water mist rather than specifically the soluble nickel aerosol. This was shown by the same or very similar read out being produced when taking reading over the tank (at operating temperature) irrespective of whether plating or not.

The optimum sampling position is where the aerosol is uniformly mixed in the duct and where losses of the aerosol are minimised. This was identified by measuring at three locations in the measurement duct using sample times of 20 and 40 minutes. Isokinetic samplers were positioned in the centre of the duct at all three sampling positions. Sampling was carried out at $22 \text{ l}\cdot\text{min}^{-1}$ using a 47 mm inline sampling head fitted with 47 mm mixed cellulose ester filters with a $1.2 \mu\text{m}$ pore size. The data gave good agreement at the different positions. However, the absolute amount of nickel on the filter was lower than was required. See section 2.1.5 for steps taken to increase the amount of nickel measured.

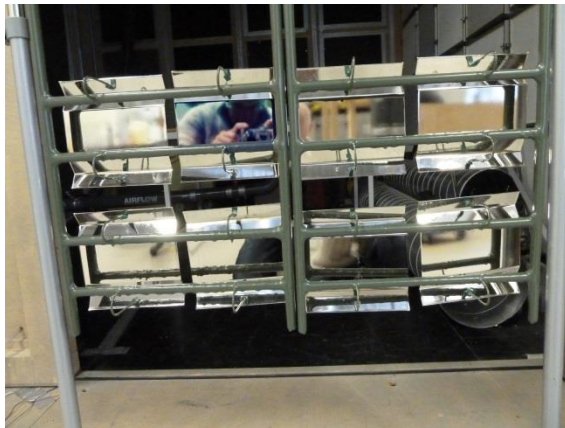
The filters were analysed for soluble nickel content using a method described in BS ISO 15202-2. Filters were extracted in deionised water at 37°C and the nickel content in the extract was determined using inductively coupled plasma atomic emission spectroscopy (ICP-AES). The limit of detection on each filter was around $0.2 \mu\text{g}$ soluble nickel.

2.1.5 Sensitivity

During the commissioning, there was a significant amount of effort spent setting up the electroplating line, producing plating of acceptable quality and finalising the sampling set up. From an experimental point of view, the most important factor was ensuring that sufficient sensitivity was present with the base condition scenario of high air agitation rate and no exposure control in place.

A figure of more than 50 times the limit of the analytical method was considered acceptable. This was necessary so that as other plating scenarios with controls applied were run, with lower emissions anticipated, that emission reductions of 90 % or more would still produce a result that could be measured with confidence. The main steps taken to achieve this were:

- increasing the size and number of the test pieces being plated to increase the surface area plated (see Photographs 6 and 7 for the test pieces and jigs used); to increase the nickel mist in air concentration
- increasing the plating time from 30 minutes to 90 minutes; to increase the absolute amount of nickel measured on the sampling filter
- increasing the sampling flow rate; to increase the absolute amount of nickel measured on the sampling filter
- typically running the surfactant concentration lower than recommended; to increase the nickel mist in air concentration



Photograph 6. Test pieces and jigs, view 1.



Photograph 7. Test pieces and jigs, view 2.

2.1.6 Reproducibility

It was necessary to confirm the emissions generated from the plating tank were reproducible. This was carried out by running the plating tank at a high air agitation rate (approximately $21 \text{ l}\cdot\text{min}^{-1}$ for our set up), low freeboard height (50 mm) and no extraction applied.

Three sets of five repeat tests runs were carried out over a period of two months; each individual set of five taking no more than three days to complete.

To ensure consistency between individual tests, each test was carried out according to a standard protocol, with fixed dwell times in each of the different pre-treatment tanks. The duration of time test pieces spent in the plating tank with the current applied was 90 minutes. Fresh test pieces were used for each test, each batch of test pieces were weighed before and after plating to ensure consistency in the amount of nickel applied.

2.1.7 Experimental parameters determined for Phase 2

The final parameters, to be used in Phase 2 were determined as:

- two jigs each with four test pieces (each 160 mm x 175 mm) on, total surface area being plated = 0.224 m²
- total plating time, i.e. time when current applied = 90 minutes
- in duct air sampling flow typically around 85 l.min⁻¹ (measured during each test)
- surface tension (controlled by surfactant concentration) maintained at 49 (±1) dynes (determined for each test), unless this was the parameter under review
- air agitation to be the default method of solution mixing for all tests, except where eductors were being tested
- LEV not used, except for the tests evaluating LEV
- freeboard height was maintained at 150 mm unless this was the parameter under review

2.2 PHASE 2

2.2.1 Surface contamination evaluation

Following a discussion with HSE colleagues, it was decided to obtain additional data to help inform the effect that the different exposure control techniques have on the dermal exposure potential as part of Phase 2. Surface wipes were taken using a pre-moistened surface wipe on a standardised area (100 cm x 5 cm) on the front lip of the plating tank. The surface wipes used (Ghost wipes) were of a type that can be easily digested during the sample preparation step prior to analysis. Jigs were loaded into the plating tank and then the front lip was wiped to remove any contamination that may have arisen as a result of loading into the tank. The plating run was completed and then, prior to removal of the jigs, the standardised area was wiped in a consistent manner using one ghost wipe. The process was then repeated using a second ghost wipe, with both wipes being analysed separately. Samples were hot block digested in nitric acid and analysis for nickel was carried out by ICP-AES using the same procedure as that employed for the air sampling. It should be noted that the acid digestion results in measurement of total nickel, however, for the wipe samples it is considered that the source of nickel means that the result will equate to soluble nickel, although there is no data to confirm this.

The surface wipe procedure was added on after the completion of phase one. This meant that the emission rate reproducibility tests had already been completed and so no reproducibility tests were carried out for the surface wiping.

2.2.2 Test regime

Each test was carried out according to the standard protocol as described in section 2.1.6 and the standard test conditions which are shown in section 2.1.7.

As a check where necessary, as part of some test scenarios, a worst case scenario test (no LEV with high air agitation rate) was carried out. Air agitation was used as the solution mixing method for all tests except the eductor evaluation.

Eductors

Tests were carried out using eductors as the method for solution mixing, as set up by the manufacturer. No alterations were made to the eductor set up throughout the eductor tests.

Air agitation

Tests were carried out at a range of air agitation rates to determine if this affected the emission rate of nickel from the tank. The air flow rates selected were 5, 9, 13, 16, 19, 21 and 24 l.min⁻¹. It was noted that at the lower flow rates the air agitation did not appear to be uniform across the surface of the tank.

It is important to note that the effect of air agitation was assessed without LEV in use. In an industrial setting, the use of air agitation without LEV for nickel plating is not in accordance with the requirement under the COSHH regulations to control exposures to carcinogens and asthmagens to a level as low as is reasonably practicable. BS EN 17059:2018 (BSI, 2018) indicates that "*air agitation systems shall be avoided.*"

Freeboard height

Three freeboard heights were considered: 50, 150 and 300 mm.

Surface tension

The surface tension of the solution was adjusted by varying the concentration of surfactant in the plating solution. Four surface tension values were considered: 37, 42, 45 and 49 dynes. Two of these (37 and 49) were, according to the manufacturer's data, outside the recommended specification. However, these were chosen to better determine the effect of surface tension on tank emissions rather than focusing on the quality of the plating finish. It should be noted that the lower the numerical value of the surface tension, the higher the surfactant concentration.

LEV extraction

The maximum flow rate investigated was 1260 m³.h⁻¹, which was recommended by the electroplating tank manufacturer. This is consistent with the upper design flow rate from ACGIH guidance (ACGIH, 2016). In addition to this, flow rate tests were also carried out at a range of flows between 0 % (i.e. LEV off) and 50 % of the manufacturer's recommendations. When not in use the LEV duct was blanked off.

Chroffles

Chroffles of 38 mm diameter were used to reduce the open surface area of plating solution. A single layer of chroffles was used and a range between 50 % and 100 % covering was investigated as well as a 0 % (no chroffles) check to act as a reference point. It is acknowledged that the description of 100 % chroffle coverage is a notional one as total coverage cannot be achieved given the spherical shape of the chroffle. The actual tank surface area covered with a 100 % coverage was calculated to be 78.5 %. In addition, when the air agitation was switched on, the chroffles coverage tended to decrease slightly as the air agitation caused the chroffles to form a double layer in places. The percentage coverage in the report refers to the when the air agitation was off.

Static sampling using IOM samplers

In order to give some context relative to the WEL, in a small number of cases sampling above the tank but beneath the capturing hood was carried out at heights of 25 cm and 50 cm above the tank lip. This was undertaken using the same type of sampling equipment as is used for personal sampling; i.e. membrane filters were used in stainless steel cassettes with IOM sampling heads. Sampling flow was 2 l.min⁻¹. A review of the data obtained confirmed that the presence of the

additional sampler above the tank did not have any significant effect on the emission rate measured in the duct.

Estimation of efficiency/cost savings

Some initial tests were carried out in an attempt to evaluate some of the potential efficiency/cost savings from the use of eductors. The theory being that less energy is required with eductor use as there is not the constant cooling effect of the air being bubbled through the tank solution. Gas usage was monitored during a number of plating runs of the standard 90 minute duration carried out within a few days of each other. Four air agitated runs were carried out at 16, 9, 24 and 24 l.min⁻¹ respectively. It should also be remembered that 9 l.min⁻¹ did not appear to provide adequate mixing. A final test was carried out monitoring gas consumption when using eductors over the 90 minute period.

In addition, a test was carried out monitoring the gas usage for maintaining the tank at plating temperature (but not plating) with an air agitation rate of 24 l.min⁻¹ over a period of four hours. The test was then repeated using eductors.

2.2.3 Composition of emissions

Following completion of the main work, there was consultation with other divisions of HSE. It was decided that, from a regulatory position, identification of the soluble nickel compounds present in the emissions would be desirable. To achieve this, larger amounts of material were needed on the sampling filter to provide sufficient analytical sensitivity. Several plating runs were carried out with the same sampling filter in place when it would normally be replaced. Following sampling the filter was scanned using an x-ray diffraction technique to identify the crystalline phases present on the filter.

2.2.4 Data handling

The efficacy of different control measures was assessed by comparison of emission generation rates ($\mu\text{g Ni per second}$) from the tank. These were calculated from the nickel concentration determined in the measuring duct (amount of nickel on the filter, sampling time, sampling flow rate) and air flow rate through the sampling hood.

Surface contamination results were calculated by simply adding together the two post plate wipes and then dividing by the surface area wiped which was a standard 500 cm² in all cases.

Statistical modelling was carried out on both the air emission rate and the surface contamination using Gaussian location-scale Generalized Additive Model (GAM) models.

The purpose of such modelling was to confirm the conclusions drawn from the results of individual tests and also to look for interactions between control measures that might not otherwise have been apparent. The statistical fit of the surface contamination was not as good as that obtained for emissions and as reproducibility data was not obtained for the surface contamination results, it was decided not to attempt further statistical analysis on the surface contamination data and interpret the data by comparing individual data sets.

3 RESULTS

3.1 REPRODUCIBILITY OF EMISSION MEASUREMENTS – PHASE 1

A total of 15 replicate tests to determine reproducibility were carried out in three groups of five tests. The tests were carried out over a period of around two months with the second two groups being within two weeks of each other. Table 1 summarises the emission rate data obtained from the reproducibility tests.

Table 1. Summary of reproducibility tests.

emission rate ($\mu\text{g Ni s}^{-1}$)	Reproducibility test			
	Test 49-53	Test 54-58	Test 59-63	All tests
Mean	1.330	1.532	1.418	1.427
SD	0.020	0.114	0.063	0.111
% RSD	1.51	7.43	4.43	7.77

Results are considered reproducible but not repeatable. This means that tests carried out more than a week or so apart, may not be directly comparable. This should be borne in mind when attempting to read across emission rate results listed in different tables. It is for this reason that some data evaluating the same effect are not presented in the same table, i.e. it may not be comparable. This variation in the data could be as a result of small changes in the concentration of the brightener additives in the plating solution but this was not confirmed.

3.2 ASSESSMENT OF DIFFERENT CONTROL MEASURES – PHASE 2

3.2.1 Eductors

Table 2 shows the average emission rate obtained from the use of eductors at a freeboard height of 150 mm, across a range of surface tension. Also included is the reduction calculated relative to the emission rate obtained using 24 l.min⁻¹ air agitation without LEV at same surface tension and freeboard (air agitation data obtained in same campaign of tests).

Table 2. Emission rate data from use of eductors.

	Surface tension, dynes (relative to manufacturers spec)			
	50 (out of spec high)	44.5 (in spec, upper)	42.5 (in spec, lower)	37 (out of spec low)
Average Emission rate $\mu\text{g Ni s}^{-1}$ for eductors	0.023 (n=5)	0.033 (n=4)	0.015 (n=3)	0.019 (n=3)
% Reduction in emission rate*	98.6	97.6	98.8	97

* Relative to emission rate obtained using 24 l.min⁻¹ air agitation without LEV at same surface tension.

Table 3 summarises surface wipe data from tests at 150 mm freeboard height using eductors at differing surface tensions together with the baseline check air agitation runs for comparative purposes. The data are presented in Figure 2.

Table 3. Summary of surface wipe data obtained with use of eductors and with differing surface tension.

Surface tension (dynes)	Average nickel surface contamination on tank front lip ($\mu\text{g Ni cm}^{-2}$)			
	24 l.min ⁻¹ air agitation	% Reduction relative to 50 dynes	Eductors	% Reduction with eductors
50	1.97 (n=3)	N/A	0.36 (n=5)	82
45	1.36 (n=1)	31	0.44 (n=1)	68
42	0.67 (n=1)	66	0.42 (n=1)	36
37	0.44 (n=1)	78	0.11 (n=1)	75

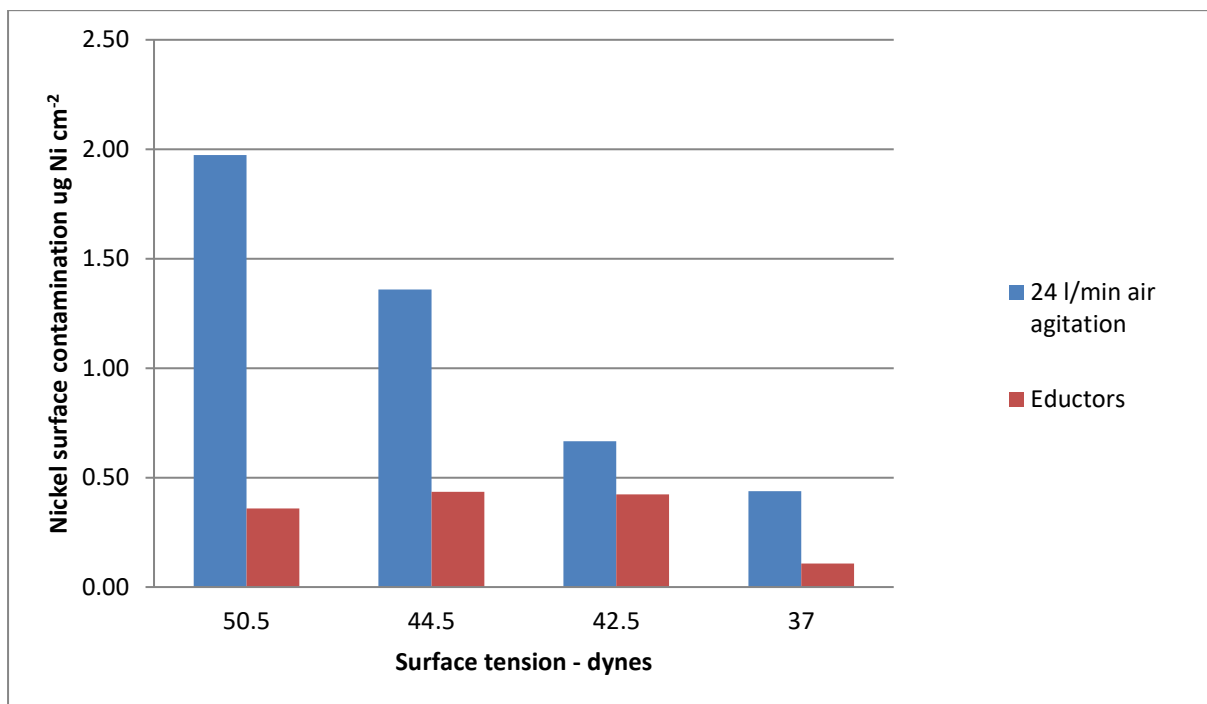


Figure 2. Effect of eductors and surface tension on surface contamination.

3.2.2 Air agitation and freeboard

Table 4 summarises the emission rate data determined when operating the tank without LEV at a surface tension of 49 dynes with differing air agitation rates and at differing freeboard heights. The data are plotted in Figure 3.

Table 5 presents emission rate data obtained under the same conditions as for table 4 but at a surface tension of 45 dynes. The data are plotted in Figure 4.

Table 6 shows emission rate data obtained at 42 dynes and 150 mm freeboard heights only. The data are plotted in Figure 5.

Table 7 shows the percentage reduction in emission rate with varying air agitation rate with tank operating at a fixed 150 mm freeboard. The reduction is calculated using the data obtained at the assumed worst case scenario of 24 l.min⁻¹ air agitation as a reference point. The data are plotted in Figure 6.

Table 8 summarises surface wipe data obtained from operation of the tank without the use of LEV at a range of air agitation rates and with varying freeboard and surface tension. The data are presented in Figure 7.

Table 9 shows surface wipe data from tests carried out when operating the plating tank at 24 l.min⁻¹ air agitation at differing freeboard measurements of 50 mm, 150 mm and 300 mm. The data shown are averages from runs at differing LEV flow rates. The data are presented in Figure 8.

Table 4. Summary of emission rate variation as a function of air agitation rate (no LEV applied). (49 dynes).

Freeboard height (mm)	Emission rate ($\mu\text{g Ni s}^{-1}$)						
	Air agitation rate ($\text{l}\cdot\text{min}^{-1}$)						
	5	9	13	16	19	21	24
50 mm	0.403	0.629	0.957	1.467	1.808	2.298	2.734
150 mm	0.369	0.506	0.784	1.182	1.585	2.061	2.472
300 mm	0.343	0.469	0.702	1.227	1.528	1.801	2.625

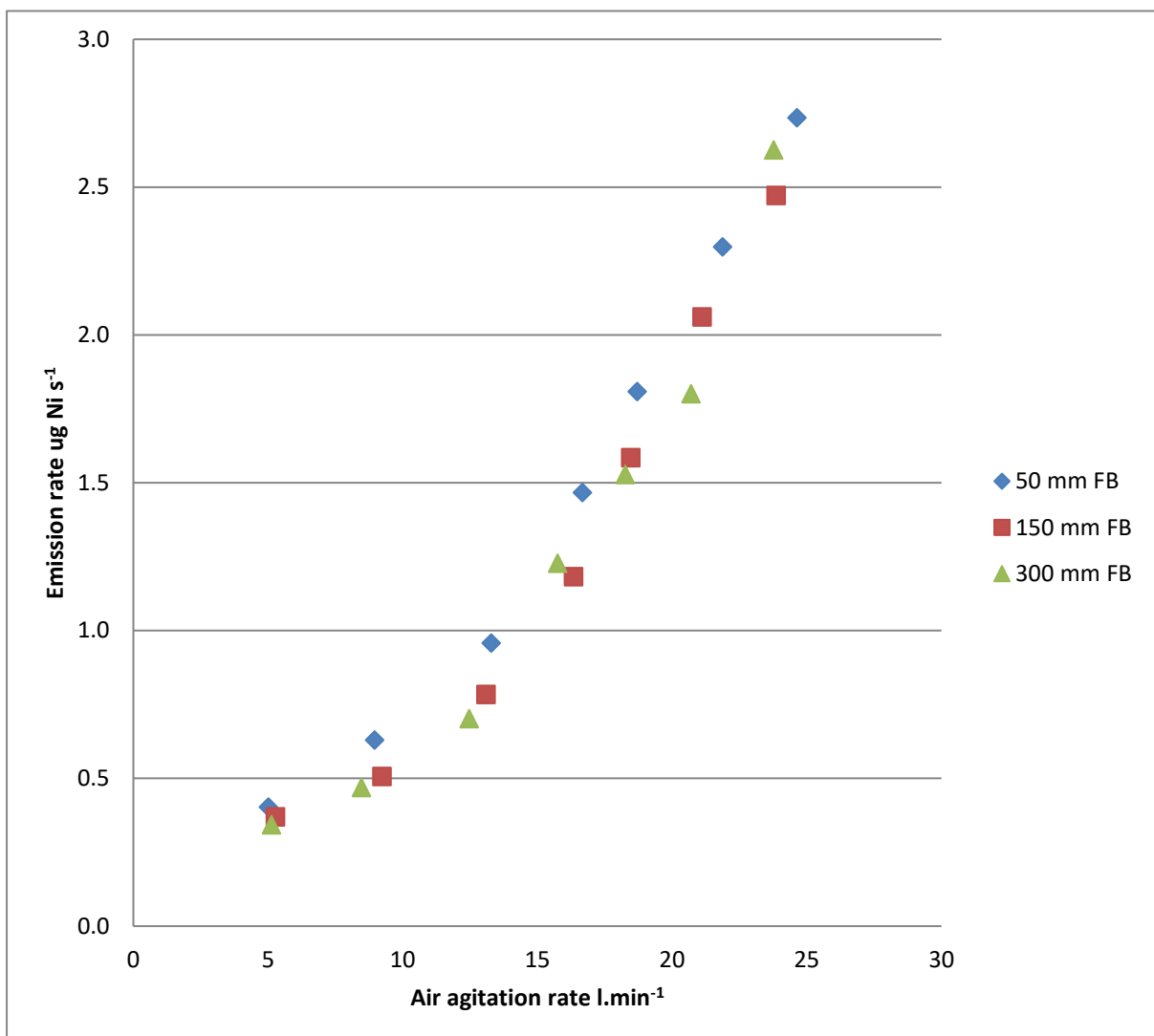


Figure 3. Effect of freeboard height and air agitation rate on emission rate (at 49 dynes).

Table 5. Summary of emission rate variation as a function of air agitation rate (no LEV applied). (45 dynes).

Freeboard height (mm)	Emission rate ($\mu\text{g Ni s}^{-1}$)						
	Air agitation rate ($\text{l}\cdot\text{min}^{-1}$)						
	5	9	13	16	19	21	24
50 mm	no data*	no data*	no data*	no data*	no data*	no data*	no data*
150 mm	0.263	0.411	0.654	0.842	1.112	1.249	1.524
300 mm	0.226	0.336	0.522	0.744	0.988	1.056	1.438

* No data obtained due to time constraints

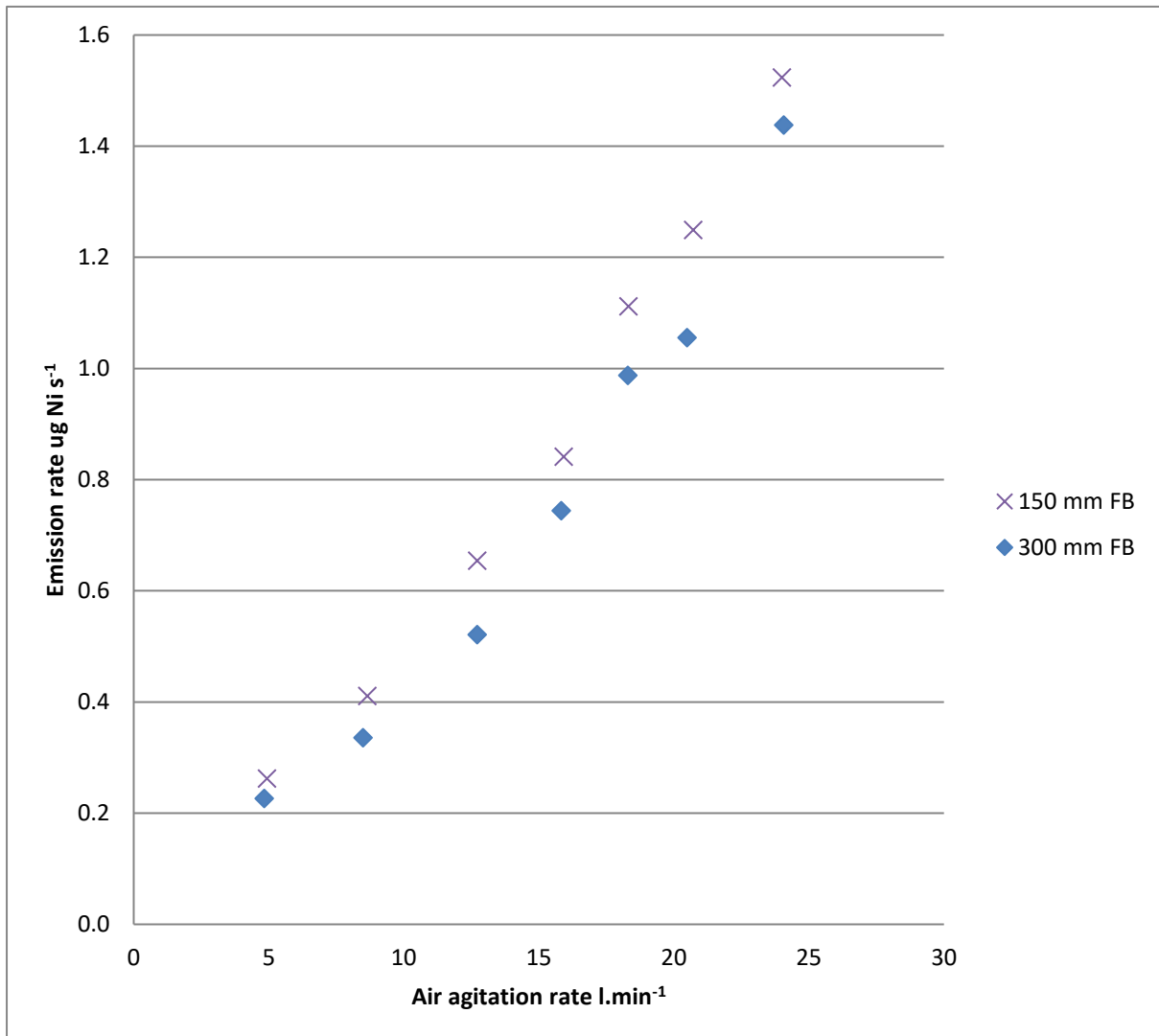


Figure 4. Effect of freeboard height and air agitation rate on emission rate (at 45 dynes).

Table 6. Summary of emission rate variation as a function of air agitation rate (no LEV applied). (42 dynes and 150 mm freeboard).

	Emission rate ($\mu\text{g Ni s}^{-1}$)					
	Air agitation rate ($\text{l}\cdot\text{min}^{-1}$)					
Freeboard height (mm)	9	13	16	19	21	24
150 mm	0.402	0.555	0.767	0.853	1.023	1.312

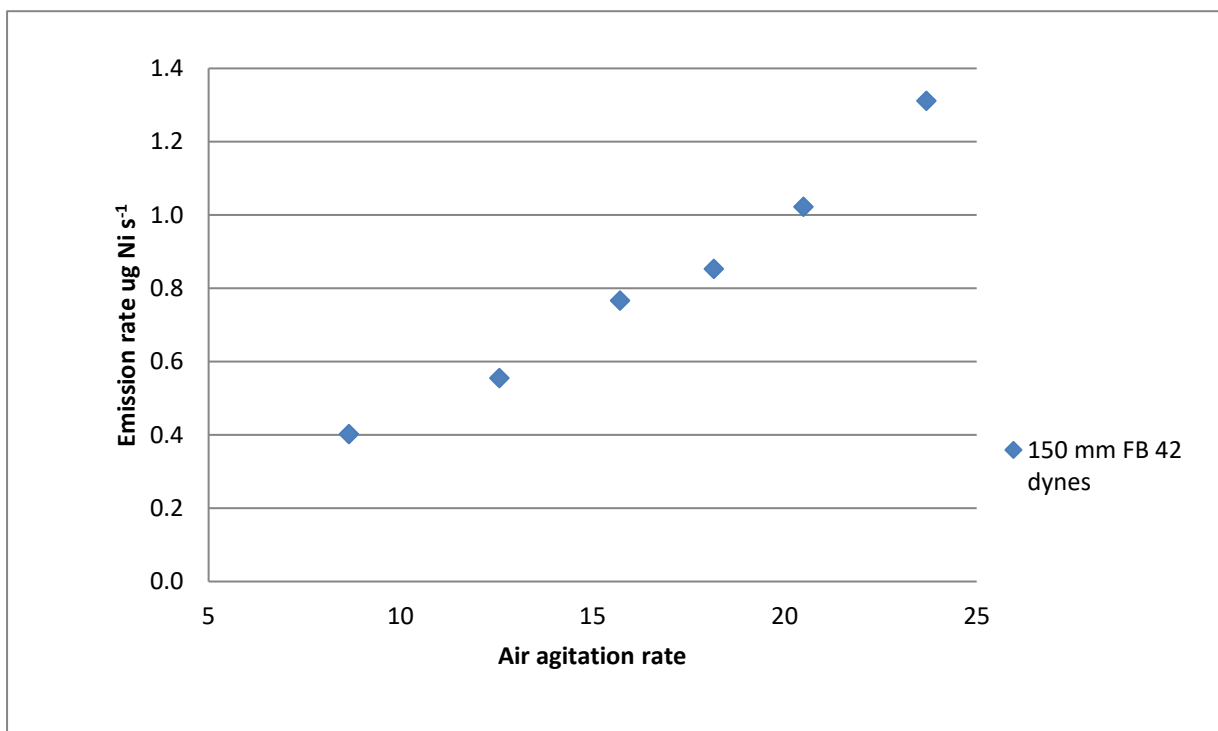


Figure 5. Effect of air agitation rate on emission rate (at 42 dynes and 150 mm freeboard).

Table 7. Data showing the percentage reduction in emission rate with varying air agitation rate, using 24 l.min⁻¹ air agitation emission rate data as the reference point (no LEV applied). Tank at 150 mm freeboard with a range of surface tensions studied.

	% Reduction in emission rate (relative to 24 l.min ⁻¹ emission rate)						
	Air agitation rate (l.min ⁻¹)						
Surface tension	5	9	13	16	19	21	24
49	85.1	79.5	68.3	52.2	35.9	16.6	N/A
45	82.8	73.0	57.1	44.8	27.0	18.0	N/A
42	No data	69.3	57.7	41.5	35.0	22.0	N/A

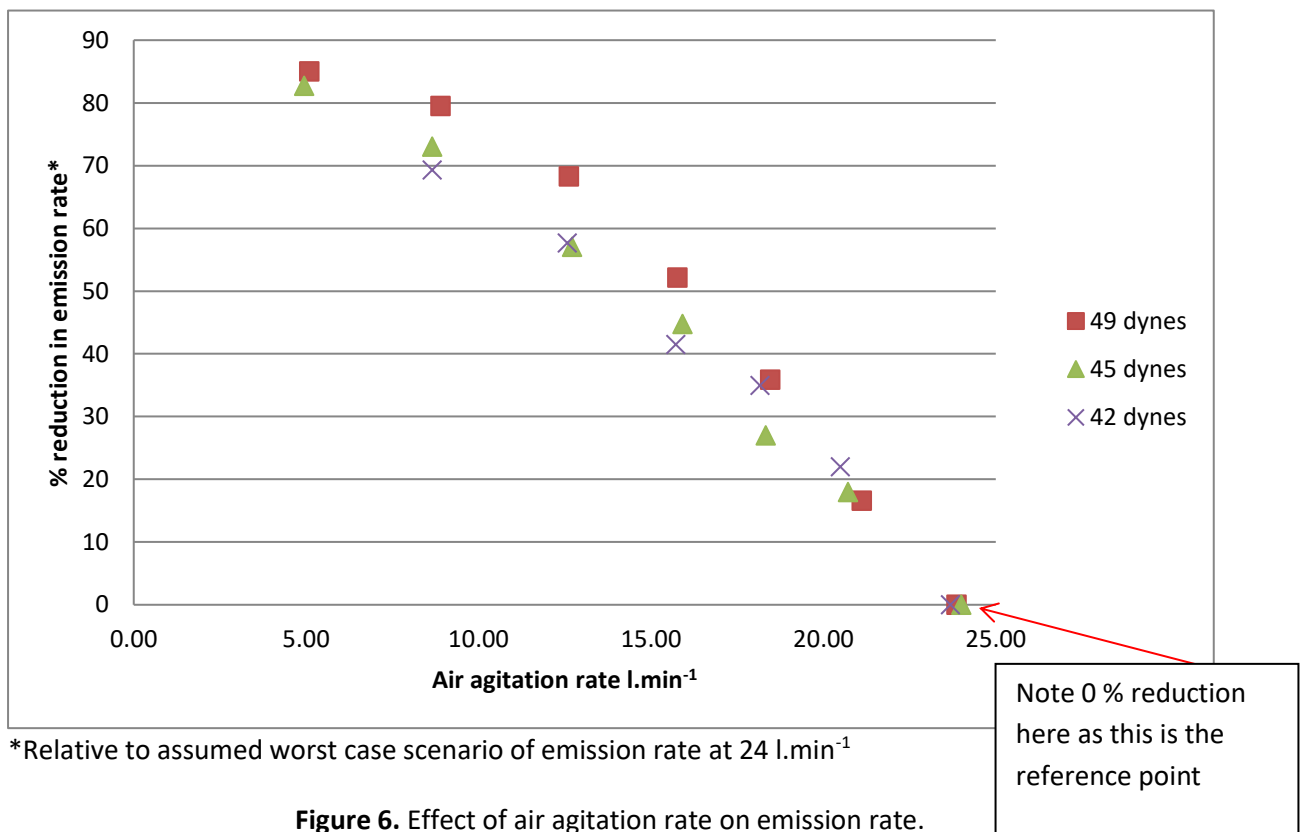


Table 8. Summary of surface contamination data obtained at a range of air agitation rates and different freeboard (FB) heights and surface tensions, all without the use of LEV

Nickel surface contamination ($\mu\text{g Ni cm}^{-2}$)								
Conditions	Air agitation rate (l.min^{-1})							Average
	5	9	13	16	21	21	24	
150 mm FB 49 dynes	0.54	1.44	2.76	1.36	1.7	2.1	2.22	1.73
300 mm FB 49 dynes	0.326	0.628	0.8	0.652	1.38	0.716	1.03	0.79
150 mm FB 45 dynes	0.228	0.388	0.508	0.642	0.874	1.76	1.44	0.83
300 mm FB 45 dynes	0.25	0.36	0.92	0.41	0.49	0.582	0.612	0.52

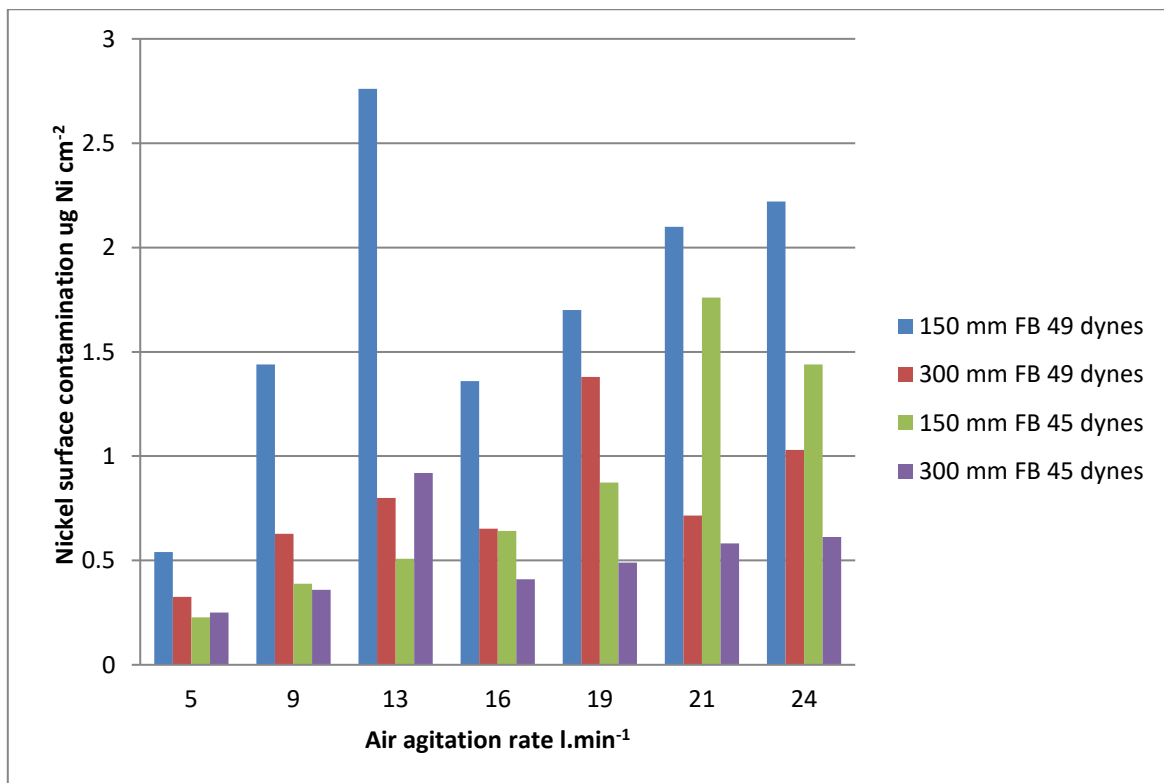


Figure 7. Surface contamination data obtained at a range of air agitation rates and different freeboard height and surface tensions, all without the use of LEV.

Table 9. Summary of average surface contamination data from operation of tank at 24 l.min⁻¹ air agitation across a range of freeboard height measurements (no LEV used).

Freeboard height	Average nickel surface contamination ($\mu\text{g Ni cm}^{-2}$)	% Reduction in contamination (relative to 50 mm)
50 mm	21.14 (n=5)	N/A
150 mm	1.98 (n=7)	90.6
300 mm	0.95 (n=6)	95.5

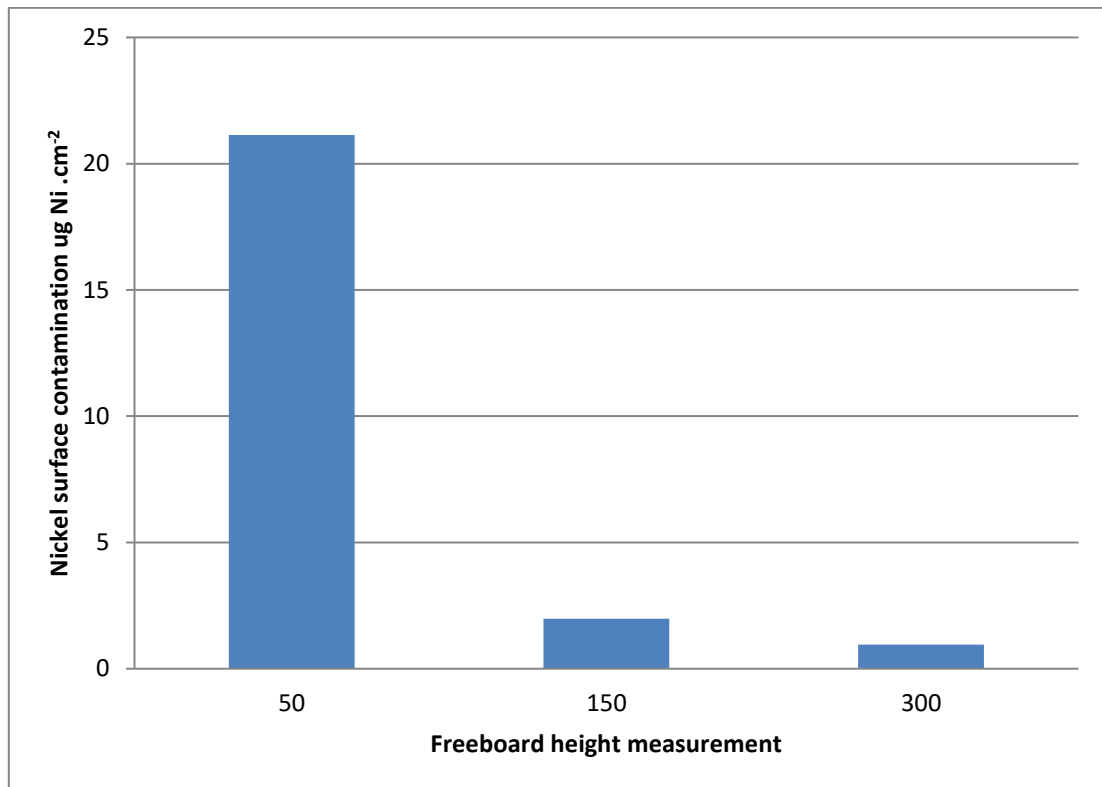


Figure 8. Summary of average surface contamination data from operation of plating at an air agitation rate of 24 l/min across different freeboard heights

3.2.3 LEV flow rate

Table 10 shows initial emission rate data obtained using LEV when operating the plating tank at 50 mm freeboard using a worst case scenario of high air agitation rate ($24 \text{ l}\cdot\text{min}^{-1}$) and high surface tension (49 dynes). The table also shows the effective reduction in emissions for the use of LEV compared to an emission rate obtained with the LEV off. Note the effective emission reduction for 100 % LEV flow rate can only be determined as a greater than figure. This is because the analytical result from which the emission rate is determined was less than the analytical limit of detection.

Table 10. Emission rate data from initial LEV tests, 50 mm freeboard, $24 \text{ l}\cdot\text{min}^{-1}$, 49 dynes

	LEV flow rate (as a % of manufacturer's recommended flow rate)		
	100	50	0 (LEV off)
Emission rate $\mu\text{g Ni s}^{-1}$	<0.004	0.004	1.26
Effective reduction in emissions	>99.7 %	99.7 %	N/A

Following the initial LEV tests, a further round of tests operating the plating tank at the same conditions as described above (50 mm freeboard, $24 \text{ l}\cdot\text{min}^{-1}$ air agitation and 49 dynes) were carried out with the LEV running at lower flow rates (expressed as a % of manufacturer's recommendations). These data are presented in Table 11 and plotted in Figure 9. Table 12 shows data obtained under the same conditions but at 150 mm and 300 mm freeboard heights respectively. The data are plotted in Figure 10.

Table 11. Emission rate data from LEV tests, 50 mm freeboard, 24 l.min⁻¹, 49 dynes.

	LEV flow rate (as a % of manufacturer's recommended flow rate)						
	10	15	20	25	30	40	50
Emission rate μg Ni s ⁻¹	0.335	0.127	0.123	0.070	0.088	0.013	0.013

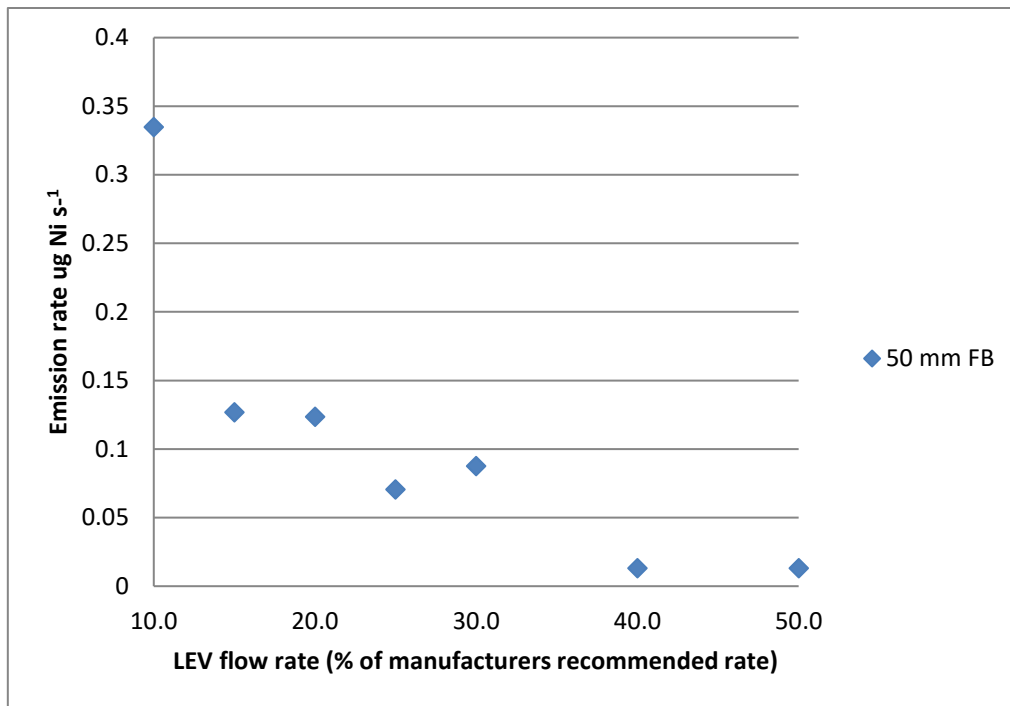


Figure 9. Effect on emission rate as a function of LEV rate (expressed as a % of manufacturers recommended flow rate). 50 mm freeboard, 24 l.min⁻¹, 49 dynes.

Table 12. Emission rate data from LEV tests, 150 mm freeboard, 24 l.min⁻¹, 49 dynes.

	LEV flow rate (as a % of manufacturer's recommended flow rate)					
	0 (LEV off)	10	20	30	40	50
150 mm freeboard						
Emission rate μg Ni s ⁻¹	1.442*	0.544	0.258	0.153	0.013	0.018
Effective reduction in emissions	N/A	62.3 %	82.1 %	89.4 %	99.1 %	98.8 %
300 mm freeboard						
Emission rate μg Ni s ⁻¹	1.433	0.600	0.367	0.140	0.017	0.009
Effective reduction in emissions	N/A	58.1%	74.4 %	90.2 %	98.8 %	99.4 %

* An average determined from two tests

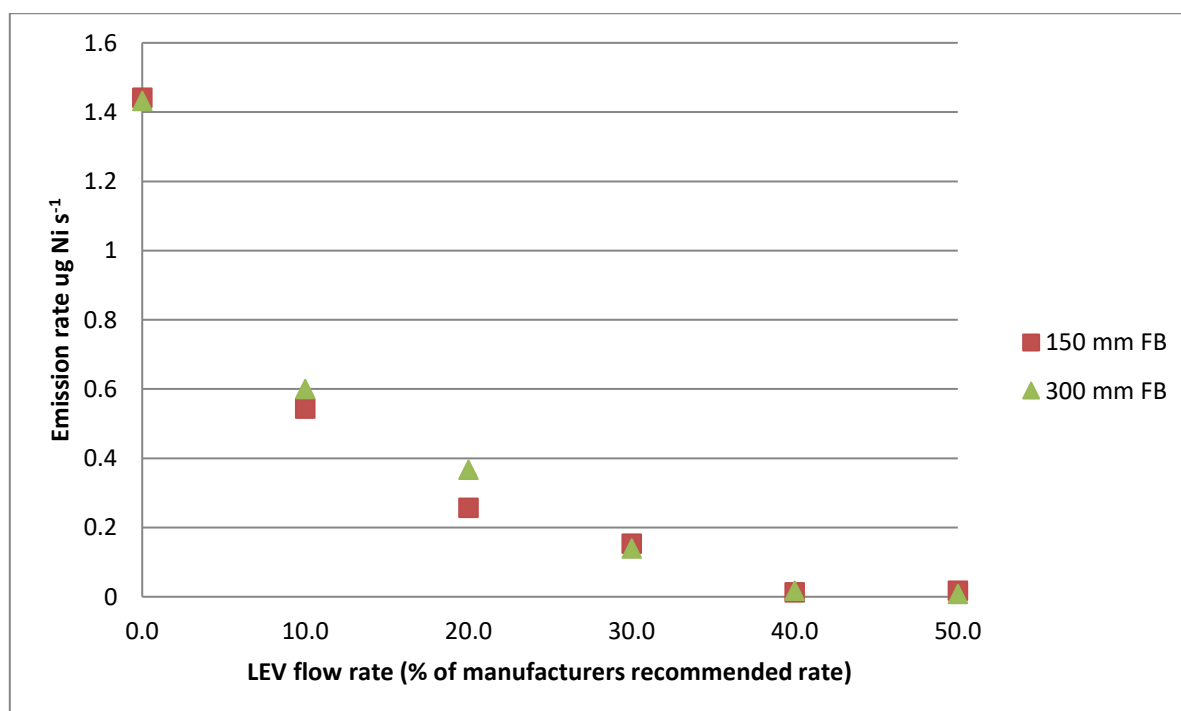


Figure 10. Effect on emission rate as a function of LEV rate (expressed as a % of manufacturers recommended flow rate) at 24 l.min⁻¹, 49 dynes surface tension at both 150 mm and 300 mm freeboard heights.

Table 13 summarises the surface contamination data obtained to evaluate the effect of LEV at 24 l.min⁻¹ air agitation and 49 dynes surface tension, but at different LEV flow rates and freeboard heights of 150 mm and 300 mm. The data are presented in Figure 11.

Table 13. Summary of the surface contamination data obtained to evaluate the effect of LEV.

Nickel surface contamination ($\mu\text{g Ni cm}^{-2}$)						
Conditions	LEV flow rate (as a % of manufacturers recommended)					
	0 (LEV off)	10	20	30	40	50
150 mm FB	1.52	1.98	1.598	1.768	2.56	2.88
300 mm FB	0.47	1.09	0.758	1.154	0.946	1.298

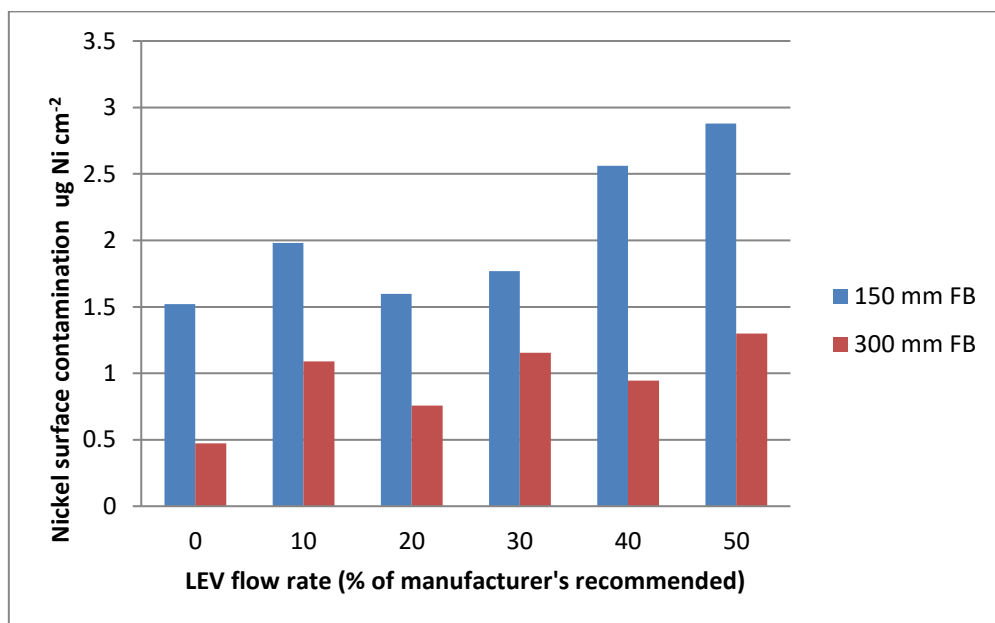


Figure 11. Summary of surface contamination data obtained to assess effect of LEV.

3.2.4 Chroffles

Table 14 shows the emission rate data generated with 100 % coverage of chroffles at 49 dynes, at differing air agitation rates with a 150 mm freeboard height. Also included are the nearest equivalent emission rate data obtained without the use of chroffles from which a % reduction in emissions is calculated. Figure 12 plots the data presented in Table 14.

Table 15 presents the emission rate data obtained when using partial chroffle coverage at a fixed 150 mm freeboard height, 49 dynes surface tension and air agitation rate of 16 l.min⁻¹. The data are also plotted in Figure 13.

Table 14. Reduction in emission rate when using chroffles (100 % coverage) on plating tank operating at constant 150 mm freeboard height and around 49 dynes surface tension but with varying air agitation rate.

	Emission rate ($\mu\text{g Ni s}^{-1}$) at 150 mm freeboard						
	Air agitation rate ($\text{l}\cdot\text{min}^{-1}$)						
	5	9	13	16	19	21	24
100 % chroffles	0.070	0.118	0.212	0.296	0.344	0.467	0.619
No chroffles	0.369	0.506	0.784	1.182	1.585	2.061	2.472
% Reduction in emission rate	81.0	76.7	73.0	75.0	78.3	77.4	75.0

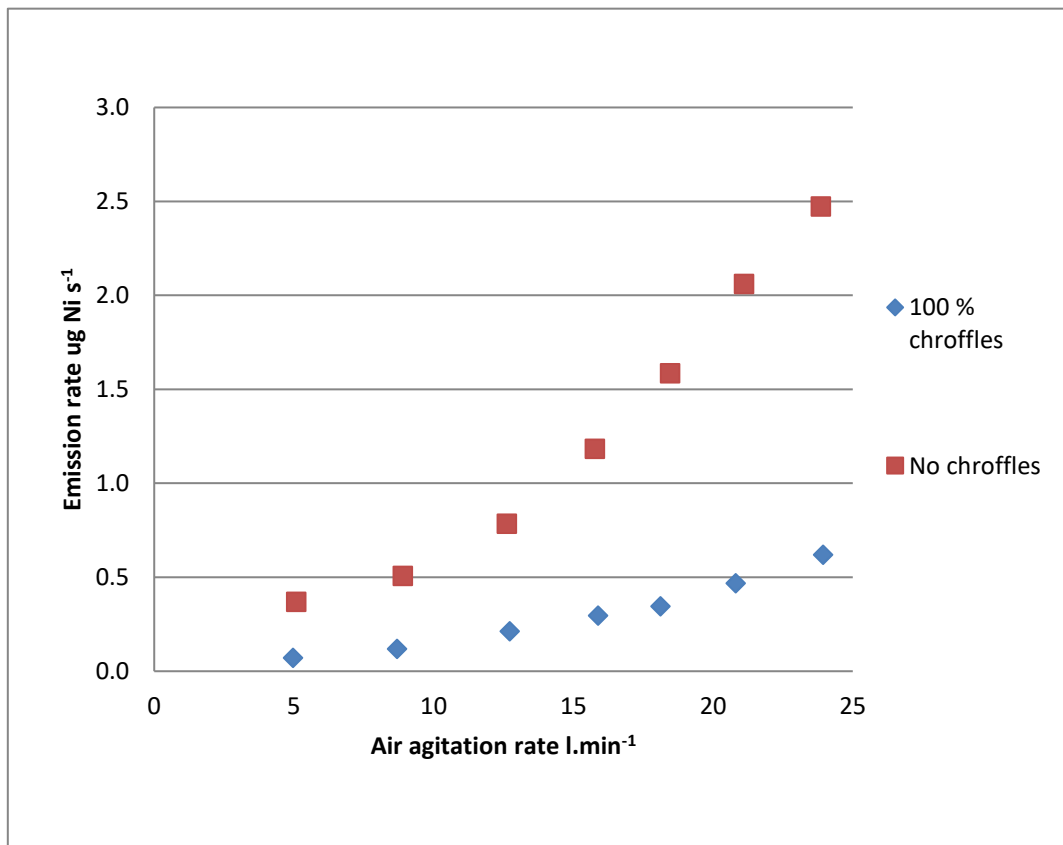


Figure 12. Effect of chroffles at 150 mm freeboard height.

Table 15. Emission rate data obtained at varying levels of chroffle coverage when operating the tank at a freeboard height of 150 mm, 16 l.min⁻¹ air agitation rate and 49 dynes surface tension.

	% Chroffle coverage				
	100	83	66	50	0 (no chroffles)
Emission rate μg Ni s ⁻¹	0.344	0.443	0.516	0.782	1.182
% Reduction in emission rate	70.9	62.5	56.4	33.8	N/A

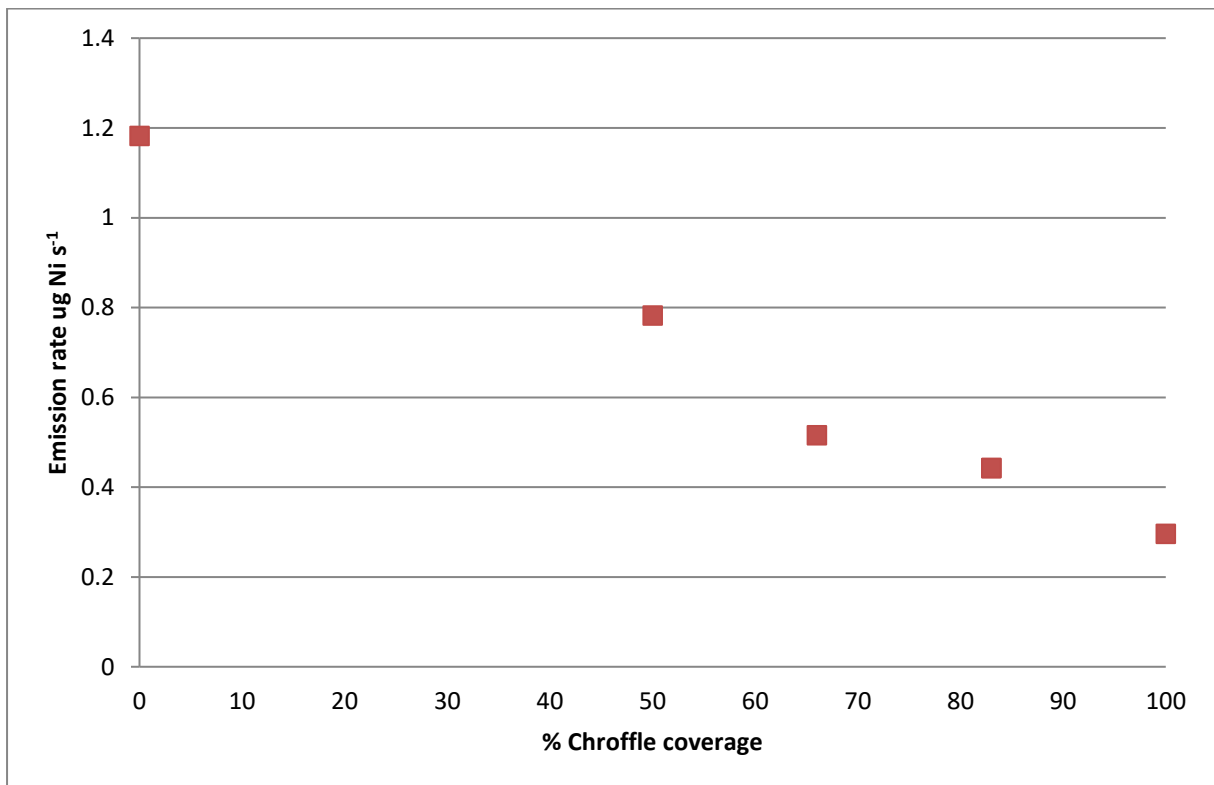


Figure 13. Effect of partial chroffle coverage at 150 mm freeboard, 16 l.min⁻¹ agitation.

Table 16 shows the surface contamination data obtained from operation of the tank at 49 dynes surface tension and a 150 mm freeboard height, both with chroffles (100 % coverage) and without. The data are also plotted in Figure 14.

Table 16. Summary of nickel surface contamination data assessing the effect of chroffles.

Nickel surface contamination ($\mu\text{g Ni cm}^{-2}$)								
Conditions	Air agitation rate (l.min^{-1})							Average
	5	9	13	16	21	21	24	
No chroffles	0.54	1.44	2.76	1.36	1.7	2.1	2.22	1.73
Chroffles	0.266	0.52	0.496	0.338	0.468	0.94	0.726	0.54
% Reduction in surface contamination	50.7	63.9	82	75.1	72.5	55.2	67.3	68.8

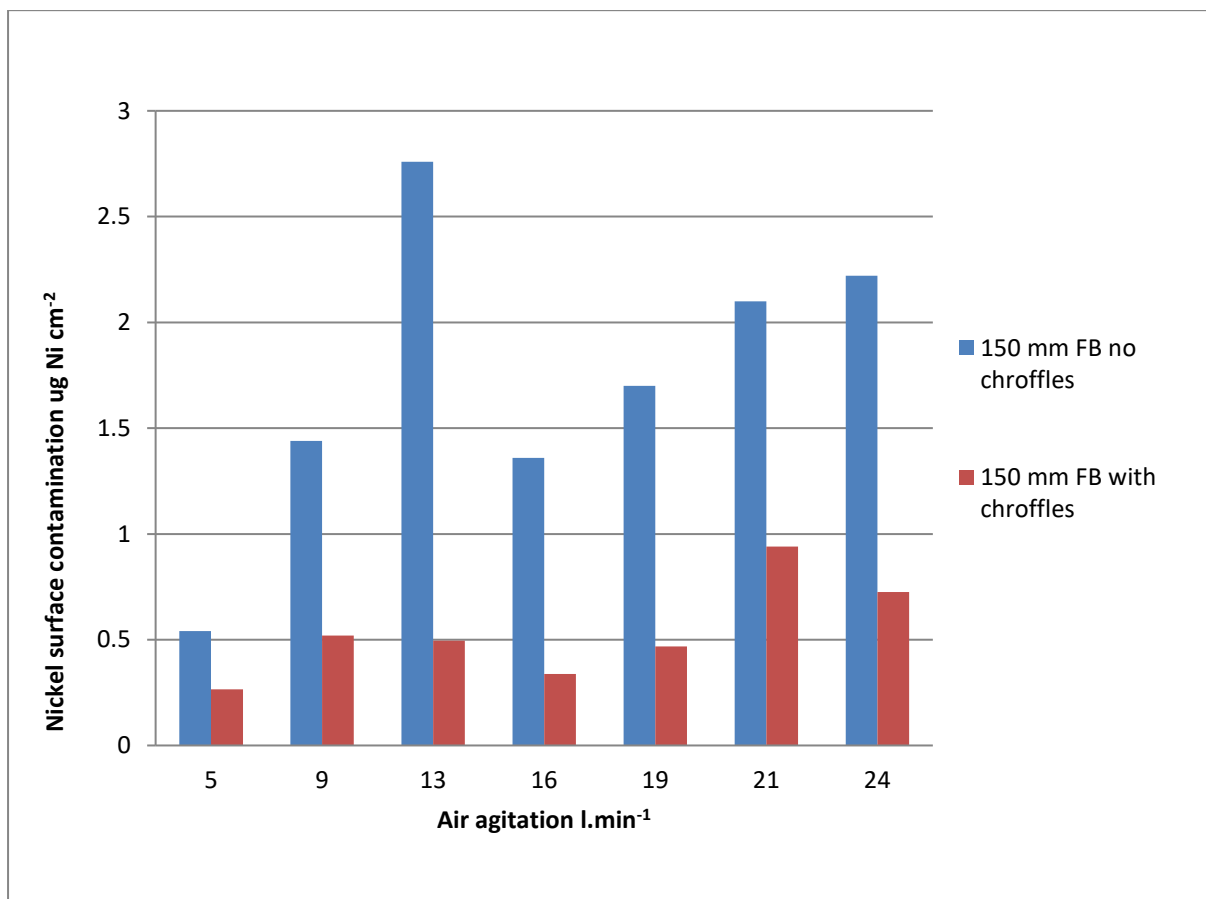


Figure 14. Effect of chroffles on surface contamination at 150 mm freeboard.

3.2.5 Surface tension

Table 17 below shows data obtained at 150 mm freeboard, 24 l.min⁻¹ air agitation, no LEV, but at differing surface tension. The data are also plotted in Figure 15.

Table 17. Summary of emission rate data obtained at 150 mm freeboard height and 24 l.min⁻¹ air agitation at differing surface tension measurements.

	Surface tension in dynes (relative to manufacturer's specification)			
	50 (out of spec high)	44.5 (in spec, upper)	42.5 (in spec, lower)	37 (out of spec low)
Surfactant concentration increasing				
Emission rate $\mu\text{g Ni s}^{-1}$	1.631	1.363	1.267	0.634
% Change in emission rate*	+19.7	N/A	-7.0	-53.5

* Relative to that obtained at 44.5 dynes.

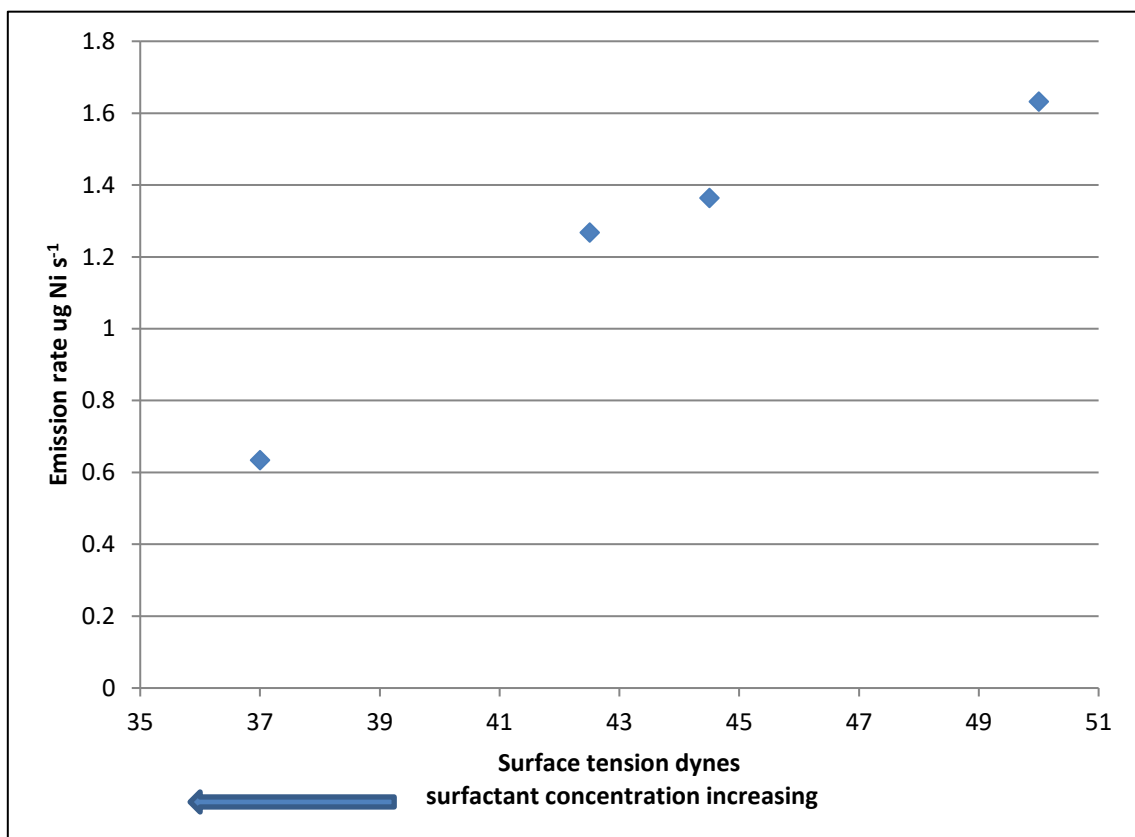


Figure 15. Effect of surface tension on emission rate at 150 mm FB.

3.3 STATIC SAMPLING USING IOM SAMPLERS

Table 18 summarises the static (inhalable) air concentration data obtained when carrying out air sampling over the tank using personal sampling equipment. The data were obtained at 49 dynes surface tension and 150 mm freeboard height, without the use of LEV but at three different air agitation rates. This is shown graphically in Figure 16. Figure 17 shows the relationship between the static concentrations measured against the emission rates determined for the same tests runs, R² values are shown as this give an indication of the correlation between nickel in air static concentrations and emission rate.

Table 18. Summary of over the tank air sampling using personal sampling equipment.

Nickel in air concentration (mg.m ⁻³)			
	Air agitation rate (l.min ⁻¹)		
	13	19	24
Overall average (n=10)	0.021	0.032	0.047
Average of data at 25 cm above tank (n=6)	0.028	0.04	0.061
Average of data at 50 cm above tank (n=4)	0.011	0.019	0.025
WEL*	0.1		
Emission rate obtained	0.69 µg Ni s ⁻¹	1.30 µg Ni s ⁻¹	1.69 µg Ni s ⁻¹

* WEL as an 8-hour TWA. Note included for information, WEL relates to worker exposure and direct comparison of static sampling results with a WEL is not appropriate.

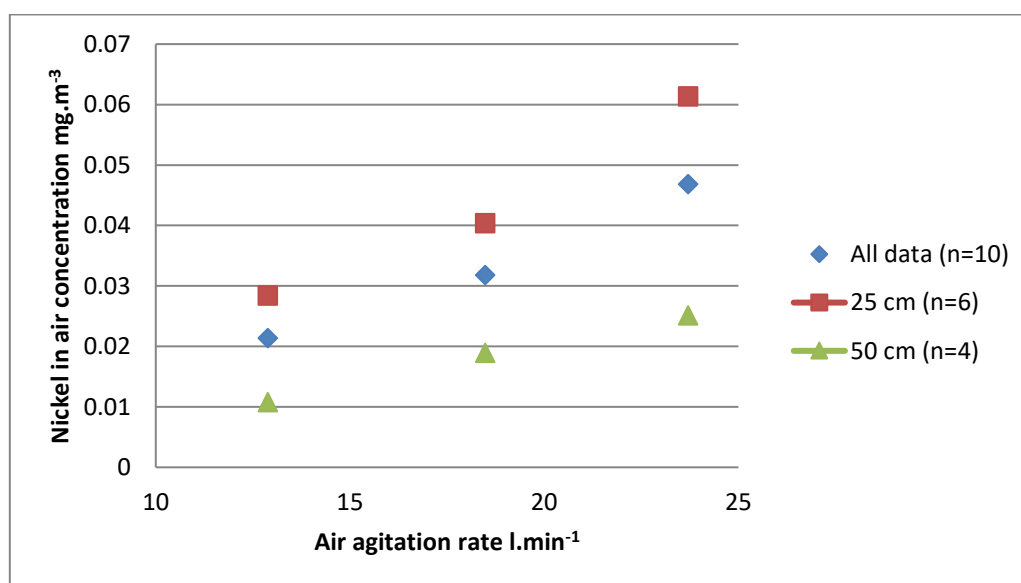


Figure 16. Static air sampling data obtained at 150 mm freeboard, 49 dynes with varying air agitation.

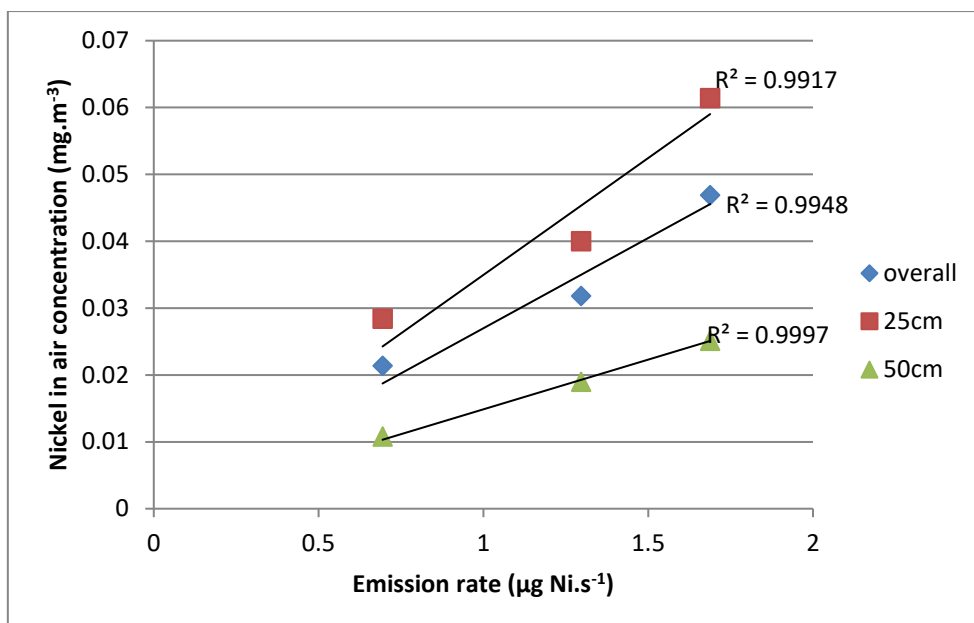


Figure 17. Emission rate data and static air sampling data obtained at 150 mm freeboard, 49 dynes with varying air agitation rate.

3.4 EFFICIENCY/COST SAVINGS

Gas usage, to maintain tank at plating temperature, was monitored during a number of plating runs of the standard 90 minute duration carried out within a few days of each other. Four air agitated runs were carried out at 16, 9, 24 and 24 l.min⁻¹ and one eductor agitated run. The gas consumption rates are shown in Table 19 below.

Table 19. Summary of gas consumption tests.

Test conditions	Gas consumption over test (m ³)
90 minute plating runs	
16 l.min ⁻¹ air agitation	0.308
9 l.min ⁻¹ air agitation	0.172
24 l.min ⁻¹ air agitation repeat 1	0.242
24 l.min ⁻¹ air agitation repeat 2	0.287
Eductor agitation	0.182
4-hour test, maintaining tank temperature but not plating	
24 l.min ⁻¹ air agitation	1.226
Eductor agitation	0.642

3.5 COMPOSITION OF EMISSIONS

The presence of nickel sulphate hexahydrate was identified following the test described in 2.2.3.

4 DISCUSSION

4.1 EXPERIMENTAL OVERVIEW

A small scale electrolytic nickel plating process was successfully set up for testing purposes. A number of steps had to be taken in order to ensure that emission reductions of 95 % from the worst case scenario of high air agitation rate and no LEV could be determined with confidence. The primary steps taken to achieve this were increases in the surface area being plated, the sampling flow rate and the sample run time. The sample run was increased to 90 minutes which is longer than the 15 – 35 minutes that industrial processes would typically run for.

The metric used to assess the efficacy of different agitation/exposure control techniques was the emission rate measured in the sampling hood duct. This is the amount of airborne nickel generated from the plating tank per unit time, μg nickel per second. It is not a direct measure of concentration over the tank and does not allow comparison to the WEL. However, comparing emission rates from different control scenarios does allow the relative inhalation exposure potential between them to be assessed.

Emission rates were shown to be reproducible over short time periods, i.e. within a week or so. Over longer time periods repeat tests were more variable, though the statistical model showed no obvious evidence of a systematic effect on emission rates with time. This tends to make it generally more difficult to detect real effects of control measures for tests carried out over longer time periods. Due to the longer term variability observed, when testing control scenarios other than air agitation without LEV, a “base condition check” test was also carried out. This was so that a reference point was available to enable some comparison between data sets obtained some time apart. The base condition check was the worst case scenario of no LEV and high air agitation rate (24 l.min^{-1}).

To give the emission rate findings some context to the occupational exposure environment, over the tank sampling was carried out using “conventional” sampling equipment of the type used for determining worker exposures. This was carried out with a freeboard height of 150 mm, 49 dynes surface tension, and without LEV in use with sample run times of 90 minutes. The highest static nickel in air (inhalable) concentration measured was 0.061 mg.m^{-3} at a height of 25 cm above the tank. There was a good linear correlation of the emission rate of nickel from the tank compared with the over the tank sampling, as shown in section 3.3. Extrapolating the over the tank sampling results with the differing emission rates obtained over the testing period, it is estimated that inhalable nickel concentrations at 25 cm above the tank would be unlikely to exceed 0.12 mg.m^{-3} . It is worth noting that the WEL for soluble (inhalable) nickel is 0.1 mg.m^{-3} as an 8-hour TWA, although direct comparison of static sampling results with a WEL is not appropriate without occupational hygiene expertise. The over the tank static air concentrations are in a similar range to those found in previous HSE work (HSE, 2013a).

The scope of work was expanded to consider the effect that the different control measures had on the dermal exposure potential. This was done by carrying out surface wiping on the front lip of the plating tank both before and after the plating run and then the amount of soluble nickel found was calculated per unit area i.e. $\mu\text{g Ni cm}^{-2}$. Whilst this is not a direct measure of dermal exposure, surface contamination on the plating tank itself is one of the main sources of contamination which

can potentially lead to dermal exposure and therefore may be considered a good indicator for potential dermal exposure. There are no formal exposure standards against which to compare surface wiping results. However, previous HSE work in the surface engineering sector (HSE, 2013a) interpreted such data using median and 90th percentile data generated from surface wipes. Values were calculated for data collected from “production” areas and from “clean” areas. For production areas median soluble nickel wipe data was 1.33 $\mu\text{g}\cdot\text{cm}^{-2}$ and the 90th percentile was 10.8 $\mu\text{g}\cdot\text{cm}^{-2}$. For clean areas the median was 0.05 $\mu\text{g}\cdot\text{cm}^{-2}$ and the 90th percentile was 0.48 $\mu\text{g}\cdot\text{cm}^{-2}$. It should be noted that in the previous HSE research, the types of surfaces wiped in production areas were not tank lips but those which may have been contacted by hand, for example tool handles. Using this method does not consider any contamination arising from transferring items into and out of the plating tank i.e. drag out. In reality, this is likely to make a more significant contribution to the dermal exposure potential than that deposited during the plating run, and this effect will occur irrespective of engineering control measures applied. Also where air agitation was used, there is a possibility of tank lip contamination arising from the initial switching on of the air agitation after the jigs were lowered into the plating tank. The protocol followed by the scientist carrying out the tests was that the air was switched on gradually to minimise this effect.

4.2 EFFECT OF EDUCTORS

The emission rate data for the evaluation of eductors is shown in Table 2. With the tank having a 150 mm freeboard height, experiments were carried out at four different surface tension levels with eductors and then repeated but using 24 $\text{l}\cdot\text{min}^{-1}$ air agitation and no LEV. Emission rate reductions of between 97 and 99 % were achieved with the use of eductors. The statistical modelling verified these findings, with the emission rates fitted values calculated by the model showed reductions of more than 98 % across a range of surface tension measurements. The results show that whilst eductors do not entirely eliminate emissions, a significant reduction occurred with the use of eductors which appears to be independent of plating solution surface tension. The main mode by which eductors reduce emissions is by eliminating the need to bubble air constantly through a warm solution. As the bubbles burst through the surface of the solution, they generate an aerosol creating an inhalation risk.

It is estimated that over the tank soluble (inhalable) nickel in air concentrations on the plating tank studied were no more than 0.001 $\text{mg}\cdot\text{m}^{-3}$ which is 1 % of the current WEL (0.1 $\text{mg}\cdot\text{m}^{-3}$ 8-hr TWA). This is based on extrapolation of emission rate data and the over the tank static sampling data obtained using conventional sampling approaches on an air agitated tank as shown in section 3.3.

The effect that eductors have on the surface contamination level was also studied and the data are presented in Table 3 and Figure 2. They do reduce the amount of nickel deposited on the tank lip, but not to the same degree as the effect observed for the emissions. Surface contamination levels were reduced between 36 and 82 %, depending on the surface tension. These data further support the use of eductors as an effective exposure control for electrolytic nickel plating processes.

4.3 EFFECT OF AIR AGITATION (NO LEV APPLIED).

Air agitation rate was found to have a significant effect on the emission rate; when going from 5 $\text{l}\cdot\text{min}^{-1}$ to 24 $\text{l}\cdot\text{min}^{-1}$ air agitation the emission rate increased by a factor between 6.7 to 7.7, as shown in Figure 3. The minimum air agitation rate for the plating tank used was considered to be around 16 $\text{l}\cdot\text{min}^{-1}$ in order to achieve acceptable plating quality. At this level, typically emission rates

were half that obtained at 24 l.min⁻¹ thus offering a significant reduction in the inhalation potential. The statistical analysis carried out on the data confirmed that that emission rate increases as air agitation rate increases. The statistics verified emission rate reductions of between 44 and 57 % (depending on freeboard measurement) at the lowest air agitation rate at which acceptable plating quality was achieved (16 l.min⁻¹) when compared to the highest air agitation rate studied (24 l.min⁻¹).

The technical documentation provided by the chemical supply house on typical air agitation rates, suggested that agitation rates should be 20 -30 m³ air per hour per m² of tank surface. This equates to 180 – 270 l.min⁻¹ which is significantly higher than that used in our tank. The manufacturer of our equipment suggested an air agitation rate of around 60 l.min⁻¹. So when referring to “high” air agitation rates for the experimental work described in this report these are low relative to recommendations. We do not have any information on the actual air agitation rates used in industry as they are not measured and are typically set at operator discretion. This suggests that nickel in air concentrations in some industrial settings could potentially be higher than those measured in this work as we have demonstrated a link between air agitation rate and emission rate. As we achieved acceptable plating quality there would be little point in running unnecessarily high air agitation rates as this would increase exposure potential and plant running costs caused by both an increased rate of cooling of the plating solution and the cost of compressed air. It should be noted that plating quality can be subjective and, as plating times were artificially high (to generate sufficient emissions), effects such as overplating on the edges of the tests pieces were inevitable and expected.

We do not have data to support the wider applicability of our findings on tanks of different geometries. Nickel plating in industrial settings involves tanks that are typically larger than those in the HSE SD set up. It would be best for industry to operate the air agitation at the lowest level possible that achieves an acceptable plating quality. Ideally there should be some means of achieving this repeatably without relying on operator judgement. Anecdotal evidence indicated that there can be significant variation between the rates set by different operators. Measures to achieve this could include a graduated needle valve on the air line or an in line flow meter. Anecdotally we understand that generally surface engineering companies are good at minimising air agitation rates because they are aware of the cost implications. It should be noted that BS EN 17059:2018 (BSI, 2018) which is the GB implementation of European Standard EN 17059:2018 states that “*air agitation systems shall be avoided*”.

The effect of differing air agitation rate on surface contamination is less clear cut. The data are shown in Table 8 and Figure 7 and shows there is an overall upward trend in the amount of nickel deposited on the tank lip as air agitation rate increases. However, there are variations in the data obtained meaning that the relationship is inconsistent. For this reason when comparing different plating scenarios it was decided to take an average of the data across the range of air agitation rates studied. The data do demonstrate the benefit of keeping the air agitation rate to the minimum required for acceptable plating quality. It is also suggested that, when switching air agitation on, it is done in a gradual manner as there is the potential for surface deposition to occur through splashing during the initial surge of pressure created.

4.4 EFFECT OF FREEBOARD MEASUREMENT

This effect was evaluated at the “worst case” scenario of highest air agitation rate without the use of LEV. Emission rate generally increased as the freeboard measurement was decreased but the effect was relatively minimal as can be seen in Table 4 and Figure 3. The statistical analysis of the data showed emission rate reductions of 12 % (at 150 mm freeboard) and 18 % (at 300 mm freeboard) were noted when compared to that obtained at 50 mm freeboard.

The effect of freeboard on surface contamination is far more pronounced. As with emission rate, the effect was assessed without the use of LEV but at a fixed 24 l.min⁻¹ air agitation rate with a number of replicates being performed. The data are presented in Table 9 and Figure 8. Average nickel surface contamination at a freeboard of 50 mm was 21.14 µg Ni cm⁻² (n=5). Increasing the freeboard height to 150 mm resulted in a 90.6 % reduction in the surface contamination observed (average = 1.98 µg Ni cm⁻², n=7). Increasing the freeboard height further to 300 mm decreased average surface contamination by over 95 % relative to that obtained at 50 mm (average at 300 mm = 0.95 µg Ni cm⁻² n=6). BS EN 17059 refers only to *suitable freeboard* rather than specifying particular values. The joint HSE/SEA guidance on control of nickel inhalation exposure recommends a minimum freeboard height of 150 mm with 300 mm being ideal. For air agitation, these data support this guidance and clearly demonstrate the benefits in operating the tank with increased freeboard measurement. This is because the surface contamination is significantly reduced thus reducing the potential for workers to be exposed via the dermal route. However, whilst there are clear exposure control benefits shown in using a 150 mm freeboard over a 50 mm freeboard, the reductions in going from 150 mm to 300 mm freeboard are not as great. As use of eductors reduces emissions to near zero, the freeboard is essentially irrelevant for emissions. For the use of eductors, data was only obtained at 150 mm freeboard due to time constraints. Therefore, the effect of freeboard on the surface contamination potential was not considered. The HSE project team would not expect the level of surface contamination with the use of eductors at 50 mm freeboard to be as high as when using 50 mm freeboard with a high air agitation rate. However, it is considered that a 150 mm freeboard would offer greater protection than 50 mm against the risk from splashes when adding or removing workpieces from the plating tank. This risk is present irrespective whether eductors or air agitation are used.

To give some context to the surface contamination results, soluble nickel surface wipe data from previous HSE research in the surface engineering industry can be used (HSE, 2013a); 91 measurements were taken from the production areas of 15 different companies. The median nickel contamination was 1.33 µg Ni cm⁻² and the 90th percentile was 10.8 µg Ni cm⁻².

4.5 EFFECT OF LEV

The set up used for evaluation of LEV efficacy was high air agitation rate and, initially a 50 mm freeboard. The experiments showed that the use of LEV has a significant effect on controlling the emission rate. The data are presented in Tables 10 – 12 and Figures 9 and 10. Running the LEV at 100 % of the manufacturer’s recommended flow rate reduced emissions by greater than 99.7 %. Note the exact reduction at 100 % could not be calculated as the result from which emission rate was determined was less than the analytical limit of detection. Reducing the flow rate down to 50 % of that recommended reduced emissions by 99.7 %. This suggests that the recommendations are over specified, although they are in line with ACGIH recommended flow rates which are also referenced in BS EN 17059:2018. However, it should be remembered that lip extraction applied to plating tanks

are classed as capture hoods and therefore their efficacy is susceptible to workroom draughts and general air turbulence. In a real workplace the background air disturbances are likely to be higher than in the test room, and higher extraction rates may be required to ensure effective capture.

A series of other LEV tests were carried out at flow rates between 10 and 50 % of the manufacturer's recommendations. Figures 9 and 10 show that the effect is not linear and that significant emission rate reductions (> 70 %) were achieved with the LEV running at 20 % of the recommended flow.

The statistical analysis verified the overall findings, showing that emission rate decreases as LEV flow rate increases and reductions in emission rate of more than 98 % occurred when using a high air agitation rate and running LEV at manufacturer's recommended flow rate.

It should be noted that the LEV has not eliminated the production of nickel aerosol from the plating tank. The nickel aerosol generated from the tank has been captured by the LEV and then ducted away through the filtration media before external discharge. The significance of this is that should the LEV performance decline or the system fail totally then the nickel aerosol that is normally captured by effective, well maintained LEV would then present an inhalation exposure risk.

Tests were carried out which explored the effect of LEV flow rate on the surface contamination data. The results are presented in Table 13 and Figure 11. The effect does not appear to have a clearly defined relationship, although it does suggest that use of LEV increases the surface contamination on the front lip of the tank, particularly for 150 mm freeboard.

4.6 EFFECT OF CHROFFLES

The emission rate data from the evaluation of chroffles are shown in Tables 14 and 15 and Figures 12 and 13. Chroffles reduced emissions between 73 and 81 % depending on the air agitation rate. This indicates that chroffles covering the surface of the plating solution do have a significant effect on the emission rate and that the effect is not influenced by air agitation rate to any great degree. Further testing to evaluate the effect of partial chroffle coverage, indicated that there was a linear relationship between the emission rate and the percentage coverage. The statistical analysis verified that use of chroffles decreases the emission rate in a linear relationship i.e. the more chroffles there were on the tank surface, the greater the emission rate reduction was. The statistically derived emission rate data showed emission rate reductions of around 70 % over a range of different air agitation rates when evaluated at 49 dynes and 150 mm freeboard. As has already been stated earlier in the report, with notional chroffle coverage of 100 %, the actual tank surface area covered is around 78.5 %. The scientist carrying out the tests noted that during operation of the tank with a notional 100 % coverage, the chroffles separate leaving an obviously uncovered section of tank surface area. Subjectively, the size of this area was greater as the air agitation rate was increased.

The use of chroffles also had a significant effect on reducing surface contamination as can be seen in Table 16 and Figure 14. With a notional 100 % chroffle coverage, reductions of up to 82 % were observed depending on the air agitation rate with an overall average reduction of 69 %. However it should be noted that whilst the use of chroffles reduces the level of surface contamination, thereby reducing the dermal exposure potential, it is also likely that the handling of the chroffles between plating runs, for example replacing any lost during drag out of jigs, could bring an increased risk of dermal exposure. This means that the real world impact on the dermal exposure potential may not

be as significant as the experimental data suggests and using chroffles could potentially even result in an increase in dermal exposure.

It should also be noted that there are practical considerations with chroffles and they are likely to be impractical for short term plating times, typical of decorative plating. The scientist carrying out the majority of the experimental work had significant previous experience as an electroplater and reported the inconvenience of using chroffles and considerations such as them becoming trapped between pipework and also transferred into rinse tanks. For longer plating times, more typical of engineering grade plating, chroffles may be a viable option. Anecdotally there is also reportedly potential energy savings from the insulating effect of the chroffle blanket; during informal discussions with a supplier of chroffles, energy savings of 75 % or more were reported. Resource was not available to evaluate this effect as part of this work.

4.7 EFFECT OF SURFACE TENSION

We understand that for electrolytic nickel plating processes, the primary purpose of the surfactant is to ensure good solution mixing, rather than as a means of controlling emissions. However, for other plating processes e.g. chromium where surface tension is used as a control measure it is known that emissions are likely to vary depending on the surface tension.

A series of experiments without LEV were carried out at a fixed 150 mm freeboard and 24 l.min⁻¹ air agitation. The emission rate results are shown in Table 17 and Figure 15. As has already been stated, the surfactant was used at a lower concentration level than the solution manufacturer specified (i.e. surface tension was numerically high at 50 dynes) to generate sufficient emissions. When comparing emission rate results with the rate obtained at 50 dynes, we measured a 16 % reduction in emission rate at 44.5 dynes, which represented the upper end of the manufacturer's recommended level. At 42.5 dynes, which represents the lower end of the manufacturer's recommended range, a 22 % reduction was measured. Adding more surfactant to reduce the surface tension (out of manufacturer's specification) to 37 dynes, gave a 61 % reduction in emission rate, which is significant. The statistical analysis carried out on the emission rates data confirmed that the more surfactant there was in the solution, the lower the emission rate was.

The effect of surface tension on surface contamination was also evaluated. The data are presented in Table 3 and Figure 2. Operation of the tank with a 150 mm freeboard without LEV at 24 l.min⁻¹ air agitation and at 50 dynes surface tension gave an average surface contamination of 1.97 µg Ni cm⁻². Increasing the surfactant concentration reduced the surface contamination in a linear trend; a 31% reduction at 45 dynes, a 66 % reduction at 42 dynes and a 78 % reduction at 37 dynes. We consider the reduction may be a result of the particles that do escape having lower energy and so are less likely to travel as far as the tank lip before falling back down. This effect may not be the same when using freeboard heights less than 150 mm, but this would not be in accordance with the current HSE/SEA guidance.

Whilst surfactant chemicals can be expensive, there may be exposure control benefits in plating at concentrations higher than manufacturer's recommendations. Doing so could represent a cost effective way to minimise emissions with relatively low initial outlay and no ongoing maintenance costs that can be associated with engineering controls such as LEV. However, we would not normally anticipate surface tension control being the primary exposure control mechanism. Similarly surface sampling showed potentially significant benefits in the control of surface deposition. We achieved

acceptable plating quality at 37 dynes, although the potential effect on the properties of the coating would need to be evaluated by operators before considering lowering the surface tension.

4.8 EFFICIENCY SAVINGS/COST CONSIDERATIONS

A full systematic evaluation of potential efficiency/cost savings was not part of the scope of work, however, we did carry out some work in this area. Initial discussions with the manufacturers of our plating line indicated that installation costs of retrofitting LEV to an air agitated tank would be higher than the cost of retrofitting eductors. They also reported that for new electroplating plant an eductor agitated system would be cheaper to supply and install than an air agitated system with LEV. There are also significant ongoing costs associated with running an LEV system. These include day to day running costs from powering the LEV fan(s), generating the compressed air, reheating the work environment following the cooling effect of the incoming air, and the costs of regular maintenance and thorough examination and testing to ensure compliance with the COSHH regulations.

Initial tests were carried out in an attempt to evaluate some of the potential efficiency savings from the use of eductors. The theory being that less energy is required with eductor use as there is not the constant cooling effect of the air being bubbled through the tank solution. Gas usage was monitored during a number of actual test plating runs of the standard 90 minute duration carried out within a few days of each other. A range of air agitation rates were used and one test with eductors was also carried out. The results which are shown in Table 19 were inconclusive. To investigate this further, two tests were carried out monitoring gas consumption rates to maintain the tank at working temperature over a four hour period. One test was carried out using 24 l.min⁻¹ air agitation and the other using eductors. These results are also shown in Table 19. Eductors gave a 48 % saving in gas usage over air agitation.

We understand that there are potential energy savings to be made through the use of eductors due to the solution conducting more efficiently. We did observe a small but consistent decrease in the voltage required when using eductors, this effect was not fully explored.

4.9 CONSIDERATIONS FOR APPLICABILITY OF THE FINDINGS TO OTHER PLATING TANKS AND PROCESSES

We do not have the data to support the wider applicability of our findings to electrolytic nickel plating tanks of different geometries. We consider that the overall effects i.e. the relative effect on emissions that we observed, would be similar for all tanks studied. However the absolute amount of emissions will be different and would potentially be more than those reported here. The absolute emissions will depend on a number of factors over and above those assessed for this work. These include the current applied which is directly related to the surface area being plated and also the surface area of the plating solution.

We do not have data to support the wider applicability of the findings to other electrolytic plating processes. However, the opinion of the authors is that there are no obvious reasons to suspect the data obtained for use of different controls would not be applicable to other electrolytic plating processes.

4.10 HIERARCHY OF CONTROL CONSIDERATIONS

It should be considered that all controls studied, except for LEV, work by actually reducing the amount of nickel aerosol generated and so would be considered to be preferable exposure controls

in terms of their efficacy. LEV does not reduce the nickel emissions, but achieves control by removing the contaminant before it can pose an exposure risk. Should the efficacy of the LEV reduce or the system fail then control will be lost and exposure will occur, i.e. it fails to danger. It is noted that BS EN 17059 specifies *“appropriate protective measures shall be taken in case of failure or insufficient forced ventilation so that hazards for persons present are indicated”*, and such measures could include *“interruption of electrolytic operations by shutdown of rectifiers”*. This standard applies to new equipment and does not apply retrospectively to existing equipment. It should be noted that the majority of nickel plating lines with LEV will have been designed prior to introduction of BS EN 17059.

When considering the hierarchy of control and the options studied, it is generally accepted that process driven exposure controls are far more likely to remain effective. Eductors are the means by which the plating tank solution is mixed and since this a requirement for the plating process to work satisfactorily, eductors could be considered a “fail safe” exposure control because plating work would be halted if the eductors failed. Businesses can be expected to be more motivated to maintain critical process controls than standalone exposure controls. Eductors are considered the best control of those studied as they are effective and less prone to failure. Initial investigations also indicate that they are cheaper than LEV and therefore should be considered to be reasonably practicable when choosing exposure controls for an electrolytic nickel plating tank. The presence of nickel sulphate hexahydrate in the emissions was confirmed in a test. Nickel sulphate hexahydrate is classified as a carcinogen (ECHA, 2019), which therefore indicates that the requirement under COSHH should be for exposure to be controlled to ALARP.

5 CONCLUSIONS

An evaluation of different exposure controls for electrolytic nickel plating has been carried out. The efficacy of these controls is now much better understood, supported by robust quantitative scientific evidence.

Different exposure control scenarios for electrolytic nickel plating were tested and the potential effects on emissions and the surface contamination on the front tank lip have been evaluated. The results are summarised in Table 20 overleaf. The findings for the emission rate data were verified by use of statistical modelling.

Eductors and LEV offer the biggest reductions in emission rate with both being similarly effective. LEV captures the nickel aerosol and moves it elsewhere to prevent worker exposure, which means there could be a loss of control should the LEV system deteriorate or fail. An LEV system should be designed to cut the power in such an event, so that the plating process stops and does not fail to danger. As the eductors are required by the process to achieve adequate mixing, then more robust emission control is more likely to be achieved on a consistent and sustained basis because they virtually eliminate the nickel aerosol emitted from the plating tank.

Cost implications were not fully explored, but retro fitment of eductors is likely to be cheaper to install, compared to fitting LEV to an air agitated tank. Eductor agitated systems are also considered to be cheaper for new plant. Ongoing running and maintenance costs of eductor plant are considered lower than air agitated systems.

Air agitation rate was found to have an effect on both emission rate and surface contamination, with a bigger effect observed on the surface contamination but in a less consistent relationship. Varying the freeboard height had a limited effect on the emission rate but a significant effect on surface contamination, particularly at 50 mm. Use of chroffles had a significant effect on both emission rate and surface contamination. However, the surface contamination measurement does not fully assess the dermal exposure potential and so the real world impact on the dermal exposure potential may not be as significant as the experimental data suggests. This means that reductions may not be as great as indicated and potentially could even result in an overall increase in dermal exposure, particularly so with use of chroffles given the handling of them required. Surface tension control does appear to show potentially significant reductions in both emission rate and surface contamination, however, the effect on properties of the coating were not formally evaluated and this would be an important consideration for dutyholders.

Table 20. Summary of the effect of different exposure control scenarios.

Exposure control scenario	Effect on nickel emission rate	Effect on nickel surface contamination
Eductors	Use of eductors reduced emission rate by more than 98 % compared to air agitation at a high rate with no LEV across a range of surface tension concentrations.	Use of eductors reduced surface contamination compared to air agitation with no LEV.
Air agitation rate	Emission rate increased as air agitation rate increased. Depending on the freeboard height, emission rate reductions of between 44 and 57 % were observed at the lowest air agitation at which acceptable plating quality was achieved (16 l.min ⁻¹) when compared to the highest air agitation rate studied (24 l.min ⁻¹).	In general as air agitation rate increased so did the surface contamination but the relationship was not consistent. Depending on the conditions, surface contamination increased between 50 % and more than 200 % at the highest air agitation rate studied (24 l.min ⁻¹) compared to lowest rate at which acceptable plating quality was achieved (16 l.min ⁻¹).
Freeboard height	Emission rate increased as freeboard height measurement decreased albeit with limited effect. Compared to 50 mm, emission rate reductions of 12 and 18 % were noted at freeboard height measurements of 150 mm and 300 mm respectively.	Increasing the freeboard height reduced the surface contamination. Surface contamination at 150 mm was twice that measured at 300 mm and that at 50 mm was 22 times more than at 300 mm.
LEV flow rate	Emission rate decreased as LEV flow rate increased. With the highest air agitation rate and the LEV set to the manufacturer's recommended flow rate, emissions were reduced by more than 98 % irrespective of the freeboard height measurement.	In general as LEV flow rate increased so did the surface contamination but the relationship was not consistent.
Chroffles	Use of chroffles decreased the emission rate. The higher the level of chroffle coverage, the greater the emission rate reduction. A notional 100 % chroffle coverage reduced the emission rate by around 70 % over a range of different air agitation rates.	Use of chroffles reduced the surface contamination between 50 and 80 % depending on the air agitation rate.
Surfactant concentration (surface tension control)	As tank surfactant concentration was increased, the emission rate decreased. There would appear to be exposure control benefits in running the surface tension lower than manufacturer's recommendations i.e. with high surfactant concentrations. The effect on coating properties was not considered. Compared to the upper end of the manufacturer's specification, running below the specification reduced emissions by 57 %.	As tank surfactant concentration was increased, surface contamination decreased. There would appear to be exposure control benefits in running the surface tension lower than manufacturer's recommendations i.e. with high surfactant concentrations. The effect on coating properties was not considered. Compared to the upper end of the manufacturer's specification, running below the specification more than halved the surface contamination.

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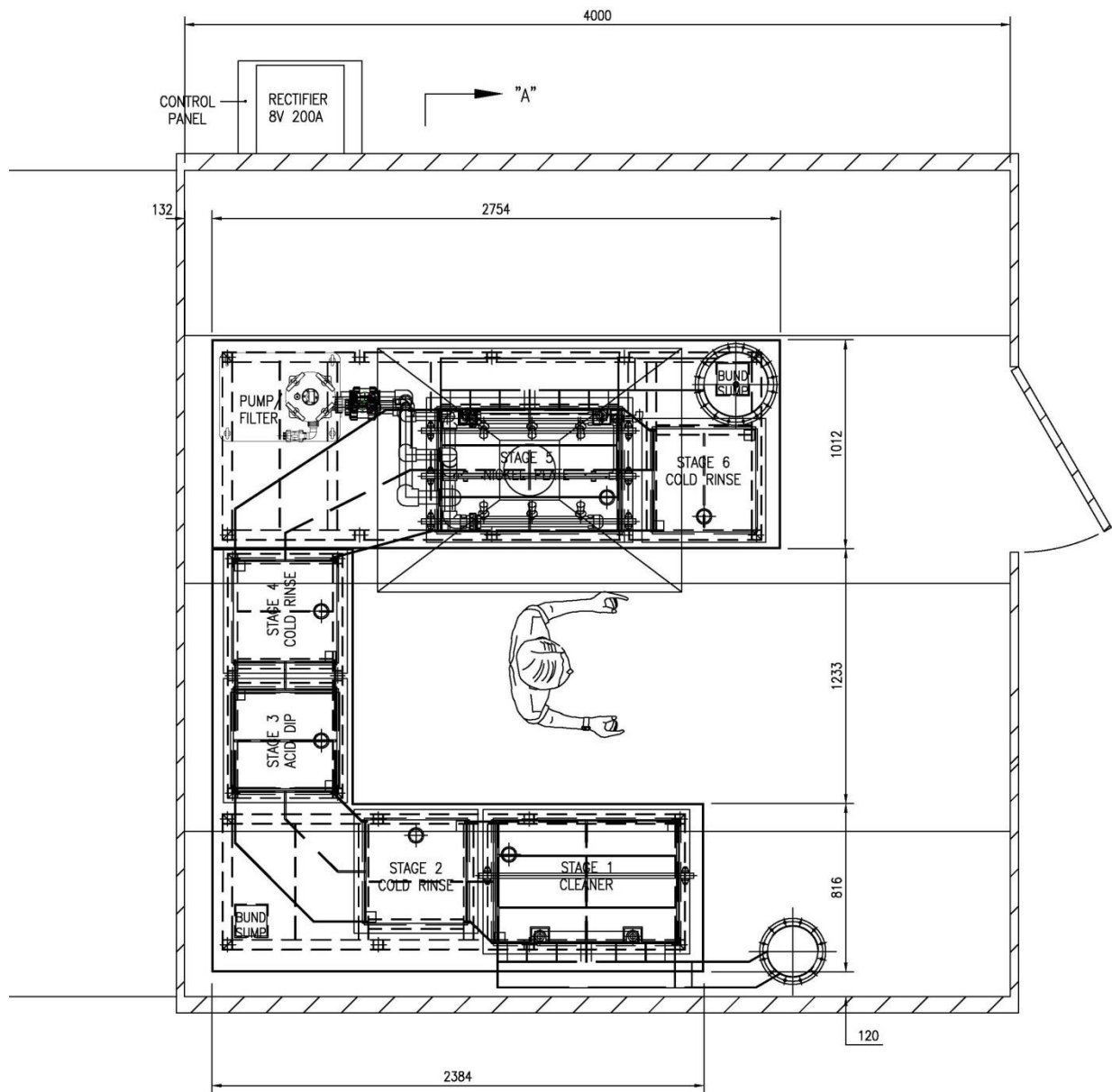
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7 APPENDICES

7.1 APPENDIX 1 – COSHH SCHEDULE 2A PRINCIPLES OF GOOD CONTROL PRACTICE FOR THE CONTROL OF EXPOSURE TO SUBSTANCES HAZARDOUS TO HEALTH

- (a) Design and operate processes and activities to minimise emission, release and spread of substances hazardous to health.
- (b) Take into account all relevant routes of exposure – inhalation, skin absorption and ingestion – when developing control measures.
- (c) Control exposure by measures that are proportionate to the health risk.
- (d) Choose the most effective and reliable control options which minimise the escape and spread of substances hazardous to health.
- (e) Where adequate control of exposure cannot be achieved by other means, provide, in combination with other control measures, suitable personal protective equipment.
- (f) Check and review regularly all elements of control measures for their continuing effectiveness.
- (g) Inform and train all employees on the hazards and risks from the substances with which they work and the use of control measures developed to minimise the risks.
- (h) Ensure that the introduction of control measures does not increase the overall risk to health and safety.

7.2 APPENDIX 2 – PLAN DRAWING OF THE PLATING LINE USED



7.3 APPENDIX 3 – SUMMARY OF WEB OF SCIENCE SEARCH TERMS

Table A1. Summary of Web of Science search terms used and results obtained.

Search terms	Results	Papers of interest highlighted through abstract reading
“nickel”	191645	N/A*
“nickel” & “electroplat*”	2537	N/A*
“nickel” & “occup*”	36	0
“nickel” & “emission”	82	0
“nickel” & “exposure”	103	0
“nickel” & “educt”	1	1**

* Number of abstracts generated too large to process therefore search terms revised

** Paper already known from previous literature search.

Workers in the electroplating industry are potentially exposed to a range of hazardous substances including nickel compounds. Exposure can cause serious health effects including cancer, asthma and dermatitis. Exposure can occur via inhalation, dermal and ingestion routes.

This report describes an evaluation of six engineering control measures that can potentially reduce exposure to nickel compounds at nickel plating plants. The evaluation considered airborne emissions of soluble nickel compounds and surface contamination of the front lip of the plating tank. The research used laboratory tests on a commercially available small scale plating plant. The control measures considered are: (i) eductors - a pumped circulation system used for solution mixing; (ii) the rate of air agitation used for solution mixing; (iii) local exhaust ventilation (LEV); (iv) freeboard height - the distance between the liquid surface and the tank lip; (v) chroffles - plastic balls used to insulate the liquid surface; and (vi) surfactant concentration – process additives for the surface tension of the plating solution.

The research found that the most effective engineering control was to use eductors or add LEV to an air agitated tank. Using basic principles of occupational hygiene, the researchers identified that use of eductors was best because this eliminates emissions at source and is the most reliable option.