ASSESSMENT REPORT ON

NICKEL

FOR DEVELOPING AMBIENT AIR QUALITY OBJECTIVES

Alberta
Environment

ASSESSMENT REPORT ON

NICKEL

FOR DEVELOPING AN AMBIENT AIR QUALITY OBJECTIVES

Prepared by
WBK & Associates Inc.

for
Alberta Environment

November 2004

Pub. No: T/776
ISBN No. 0-7785-3951-2 (Printed Edition)
ISBN No. 0-7785-3953-9 (On-line Edition)
Web Site: http://www3.gov.ab.ca/env/info/infocentre/publist.cfm

Any comments, questions, or suggestions regarding the content of this document may be directed to:

Science and Standards Branch
Alberta Environment
4th Floor, Oxbridge Place
9820 – 106th Street
Edmonton, Alberta T5K 2J6
Fax: (780) 422-4192

Additional copies of this document may be obtained by contacting:

Information Centre
Alberta Environment
Main Floor, Oxbridge Place
9820 – 106th Street
Edmonton, Alberta T5K 2J6
Phone: (780) 427-2700
Fax: (780) 422-4086
Email: env.infocent@gov.ab.ca

FOREWORD

Alberta Environment maintains Ambient Air Quality Objectives[1] to support air quality management in Alberta. Alberta Environment currently has ambient objectives for more than thirty substances and five related parameters. These objectives are periodically updated and new objectives are developed as required.

With the assistance of the Clean Air Strategic Alliance, a multi-stakeholder workshop was held in October 2000 to set Alberta's priorities for the next three years. Based on those recommendations and the internally identified priority items by Alberta Environment, a three-year work plan ending March 31, 2004 was developed to review four existing objectives, create three new objectives for three families of substances, and adopt six new objectives from other jurisdictions.

In order to develop a new three-year work plan, a multi-stakeholder workshop was held in October 2004. This study was commissioned in preparation for the workshop to provide background information on alternative, science based, and cost effective methods for setting priorities.

This document is one of a series of documents that presents the scientific assessment for these adopted substances.

Long Fu, Ph. D.
Project Manager
Science and Standards Branch

---

[1] **NOTE**: The *Environmental Protection and Enhancement Act,* Part 1, Section 14(1) refers to "ambient environmental quality objectives" and uses the term "guidelines" in Section 14(4) to refer to "procedures, practices and methods for monitoring, analysis and predictive assessment." For consistency with the *Act*, the historical term "ambient air quality guidelines" is being replaced by the term "ambient air quality objectives." This document was prepared as the change in usage was taking place. Consequently any occurrences of "air quality guideline" in an Alberta context should be read as "air quality objective."

ACKNOWLEDGEMENTS

The authors of this report would like to thank Dr. Long Fu of Alberta Environment for inviting them to submit this report. The authors are grateful for the help and guidance provided by Dr. Fu and his colleagues at Alberta Environment.

WBK & Associates Inc. would also like to acknowledge the authors who participated in the completion of this report:

Deirdre Treissman
Treissman Environmental Consulting Inc.
Calgary, Alberta

Dr. Selma Guigard
Edmonton, Alberta

Dr. Warren Kindzierski
WBK & Associates Inc.
St. Albert, Alberta

Jason Schulz
Edmonton, Alberta

Emmanuel Guigard
Edmonton, Alberta

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

Nickel is an element that exhibits valencies of 0, +1, +2 and +3. Metallic nickel is not commonly found in nature but nickel is found in many minerals. Nickel is used primarily in the manufacturing of stainless steel and other alloys due to its favourable properties of hardness, corrosion-resistance, heat-resistance and strength. Examples of alloys include copper-nickel alloys and nickel-chromium alloys. Nickel is also used as a catalyst, in plating, coins, batteries, electrodes, electrical contacts, spark plugs and machinery parts.

Natural sources of nickel to the atmosphere include soil dust, forest fires, particle releases from vegetation, sea salt, and meteoric dust. Anthropogenic sources of nickel released to the atmosphere are primarily from fossil fuel (oil and coal) combustion, high-temperature metallurgical operations, nickel primary production operations and municipal waste incineration. Other sources include coke ovens, cement manufacturing, asbestos mining/milling and cooling towers. In Canada, the most important anthropogenic sources of nickel to air are the primary base metal smelters and refineries, followed by fossil fuel combustion. Alloy production and incineration of municipal waste are relatively small sources of nickel.

Nickel in air is mainly in the particulate form, with particle sizes ranging from 0.1 to 2 µm. Nickel associated with these particles is mainly in the form of nickel sulphate, nickel chloride, nickel nitrate and nickel oxide, the sulphates resulting from the oxidation of nickel by sulphur dioxide. The processes governing the fate of nickel in the atmosphere are the same processes that govern the transport and removal of these small particles from the atmosphere.

The respiratory system is the prime target of nickel inhalation toxicity in both animals and humans. Acute 90-minute exposure to 383,000 µg Ni/m^3 caused death to a worker who did not wear protective equipment while spraying Ni in a metal arc process. Short-term exposures to animals are reported to cause: laboured breathing, pneumonia, degeneration of respiratory epithelium and atrophy of olfactory epithelium, significant decreases in body weight (rats exposed to 800 µg Ni sulphate/m^3 for 6 hours/day and 5 days/week over 12 days); chronic active inflammation of the lungs (rats exposed to 200 µg Ni sulphate/m^3 and 2,000 µg Ni sulphate/m^3 for 6 hours/day and 5 days/week over 13 weeks); and 30% decrease in body weight gain (male rats exposed to 400 µg Ni oxide/m^3 for 23.6 hours/day over 28 days); and death (rats and mice exposed to 1,600 to 6,700 µg Ni sulphate/m^3 for 6 hour/day and 5 days/week over 12 days).

Nickel exposure in the workplace is reported to cause increased urinary excretion of proteins in women (750 µg Ni sulphate and chloride/m^3) and lung and nasal cancers (>10,000 µg Ni/m^3). Long-term (chronic) inhalation exposure to animals is reported to cause: increased lung weight (rats exposed to 60 µg Ni oxide/m^3 for 23 hours/day and 7 days/week over 31 months); mild to moderate chronic active inflammation of the lungs (rats exposed to 1,000 µg Ni oxide/m^3 for 6 hours/day and 5 days/week over 2 years); body weight decreases (rats and mice exposed to 220 to 880 µg Ni sulphates and subsulphides/m^3 for 6 hours/day and 5 days/week over 2 years); alveolar/bronchiolar adenomas or carcinomas (rats exposed to 1,000 µg Ni oxide/m^3 for 6 hours/day and 5 days/week over 2 years); and death (rats exposed to 60 µg Ni oxide/m^3 for 23 hours/day and 7 days/week over 31 months). Nickel refinery dust (mostly nickel subsulphide) has been classified as a class A human carcinogen by the US Environmental Protection Agency.

The majority of trace metals present in ambient air, including nickel, are particle-bound. Sample collection schemes suitable for collection of trace metals follow methods appropriate for particulate matter measurement. Many analytical methods exist to characterize trace metals and each has its own advantages and disadvantages.

Urban settings – in which most air quality data are available for – are settings with higher metal concentrations in ambient air compared to rural settings. Ambient air data in central Edmonton and central Calgary are available for the period June 1991 to November 2000. Median and maximum nickel concentrations associated with $PM_{2.5}$ in ambient air were <0.0001 and 0.0045 $\mu g/m^3$ (central Edmonton) and <0.0001 to 0.003 $\mu g/m^3$ (central Calgary).

1.0 INTRODUCTION

Alberta Environment establishes Ambient Air Quality Guidelines under Section 14 of the Environmental Protection and Enhancement Act (EPEA). These guidelines are part of the Alberta air quality management system (AENV, 2000).

The main objective of this assessment report was to provide a review of scientific and technical information to assist in evaluating the basis and background for an ambient air quality guideline for nickel. The following aspects were examined as part of the review:

- physical and chemical properties,
- existing and potential anthropogenic emissions sources in Alberta,
- effects on humans, animals, vegetation, and materials,
- ambient air guidelines in other Canadian jurisdictions, United States, World Health Organization and New Zealand, and the basis for development and use,
- characterization of risks to exposed receptors,
- monitoring techniques,

Important physical and chemical properties that govern the behaviour of nickel in the environment were reviewed and presented in this report. Existing and potential anthropogenic sources of nickel emissions in Alberta were also presented. Anthropogenic emissions are provided in Environment Canada's National Pollutant Release Inventory (NPRI).

Scientific information about the effects of nickel on humans and animals is reported in published literature and other sources. This information includes toxicological studies published in professional journals and reviews and information available through the US Agency for Toxic Substances and Disease Registry (ATSDR) and US Environmental Protection Agency's Integrated Risk Information System (IRIS). These sources provided valuable information for understanding health effects of nickel exposure.

Ambient air guidelines for nickel are used by numerous jurisdictions in North America for different averaging-time periods. These guidelines can be developed by using an occupational exposure level and dividing it by safety or adjustment factors, using cancer risk assessment procedures, or by using non-cancer risk assessment procedures. Examples of cancer and non-cancer risk assessment procedures are provided in WBK (2003). The basis for how these approaches are used by different jurisdiction to develop guidelines was investigated in this report.

Accurate measurement of trace metals, including nickel, in ambient air is often difficult in part because of the variety of substances, the variety of potential techniques for sampling and analysis, and the lack of standardized and documented methods. The United States Environmental Protection Agency (US EPA), National Institute of Occupational Safety and Health (NIOSH), and Occupational Safety and Health Administration (OSHA) are the only organizations that provide documented and technically reviewed methodologies for determining the concentrations of selected trace metals of frequent interest in ambient and indoor air. These methods, which are generally accepted as the preferred methods for trace metal sampling and analysis, were reviewed and presented in this report.

2.0 GENERAL SUBSTANCE INFORMATION

Nickel (Ni) is an element that exhibits valencies of 0, +1, +2 and +3 (Lide, 2002). Metallic nickel is not commonly found in nature (CEPA, 1994) but nickel is found in many minerals, such as pentlandite, pyrrhotite (Lide, 2002), millerite, niccolite, annabergite, bravoite, skutterudite and heazlewoodite (Duke, NRCC cited in CEPA, 1994).

Nickel is used primarily in the manufacturing of stainless steel and other alloys (Lide, 2002) due to its favourable properties of hardness, corrosion-resistance, heat-resistance and strength (ATSDR, 1997). Examples of alloys include copper-nickel alloys and nickel-chromium alloys (ATSDR, 1997). Nickel is also used as a catalyst (in the hydrogenation of vegetable oils and other organic compounds); in plating (as a protective coating for other metals); in coins, batteries, electrodes, electrical contacts, spark plugs and machinery parts; and as an additive for glass to give it a green colour (Lide, 2002; Genium, 1999; RSC, 1999).

Table 1 provides a list of important identification numbers and common synonyms for nickel and select nickel compounds.

2.1 Physical and Chemical Properties

The physical and chemical properties of nickel and select nickel compounds are summarized in Table 2.

2.2 Emission Sources and Ambient Levels

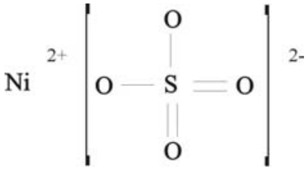
2.2.1 Natural Sources

Natural sources of nickel to the atmosphere include soil dust, sea salt, volcanoes, forest fires, particle exudates from vegetation and meteoric dust (Nriagu cited in European Communities, 2001; NRCC, Schmidt and Allne, Warren and Delavaut cited in CEPA, 1994). According to Lewis and Caldwell (1999) (cited in European Communities, 2001), natural emissions of nickel correspond to approximately 15% of the total global nickel emissions. Nriagu (cited in European Communities, 2001) estimates natural emissions to be 35% of the total global nickel emissions. In Canada, natural sources of airborne nickel for 1975 were estimated to range between 595 and 11,200 tonnes (NRCC cited in CEPA, 1994).

2.2.2 Anthropogenic Sources

The anthropogenic sources of nickel to the atmosphere are primarily from fossil fuel (oil and coal) combustion, high-temperature metallurgical operations, nickel primary production operations (European Communities, 2001) and municipal waste incineration (Bennett, Schmidt and Andren cited in ATSDR, 1997). Other sources include coke ovens, cement manufacturing, asbestos mining/milling and cooling towers (CEPA, 1994).

Table 1 Identification of Nickel and Select Nickel Compounds[a]

Property	Nickel	Nickel Sulphate	Nickel Oxide	Nickel Subsulphide
Chemical Formula	Ni	$NiSO_4$	NiO	Ni_3S_2
Chemical Structure	Ni		Ni = O	
CAS Registry number	7440-02-0	7786-81-4	1313-99-1	12035-72-2
RTECS number	QR5950000	QR9350000	QR8400000	QR9800000
UN Number	UN1325, UN2881	no data	no data	no data
Common Synonyms and Tradenames	Alcan 756 C.I. 77775 Carbonyl nickel powder EL 12 Fibrex or Fibrex P NI 0901-S, NI 4303-S, NI 270 NI 4303T or NI-4303T NI 0901-S Nickel 200, 201, 205, 207, 270 Nickel catalyst Elemental nickel Nickel particles Nickel sponge Nickel, metal Nickel catalyst, wet NP-2 or NP 2 Pulverized nickel Raney alloy Raney nickel RCH 55/5	Nickel (II) sulphate Nickel monosulphate Nickel (+2) sulphate	Black nickel oxide Bunsenite C.I. 77777 Green nickel oxide Mononickel oxide Nickel monoxide Nickel (2+) oxide Nickel oxide sinter 75 Nickel protoxide Nickel (II) oxide Nickel (II) oxide (1:1) Nickel (II) oxide, black Nickelous oxide	Heazlewoodite Nickel sesquisulphide Nickel subsulfide Nickel sulphide Nickel sulphide (3:2) Alpha-nickel sulphide (3:2) crystalline Nickel tritadisulphide Trinickel disulphide

[a] all data from Genium (1999) unless otherwise stated

Table 2 Physical and Chemical Properties of Nickel and Select Nickel Compounds[a]

Property	Nickel	Nickel Sulphate	Nickel Oxide	Nickel Subsulphide
Molecular Weight (g/mol)	58.693	154.757	74.692	240.212
Oxidation State	0	+II	+II	+III
Physical state	white metal	green-yellow orthorhombic crystals	green cubic crystals	hexagonal crystals
Melting Point (°C)	1455	840 (decomposes)	1955	787
Boiling Point (°C)	2913	no data	no data	no data
Density (g/cm^3)	8.90	4.01	6.72	5.87
Specific gravity (gas) (air =1)	no data	no data	123[b]	no data
Vapour pressure	1mm Hg at 1810°C[b]	no data	0 mm Hg at 25°C[b]	no data
Solubility in water	insoluble	40.4g/100g H_2O at 25°C	insoluble	insoluble in cold water[b]
Solubility in other solvents	slightly soluble in dilute acid solutions	insoluble in ether, acetone, 95% ethanol[b] 0.11% in methanol at 35°C[b]	soluble in acid solutions	soluble in nitric acid[b] slightly soluble in methanol, DMSO, acetone, toluene, 95% ethanol[b]
Henry's Law Constant (atm.m^3/mol)	no data	no data	no data	no data
Octanol water partition coefficient (log K_{ow})	no data	no data	no data	no data
Organic carbon partition coefficient (Log K_{oc})	no data	no data	no data	no data
Odour threshold (mg/m^3)	odourless[b]	odourless[b]	odourless[b]	no data
Bioconcentration factor in fish (log BCF)	no data	no data	no data	no data
Conversion factors for vapour (at 25 °C and 101.3 kPa)	no data	no data	no data	no data

a all data from Lide, 2002 unless otherwise indicated

[b] Genium, 1999

In Canada, the most important anthropogenic sources of nickel to air are the primary base metal smelters and refineries, followed by fuel combustion (CEPA, 1994). Alloy production and incineration of municipal waste are relatively small sources of nickel (CEPA, 1994).

Table 3 and 4 summarizes anthropogenic nickel emissions in Alberta, according to the National Pollution Release Inventory (NPRI) 2001 database (NPRI, 2002). Nickel emissions for Canada are presented in Appendix A. In Alberta, the industrial sectors contributing the greatest amount to nickel emissions to air are the crude oil and natural gas sector followed by the utilities sector. In most cases, the air emissions occur through stacks and point sources.

2.2.3 Ambient Levels

According to IPCS (1991), nickel concentrations in air in remote areas range from <0.1 to 3 ng/m^3. Schroeder *et al.* (cited in ATSDR, 1997) provide ranges of nickel concentrations in air for remote, rural and urban areas, ranging from 0.01 to 60 ng/m^3, 0.6 to 78 ng/m^3 and 1 to 328 ng/m^3, respectively. In a survey of 11 Canadian cities from 1987 to 1990, the annual mean nickel concentrations in air ranged from 1 to 20 ng/m^3 (Dann cited in CEPA, 1994). In a rural area (Walpole Island), the annual mean concentration was 1 ng/m^3 (Dann cited in CEPA, 1994). In a remote area over the Canadian Artic in the early 1980s, the annual mean concentration was 0.38 ng/m^3 (Hoff and Barrie cited in CEPA, 1994).

Ambient air data in central Edmonton and central Calgary are available for the period June 1991 to November 2000 (AENV, 2003). Median and maximum nickel concentrations associated with $PM_{2.5}$ in ambient air were <0.1 and 4.5 ng/m^3 (central Edmonton) and <0.1 to 3 ng/m^3 (central Calgary) (AENV, 2003).

Table 3 Alberta Emissions of Nickel and Its Compounds According to NPRI (NPRI, 2002)

NPRI ID	Company	City	Province	Alberta Emissions of Nickel and Its Compounds (tonnes)				
				Air	Water	Land	Underground	Total
2284	TransAlta Corporation	Duffield	AB	0.389	0.000	21.170	0.000	21.559
1036	Sheerness Generating Station	Hanna	AB	0.000	0.000	12.581	0.000	12.581
2230	Suncor Energy Inc.	Fort McMurray	AB	1.277	0.628	0.000	0.000	1.905
2274	Syncrude Canada Ltd.	Fort McMurray	AB	1.298	0.000	0.000	0.000	1.298
1106	AltaSteel Ltd.	Edmonton	AB	0.406	0.001	0.432	0.000	0.839
0267	Edmonton Power Inc.	Warburg	AB	0.468	0.000	0.000	0.000	0.468
4650	Criterion Catalysts & Technologies Canada Inc.	Medicine Hat	AB	0.196	0.000	0.000	0.000	0.196
0280	Dow Chemical Canada Incorporated	Fort Saskatchewan	AB	0.000	0.000	0.186	0.000	0.186
4874	Agrium Products Inc.	Fort Saskatchewan	AB	0.000	0.000	0.000	0.150	0.150
5293	All Brite Metal Finishing Ltd.	Edmonton	AB	0.000	0.000	0.000	0.000	0.093
5253	Cutler-Hammer	Airdrie	AB	0.080	0.000	0.000	0.000	0.080
3903	Petro-Canada	Edmonton	AB	0.029	0.000	0.005	0.000	0.034
2134	Agrium Products Inc.	Redwater/Municipal District of	AB	0.000	0.020	0.000	0.013	0.033
5313	Foothills Steel Foundry Ltd.	Calgary	AB	0.000	0.000	0.000	0.000	0.018
4868	The Cobalt Refinery Company Inc.	Fort Saskatchewan	AB	0.013	0.000	0.004	0.000	0.017
1779	NOVA Chemicals Corporation	Red Deer	AB	0.000	0.014	0.000	0.000	0.014
2963	Shell Chemicals Canada Ltd.	Fort Saskatchewan	AB	0.001	0.006	0.000	0.000	0.007
2960	Shell Canada Products	Fort Saskatchewan	AB	0.000	0.003	0.000	0.000	0.003
				4.157	0.672	34.378	0.163	39.481

Table 4 Alberta Air Emissions of Nickel and its Compounds According to NPRI (NPRI, 2002)

NPRI ID	Company	City	Air Emission of Nickel and its Compounds (tonnes)					
			Stack and Point Sources	Storage and Handling	Fugitive	Spills	Other Non-Point Sources	Total
2274	Syncrude Canada Ltd.	Fort McMurray	1.298	0.000	0.000	0.000	0.000	1.298
2230	Suncor Energy Inc.	Fort McMurray	1.277	0.000	0.000	0.000	0.000	1.277
0267	Edmonton Power Inc.	Warburg	0.468	0.000	0.000	0.000	0.000	0.468
1106	AltaSteel Ltd.	Edmonton	0.302	0.006	0.098	0.000	0.000	0.406
2284	TransAlta Corporation	Duffield	0.389	0.000	0.000	0.000	0.000	0.389
4650	Criterion Catalysts & Technologies Canada Inc.	Medicine Hat	0.196	0.000	0.000	0.000	0.000	0.196
5253	Cutler-Hammer	Airdrie	0.000	0.000	0.08	0.000	0.000	0.080
3903	Petro-Canada	Edmonton	0.029	0.000	0.000	0.000	0.000	0.029
4868	The Cobalt Refinery Company Inc.	Fort Saskatchewan	0.000	0.013	0.000	0.000	0.000	0.013
2963	Shell Chemicals Canada Ltd.	Fort Saskatchewan	0.001	0.000	0.000	0.000	0.000	0.001
			3.960	0.019	0.178	0.000	0.000	4.157

3.0 ATMOSPHERIC CHEMISTRY AND FATE

Nickel in air is mainly is the particulate form, with particle sizes ranging from 0.1 to 2µm. Nickel associated with these particles is mainly in the form of nickel sulphate, nickel chloride, nickel nitrate and nickel oxide (Muller cited in European Communities, 2001), the sulphates resulting from the oxidation of nickel by sulphur dioxide (Schmidt and Andren cited in ATSDR, 1997).

The processes governing the fate of nickel in the atmosphere are the same processes that govern the fate of the released particulate matter. These processes include wet and dry deposition and both of these processes are expected to contribute equally to the removal of particles from the atmosphere (CEPA, 1994).

Schmidt and Andren (cited in CEPA, 1984) estimated that the atmospheric residence time of nickel-containing particles ranged from 5 to 8 days.

4.0 EFFECTS ON HUMANS AND ANIMALS

Inorganic nickel (Ni) compounds occur in the environment from natural (soil dust, sea salt, volcanoes, forest fires, and particulate exudates from vegetation) (Warren and Devalt, NRCC, Schmidt and Andren cited in CEPA, 1994) and anthropogenic sources (mining, smelting, and refining of base metals, and fuel combustion) (NRCC, 1981, Jaques, 1987, MacLatchy cited in CEPA, 1994). Nickel is also found in most foods, and in cigarette smoke (CEPA, 1994).

There is some evidence to suggest that Ni may be an essential element in animals, and also may be for humans. However, Ni deficiency has not been adequately demonstrated in humans (Anke *et al.* cited in Goyer, 1996; ATSDR, 1997; IPCS cited in CEPA, 1994).

Inorganic Ni compounds can be listed in three groups: i) metallic Ni; ii) soluble Ni compounds (includes: nickel chloride, nickel sulphate, nickel, nitrate); and, iii) less soluble Ni compounds (nickel oxide and subsulphide). As there is not enough data to determine the potential health effects associated with each individual Ni compound (CEPA, 1994; ATSDR, 1997), the following report summarizes effects associated with inorganic Ni compounds as a group. Due to it's instability (half-life in air of about 100 seconds) the highly toxic nickel carbonyl was not included in the ATSDR, (1997) or CEPA (1991) assessments; it is also not considered in this report.

The focus of this assessment was the adverse health effects associated with inhalation of inorganic Ni compounds, oral and dermal effects were not reviewed in detail. The primary literature source for this assessment was the Toxicology Profile for Nickel Agency for Toxic Substances and Disease Registry (ATSDR, 1997).

4.1 Overview of Chemical Disposition

Absorption of Ni depends on the solubility of the particular compound (the more water soluble, the more bioavailable). The more soluble compounds also tend to be more toxic; however, the insoluble compounds may be more carcinogenic at the site of deposition (ATSDR, 1997).

Deposition of inhaled Ni in the respiratory tract is also dependant on particle size. About 20-35% of the Ni that is deposited in the lungs is absorbed into the blood stream; only 1-10% of Ni mechanically cleared and swallowed is absorbed by the gastrointestinal tract (IPCS cited in CEPA, 1994; ATSDR, 1997). Insoluble Ni compounds are removed from the respiratory tract very slowly and can accumulate over time (IPCS cited in CEPA, 1994). The highest concentrations of Ni after exposure by inhalation were found in the lung tissues, with lesser concentrations in the liver and kidneys (CEPA, 1994).

Nickel is absorbed into skin tissue, but most of the Ni is retained in the skin tissue and not available for circulation in the blood stream (ATSDR, 1997).

Once in the blood Ni is mostly bound to albumin and other unltrafiltrable ligands (Sunderman and Oskarsson cited in ATSDR, 1997). A small amount tightly binds to nickeloplasmin (an α-macroglobulin) forming a nonexchangable pool of Ni in the serum (Sunderman cited in ATSDR, 1997). Some studies indicated that Ni in the blood stream crossed the placental barrier in humans and animals (IPCS cited in CEPA, 1994).

Once in the blood stream, the major route of excretion of absorbed Ni, regardless of route of exposure, is via the urine (the majority of ingested Ni is excreted unabsorbed in the feces). In humans, Ni is also eliminated in hair, skin, milk, and sweat (ATSDR, IPCS cited in CEPA, 1994).

4.1.1 Interaction with Other Chemicals

Nickel has been reported to interact with a number of other chemicals.

Shirakawa *et al.* (cited in ATSDR, 1997) reported a cross-reactivity between Ni and cobalt (Co) sensitive individuals.

Interactions between Ni and other metals (iron, chromium, magnesium, manganese, zinc, and cadmium) have also been documented. Zinc and magnesium mitigated Ni toxicity. (Sunderman and McCully *et al.*, Waalkes *et al.*, Karprzak *et al.* cited in ATSDR, 1997). Pretreatment of animals with cadmium also affected Ni toxicity (mechanism undetermined); in one case, enhanced Ni toxicity was reported, in another, reduced toxicity occurred (Khandelwal and Tandon, Srivastava *et al.* cited in ATSDR, 1997).

Rabbits exposed by inhalation to Ni and chromium demonstrated more severe respiratory effects than seen with Ni exposures alone (Johansson *et al.* cited in ATSDR, 1997). One study reported Ni and Co cross-reactivity; Co sensitive individuals also reacted (asthma) when challenged with $NiSO_4$ (Shirakawa *et al.* cited in ATSDR, 1997).

4.2 Genotoxicity

Bacterial *in vitro* mutagenicity studies were inconclusive (RIVM, 2001). DNA damage was produced by some Ni compounds and not others.

Workers exposed to Ni via inhalation demonstrated an increased incidence of chromosomal aberrations (gaps) (concentrations of 0.2 or 0.5 mg nickel/m^3), but not in chromosomal breaks or sister chromatid exchanges (Waksvik and Boyson cited in ATSDR, 1997). Human lymphocytes from individuals not sensitized to Ni took up more Ni and showed greater clastogenic (chromosomal breakage) activity than lymphocytes from Ni sensitized individuals at unspecified exposure concentrations (Arrouijal *et al.* cited in ATSDR, 1997). Once Ni is inside a cell it is genotoxic (ATSDR, 1997). Ni can interact with DNA producing crosslinks and strand breaks (Ciccarelle and Weterhan, Robinson and Costa, Patiemo and Costa, 1985, 1987 cited in ATSDR, 1997).

4.3 Acute Effects

4.3.1 Acute Human Effects

Acute effects usually occur rapidly as a result of short-term exposures to high concentrations, and are of short duration – generally for exposures less than 24 hours (after Gallo, 1996). Acute exposure (90 minutes exposure to an estimated 383 mg Ni/m^3) to Ni was reported in a worker who did not wear protective equipment while spraying Ni in a metal arc process (Sunderman cited in ATSDR, 1997). Death occurred 13 days after the exposure. Autopsy of the subject revealed alveolar wall damage and edema in alveolar spaces in the lungs and marked tubular necrosis in the kidneys.

No humans studies of dermal effects associated with Ni inhalation were identified; however, contact dermatitis is one of the most common effects reported by people exposed to Ni compounds via other exposure routes (ATSDR, 1997). In addition, Ni inhalation has been reported to stimulate the immune system (see Section 4.3.2.5 sections below).

4.3.2 Acute and Sub-Acute Animal Effects

Sub-acute effects usually occur as a result of exposures to moderately high concentrations that are of an intermediate duration – generally for exposures lasting a few days to about 21 days. Table 5 lists some examples of the lowest and highest NOAELs (No Observable Adverse Effect Level) and LOAELs (Lowest Observable Adverse Effect Level) reported in the literature from acute animal studies. Table 6 lists some examples of the lowest and highest NOAELs (No Observable Adverse Effect Level) and LOAELs (Lowest Observable Adverse Effect Level) reported in the literature from sub-acute animal.

Below is a summary of potential effects associated with acute and sub-acute Ni inhalation. Details regarding exposure concentrations, duration of exposure and animal species examined are included in Tables 5 and 6.

4.3.2.1 Death

Acute inhalation of Ni produced severe haemorrhage of the lungs and death within two days of a single exposure (Hirano *et al.* cited in ATSDR, 1997). Sub-acute exposures to Ni sulphate and Ni subsulphide (but not Ni oxide) was lethal to rats and mice. Mice appeared to be more sensitive than rats (Benson *et al.* 1987 cited in ATSDR, 1997; Benson *et al.*, 1988 cited in CEPA, 1994 and ATSDR, 1997).

4.3.2.2 Respiratory Effects

There are many experimental rat and mice studies that report the toxic effects of acute and sub-acute Ni inhalation on the respiratory system and olfactory epithelium. The reported effects in the lungs included: chronic active inflammation in the lungs, alveolitis, interstitial pneumonia, fibrosis, macrophage hyperplasia, interstitial infiltrates and increased lung weight. Olfactory

Table 5 Examples of NOAELs and LOAELs Associated with Acute Nickel Inhalation (Experimental Animals)

Effects Reported[a]	Exposure Period	Air Concentration ($mgNi/m^3$)	Species	Reference
Death:				
	12 d, 5d/wk, 6hr/d	6.7 (sulphate)	Rat	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
	12 d, 5d/wk, 6hr/d	1.6 (sulphate)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Respiratory Effects:				
NOAEL	12 d, 5d/wk, 6hr/d	2.0 (oxide)	Rat	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Alveolitis. Less serious LOAEL	1,2,4,7,12 d 6 hr/d	0.22 (subsulphide)	Rat	Benson *et al.*, 1995b cited in ATSDR, 1997.
Alveolar macrophage hyperplasia. Less serious LOAEL	12 d, 5d/wk, 6hr/d	3.9 (oxide)	Rat	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Pneumonia; atrophy of the olfactory epithelium. Serious LOAEL	12 d, 5d/wk, 6hr/d	0.4 (subsulphide)	Rat	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Laboured breathing; pneumonia; degeneration of respiratory epithelium and atrophy of olfactory epithelium. Serious LOAEL.	12 d, 5d/wk, 6hr/d	0.8 (sulphate)		Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Pneumonia; atrophy of the olfactory epithelium. Serious LOAEL	12 d, 5d/wk, 6hr/d	23.6 (oxide)	Rat	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
NOAEL	12 d, 5d/wk, 6hr/d	3.9 (oxide)	Mice	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.

Table 5 Examples of NOAEL's and LOAEL's Associated with Acute Nickel Inhalation (Experimental Animals) (continued)

Effects Reported[a]	Exposure Period	Air Concentration (mgNi/m^3)	Species	Reference
NOAEL	12 d, 5d/wk, 6hr/d	0.4 (subsulphide)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Alveolar macrophage hyperplasia. Less serious LOAEL	12 d, 5d/wk, 6hr/d	7.9 (oxide)	Mice	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Lung inflammation. Serious LOAEL	12 d, 5d/wk, 6hr/d	23.6 (oxide)	Mice	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Pneumonia; atrophy of the olfactory epithelium; degeneration of the respiratory epithelium. Serious LOAEL	12 d, 5d/wk, 6hr/d	0.9 (subsulphide)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Body Weight:				
NOAEL	12 d, 5d/wk, 6hr/d	23.6 (oxide)	Rat	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Significant decrease in body weight; emaciation. Serious LOAEL	12 d, 5d/wk, 6hr/d	0.8 (sulphate)	Male rat	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Significant decrease in body weight. Serious LOAEL	12 d, 5d/wk, 6hr/d	3.6 (subsulphide)	Rat	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
NOAEL	12 d, 5d/wk, 6hr/d	0.8 (sulphate)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.

Table 5 Examples of NOAEL's and LOAEL's Associated with Acute Nickel Inhalation (Experimental Animals) (continued)

Effects Reported[a]	Exposure Period	Air Concentration (mgNi/m^3)	Species	Reference
NOAEL	12 d, 5d/wk, 6hr/d	23.6 (oxide)	Mice	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
NOAEL	12 d, 5d/wk, 6hr/d	1.8 (subsulphide)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Significant decrease in body weight. Less serious LOAEL	12 d, 5d/wk, 6hr/d	3.6 (subsulphide)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Immunological and Lymphoretic Effects:				
NOAEL	12 d, 5d/wk, 6hr/d	7.9 (oxide)	Rat	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Atrophy of the thymus; hyperplasia of the lymph nodes. Less serious LOAEL	12 d, 5d/wk, 6hr/d	23.6 (oxide)	Rat	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
NOAEL	2 hr	0.1 (chloride)	Female mice	Graham *et al.* cited in ATSDR, 1997
NOAEL	12 d, 5d/wk, 6hr/d	7.9 (oxide)	Mice	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Decrease in the number of antibody-producing spleen cells. Less serious LOAEL	2 hr	0.25 (chloride)	Female mice	Graham *et al.* cited in ATSDR, 1997.
Increased susceptibility to streptococcal infection. Less serious LOAEL	2 hr	0.46 (chloride or sulphate)	Female mice	Adkins *et al.* cited in ATSDR, 1997.
Atrophy of the thymus; hyperplasia of the lymph nodes. Less serious LOAEL	12 d, 5d/wk, 6hr/d	23.6 (oxide)	Mice	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.

Table 5 Examples of NOAEL's and LOAEL's Associated with Acute Nickel Inhalation (Experimental Animals) (continued)

Effects Reported[a]	Exposure Period	Air Concentration ($mgNi/m^3$)	Species	Reference
Neurological Effects:				
NOAEL	12 d, 5d/wk, 6hr/d	23.6 (oxide)	Rat	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
NOAEL	12 d, 5d/wk, 6hr/d	23.6 (oxide)	Mice	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Lowest NOAELs for Other Systems:				
Cardiovascular; gastrointestinal, muscular/skeletal; Hepatic; Renal; endocrine; dermal.	12 d, 5d/wk, 6hr/d	1.8 (subsulphide)	Rat	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Cardiovascular; gastrointestinal, muscular/skeletal; Hepatic; Renal; endocrine; dermal.	12 d, 5d/wk, 6hr/d	0.8 (sulphate)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.

[a] NOAEL, Less serious LOAEL, and Serious LOAEL as identified by ATSDR (1997).

Table 6 Examples of NOAELs and LOAELs Associated with Sub-Acute Nickel Inhalation (Experimental Animals)

Effects Reported[a]	Exposure Period	Air Concentration (mg Ni/m^3)	Species	Reference
Respiratory System:				
NOAEL	Up to 6 mo, 5 d/wk, 6 hr/d	0.49 (oxide)	Male rat	Benson *et al.* cited in ATSDR, 1997.
Increased lung weight. Less serious LOAEL	28 d, 23.6 hr/d	0.2 (oxide)	Male rat.	Weischer *et al.* cited in CEPA, 1994.
Increased lung weight. Less serious LOAEL	21 d, 23.6 hr/d	0.8 (oxide)	Female rat	Weischer *et al.* cited in CEPA, 1994.
Alveolar macrophage hyperplasia; increased relative lung weights. Less serious LOAEL	13 wk, 5 d/wk 6hr/d	0.11 (subsulphide)	Rat	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Chronic active inflammation of the lungs. Serious LOAEL	13 wk, 5 d/wk 6hr/d	2 (oxide)	Rat	Benson *et al.*, Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Chronic active inflammation of the lungs. Serious LOAEL	13 wk, 5 d/wk 6hr/d	0.2 (subsulphide)	Rat	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
NOAEL	13 wk, 5 d/wk 6hr/d	0.11 (subsulphide)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
NOAEL	13 wk, 5 d/wk 6hr/d	0.06 (sulphate)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Alveolar macrophage hyperplasia. Less serious LOAEL	13 wk, 5 d/wk 6hr/d	2.0 (oxide)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.

Table 6 Examples of NOAEL's and LOAEL's Associated with Sub-Acute Nickel Inhalation (Experimental Animals) (continued)

Effects Reported[a]	Exposure Period	Air Concentration (mg Ni/m^3)	Species	Reference
Alveolar macrophage hyperplasia. Less serious LOAEL	13 wk, 5 d/wk 6hr/d	0.2 (subsulphide)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Alveolar macrophage hyperplasia. Less serious LOAEL	13 wk, 5 d/wk 6hr/d	0.11 (sulphate)	Mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Interstitial pneumonia. Less serious LOAEL	Up to 6 mo, 5 d/wk, 6 hr/d	0.98 (oxide)	Male mice	Benson *et al.*, 1995a cited in ATSDR, 1997.
Interstitial pneumonia. Less serious LOAEL	Up to 6 mo, 5 d/wk, 6 hr/d	0.22 (sulphate)	Male mice	Benson *et al.*, 1995a cited in ATSDR, 1997.
Increased volume density of alveolar type II cells. Less serious LOAEL	1-8 mo, 5 d/wk, 6 hr/d	0.2 (chloride or metallic)	Male rabbit	Johansson and Camner cited in CEPA, 1994 and ATSDR, 1997.
Hematological Effects:				
Decreased hematocrit. Less serious LOAEL	28 d, 23.6 hr/d	0.2 (oxide)	Male rat.	Weischer *et al.* cited in CEPA, 1994.
Increased hematocrit. Less serious LOAEL	21 d, 23.6 hr/d	0.8 (oxide)	Female rat.	Weischer *et al.*, 1980, cited in CEPA, 1994.
Hepatic System:				
NOAEL	13 wk, 5 d/wk 6hr/d	7.9 (oxide)	Rats, mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
NOAEL	13 wk, 5 d/wk 6hr/d	1.8 (subsulfite)	Rats, mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.

Table 6 Examples of NOAEL's and LOAEL's Associated with Sub-Acute Nickel Inhalation (Experimental Animals) (continued)

Effects Reported[a]	Exposure Period	Air Concentration (mg Ni/m^3)	Species	Reference
NOAEL	13 wk, 5 d/wk 6hr/d	0.44 (sulphate)	Rats, mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Decreased liver weight. Less serious LOAEL	28 d, 23.6 hr/d	0.8 (oxide)	Male rats.	Weischer *et al.* cited in CEPA, 1994.
Decreased liver weight. Less serious LOAEL	21 d, 23.6 hr/d	0.8 (oxide)	Female rats.	Weischer *et al.* cited in CEPA, 1994.
Renal System:				
NOAEL	28 d, 23.6 hr/d	0.8 (oxide)	Male rats.	Weischer *et al.* cited in CEPA, 1994.
NOAEL	13 wk, 5 d/wk 6hr/d	7.9 (oxide)	Rats, mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
NOAEL	13 wk, 5 d/wk 6hr/d	1.8 (subsulphide)	Rats, mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
NOAEL	13 wk, 5 d/wk 6hr/d	0.44 (sulphate)	Rats, mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Decreased kidney weight. Less serious LOAEL	21 d, 23.6 hr/d	0.8 (oxide)	Female rats.	Weischer *et al.* cited in CEPA, 1994.
Body Weight:				
NOAEL	28 d, 23.6 hr/d	0.2 (oxide)	Male rats.	Weischer *et al.* cited in CEPA, 1994.

Table 6 Examples of NOAEL's and LOAEL's Associated with Sub-Acute Nickel Inhalation (Experimental Animals) (continued)

Effects Reported[a]	Exposure Period	Air Concentration (mg Ni/m^3)	Species	Reference
NOAEL	13 wk, 5 d/wk 6hr/d	0.44 (sulphate)	Rats, mice	Benson *et al.*, Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
30% decrease in body weight gain. Serious LOAEL	28 d, 23.6 hr/d	0.4 (oxide)	Male rats.	Weischer *et al.* cited in CEPA, 1994.
36% decrease in body weight gain. Serious LOAEL	21 d, 23.6 hr/d	0.8 (oxide)	Female rats.	Weischer *et al.* cited in CEPA, 1994.
Immunological/Lymphoreticular System:				
NOAEL	13 wk, 5 d/wk 6hr/d	0.11 (sulphate)	Rats	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
NOAEL	4 mo Continuous	0.025 (oxide)	Rats	Spiegelberg *et al.* cited in ATSDR, 1997
Mild lymphoid hyperplasia. Less serious LOAEL	13 wk, 5 d/wk 6hr/d	0.22 (sulphate)	Rats	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
NOAEL	13 wk, 5 d/wk 6hr/d	0.22 (sulphate)	Mice	Dunnick *et al.* cited in ATSDR, 1997.
Mild lymphoid hyperplasia. Less serious LOAEL	13 wk, 5 d/wk 6hr/d	0.44 (sulphate)	Mice	Dunnick *et al.* cited in ATSDR, 1997.
Decreased resistance to tumour challenge. Serious LOAEL	65 d, 5 d/wk 6 hr/d	0.45 (sulphate)	Mice	Haley *et al.* cited in ATSDR, 1997.
Reproductive:				
NOAEL	13 wk, 5 d/wk 6hr/d	3.9 (oxide)	Male rats	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
NOAEL	13 wk, 5 d/wk 6hr/d	0.44 (sulphate)	Rats	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.

Table 6 Examples of NOAEL's and LOAEL's Associated with Sub-Acute Nickel Inhalation (Experimental Animals) (continued)

Effects Reported[a]	Exposure Period	Air Concentration (mg Ni/m^3)	Species	Reference
Decreased sperm counts. Less serious LOAEL	13 wk, 5 d/wk 6hr/d	7.9 (oxide)	Male rats	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
NOAEL	13 wk, 5 d/wk 6hr/d	0.44 (sulphate)	Mice	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Developmental Effects:				
NOAEL	Gd 1-21, 23.6 hr/d	0.8 (oxide)	Rats	Weischer *et al.* cited in CEPA, 1994
Decreased fetal weights. Less serious LOAEL	Gd 1-21, 23.6 hr/d	1.6 (oxide)	Rats	Weischer *et al.* cited in CEPA, 1994

[a] NOAEL, Less serious LOAEL, and Serious LOAEL as identified by ATSDR (1997).

epithelial atrophy was reported in the nose (Bingham *et al.* cited in ATSDR, 1997; Weischer *et al.* cited in CEPA, 1994; Horie *et al.*, Benson *et al.*, 1987, 1988 cited in CEPA, 1994 and ATSDR, 1997; Benson *et al.*, 1989, 1995a, 1995b, Dunnick *et al.*, 1988, 1989, Tanaka *et al.*, Evans *et al.* cited in ATSDR, 1997).

Rats seemed to be more sensitive to Ni toxicity than mice. Nickel sulphate appeared to be the most toxic with Ni subsulphide less toxic and Ni oxide the least toxic (ATSDR, 1997).

4.3.2.3 Haematological Effects

Low sub-chronic exposure produced a significant decrease in hematocrit in male rats (females were not exposed), and high exposures produced a significant increase in hematocrit in female rats (males were not exposed) (Weischer *et al.* cited in CEPA, 1994).

4.3.2.4 Renal Effects

Sub-chronic Ni oxide exposures were reported to produce decreased kidney weight in female rats (not observed in males) (Weischer *et al.* cited in CEPA, 1994). Microscopic changes in the kidneys were not observed after sub-chronic exposures (Ni oxide, Ni sulphate and Ni subsulphide) in rats or mice (Benson *et al.*, 1989, Dunnick *et al.*, 1989 cited in ATSDR, 1997).

4.3.2.5 Immunological and Lymphoreticular Effects

Acute Ni inhalation in mice has been reported to decrease the number of anti-body producing spleen cells (Graham *et al.* cited in ATSDR, 1997) and increase susceptibility to *Streptococci* infections (Adkins *et al.* cited in ATSDR, 1997).

Changes in alveolar macrophages have been associated with sub-acute exposures in rats including: increased production of tumour necrosis factor and decreased macrophage phagocytic activity (Haley *et al.*, 1990, Morimoto *et al.* cited in ATSDR, 1997).

In rat and mice, sub-acute exposures produced atrophy of the spleen and thymus and lymphoid hyperplasia in bronchial and mediastinal lymph nodes (Benson *et al.*, 1987, 1988, 1989, Dunnick *et al.*, 1988, 1989, Haley *et al.*, NTP, 1996c cited in ATSDR, 1997).

4.3.2.6 Reproductive and Developmental Effects

Testicular lesions, thought to be secondary to emaciation were reported in rats and mice after sub-acute Ni exposures (Benson *et al.*, 1987, 1988 cited in CEPA, 1994 and ATSDR, 1997).

Maternal exposure (1.6 mg Ni/m^3 during gestational days 1-21) resulted in decreased fetal body weight. No effects were observed in fetal and placental weight in studies of lower exposure concentrations (Weischer *et al.* cited in CEPA, 1994).

4.3.2.7 Body Weight

Decreases in body weight have been reported in animals exposed to nickel concentrations that produced respiratory tract effects (ATSDR, 1997).

4.3.2.8 Other Effects

Microscopic examination of rat and mouse tissues revealed no adverse: cardiovascular; gastrointestinal; hepatic; musculoskeletal; endocrinological; neurological; or, dermal changes associated with sub-acute inhalation exposures (Benson *et al.*, 1987, 1988, Dunnick *et al.*, 1988 cited in ATSDR, 1997).

Weischer *et al.* (cited in CEPA, 1994) reported a significant decrease of liver weights in rats after sub-acute exposures. Also reported in this study was decreased serum glucose in female rats exposed to low Ni oxide levels (0.8 mg Ni/m^3 - no males were exposed) and an increased serum glucose in Male rats exposed to high Ni oxide levels (20.4 mg Ni/m^3 - no females were exposed). Changes in serum glucose levels may be due to an effect on the pancreas (ATSDR, 1997).

Histological changes were reported after sub-acute exposure in the olfactory epithelium; however, no changes in function were detected (Benson *et al.*, 1987, 1988, 1989, Dunnick *et al.*, 1988, 1989, Evans *et al.* cited in ATSDR, 1997).

4.4 Chronic Effects

4.4.1 Chronic Human Effects

Chronic effects generally occur as a result of long-term exposures to low concentrations, and are of long duration – generally as repeated exposures for more than 12 months (after Gallo, 1996). The majority of human inhalation exposure data available has been collected after occupational exposures. There are a number of limitations to be considered when using data from people exposed in the work place. Generally, the person exposed is a healthy, young to middle aged, male adult; concurrent exposures to other chemicals are very likely; and, the exposure concentrations are often difficult to define.

Table 7 lists some examples of the lowest and highest NOAELs (No Observable Adverse Effect Level) and LOAELs (Lowest Observable Adverse Effect Level) reported in the literature.

Table 7 Examples of NOAELs and LOAELs Associated with Chronic Nickel Inhalation (Human)

Effects Reported[a]	Exposure Period	Air Concentration (mg Ni/m^3)	Reference
Renal System:			
Increased urinary excretion proteins in women Serious LOAEL	Occupational	0.75 (sulphate, chloride)	Vyskocil *et al.* cited in ATSDR, 1997.
Cancer:			
Lung and nasal cancers. Serious LOAEL	**OCCUPAT IONAL**	>10 (less soluble)	International Committee on Ni Carcinogenesis in Man cited in ATSDR, 1997.

[a] NOAEL, Less serious LOAEL, and Serious LOAEL as identified by ATSDR (1997).

Below is a summary of potential effects associated with chronic human Ni inhalation. Details regarding exposure concentrations and duration of exposure are included in Table 7.

4.4.1.1 Death

Occupational inhalation of Ni has been reported to increase mortality in workers was due to lung and nasal cancers (ATSDR, 1997). Polednak and Cornell and Landis (cited in ATSDR, 1997) reported increased mortality due to non-malignant respiratory disease (chronic bronchitis, emphysema, and reduced vital capacity) in two studies of occupational exposures; however, the increase was not significant and the workers were also exposed to other metals. Other occupational studies of chronic Ni inhalation did not identify increased rates mortality due of non-malignant respiratory diseases (Cox *et al.*, Enterline and Marsh, Cragle *et al.*, Redmond, Shannon *et al.*, 1984, 1991 cited in ATSDR, 1997).

4.4.1.2 Respiratory Effects

The respiratory system is the prime target for toxicity with Ni inhalation. Reported effects included: chronic bronchitis; emphysema; reduced vital capacity; and, lung and nasal cancers. Chronic exposures have been reported to produce asthma either by direct irritation, or from an allergic response (Dolovich *et al.*, Novey *et al.*, Shirakawa *et al.* cited in ATSDR, 1997).

Muir *et al.* (cited in ATSDR, 1997) reported no evidence of inflammatory or fibrogenic response in the lungs of workers from a Ni sinter plant.

4.4.1.3 Renal Effects

Increased proteins in the urine have been reported in men and women with chronic occupational Ni exposures (Sunderman and Horak, Vyskocil *et al.* cited in ATSDR, 1997). The changes may reflect tubular dysfunction in the kidneys (ATSDR, 1997).

Urine is the primary route of exposure for absorbed Ni, which may indicate that persons with kidney dysfunction may be more sensitive to Ni toxicity (ATSDR, 1997).

4.4.1.4 Immunological and Lymphoreticular Effects

Increased levels of immunoglobins and other serum proteins associated with cell-mediated immunity were identified in Ni exposed workers, indicating possible immune system stimulation (Bencko *et al.*, Bencko *et al.* cited in ATSDR, 1997). There may also be an association between Ni and cobalt sensitization (Shirakawa *et al.* cited in ATSDR, 1997).

4.4.1.5 Reproductive/Developmental Effects

An increase in spontaneous abortions and fetal structural malformations was reported among women working in a Russian nickel hydrometallurgy refining plant (Chashschin *et al.* cited in ATSDR, 1997). Heavy manual lifting and heat stress may also have been a factor.

4.4.1.6 Carcinogenic Effects

Occupational exposure to Ni has been demonstrated to be carcinogenic, causing an increased risk of lung and nasal cancer in exposed workers (Penderson *et al.*, Doll *et al.*, Chovil *et al.*, Enterline and Marsh, Magnus *et al.* cited in ATSDR, 1997). The risk of cancer was not seen to decrease even 30-40 years after exposures ceased, possible due to persistent deposits of Ni in the lung and nasal tissues (Muir *et al.* cited in ATSDR, 1997).

The lung and nasal cancers reported in epidemiological studies of workers appears to be related to the less soluble forms of inorganic Ni, although an interaction between soluble and less soluble Ni compounds may exist producing higher risks of lung and nasal cancer (International Committee on Nickel Carcinogenesis in Man cited in ATSDR, 1997). This same report found no association between metallic Ni and respiratory cancers, and no association between Ni exposures and other types of cancer.

The US EPA (IRIS, 1991; 1996 cited in ATSDR, 1997) classifies nickel refinery dust (mostly Ni subsulphide) as a class A carcinogen. IARC (1990) classifies nickel and nickel compounds as group 1, human carcinogens, and metallic nickel as group 2B, possible human carcinogen.

4.4.1.7 Other Effects

No human studies of dermal effects associated with Ni inhalation were identified, however, contact dermatitis is one of the most common effects reported by people exposed to Ni compounds via other exposure routes (usually metal objects on the skin) (ATSDR, 1997). (see Sections 4.4.1.4 and 4.4.2.3).

4.4.2 Chronic Animal Effects

Table 8 lists some examples of the lowest and highest NOAELs (No Observable Adverse Effect Level) and LOAELs (Lowest Observable Adverse Effect Level) reported in the literature from chronic animal studies.

Below is a summary of potential effects associated with chronic Ni inhalation in animals. Details regarding exposure concentrations, duration of exposure, and animal species studied are included in Table 8.

4.4.2.1 Death

Significant mortality was reported in rats, guinea pigs, and mice after chronic inhalation of inorganic Ni compounds (Hueper, Ottolenghi *et al.*, Takenaka *et al.* cited in ATSDR, 1997).

4.4.2.2 Respiratory Effects

Chronic inhalation of Ni compounds has been reported to be extremely toxic to the respiratory tract in experimental animals (rats, mice, rabbits, guinea pigs, hamsters). The reported effects included, but were not limited to: lung lesions (including pnuemonitis, bronchitis, and emphysema), morphological alterations in alveolar macrophages, increased volume density of alveolar cells, increased lung weight, focal alveolar/bronchiolar hyperplasia, focal fibrosis, and pneumoconiosis (Ottolenghi *et al.*, Wehner *et al.*, 1975, 1979, Johansson *et al.*, Takenaka *et al.*, Johansson and Camner, Wehner, 1986, Dunnick *et al.*, 1995, NTP, 1996a, 1996b, 1996c cited in ATSDR, 1997).

Mice appeared to be less susceptible than rats. Respiratory effects appeared to be more severe after exposure to Ni oxide and Ni subsulphide than Ni sulphate (ATSDR, 1997).

Table 8 Examples of NOAELs and LOAELs Associated with Chronic Nickel Inhalation (Experimental Animals)

Effects Reported[a]	Exposure Period	Air Concentration (mg Ni/m^3)	Species	Reference
Death:				
	31 mo, 7 d/wk, 23 hr/d	0.06 (oxide)	Rat	Takenaka *et al.* cited in ATSDR, 1997.
	21 mo, 4-5 d/wk, 6 hr/d	15 (Metallic)	Guinea pigs	Hueper cited in ATSDR, 1997.
Respiratory System:				
NOAEL	2 yr, 5 d/wk, 6hr/d	0.03 (sulphate)	Rats	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Increased lung weight; congestion; alveolar proteinosis. Serious LOAEL	31 mo, 7 d/wk, 23 hr/d	0.06 (oxide)	Rat	Takenaka *et al.* cited in ATSDR, 1997.
Mild to moderate chronic active inflammation of the lungs. Serious LOAEL	2 yr, 5 d/wk, 6hr/d	1 (oxide)	Rats	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Minimal to mild chronic active inflammation and alveolar epithelial hyperplasia. Less serious LOAEL	2 yr, 5 d/wk, 6hr/d	0.06 (sulphate)	Rats	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Minimal to mild chronic active inflammation of the lungs. Less serious LOAEL	2 yr, 5 d/wk, 6hr/d	1 (oxide)	Rats	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Endocrine Effects:				
NOAEL	2 yr, 5 d/wk, 6hr/d	0.11 (subsulphide and sulphate)	Rats	Dunnick *et al.*, NTP, 1996b, 1996c cited in ATSDR, 1997.
NOAEL	2 yr, 5 d/wk, 6hr/d	1 (oxide)	Rats	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Adrenal medulla hyperplasia. Less serious LOAEL	2 yr, 5 d/wk, 6hr/d	1 (oxide)	Rats	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.

Table 8 Examples of NOAEL's and LOAEL's Associated with Chronic Nickel Inhalation (Experimental Animals) (continued)

Effects Reported[a]	Exposure Period	Air Concentration (mg Ni/m^3)	Species	Reference
Body Weight:				
NOAEL	2 yr, 5 d/wk, 6hr/d	0.11 (subsulphide and sulphate)	Rats	Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Body weight 20-30% less than controls. Serious LOAEL	78 wk, 5 d/wk, 6 hr/d	0.7 (subsulphate)	Rats	Ottolenghi *et al.* cited in ATSDR, 1997.
NOAEL	2 yr, 5 d/wk, 6hr/d	0.11 (sulphate)	Mice	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
NOAEL	2 yr, 5 d/wk, 6hr/d	0.44 (subsulphide)	Mice	Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Body weight 14% lower than controls. Less serious LOAEL	2 yr, 5 d/wk, 6hr/d	0.22 (sulphate)	Mice	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Body weight 12% lower than controls. Less serious LOAEL	2 yr, 5 d/wk, 6hr/d	0.88 (subsulphide)	Mice	Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Lowest NOAELs for Other Systems:				
Cardiovascular; gastrointestinal; hematologic; hepatic; renal; dermal.	2 yr, 5 d/wk, 6hr/d	0.11 (sulphate)	Rat	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Cardiovascular; gastrointestinal; hematologic; hepatic; renal; endocrine; dermal.	2 yr, 5 d/wk, 6hr/d	0.22 (sulphate)	Mice	Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997.
Immunological/Lymphoreticular System:				
NOAEL	2 yr, 5 d/wk, 6hr/d	0.06 (sulphate)	Rats	NTP, 1996c cited in ATSDR, 1997.
Bronchial lymph node hyperplasia. Less serious LOAEL	2 yr, 5 d/wk, 6hr/d	0.06 (sulphate)	Rats	NTP, 1996c cited in ATSDR, 1997.
NOAEL	2 yr, 5 d/wk, 6hr/d	0.11 (sulphate)	Mice	NTP, 1996c cited in ATSDR, 1997.

Table 8 Examples of NOAEL's and LOAEL's Associated with Chronic Nickel Inhalation (Experimental Animals)

Effects Reported[a]	Exposure Period	Air Concentration (mg Ni/m^3)	Species	Reference
Bronchial lymph node hyperplasia. Less serious LOAEL	2 yr, 5 d/wk, 6hr/d	0.22 (sulphate)	Mice	NTP, 1996c cited in ATSDR, 1997.
Neurological and reproductive Effects:				
NOAEL	2 yr, 5 d/wk, 6hr/d	2 (oxide)	Rats	NTP, 1996a cited in ATSDR, 1997.
NOAEL	2 yr, 5 d/wk, 6hr/d	3.9 (oxide)	Mice	NTP, 1996a cited in ATSDR, 1997.
Cancer:				
Alveolar/bronchiolar adenoma or carcinoma. Serious LOAEL	2 yr, 5 d/wk, 6hr/d	1 (oxide)	Rats	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Benign or malignant pheochromocytoma of the adrenal medulla. Serious LOAEL	2 yr, 5 d/wk, 6hr/d	2 (oxide)	Rats	Dunnick *et al.*, NTP, 1996a cited in ATSDR, 1997.
Alveolar/bronchiolar adenoma or carcinoma. Serious LOAEL	2 yr, 5 d/wk, 6hr/d	0.11 (subsulphide)	Rats	Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Benign or malignant pheochromocytoma of the adrenal medulla. Serious LOAEL	2 yr, 5 d/wk, 6hr/d	0.11 (subsulphide)	Male rats	Dunnick *et al.*, NTP, 1996b cited in ATSDR, 1997.
Lung adenomas, adenocarcinomas, squamous cell carcinoma. Serious LOAEL	78 wk, 5 d/wk, 6 hr/d	0.7 (subsulphate)	Rats	Ottolenghi *et al.* cited in ATSDR, 1997.

[a] NOAEL, Less serious LOAEL, and Serious LOAEL as identified by ATSDR (1997).

4.4.2.3 Immunological and Lymphoreticular Effects

A number of animal studies (rat, mouse, rabbit) reported significant immune changes with chronic inhalation of nickel compounds. These changes include: alterations in alveolar macrophage activities, decreased number of alveolar macrophages, increased susceptibility to infections, and decreased resistance to tumour challenge (Johansson *et al.*, Spiegelberg *et al.*, Haley *et al.*, Morimoto *et al.* cited in ATSDR, 1997).

Bronchial lymph node hyperplasia was reported in rats and mice after chronic Ni inhalation (as sulphate, oxide and subsulphide) (NTP, 1996a, 1996b, 1996c cited in ATSDR, 1997).

4.4.2.4 Body Weight

Decreases in body weight have been reported in animals exposed to concentration of Ni that produced respiratory tract effects (ATSDR, 1997).

4.4.2.5 Carcinogenic Effects

Studies of chronic Ni oxide and Ni subsulphide inhalation reported significant increases in lung tumours in rats (Ottolenghi *et al.*, Dunnick *et al.*, 1995, NTP, 1996a, 1996b cited in ATSDR, 1997). No carcinogenic effect was observed in mice exposed to Ni subsulphide, and equivocal carcinogenic evidence was reported in female mice exposed to Ni oxide (Dunnick *et al.*, NTP, 1996c cited in ATSDR, 1997).

Chronic intratrachial instillation[2] of Ni subsulphide in mice did not produce lung tumours (Fisher *et al.*, McNeill *et al.* cited in ATSDR, 1997).

No carcinogenic activity was observed in rats or mice exposed to Ni sulphate (Dunnick *et al.*, 1995, NTP, 1996c cited in ATSDR, 1997).

4.4.2.6 Other Effects

Chronic exposure to Ni oxide and Ni subsulphide was reported to produce adrenal medulla hyperplasia in female mice only. This effect was not seen in rats, or in mice exposed to Ni sulphate (NTP, 1996a, 1996b, 1996c cited in ATSDR, 1997).

Microscopic examination of rat and mouse tissues revealed no adverse cardiovascular, gastrointestinal, hepatic, hematological, renal, reproductive, endocrinological, neurological, or dermal changes associated with chronic or intermittent Ni exposures (Ottolenghi *et al.*, Tanaka *et al.*, NTP, 1996a, 1996b, 1996c cited in ATSDR, 1997).

---

[2] Intratrachial instillation mimics inhalation exposure.

4.5 Summary of Adverse Health Effects of Nickel Inhalation

Respiratory system is the prime target of nickel (Ni) inhalation toxicity in both animals and humans. Nickel inhalation has also been reported to affect the immune and renal systems.

Acute exposure to high concentrations of nickel compounds was fatal in one man. Death was due to severe respiratory tract damage; there was significant alveolar wall damage and edema in alveolar spaces in the lungs. Chronic Ni inhalation can produce: asthma, chronic bronchitis, emphysema, reduced vital capacity, and lung and nasal cancers.

Acute animal exposures were also fatal after severe haemorrhage in the lungs. Sub-acute exposures to Ni sulphate and Ni subsulphide (but not Ni oxide) was lethal to rats and mice. Non-lethal toxic effects of acute and sub-acute Ni inhalation reported: chronic active inflammation in the lungs, alveolitis, interstitial pneumonia, fibrosis, macrophage hyperplasia, interstitial infiltrates into the lung, increased lung weight, lung tumours, and, olfactory epithelial atrophy in the nose.

Occupational exposure to Ni has been demonstrated to be carcinogenic, causing an increased risk of lung and nasal cancer in exposed workers. The U.S. EPA (IRIS, 1991; 1996 cited in ATSDR, 1997) classifies Ni refinery dust (mostly Ni subsulphide) as a class A carcinogen. IARC (1990) classifies Ni and Ni compounds as group 1, human carcinogens, and metallic Ni as group 2B, possible human carcinogens.

5.0 EFFECTS ON MATERIALS

Most of the metals emitted to the atmosphere are associated with particulate matter at ambient temperatures or – less frequently – in the vapor state. Metal oxides tend to be adsorbed to or associated with particles. This is the case for numerous individual metals (after WBK, 2003):

- Arsenic occurs naturally in soil and minerals and may enter the air as wind-blown dust particles. Arsenic released from combustion processes is usually attached to very small particles.
- Cobalt is probably emitted in the particulate form to the air, since compounds of cobalt are not usually volatile.
- Copper is released to the atmosphere in the form of particulate matter or adsorbed to particulate matter.
- Elemental manganese and inorganic manganese compounds have negligible vapor pressures but may exist in air as suspended particulate matter derived from industrial emissions or the erosion of soils.
- Nickel releases to the atmosphere are mainly in the form of aerosols that cover a broad spectrum of sizes. Nickel from power plants and smelters tend to be associated with small particles.
- Vanadium generally enters the atmosphere as an aerosol. Vanadium attributed to combustion of residual fuel oils and coal is generally in the form of vanadium oxides and contributes to approximately two-thirds of the atmospheric vanadium.
- Zinc occurs in the environment mainly in the divalent (+2) oxidation state. It is found in the atmosphere at the highest concentrations in small particles.

Thus the predominant issue with respect to ambient emissions of metals negatively affecting material surfaces will be because of its association with deposited airborne particulate matter. Excluding acidic particles, deposition of airborne particles on material surfaces can cause soiling (Baedecker *et al.*, 1991). In addition, particles deposited on a surface can adsorb or absorb acidic gases (e.g. SO_2 and NO_2), thus serving as nucleation sites for these acidic gases. This may accelerate physical and chemical degradation of material surfaces that normally occur when materials are exposed to environmental factors such as wind, sun, temperature fluctuations, and moisture.

Haynie and Lemmons (1990) described soiling as the contrast in reflectance of particles on a substrate compared to the reflectance of a bare substrate. Soiling of materials is a concern because it results in more frequent cleaning and repainting, thereby reducing its lifetime usefulness and increasing costs associated with maintenance of the materials.

Haynie (1986) reported that it is difficult to determine the amount of deposited particles that cause an increase in soiling. However, Haynie (1986) indicated that soiling is dependent on the particle concentration in the ambient environment, particle size distribution, and the deposition rate and the horizontal or vertical orientation and texture of the surface being exposed. Schwar (1998) reported that the buildup of particles on a horizontal surface is counterbalanced by an equal and opposite depletion process. The depletion process is based on the scouring and washing effect of wind.

6.0 AIR SAMPLING AND ANALYTICAL METHODS

6.1 Introduction

Accurate measurement of trace metals in ambient air is often difficult, in part because of the variety of substances, the variety of potential techniques for sampling and analysis, and the lack of standardized and documented methods. The United States Environmental Protection Agency (US EPA, 1999a), National Institute of Occupational Safety and Health (NIOSH, 1994), and Occupational Safety and Health Administration (OSHA, 2002a; 2002b) are the only organizations that provide documented and technically reviewed methodologies for determining the concentrations of selected trace metals of frequent interest in ambient and indoor air. It is these methods, which are presented here, that are generally accepted as the preferred methods for trace metal sampling and analysis.

6.2 Sampling Methods

The majority of trace metals present in ambient air are particle-bound. Therefore, the sample collection schemes appropriate for the collection of trace metals follow the methods appropriate for particulate matter measurements. There are many sampling systems available for particulate matter measurements, each with its own advantages and disadvantages. Only some, however, are capable of collecting samples that are suitable for elemental analysis. The major prerequisites in selecting a sampling system are to determine what size range of particles are to be monitored, what trace metals are of interest, and the appropriate method of analysis. The analytical method selection is very important, because only some methods are compatible with each sampling system. The available documented and technically reviewed methods include high volume samplers for collecting TSP (total suspended particulate with aerodynamic diameters less than 100 µm) and PM_{10} (particulate matter with aerodynamic diameters less than 10 µm) and low volume samplers for collecting PM_{10} and $PM_{2.5}$ (particulate matter with aerodynamic diameters less than 2.5 µm) utilizing dichotomous and Partisol samplers. Each of these samplers has the ability to collect particulate matter uniformly across the surface of the filters and they are commonly used in Alberta. They can be used to determine average ambient particulate matter concentration over the sampling period, and the collected material can subsequently be analyzed for inorganic metals and other materials present in the collected sample. Some of the advantages and disadvantages associated with the sampling options are summarized in Table 9.

6.2.1 Hi-Vol Sampler

The primary method used to sample airborne particulate matter in a volume of ambient air with the objective of identifying and quantifying the inorganic metals present has historically been the high volume (hi-vol) sampler (US EPA, 1999a). Air is drawn into the sampler and through a glass fiber or quartz filter by means of a blower (typically at a rate of 1.13 to 1.70 m^3/min), so that particulate material collects on the filter surface. If a 10 µm size-selective inlet is used, only particles of 10-µm size and less enter the sampling inlet and are collected on the downstream filter. Without the inlet, particles of 100-µm size and less are collected. When glass fiber filters are used, particles 100 µm or less are ordinarily collected. With a size-select inlet, particles 10 µm or less are collected on quartz filters. The hi-vol's design causes the particulate matter to

Table 9 Method Advantages and Disadvantages

Method	Advantages	Disadvantages
Sampling Methods		
Hi-Vol Sampler	Reference method Well documented applications Collects a substantial amount of material Lower concentrations of metals can be detected	Many interferences Cannot sample fine fraction Not compatible with some analytical techniques Inconvenient
Dichotomous Sampler	Reference method Collects two size fractions Allows use of various filter media	Low loadings Requires a higher concentration
Partisol Sampler	Simple and convenient Allows use of various filter media	Low loadings Requires a higher concentration
Mini-Vol Sampler	Simple, convenient and inexpensive Allows use of various filter media	Low loadings Requires a higher concentration Limited documented applications
Analytical Methods:		
Flame Atomic Absorption Spectroscopy	Easy to use Extensive applications Low detection limits Well documented applications	Higher concentration required Sample dissolution is required One element at a time Limited working range sample
Graphite Furnace Atomic Absorption Spectroscopy	Lower detection limits than FAA	Low sample throughput One element at a time More operator skill Sample dissolution is required
X-Ray Fluorescence Spectroscopy	Multi-element Non-destructive Minimal sample preparation	Standard/sample must match closely Matrix offsets and background impurities may be a problem
Inductively Coupled Plasma Spectroscopy	Multi-elemental High sample throughput Well documented applications Intermediate operator skill Linear range over 5 orders of magnitude	More expensive (~120K) Sample dissolution is required Other elements can interfere
Inductively Coupled Plasma/Mass Spectroscopy	Multi-elemental Low concentrations Isotopic analysis Intermediate operator skills	Most expensive (~250K) Limited documented applications Sample dissolution is required
Proton Induced X-Ray Emission Spectroscopy	Multi-element Non-destructive Minimal sample preparation	Standard/sample must match closely Matrix offsets and background impurities may be a problem
Instrumental Neutron Activation Analysis Spectroscopy	Multi-element Non-destructive Minimal sample preparation Detection limit to ppt range High sample throughput Well documented applications	Some elemental interferences Standard sample matrix corrections Required access to research nuclear reactor
Scanning Electron Microscopy with Energy Dispersive X-Ray Spectroscopy	Chemical and physical characterization Non-destructive Minimal sample preparation	Poor sensitivity Time consuming Limited documented applications

be deposited uniformly across the surface of the filter. The mass concentration of suspended particulates in the ambient air is computed by measuring the mass of collected particulates and the volume of air sampled. After the mass is measured, the filter is ready for extraction to determine the metal concentration.

Because of its higher flow rates, the hi-vol collects more material so lower ambient concentrations of inorganic materials can be detected (assuming identical filter medium and analysis technique). The major interferences in suspended particulate matter determination are collection of large extraneous objects (e.g., insects), collection of liquid aerosols and gas or vapours that may react with some filter types and/or collected materials to add artificial weight (ARPEL, 1998). The high-volume sampling technique has been recommended as the method for sampling ambient particulate matter by most air quality agencies including the US EPA and Environment Canada. As delineated later, airborne particulate matter retained on the filter may be examined or analyzed chemically by a variety of methods including inductively coupled plasma (ICP) spectroscopy, inductively coupled plasma/mass spectroscopy (ICP/MS), flame atomic absorption (FAA) spectroscopy, graphite furnace atomic absorption (GFAA) spectroscopy, and instrumental neutron activation analysis (INAA).

6.2.2 Dichotomous Sampler

Dichotomous samplers are used to sample airborne particulate matter in coarse (2.5 to 10 µm) and fine (<2.5 µm) size fractions. In dichotomous samplers, ambient air is drawn at a flow rate of approximately 1 m^3/hr. The coarse fraction of particulate matter is accelerated into the central collection filter while the fine fraction is drawn onto a second collection filter. Particles that are <10 µm are collected via a 10 µm inlet and separated into fine (<2.5 µm) and coarse (2.5 to 10 µm) fractions by a virtual impactor. In recent literature of ambient air particulate sampling and elemental analysis, the duration of sampling ranges from 12 to 24 hours depending upon experimental design and amount of ambient particulate present (US EPA, 1999). The mass concentration of airborne particles within each size range is determined gravemetrically. The detection limit for the method depends on the sensitivity of the analytical balance utilized for the gravimetric determination and the volume of air sampled. The dichotomous sampler has the advantage of collecting two fractions so that information can be obtained about total PM_{10} and/or both of the two fractions. In addition, the dichotomous sampler operates at a low flow rate, which allows the use of filter media that would otherwise quickly clog at high-volume flow rates. The particles are collected on Teflon filters and once at the laboratory are analyzed by X-ray fluorescence (XRF) spectrometry, proton induced X-ray emissions (PIXE) spectrometry, or instrumental neutron activation analysis (INAA).

6.2.3 Partisol Sampler

The Ruppecht and Patashnick (R&P) Low-Volume Partisol Air Sampler is a microprocessor-controlled manual sampler with a unique set of features that make it a suitable platform for measuring particulate and other constituents found in the atmosphere (US EPA, 1999a). Ambient air is drawn through a low flow (16.7 L/min) PM_{10} or $PM_{2.5}$ inlet where particle size selection takes place. The particulate-laden air is then directed through a collection filter composed of quartz, Teflon-coated glass, or Teflon where the particulate matter is collected. A mass flow control system maintains the sample flow through the system at the prescribed volumetric flow using information from sensors that measure the ambient temperature and ambient pressure. The sample filter is conditioned and weighed both before and after sample collection to determine the amount of mass collected during the sampling period. The airborne particulate collected on the 47-mm filter in the Partisol Sampler may be subjected to a number of post-collection chemical analytical techniques to ascertain the composition of the material caught by the filter. Appropriate techniques include X-ray fluorescence (XRF) spectrometry, proton induced X-ray emissions (PIXE) spectrometry, and instrumental neutron activation analysis (INAA). The type of filter media should be compatible with the analytical method used.

6.2.4 Alternative Sampling Methods

In addition to the documented and technically reviewed methodologies for collecting trace metals in ambient air there are alternative methods. One such method is the Portable Minivolume Air Sampler (MiniVol) made by Airmetrics (Airmetrics, 1998). The MiniVol works by drawing air through a size-selective impactor that removes the unwanted larger sizes of particulate and captures the smaller sizes on a filter. It has a twin cylinder vacuum pump that is designed to pull air at 5 L/min (at standard temperature and pressure) through an impactor that is capable of removing particles larger than the cut-points of either 10 µm or 2.5 µm. This active sampler is operated by the principle of inertial impaction using a single stage impactor with a filter. In this device, the particle-laden air is accelerated through one nozzle and the exiting jet impinges upon a plate. The impactor dimensions are chosen such that particles smaller than the desired cut-point follow the streamlines as they bend at the impaction plate, while the larger particles with sufficient inertia depart from the streamlines and impact against the plate. The elemental and morphological properties of the deposited material are later analyzed using an appropriate technique (Jones *et al.*, 1998; Tropp *et al.*, 1998). Environment Canada uses the MiniVol as a saturation sampler and they have been used extensively in several parts of Alberta under a variety of climatic conditions (Alberta Health, 1997).

6.3 Analytical Methods

Many analytical methods exist to characterize trace metals collected on a filter substrate and each has its own attributes, specificities, advantages and disadvantages. Though several methods are multi-species (able to quantify a number of different chemical components simultaneously) no single method is sufficient to quantify both the majority of the collected particulate matter mass and those trace elements which may be of interest. The type of analytical technique used is generally dictated by the specific sampling method employed to collect the particulate matter. Furthermore, the type of filter medium used to capture the sample is a factor in the choice of analytical technique and vice-versa. Most importantly, the choice of analytical method will depend on the metals of interest and the detection limits desired. Some of the advantages and disadvantages associated with the analytical options are summarized in Table 9. While factors such as element specificity and sensitivity are critically important, considerations such as cost and throughput (the number of samples and number of elements to be determined per sample) are also significant.

6.3.1 Atomic Absorption Spectroscopy

Atomic Absorption Spectroscopy (AAS) has occasionally been used as the primary method for metals determination (Beceriro-Gonzalez *et al.*, 1997), but is more commonly used as a supplementary technique for elements not amenable to analysis by one of the multi-elemental techniques described later (Kowalczyk *et al.*, 1982; Rizzio *et al.*, 2000). In this method, trace metals in a particulate matter sample are extracted by either a hot acid or microwave extraction procedure into a solution and subsequently vaporized in a flame. A light beam with a wavelength matching the absorption wavelength of the metal of interest passes through the vaporized sample. The light attenuated by the sample is then measured and the amount of the metal present is determined using Beer's Law (Koutrakis and Sioutas, 1996).

AAS describes both flame atomic absorption (FAA) spectroscopy and graphite furnace atomic absorption (GFAA) spectroscopy (US EPA, 1999a). The two atomic absorption analyses options are similar in that the measurement principle is the same. However, they differ in how the sample is introduced into the instrument. Both types of atomic absorption spectroscopy involve irradiating the sample with light of a single wavelength and measuring how much of the input light is absorbed. Each element absorbs light at a characteristic wavelength and, therefore, analysis for each element requires a different light source. This means only one element can be determined at a time. In FAA, the sample is atomized and introduced into the optical beam using a flame, typically air/acetylene or nitrous oxide/acetylene. In GFAA, a graphite furnace electrothermal atomizer is used.

AAS has the advantage of being able to accurately measure difficult elements such as cadmium, lead, zinc and magnesium. However, the necessary dissolution of collected particulate and the manipulation of a solution of trace elements is not a trivial thing. Furthermore, AAS can only analyze one element at a time thus rendering the analysis of an extensive set of elements prohibitively time consuming. The analytical technique is also destructive and requires that the sample be extracted or digested for introduction into the system in solution. The detection limit of GFAA is typically about two orders of magnitude better than FAA (US EPA, 1999a). High-volume samplers are typically used for sampling when FAA or GFAA analysis is planned.

6.3.2 X-Ray Fluorescence Spectroscopy

In X-Ray Fluorescence (XRF) (Dzubay and Stevens, 1975; Dzubay, 1977; Lewis and Macias, 1980; Price *et al.*, 1982; Dzubay *et al.*, 1988; Glover *et al.*, 1991; Schmeling *et al.*, 1997) a beam of X-rays irradiates the particulate matter sample. This causes each element in the sample to emit characteristic X-rays that are detected by a solid-state detector or a crystal spectrometer. The characteristic X-ray is used to identify the element and the intensity is used to quantify the concentration of the measured element. X-ray fluorescence spectrometry (including energy dispersive and wavelength dispersive modes) can be accurately used for all elements with atomic weights from 11 (sodium) to 92 (uranium). Furthermore, multiple elements can be determined simultaneously.

This method has the advantages of being non-destructive, requiring minimal sample preparation, providing immediate results and having low equipment cost. However, the detection limit is higher than other analysis techniques. In addition, it requires a thin collection deposit (i.e. 10 to 50 μg/cm^2) and it involves complex matrix corrections. Elements lighter than aluminum are often difficult to determine because of their low fluorescent yields and particularly because of the strong absorption of fluorescent X-rays by the substrate on which they are collected (US EPA, 1999a). Because high-volume samplers utilize quartz-filters that cause high background when employing XRF, analysis by XRF usually requires Teflon or Nylon filters used in the dichotomous or the Partisol samplers.

6.3.3 Inductively Coupled Plasma Spectroscopy

In Inductively Coupled Plasma (ICP) Spectroscopy analysis, the particulate matter sample is excited using an argon plasma torch (ARPEL, 1998; US EPA, 1999a). When the excited atoms return to their normal state, each element emits a characteristic wavelength of light. The wavelengths detected and their intensities indicate the presence and amounts of particular elements. Samples containing up to 61 preselected elements can be simultaneous analyzed by ICP at a rate of one sample per minute (US EPA, 1999a). In addition, the ICP technique has the ability to analyze a large range of concentrations. As with FAA and GFAA, the particulate matter must be extracted (via hot acid extraction or microwave extraction) and digested for ICP analysis, and the material introduced into the instrument is destroyed during analysis. An ICP instrument is more costly than many of the other instruments. The ICP detection limit for many of the elements of interest is equal to or somewhat better than most of the other instruments. High-volume samplers are typically used for sampling when ICP analysis is planned.

6.3.4 Inductively Coupled Plasma/Mass Spectroscopy

Other analytical methods such as Inductively Coupled Plasma/Mass Spectrometry (ICP/MS) can be used to determine trace metal concentrations (Broekaert *et al.*, 1982; Janssen *et al.*, 1997). In ICP/MS analysis, the sample is excited using an argon plasma torch to generate elemental ions for separation and identification by mass spectrometry. This analysis allows many more than sixty elements and the isotopes of elements to be determined simultaneously at very low detection limits. However, ICP/MS analysis is time consuming because the sample must be extracted or digested and the analysis is destructive. In addition, the procedure is very costly and its documented applications are the lowest among all the potential techniques (US EPA, 1999a). Sampling is typically conducted using high-volume samplers when ICP/MS analysis is planned.

6.3.5 Proton Induced X-Ray Emission Spectroscopy

Some work on trace metal analysis has also been performed using Proton Induced X-Ray Emission (PIXE) Spectroscopy (Heidam, 1981; Van Borm *et al.*, 1990; Flores *et al.*, 1999). PIXE analysis is very similar to XRF analysis in that the sample is irradiated by a high-energy source, in this case high-energy protons, to remove inner shell electrons. Fluorescent X-ray photons are detected employing the same detection methods as XRF and used to identify and quantify different elements in the sample.

PIXE is one of the more commonly used elemental analysis methods because of its relatively low cost, nondestructive, multi-element capabilities. It is potentially capable of determining 72 elements with molecular weights between those of sodium and uranium, simultaneously (ARPEL, 1998). The method provides the sensitivity for accurate measurements at the nanogram or less level for many important trace metals in the urban atmosphere. The PIXE method has the ability to analyze a very small sample diameter in addition to evenly distributed wide-area samples, which is advantageous because it permits analysis of individual particle size fractions collected with single orifice type cascade impactors. PIXE is capable of measuring smaller quantities of particulate matter, although it has the same limitations as with XRF concerning light elements. In addition, facilities for this method are expensive and not common and it is less suitable for routine filter analysis than other multi-elemental methods because of more complicated sample preparation (US EPA, 1994). Analysis by PIXE typically involves collecting particulate matter by dichotomous or Partisol samplers.

6.3.6 Instrumental Neutron Activation Analysis Spectroscopy

Instrumental Neutron Activation Analysis (INAA) (Zoller and Gordon, 1970; Gladney et al., 1974; Hopke et al., 1976; Mizohata and Mamuro, 1979; Kowalczyk et al., 1978, 1982; Olmez, 1989; Rizzio et al., 1999; Salma and Zemplem-Papp, 1999) bombards a sample with a high neutron thermal flux in a nuclear reactor or accelerator. The sample elements are transformed into radioactive isotopes that emit gamma rays. The distribution or spectrum of energy of the gamma rays can be measured to determine the specific isotopes present. The intensity of the gamma rays can also be measured and is proportional to the amounts of elements present.

INAA is a simultaneous, multi-element method for determining ppt, ppm or ppb levels of 40-50 elements of interest. It has the advantage of higher sensitivity compared to other methods, a fact that makes it attractive for sampling trace elements found in extremely low concentrations (US EPA, 1999a). INAA is a non-destructive technique that requires minimal sample preparation as it does not require the addition of any foreign materials for irradiation. Limitations of this method include the fact that elements such as sulphur, lead and cadmium cannot be determined accurately, as well as that INAA is more expensive than many other methods. In addition, to use this method an optimal loading of >100 µg/cm2 is generally required (Gordon et al, 1984). Analysis by INAA is compatible with sampling by high-volume, dichotomous and Partisol samplers.

6.3.7 Alternative Analytical Methods

There have been several reports of Energy Dispersive X-Ray (EDX) Spectrometry being used in conjunction with Scanning Electron Microscopy (SEM) (Linton et al., 1980; Casuccio and Janocko, 1981; Shaw, 1983; Post and Buseck, 1984; Saucy et al., 1987; Anderson et al., 1988; Dzubay and Mamane, 1989; Hamilton et al., 1994). Scanning Electron Microscopy with Energy Dispersive X-Ray (SEM-EDX) Spectrometry uses a computer-controlled scanning electron microscope equipped with image analysis software to determine the size and shape of a moderate number of particles and EDX to provide qualitative and a moderately sensitive quantitative elemental analysis in a similar manner as XRF analysis. Generally, low loadings are required to employ this technique, therefore, a low-flow device such as dichotomous, Partisol or the MiniVol samplers should be used.

The primary advantage of the SEM-EDX technique is the ability to characterize individual particles both chemically and physically. The Expert Panel on the U.S. Environmental Protection Agency PM2.5 Chemical Speciation Network has recommended using the SEM-EDX for analysis of air filters (U.S. EPA, 1999b). The panel found that microscopic techniques could be used to characterize both the morphology and the chemical composition of individual particles (Koutrakis, 1998). The disadvantages of the SEM-EDX technique include poor quantitative sensitivity (Linton et al., 1980) and practical difficulties such as excessive time for a representative analysis and the occurrence of both particle damage and compositional changes during analysis (Post and Buseck, 1984). In addition, the EDX technique often results in potential spectral interferences requiring complex spectral deconvolution procedures.

Advances in microscopic techniques, particularly in sample analysis software, now permit collection of reasonably large datasets of individual particle morphology and composition. This technology has helped to overcome the sometimes-problematic issue of only being able to analyze a moderate number of particles in a reasonable time frame with the conventional SEM-EDX technique. To illustrate this point, an increasing number of studies in recent years (Rojas et al., 1990; Van Borm et al., 1989; Xhoffer et al., 1991) have employed electron probe microanalysis to analyze individual particles. However, these technologies are very expensive, still in the developmental phase and are not readily available.

7.0 AMBIENT GUIDELINES

Current and/or recommended and proposed ambient guidelines of other jurisdictions in Canada, United States and elsewhere were reviewed for nickel. Details about guidelines that exist for each jurisdiction reviewed are presented in tabular format in Section 7.1. In general, all jurisdictions have common uses for their guidelines. These uses may include:

- reviewing permit applications for sources that emit air pollutants to the atmosphere,
- investigating accidental releases or community complaints about adverse air quality for the purpose of determining follow-up or enforcement activity,
- determining whether to implement temporary emission control actions under persistent adverse air quality conditions of a short-term nature

7.1 Nickel Air Quality Guidelines

Air quality guidelines for nickel are summarized in Table 10. The principal approaches by which guidelines are developed include:

- Using an occupational exposure level (OEL) and dividing it by safety or adjustment factors. The most common OEL used by most state agencies is the 8-hour threshold limit value (TLV) of 1,000 $\mu g/m^3$ for nickel dusts adopted by the American Conference of Governmental Industrial Hygienists (ACGIH). The safety or adjustment factors are intended to account for issues such as: differences between eight-hour exposures in the workplace and continuous 24-hour environmental exposures, increased susceptibility of some people in the general population versus the relatively healthy worker, and uncertainty in the margin of safety provided in an occupational exposure limit.
- Using carcinogenic risk assessment procedures. Pre-existing cancer risk assessments performed by others (e.g. US EPA Integrated Risk Information System) are used to establish ambient air levels based on acceptable levels of lifetime cancer risk, such as one in 100,000 (10^{-5}).
- Using non-carcinogenic risk assessment procedures. A no observed adverse effect level (NOAEL) – or lowest observed adverse effect level (LOAEL) if a NOAEL is unavailable – from a suitable animal or human study is used. It is then divided by a series of adjustment factors. The adjustment factors are intended to account for issues such as: differences between animals and humans, sensitivity of high risk individuals, use of a LOAEL instead of a NOAEL, and for extrapolation from less-than-lifetime exposures to chronic exposure.

Table 10 Summary of Air Quality Guidelines for Nickel

Agency	Guideline Title	Guideline Value [µg/m^3] Averaging Time:			
		1-hour	8-hour	24-hour	annual
Ontario MOE	Ambient Air Quality Criterion (AAQC):			2	
	Maximum point of impingement (POI) Guideline (30-min. averaging time):	5			
US ATSDR	Chronic inhalation Minimal Risk Level:				0.2
US EPA	Risk specific concentration (RsC):[a]				0.04
California EPA	Acute reference exposure level (REL):	6			
	Chronic REL:				0.05
	Risk specific concentration (RsC):[a]				0.04
Louisiana DEQ	Ambient air standard (AAS) for nickel:				0.21
	AAS for nickel refinery dust:				0.42
Massachusetts DEP	Threshold Effects Exposure Limit (TEL):			0.27	
	Allowable Ambient Limit (AAL):				0.18
Michigan DEQ	Initial risk screening level (IRSL):				0.0042
	Secondary risk screening level (SRSL):				0.042
New Hampshire DES	24-hour ambient air limit (AAL):			3.57	
	Annual AAL:				2.38
New Jersey DEP	Risk assessment approach is used:				
	Risk specific concentration (RsC):[a]				0.04
North Carolina ENR	Acceptable ambient level (AAL):			0.006	
Ohio EPA	Maximum acceptable ground-level concentration (MAGLC):[b]	23.8			
Oklahoma DEQ	Maximum acceptable ambient concentration (MAAC):			0.15	
Rhode Island DEM	Acceptable ambient level (AAL):				0.002
Texas CEQ	Effects screening level (ESL):	0.15			0.015
Vermont ANR	Hazardous ambient air standard (HAAS):				0.0033
Washington DOE	Acceptable source impact level (ASIL):				0.0021
Wisconsin DNR	No guideline exists.				
New Zealand MOE	No guideline exists.				
The Netherlands (RIVM)	Tolerable concentration in air (TCA):				0.05
World Health Organization	Risk specific concentration (RsC):[a]				0.026

[a] The RsC is not used for any specific purposes by the respective agency. It is shown here to illustrate an exposure concentration in air associated with an inhalation unit risk factor used by the agency and a 1 in 100,000 lifetime cancer risk (risk criteria used in Alberta). [b] Proposed.

Agency:

Ontario Ministry of the Environment (OME).

Air Quality Guideline:

Ambient Air Quality Criterion (AAQC) = 2 µg/m^3 (for nickel).

Averaging Time To Which Guideline Applies:

24-hour averaging time.

Basis for Development:

Limiting effect based on vegetation.

Date Guideline Developed:

Unknown.

How Guideline is Used in Practice:

Used by Ontario Ministry of Environment (OME) to represent human health or environmental effect-based values not expected to cause adverse effects based on continuous exposure.

Additional Comments:

AAQC is not used by OME to permit stationary sources that emit nickel to the atmosphere. A "point of impingement" standard is used to for permitting situations.

Reference and Supporting Documentation:

Ontario Ministry of the Environment. 1999. Summary of Point Of Impingement Standards, Point Of Impingement Guidelines, and Ambient Air Quality Criteria (AAQC). Standards Development Branch, Ontario Ministry of the Environment, Toronto, ON. November 1999. 12 pp.

Agency:

Ontario Ministry of the Environment (OME).

Air Quality Guideline:

Maximum point of impingement (POI) Guideline = 5 $\mu g/m^3$ (for nickel).

Averaging Time To Which Guideline Applies:

30-minute averaging time.

Basis for Development:

Limiting effect based on vegetation.

Date Guideline Developed:

Unknown.

How Guideline is Used in Practice:

Used by OME to review permit applications for stationary sources that emit nickel to the atmosphere.

Additional Comments:

n/a

Reference and Supporting Documentation:

Ontario Ministry of the Environment. 1999. Summary of Point Of Impingement Standards, Point Of Impingement Guidelines, and Ambient Air Quality Criteria (AAQC). Standards Development Branch, Ontario Ministry of the Environment, Toronto, ON. November 1999. 12 pp.

Agency:

US Agency for Toxic Substances and Disease Registry (ATSDR).

Air Quality Guideline:

Chronic inhalation Minimal Risk Level (MRL) = 0.2 $\mu g/m^3$ (for nickel soluble salts).

Averaging Time To Which Guideline Applies:

Greater than 365-day exposure duration.

Basis for Development:

The chronic inhalation MRL of 0.2 $\mu g/m^3$ for nickel soluble salts was derived based on a 2-year study of nickel sulphate in rats in which chronic active inflammation was observed at ≥0.06 mg nickel/ m^3. Dose adjustments for intermittent exposure (6/24 hours, 5/7 days), regional deposited dose ratio (0.9714 for pulmonary region deposition), and an uncertainty factor of 30 (3 for extrapolation from animals to man, and 10 for human variability) were used to derive the MRL.

Date Guideline Developed:

Unknown.

How Guideline is Used in Practice:

MRLs are intended to serve as a screening tool to help public health professionals decide where to look more closely. Chronic inhalation MRLs are exposure concentrations that, based on current information, might cause adverse health effects in the people most sensitive to such substance-induced effects for 365 days, and longer, exposure durations.

Additional Comments:

Inhalation MRLs provide a basis for comparison with levels that people might encounter in air. If a person is exposed to nickel at an amount below the MRL, it is not expected that harmful (noncancer) health effects will occur. Because these levels are based only on information currently available, some uncertainty is always associated with them. Also, because the method for deriving MRLs does not use any information about cancer, an MRL does not imply anything about the presence, absence, or level of risk for cancer.

Reference and Supporting Documentation:

Agency for Toxic Substances and Disease Registry (ATSDR). 2003. Minimal Risk Levels (MRLs) for Hazardous Substances. ATSDR, Public Health Service, US Department of Health and Human Services. Atlanta, GA. Available at: http://www.atsdr.cdc.gov/mrls.html (accessed 22 January 2003).

Agency:

US Environmental Protection Agency (EPA).

Air Quality Guideline:

Risk specific concentration (RsC) corresponding to 1 in 100,000 risk = 0.04 $\mu g/m^3$ (for nickel refinery dust).

Averaging Time To Which Guideline Applies:

Continuous exposure (daily exposure over a lifetime).

Basis for Development:

The RsC corresponding to 1 in 100,000 risk (risk criteria used in Alberta) was derived based on a midpoint of the range of relative risk estimates from multiple epidemiological studies of nickel refinery worker exposure data (i.e. US EPA's inhalation unit risk factor of 2.4E-04 per $\mu g/m^3$).

Date Guideline Developed:

1991.

How Guideline is Used in Practice:

The risk specific concentration (RsC) is not used for any specific purposes by US EPA and is shown here to illustrate an exposure concentration in air associated with an inhalation unit risk factor derived by US EPA and a 1 in 100,000 lifetime cancer risk.

Additional Comments:

The Integrated Risk Information System (IRIS) is prepared and maintained by the US EPA. IRIS is an electronic database containing information on human health effects that may result from exposure to various chemicals in the environment.

Reference and Supporting Documentation:

US Environmental Protection Agency. Integrated Risk Information System. http://www.epa.gov/iris/ (accessed 22 January 2003).

Agency:

California Environmental Protection Agency (Cal EPA).

Air Quality Guideline:

Acute reference exposure level (REL) = 6 $\mu g/m^3$ [1-hour averaging time for nickel].

Chronic reference exposure level (REL) = 0.05 $\mu g/m^3$ [continuous (daily) exposure over a lifetime for nickel].

Risk specific concentration (RsC) corresponding to 1 in 100,000 risk = 0.04 $\mu g/m^3$ [continuous (daily) exposure over a lifetime for nickel].

Averaging Time To Which Guideline Applies:

See above.

Basis for Development:

The acute and chronic RELs, and an inhalation unit risk factor were all recently adopted by Cal EPA Office of Environmental Health Hazard Assessment (OEHHA).

Acute REL: A LOAEL was identified based on inhalation of 0.3 mg/m^3 $NiSO_4 \cdot 6H_2O$ (67 mg Ni/m^3) for a 30-minute exposure duration to seven volunteer metal plating workers with occupational asthma. A resulting extrapolated 1-hour concentration of 33 $\mu g/m^3$ was adjusted with a cumulative uncertainty factor of 6 (6 for extrapolation of a LOAEL, 1 for interspecies extrapolation, 1 for intraspecies extrapolation) to yield the acute REL of 6 $\mu g/m^3$.

Chronic REL: Based on pathological changes in lung, lymph nodes, and nasal epithelium of rats exposed by discontinuous inhalation during a chronic bioassay. A human equivalent concentration of 1.6 μg Ni/m^3 represented the NOAEL for group male rats and was adjusted with a cumulative uncertainty factor of 30 (3 for interspecies extrapolation, 10 for intraspecies extrapolation) to yield the acute REL of 0.05 $\mu g/m^3$.

RsC: Based on an unit risk factor of 2.6 E-4 per $\mu g/m^3$ calculated from Ontario nickel refinery sinter plant worker lung cancer mortality data.

Date Guideline Developed:

Acute REL: 1999.

Chronic REL: 2000.

RsC: 1999.

How Guideline is Used in Practice:

Acute and chronic RELs are for use in facility health risk assessments conducted for the AB 2588 Air Toxics “Hot Spots” Program.

The risk specific concentration (RsC) is not used for any specific purposes by Cal EPA and is shown here to illustrate an exposure concentration in air associated with an inhalation unit risk factor derived by Cal EPA and a 1 in 100,000 lifetime cancer risk.

Additional Comments:

n/a

Reference and Supporting Documentation:

California Environmental Protection Agency (Cal EPA). 1999. Determination of Acute Reference Exposure Levels for Airborne Toxicants. Office of Environmental Health Hazard Assessment, Air Toxicology and Epidemiology Section, Cal EPA. Oakland, CA. March 1999.

California OEHHA. 1999. Air Toxics Hot Spots Program Risk Assessment Guidelines. Part II. Technical Support Document for Describing Available Cancer Potency Factors OEHHA, California EPA, Sacramento, CA. April 1999.

California Office of Environmental Health Hazard Assessment (OEHHA)/Air Resources Board (ARB). 2001. Approved Chronic Reference Exposure Levels and Target Organs. Table 3 (last updated 13 September 2001). Available at: www.arb.ca.gov/toxics/healthval/chronic.pdf (accessed 22 January 2003).

Agency:

Louisiana Department of Environmental Quality (DEQ).

Air Quality Guideline:

Ambient air standard (AAS) for toxic air pollutants = 0.21 µg/m^3 (for nickel).

0.42 µg/m^3 (for nickel refinery dust).

Averaging Time To Which Guideline Applies:

Annual average.

Basis for Development:

Unknown.

Date Guideline Developed:

Unknown.

How Guideline is Used in Practice:

AASs are used by Louisiana DEQ to review permit applications for stationary sources that emit nickel to the atmosphere.

Additional Comments:

n/a

Reference and Supporting Documentation:

Louisiana Administrative Code (LAC). Title 33 Environmental Quality, Part III Air, Chapter 51. Comprehensive Toxic Air Pollutant Emission Control Program. Louisiana Department of Environmental Quality. Baton Rouge, LA.

Agency: Massachusetts Department of Environmental Protection (DEP).
Air Quality Guideline: Threshold Effects Exposure Limit (TEL) = 0.27 µg/m^3 [24-hour averaging time for nickel]. Allowable Ambient Limit (AAL) = 0.18 µg/m^3 [annual average for nickel].
Averaging Time To Which Guideline Applies: See above.
Basis for Development: TEL: Unknown. AAL: Unknown.
Date Guideline Developed: Unknown.
How Guideline is Used in Practice: Information could not be obtained to identify how the guideline is used in practice, but it is expected that the guideline is used in some manner to meet state level permitting.
Additional Comments: n/a
Reference and Supporting Documentation: Massachusetts Department of Environmental Protection (DEP). 1995. Revised air guidelines [updated list of 24-hour average Threshold Effects Exposure Limit (TEL) values and annual average Allowable Ambient Limit (AAL) values]. Massachusetts DEP, Boston, MA. 6 December 1995. Memorandum available at: http://www.state.ma.us/dep/ors/files/aallist.pdf (accessed 22 January 2003).

Agency:

Michigan Department of Environmental Quality (DEQ).

Air Quality Guideline:

Initial risk screening level (IRSL) = 0.0042 $\mu g/m^3$ (for nickel).
Secondary risk screening level (SRSL) = 0.042 $\mu g/m^3$ (for nickel).

Averaging Time To Which Guideline Applies:

Annual average.

Basis for Development:

The IRSL and SRSL are based on US EPA's inhalation unit risk factor of 2.4E-04 per $\mu g/m^3$ corresponding to 1 in 1,000,000 and 1 in 100,000 risk, respectively.

Date Guideline Developed:

1991.

How Guideline is Used in Practice:

There are two basic requirements of Michigan air toxic rules. First, each source must apply the best available control technology for toxics (T-BACT). After the application of T-BACT, the emissions of the toxic air contaminant cannot result in a maximum ambient concentration that exceeds the applicable health based screening level for non-carcinogenic effects (ITSL). Application of an ITSL is required for any new or modified emission source or sources for which a permit to install is requested and which emits a toxic air contaminant.

Additional Comments:

The applicable air quality screening level for chemical treated as non-carcinogens by Michigan DEQ is the ITSL. There are two health based screening levels for chemical treated as carcinogens by Michigan DEQ: the initial risk screening level (IRSL) – based on an increased cancer risk of one in one million, and the secondary risk screening level (SRSL) – based on as an increased cancer risk of 1 in 100,000.

Reference and Supporting Documentation:

Michigan Administrative Code (MAC). Air Pollution Control Rules. Part 2 Air Use Approval, R 336.1201 - 336.1299. Air Quality Division, Department of Environmental Quality. Lansing, MI.

Agency:

New Hampshire Department of Environmental Services (DES).

Air Quality Guideline:

24-hour ambient air limit (AAL) = 3.57 µg/m^3 (for nickel).

Annual ambient air limit (AAL) = 2.38 µg/m^3 (for nickel).

Averaging Time To Which Guideline Applies:

See above.

Basis for Development:

The AALs were developed in the following manner:

24-hour Ambient Air Limit – The American Conference of Governmental Industrial Hygienists (ACGIH) 8-hour time weighted average occupational exposure limit (OEL) of 1 mg/m^3 for nickel (metal) is divided by a safety factor (SF) of 100 and a time adjustment factor (TAF) of 2.8.

Annual Ambient Air Limit – The American Conference of Governmental Industrial Hygienists (ACGIH) 8-hour time weighted average occupational exposure limit (OEL) of 1 mg/m^3 for nickel (metal) is divided by a safety factor (SF) of 100 and a factor of 4.2.

Date Guideline Developed:

Unknown.

How Guideline is Used in Practice:

AALs are used by New Hampshire DES to review permit applications for sources that emit nickel to the atmosphere. Sources are regulated through a statewide air permitting system and include any new, modified or existing stationary source, area source or device.

Additional Comments:

n/a

Reference and Supporting Documentation:

New Hampshire Administrative Rule. Chapter Env-A 1400. Regulated Toxic Air Pollutants. New Hampshire Department of Environmental Services. Concord, NH.

Agency:

New Jersey Department of Environmental Protection (DEP).

Air Quality Guideline:

Applicants are required to carry out a risk assessment in conjunction with applying for an air pollution control pre-construction permit. In the case of nickel, the US Environmental Protection Agency inhalation unit risk factor of 2.4E-04 per $\mu g/m^3$ (for nickel soluble salts) is used to calculate a lifetime cancer risk for sources that emit nickel to the atmosphere.

Averaging Time To Which Guideline Applies:

Continuous exposure (daily exposure over a lifetime).

Basis for Development:

Based on US EPA Integrated Risk Information System (IRIS) data.

Date Guideline Developed:

December 1994.

How Guideline is Used in Practice:

n/a

Additional Comments:

n/a

Reference and Supporting Documentation:

New Jersey Administrative Code (NJAC). Title 7, Chapter 27, Subchapter 8. Permits and Certificates for Minor Facilities (and Major Facilities without an Operating Permit). New Jersey Department of Environmental Protection. Trenton, NJ.

New Jersey Department of Environmental Protection. 1994. Technical Manual 1003. Guidance on Preparing a Risk Assessment for Air Contaminant Emissions. Air Quality Permitting Program, Bureau of Air Quality Evaluation, New Jersey Department of Environmental Protection. Trenton, NJ. Revised December 1994.

Agency:

North Carolina Department of Environment and Natural Resources (ENR).

Air Quality Guideline:

Acceptable ambient level (AAL) = 0.006 µg/m^3 (for nickel).

Averaging Time To Which Guideline Applies:

24-hour averaging time.

Basis for Development:

Not stated.

Date Guideline Developed:

Unknown.

How Guideline is Used in Practice:

A facility emitting nickel must limit its emissions so that the resulting modeled ambient levels at the property boundary remain below the health-based acceptable ambient level (AAL).

Additional Comments:

n/a

Reference and Supporting Documentation:

North Carolina Administrative Code (NCAC). North Carolina Air Quality Rules 15A NCAC 2D.1100 – Air Pollution Control Requirements (Control of Toxic Air Pollutants). North Carolina Department of Environment and Natural Resources. Raleigh, NC.

North Carolina Administrative Code (NCAC). North Carolina Air Quality Rules 15A NCAC 2Q.0700 – Air Quality Permit Procedures (Toxic Air Pollutant Procedures). North Carolina Department of Environment and Natural Resources. Raleigh, NC.

Agency:

Ohio Environmental Protection Agency (EPA).

Air Quality Guideline:

Maximum acceptable ground-level concentration (MAGLC) = 23.8 µg/m^3 for nickel (proposed).

Averaging Time To Which Guideline Applies:

1-hour averaging time.

Basis for Development:

$$\text{MAGCL} = \frac{\text{TLV}}{10} \text{x} \frac{8\,\text{hr}}{24\,\text{hr}} \text{x} \frac{5\,\text{d}}{7\,\text{d}} = \frac{\text{TLV}}{42}\ .$$

The TLV is the ACGIH 8-hour time weighted average occupational exposure limit (OEL) of 1 mg/m^3 for nickel (metal). The TLV is adjusted by a safety factor of 10 to take into account greater susceptibility of the general population in comparison to healthy workers. The 8/24 and the 5/7 multipliers are used to relate the exposure to longer than 40-hour time periods and ascertain that the individual's total exposure will be no greater than that allowed by the TLV.

Date Guideline Developed:

January 1994 (proposed).

How Guideline is Used in Practice:

Used by Ohio EPA to review permit applications for sources that emit nickel to the atmosphere.

Additional Comments:

n/a

Reference and Supporting Documentation:

Ohio Environmental Protection Agency (EPA). 2003. Review of New Sources of Toxic Emissions. Air Toxics Unit, Division of Air Pollution Control, Ohio EPA. Columbus, OH. 11 pp (available at: http://www.epa.state.oh.us/dapc/atu/atu.html, accessed 22 January 2003).

Ohio Environmental Protection Agency (Ohio EPA). 1994. Review of New Sources of Air Toxic Emissions. Proposed for Public Comment. Division of Air Pollution Control, Ohio EPA. Columbus, OH. January 1994. 31 pp.

Agency:

Oklahoma Department of Environmental Quality (DEQ).

Air Quality Guideline:

Maximum acceptable ambient concentration (MAAC) = 0.15 µg/m^3 (for nickel).

Averaging Time To Which Guideline Applies:

24-hour averaging time.

Basis for Development:

Unknown. However, the MAAC is equivalent to the National Institute for Occupational Safety and Health (NIOSH) relative exposure level (REL) – 10-hour time weighted OEL of 0.015 mg/m^3 divided by a safety factor of 100.

Date Guideline Developed:

Not stated.

How Guideline is Used in Practice:

MAACs are used by Oklahoma DEQ to review permit applications for sources that emit nickel to the atmosphere.

Additional Comments:

n/a

Reference and Supporting Documentation:

Oklahoma Administrative Code (OAC). Title 252. Chapter 100. Air Pollution Control. 100:252-41 - Control of Emission of Hazardous and Toxic Air Contaminants. Oklahoma Department of Environmental Quality. Oklahoma City, OK.

Oklahoma Department of Environmental Quality (DEQ). 2002. Air Toxics Partial Listing [maximum acceptable ambient concentrations (MAAC) for air toxics]. Oklahoma City, OK. Available at: http://www.deq.state.ok.us/AQDNew/toxics/listings/pollutant_query_1.html (accessed 23 January 2003).

Agency: Rhode Island Department of Environmental Management (DEM).
Air Quality Guideline: Acceptable ambient level (AAL) = 0.002 µg/m^3 (for nickel).
Averaging Time To Which Guideline Applies: Annual average.
Basis for Development: Not stated.
Date Guideline Developed: Unknown.
How Guideline is Used in Practice: AALs are used by Rhode Island DEM to review permit applications for sources that emit nickel to the atmosphere.
Additional Comments: n/a
Reference and Supporting Documentation: *Rhode Island Department of Environmental Management. 1992. Air Pollution Control Regulation No. 22. Division of Air and Hazardous Materials, Rhode Island Department of Environmental Management. Providence, RI. Amended 19 November 1992.*

Agency:

Texas Commission on Environmental Quality (CEQ) – formerly Texas Natural Resource Conservation Commission (TRNCC).

Air Quality Guideline:

Short-term effects screening level (ESL) = 0.15 µg/m^3 (for nickel).
Long-term effects screening level (ESL) = 0.015 µg/m^3 (for nickel).

Averaging Time To Which Guideline Applies:

1-hour averaging time for short-term ESL.
Annual averaging time for long-term ESL.

Basis for Development:

Short-term Effects Screening Level – The National Institute for Occupational Safety and Health (NIOSH) relative exposure level (REL) – 10-hour time weighted OEL of 0.015 mg/m^3 is divided by a safety factor of 100.

Long-term Effects Screening Level – The National Institute for Occupational Safety and Health (NIOSH) relative exposure level (REL) – 10-hour time weighted OEL of 0.015 mg/m^3 is divided by a safety factor of 1000.

Date Guideline Developed:

Not stated.

How Guideline is Used in Practice:

ESLs are used to evaluate the potential for effects to occur as a result of exposure to concentrations of constituents in air. ESLs are based on data concerning health effects, odor nuisance potential, effects with respect to vegetation, and corrosion effects. They are not ambient air standards. If predicted or measured airborne levels of a chemical do not exceed the screening level, adverse health or welfare effects would not be expected to result. If ambient levels of constituents in air exceed the screening levels, it does not necessarily indicate a problem, but rather, triggers a more in-depth review.

Additional Comments:

n/a

Reference and Supporting Documentation:

Texas Natural Resource Conservation Commission (TNRCC) 2001. Toxicology & Risk Assessment (TARA) Section Effects Screening Levels.
http://www.tnrcc.state.tx.us/permitting/tox/index.html (accessed 23 January 2003).

Agency: Vermont Agency of Natural Resources (ANR).
Air Quality Guideline: Hazardous ambient air standard (HAAS) = 0.0033 µg/m^3 (for nickel).
Averaging Time To Which Guideline Applies: Annual average.
Basis for Development: Unknown.
Date Guideline Developed: Not stated.
How Guideline is Used in Practice: HAASs are used by Vermont ANR to review permit applications for stationary sources that emit nickel to the atmosphere.
Additional Comments: n/a
Reference and Supporting Documentation: Vermont Air Pollution Control Regulations. 2001. State of Vermont Agency of Natural Resources. Air Pollution Control Division. Waterbury, VT. 29 November 2001. 187 pp.

Agency:

Washington State Department of Ecology (DOE).

Air Quality Guideline:

Acceptable source impact level (ASIL) = 0.0021 µg/m^3. (as nickel subsulphide or nickel refinery dust).

Averaging Time To Which Guideline Applies:

Annual average.

Basis for Development:

Unknown. However, the ASIL is equivalent to 50% of a risk-based concentration that may cause an increased cancer risk of one in one million (10^{-6}) using US EPA's inhalation unit risk factor of 2.4E-04 per µg/m^3. The 50% factor is a common assumption for the mass of dust made up of the metal – in this case nickel.

Date Guideline Developed:

Unknown.

How Guideline is Used in Practice:

ASILs are used by Washington State DOE to review permit applications for sources that emit nickel to the atmosphere.

Additional Comments:

n/a

Reference and Supporting Documentation:

Washington Administrative Code (WAC). Chapter 173-460 WAC. Controls For New Sources Of Toxic Air Pollutants. Washington State Department of Ecology. Olympia, WA.

Agency: Wisconsin Department of Natural Resources (DNR).
Air Quality Guideline: Wisconsin DNR does not have an air quality guideline for nickel.
Averaging Time To Which Guideline Applies: n/a
Basis for Development: n/a
Date Guideline Developed: n/a
How Guideline is Used in Practice: n/a
Additional Comments: n/a
Reference and Supporting Documentation: *Wisconsin Administrative Code (WAC). Air Pollution Control Rules. Chapter NR 445. Control of Hazardous Pollutants. Wisconsin Department of Natural Resources. Madison WI.*

Agency: New Zealand Ministry for the Environment (MOE) and New Zealand Ministry of Health (MOH).
Air Quality Guideline: New Zealand MOE and MOH do not have air quality criteria for nickel.
Averaging Time To Which Guideline Applies: n/a
Basis for Development: n/a
Date Guideline Developed: n/a
How Guideline is Used in Practice: n/a
Additional Comments: n/a
Reference and Supporting Documentation: New Zealand Ministry for the Environment and Ministry of Health (New Zealand). 2000. Proposals for Revised and New Ambient Air Quality Guidelines. Discussion Document. Air Quality Technical Report No 16. Prepared by the Ministry for the Environment and the Ministry of Health. December 2000. 79 pp.

Agency:

The Netherlands National Institute of Public Health and the Environment (RIVM)

Air Quality Guideline:

Tolerable concentration in air (TCA) = 0.05 µg/m^3.

Averaging Time To Which Guideline Applies:

Annual average.

Basis for Development:

The TCA was developed on the basis of a NOAEC (no observed adverse effects concentration) of 30 µg/m^3 for the respiratory system of rats that was equivalent to a continuous exposure of 5 µg/m^3. An extrapolation factor of 100 was used to derive the TCA (100 for intra- and interspecies extrapolation) of 0.05 µg/m^3.

Date Guideline Developed:

2001.

How Guideline is Used in Practice:

TCAs are interventions values used to make decisions regarding air contamination. The TCA represents an air concentration that humans can inhale during their lifetime without resultant adverse health effects.

Additional Comments:

n/a

Reference and Supporting Documentation:

The Netherlands National Institute of Public Health and the Environment (RIVM). 2001. Re-evaluation of human-toxicological maximum permissible risk levels. RIVN Report 711701 025. RIVN, Bilthoven, The Netherlands. March 2001. 297 pp.

Agency: World Health Organization (WHO)
Air Quality Guideline: Risk specific concentration (RsC) corresponding to 1 in 100,000 risk = 0.026 µg/m^3 (for nickel).
Averaging Time To Which Guideline Applies: Annual average.
Basis for Development: The RsC corresponding to 1 in 100,000 risk (risk criteria used in Alberta) was derived using data from information of exposure and risk estimated in industrial populations (WHO, 2000) and a corresponding inhalation unit risk factor of 3.8E-04 per µg/m^3.
Date Guideline Developed: 2000.
How Guideline is Used in Practice: The risk specific concentration (RsC) is not used for any specific purposes by WHO and is shown here to illustrate an exposure concentration in air associated with an inhalation unit risk factor derived by WHO and a 1 in 100,000 lifetime cancer risk.
Additional Comments: n/a
Reference and Supporting Documentation: World Health Organization (WHO). 2000. Air Quality Guidelines for Europe, 2nd Edition. WHO Regional Publications, European Series, No. 91. WHO Regional Office for Europe, Copenhagen. 273 pp

7.1.1 Canada

The Ontario Ministry of the Environment (MOE) adopted an Ambient Air Quality Criterion (AAQC) of 2 μg/m^3 as a 24-hour guideline. Ontario MOE uses a maximum point of impingement (POI) guideline of 5 μg/m^3 based on a 30-minute averaging time to review permit applications for stationary sources that emit nickel to the atmosphere.

7.1.2 United States

The US Agency for Toxic Substances and Disease Registry (ATSDR) adopted a minimal risk level (MRL) of 0.2 μg/m^3. The US EPA used data from multiple epidemiological studies of nickel refinery dust worker exposure to derive an inhalation unit risk factor of 2.4E-04 per μg/m^3. The inhalation unit risk factor is intended for use by US EPA staff in risk assessments, decision-making and regulatory activities.

Three of the US agencies reviewed – those in California, Michigan, and New Jersey – have adopted or derived their annual average values from the US EPA inhalation unit risk factor. Only two state agencies – those in New Hampshire and Ohio – use the ACGIH 8-hour TLV (1 μg/m^3) in development of various ambient guidelines for nickel. Another two state agencies – those in Oklahoma and Texas – use the National Institute for Occupational Safety and Health (NIOSH) relative exposure level (REL) of 0.015 mg/m^3 in development of various ambient guidelines for nickel.

7.1.3 International Agencies

The New Zealand Ministry of Environment and Ministry of Health do not have air quality criteria for nickel. The Netherlands National Institute of Public Health and the Environment (RIVM, 2001) recently adopted a tolerable concentration in air of 0.05 μg/m^3 as an annual average for nickel. The World Health Organization (WHO, 2000) recently adopted an inhalation unit risk factor of 3.8E-04 per μg/m^3 for nickel. A risk specific concentration (RsC) corresponding to 1 in 100,000 risk and this inhalation unit risk is 0.026 μg/m^3. The RsC is not used for any specific purposes by WHO and is shown here to illustrate an exposure concentration in air associated with risk criteria used in Alberta.

8.0 RISK CHARACTERIZATION

Risk characterization of an ambient air contaminant involves the integration and evaluation of several types of key information. Where it is undertaken for a site-specific situation, such as for the screening assessment of proposed industrial emissions of nickel, quantitative approaches can be used. For ambient air exposures, this may involve taking measurements or using a computer dispersion model to estimate ambient ground-level concentrations of nickel under different averaging times and making comparisons to safe levels of exposure (air quality guidelines).

For the general case, however, use of site-specific risk characterization approaches is limited unless a number of assumptions are made. The emission characteristics for sources of nickel release to air in Alberta vary for point sources such as industrial emissions. In addition, meteorological dispersion conditions can vary from site to site. This variability is difficult to represent as a general case for quantitative assessment and the resulting risk characterization would have substantial uncertainty. As a result, a qualitative risk characterization approach is used to evaluate issues associated with nickel in ambient air. The types of key information evaluated can include, but not be limited to:

- relevant chemical forms in air
- pathways by which exposure may occur
- relevant potential effects (impacts)

These issues are discussed further below.

8.1 Relevant Chemical Forms

Nickel releases to the atmosphere are mainly in the form of aerosols that cover a broad spectrum of sizes. Nickel from power plants tends to be associated with smaller particles than those from smelters. Atmospheric aerosols are removed by gravitational settling and dry and wet deposition. The form of nickel emitted to the atmosphere varies according to the type of source. Species associated with combustion, incineration, and metals smelting and refining are often complex nickel oxides, nickel sulphate, metallic nickel, and in more specialized industries, nickel silicate, nickel subsulphide, and nickel chloride.

8.2 Exposure Assessment

In considering the potential for inhalation exposure for humans, background levels of nickel in community ambient air tend to be low. Greater variability in ambient levels of nickel is expected near industrial point sources.

8.3 Toxicity Assessment

The respiratory system is the prime target of nickel inhalation toxicity in both animals and humans. Acute exposure to high concentrations of nickel compounds was reported to be fatal in one man. Chronic nickel inhalation can produce asthma, chronic bronchitis, emphysema, reduced vital capacity, and lung and nasal cancers. Occupational exposure to nickel has been demonstrated to be carcinogenic, causing an increased risk of lung and nasal cancer in exposed workers.

8.4 Characterization of Risk

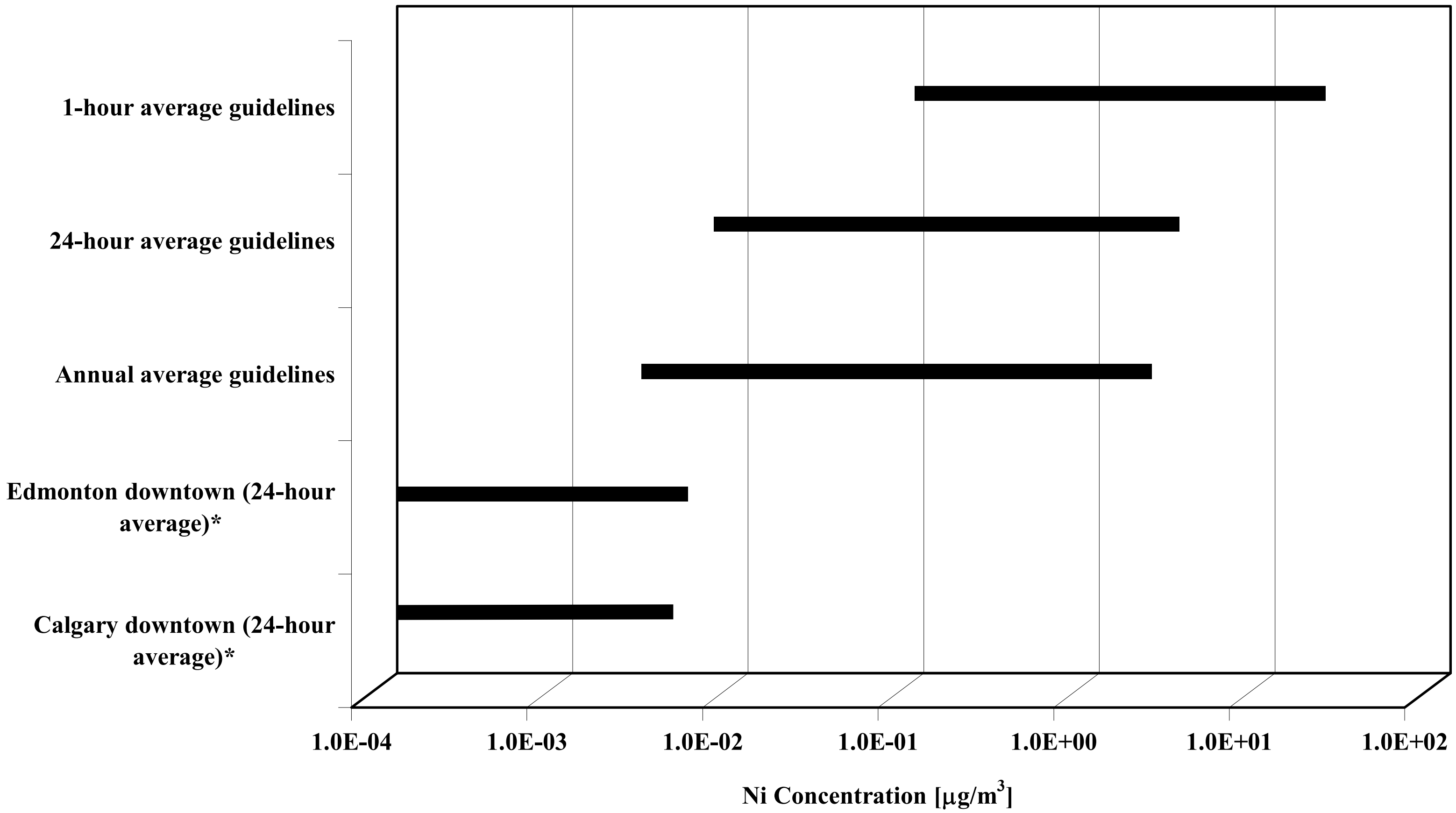
With respect to protection of the general population from inhalation exposure to nickel and other air toxics released from industrial activities, acute (short-term) exposure situations tend only to receive attention from regulatory agencies during the permitting process. An example of this is the use of computer dispersion models to estimate ambient ground-level concentrations of air toxics emitted from an industry under short-term (e.g. hourly) averaging times and making comparisons to air quality criteria with similar averaging times to meet agency permitting requirements. The occurrences of elevated levels of air toxics in the environment are in general, short-term and probably a result of stagnant meteorological conditions (poor dispersion of air) or accidental releases from industry.

However, a common approach used by regulatory agencies to protect the general population from exposure to potentially toxic chemicals in the environment is through the development and use of media guidelines for chronic (long-term) exposure conditions. For example, this is evident in Canada with how potentially toxic chemicals are addressed in the Guidelines for Canadian Drinking Water Quality for drinking water protection (Health Canada, 2001) and Canadian Environmental Quality Guidelines for soil quality protection (CCME, 1999).

With respect to chronic (long-term) exposure conditions, respiratory effects and the increased risk of lung and nasal cancer represent a health effects endpoint of interest to regulatory agencies. The ability for low ambient levels of inorganic nickel (i.e. $<<1\ \mu g/m^3$) to contribute to these effects in the general population is uncertain. As a result some regulatory agencies adopt air quality guidelines for nickel in order to protect humans.

The range of air quality guidelines proposed by various agencies for protection of human receptors is shown in Figure 1 for different averaging time periods. The data presented in Figure 1 were summarized from the previous section. Also show in this Figure is the range between the median and maximum 24-hour average concentration of nickel in respirable particulate matter ($PM_{2.5}$) from air samples collected in central Edmonton and central Calgary from June 1991 to November 2000 (after AENV, 2003).

Urban settings – in which most air quality data are available for – are settings with higher metal concentrations in ambient air compared to rural settings (WHO, 2000). Figure 1 illustrates that the range between the median and maximum 24-hour average concentration of nickel in $PM_{2.5}$ is on the low side and/or below air quality guidelines for protection of human receptors (irrespective of averaging time).



* Range between the median and maximum 24-hour average concentration of nickel in airborne PM2.5

Figure 1 Range of Air Quality Guidelines for Nickel Proposed by Various Agencies for Protection of Human Receptors

9.0 REFERENCES

Agency for Toxic Substances and Disease Registry (ATSDR). 2003. Minimal Risk Levels (MRLs) for Hazardous Substances. ATSDR, Public Health Service, US Department of Health and Human Services. Atlanta, GA. Available at: http://www.atsdr.cdc.gov/mrls.html (accessed 22 January 2003).

ATSDR. 1997. *Toxicological Profile for Nickel*. Available at http://www.atsdr.cdc.gov/toxprofiles/tp15.html

Airmetrics. 1998. *MiniVol Portable Air Sampler Operation Manual*. Airmetrics, Springfield, OR, USA. February 1998. 119 pp.

Alberta Environment (AENV). 2000. Alberta Ambient Air Quality Guidelines. Environmental Sciences Division, Alberta Environment. Edmonton, AB. February 2000. 3 pp.

Alberta Environment (AENV). 2003. Air Monitoring – Northwest Edmonton. June 2001 to March 2002. Intermin Report. Alberta Environment, Edmonton, AB. 22 pp. Available at: http://www3.gov.ab.ca/env/air.html (accessed February 26, 2003).

Alberta Health. 1997. *The Alberta Oil Sands Community Exposure and Health Effects Assessment Program*. Health Surveillance, Alberta Health, Edmonton, Alberta. July 1997. 37 pp.

Anderson, J.R., F.J. Aggett, P.R. Buseck, M.S. Germani, and T.W. Shattuck. 1988. Chemistry of Individual Aerosol Particles from Chandler, Arizona, an Arid Urban Environment. *Env. Sci. Tech.* 22: 811-819.

ARPEL. 1998. *Methods for Monitoring Air Quality*. Report # ARPELCIDA02AEREP0198. Asocicion Regional De Empresas De Petroleo Y Gas Natural En Latinoamaerica Y El Caribe, Montevideo, Uruguay. December 1998.

ATSDR (Agency for Toxic Substances and Disease Registry). 1997. *Toxicological Profile for Nickel*. www.atsdr.cdc.gov/toxprofiles/tp15.html

Baedecker, P. A., E.O. Edney, P.J. Moran, T.C. Simpson, and R.S. Williams. 1991. Effects of acidic deposition on materials. In: Irving, P. M., ed. Acidic Deposition: State of Science and Technology, Volume III: Terrestrial, Materials, Health and Visibility Effects. State of Science and Technology Report No. 19. U.S. National Acid Precipitation Assessment Program, Washington, DC.

Beceiro-Gonzalez, E., J.M. Andrade-Garda, E. Serrano-Velasco, and P. Lopez-Mahia. 1997. Metals in Airborne Particulate Matter in La Coruna (NW Spain*). Sci. Total Env.* 196: 131-139.

Broekaert, J.A.C., B. Wopenka, and H. Puxbaum. 1982. Inductively Coupled Plasma Optical Emission Spectrometry for the Analysis of Aerosol Samples Collected by Cascade Impactor. *Anal. Chem.* 54: 2174-2179.

California Environmental Protection Agency (Cal EPA). 1999. Determination of Acute Reference Exposure Levels for Airborne Toxicants. Office of Environmental Health Hazard Assessment, Air Toxicology and Epidemiology Section, Cal EPA. Oakland, CA. March 1999.

California OEHHA/Air Resources Board (ARB). 2001. Approved Chronic Reference Exposure Levels and Target Organs. Table 3 (last updated 13 September 2001). Available at: www.arb.ca.gov/toxics/healthval/chronic.pdf (accessed 22 January 2003).

California Office of Environmental Health Hazard Assessment (OEHHA). 1999. Air Toxics Hot Spots Program Risk Assessment Guidelines. Part II. Technical Support Document for Describing Available Cancer Potency Factors OEHHA, California EPA, Sacramento, CA. April 1999.

Canadian Council of Ministers of the Environment (CCME). 1999. Canadian Environmental Quality Guidelines. CCME Publications, Winnipeg, MB.

Canadian Environmental Protection Act (CEPA). 1994. *Nickel and its Compounds.* Priority Substances List Assessment Report. Environmetnal Canada, Health Canada.

Casuccio, G.S. and P.B. Janocko. 1981. *Quantifying Blast Furnace Cast House Contributions to TSP Using a Unique Receptor Model*. Paper No. 81.64.2. Air Pollution Control Association, Pittsburgh, PA. 16 pp.

Dzubay, T.G. 1977. *X-Ray Fluorescence Analysis of Environmental Samples*. Ann Arbor Science Publishers, Ann Arbor, MI., 310 pp.

Dzubay, T.G. and R.K. Stevens. 1975. Ambient Air Analysis with Dichotomous Sampler and X-Ray Fluorescence Spectrometer. *Env. Sci. Tech.* 9: 663-668.

Dzubay, T.G. and Y. Mamane. 1989. Use of Electron Microscopy Data in Receptor Models for PM_{10}. *Atmos. Env.* 23(2): 467-476.

Dzubay, T.G., R.K. Stevens, G.E. Gordon, I. Olmez, A.E. Sheffield, and W.J. Courtney. 1988. A Composite Receptor Method Applied to Philadelphia Aerosol. *Env. Sci. Tech.* 22: 46-52.

European Communities. 2001. *Ambient Air Pollution by As, Cd and Ni Compounds: Position Paper*, Office for Official Publications of the European Communities, Luxembourg, ISBN: 92-894-2054-5.

Flores, J.M., F. Aldape, R.V. Diaz, B. Hernandez-Mendez, and R.G. Garcia. 1999. PIXE Analysis of Airborne Particulate Matter from Xalostoc, Mexico: Winter to Summer Comparison. *Nuclear Instruments and Methods in Physics Research B* 150: 445-449.

Gallo, M.A. 1996. History and Scope of Toxicology. In: Klaasen, C.D., M.O. Amdur and J. Doull (eds). *Casarett and Doull's Toxicology. The Basic Science of Poisons*. McGraw-Hill Health Professions Division, Toronto, ON. 5th ed. pp 3-12.

Genium Publishing Corporation (Genium). 1999. Genium's Handbook of Safety, Heakth and Environmental Data for Common Hazardous Substances, McGraw Hill, New York, New York.

Gladney, E.S., W.H. Zoller, A.G. Jones, and G.E. Gordon. 1974. Composition and Size Distribution of Atmospheric Particulate Matter in the Boston Area. *Env. Sci. Tech.* 8: 551-557.

Glover, D.M., P.K. Hopke, S.J. Vermette, S. Landsberger, and D.R. D'Auben. 1991. Source Apportionment with Site Specific Source Profiles. *J. AWMA* 41: 294-305.

Gordon, G.E., W.R. Pierson, J.M. Daisey, P.J. Lioy, J.A. Cooper, J.G. Watson, and G.R. Cass. 1984. Considerations for Design of Source Apportionment Studies. *Atmos. Env.* 18(8): 1567-1584.

Goyer, R.A.. 1996. Toxic Effects of Metals. In: Klaasen, C.D., M.O. Amdur and J. Doull (eds). *Casarett and Doull's Toxicology. The Basic Science of Poisons.* McGraw-Hill Health Professions Division, Toronto. 5th ed. pp 691-736.

Hamilton, R.S., P.R. Kershaw, F. Segarra, C.J. Spears, and J.M. Watt. 1995. Detection of Airborne Carbonaceous Particulate Matter by Scanning Electron Microscopy. *Sci. Total Env.* 146/147: 303-308.

Haynie, F. H. 1986. Environmental factors affecting corrosion of weathering steel. In: Baboian, R., ed. Materials Degradation Caused by Acid Rain: Developed from the 20th State-of-the-Art Symposium of the American Chemical Society, Arlington, VA, June 1985. ACS Symposium Series 318, American Chemical Society, Washington, DC. pp. 163-171.

Haynie, F. H. and T.J. Lemmons. 1990. Particulate matter soiling of exterior paints at a rural site. *Aerosol Sci. Technol*. 13: 356-367.

Health Canada. 2001. Guidelines for Canadian Drinking Water Quality. Prepared by Federal-Provincial/Territorial Subcommittee on Drinking Water of the Federal-Provincial/Territorial Committee of Environmental and Occupational Health. Ottawa, ON. March 2001.

Heidam, N.Z. 1981. On the Origin of the Arctic Aerosol: A Statistical Approach. *Atmos. Env.* 16: 1421-1427.

Hopke, P.K., E.S. Gladney, G.E. Gordon, W.H. Zoller, and A.G. Jones. 1976. The Use of Multivariate Analysis to Identify Sources of Selected Elements in the Boston Urban Aerosol. *Atmos. Env.* 10: 1015-1025.

IRIS (Integrated Risk Information System). 1991. Nickel Refinery Dust (No CASRN).

International Programme on Chemical Safety (IPCS). 1988. *Environmental Health Criteria 108: Nickel*, Published under the Joint Sponsorship of the United Nations Environmental Programme, the International Labour Organisation, and the World Health Organisation (WHO), available at: http://www.inchem.org/documents/ehc/ehc/ehc108.htm (accessed on February 15, 2003).

Jassen, N.A.H., D.F.M. Van Mansom, K. Van Der Jagt, H. Harssema, and G. Hoek. 1997. Mass Concentration and Elemental Composition of Airborne Particulate Matter at Street and Background Locations. *Atmos. Env.* 31(8): 1185-1193.

Jones, K., N. Berg, S. Sleva, and S. Murchie. 1998. *EPA Saturation Monitor Repository*. 98-TA31A.04. U.S. Environmental Protection Agency, Monitoring and Quality Assurance Group, Research Triangle Park, NC, USA. 17 pp.

Koutrakis, P. 1998. *Recommendations of the Expert Panel on the EPA* $PM_{2.5}$ *Chemical Speciation Network*. Speciation Expert Panel, Seattle, WA, May 12-13, 1998. 15 pp.

Koutrakis, P. and C. Sioutas. 1996. Physico-Chemical Properties and Measurement of Ambient Particles. In: Particles in our Air: Concentrations and Health Effects. Spengler, J. and R. Wilson (eds.). Cambridge, MA, USA, pp. 15-39.

Kowalczyk, G.S., C.E. Choquette, and G.E. Gordon. 1978. Chemical Element Balances and Identification of Air Pollution Sources in Washington, D.C. *Atmos. Env.* 12: 1143-1153.

Kowalczyk, G.S., G.E. Gordon, and S.W. Rheingrover. 1982. Identification of Atmospheric Particulate Sources in Washington, D.C. Using Chemical Element Balances. *Env. Sci. Tech.* 16: 79-90.

Lewis, C.W. and E.S. Macias. 1980. Composition of Size-Fractionated Aerosol in Charleston, West Virginia. *Atmos. Env.* 14: 185-194.

Lide, D.R. (ed.). 2002. *CRC Handbook of Chemistry and Physics, 83rd Edition*. CRC Press, Boca Raton, FL.

Linton, R.W., D.F.S. Natusch, R.L. Solomon, and C.A. Evans Jr. 1980. Physiochemical Characterization of Lead in Urban Dusts. A Microanalytical Approach to Lead Tracing. *Env. Sci. Tech. Research* 14(2): 159-164.

Louisiana Administrative Code (LAC). Title 33 Environmental Quality, Part III Air, Chapter 51. Comprehensive Toxic Air Pollutant Emission Control Program. Louisiana Department of Environmental Quality. Baton Rouge, LA.

Massachusetts Department of Environmental Protection (DEP). 1995. Revised air guidelines [updated list of 24-hour average Threshold Effects Exposure Limit (TEL) values and annual average Allowable Ambient Limit (AAL) values]. Massachusetts DEP, Boston, MA. 6 December 1995. Memorandum available at: http://www.state.ma.us/dep/ors/files/aallist.pdf (accessed 22 January 2003).

Michigan Administrative Code (MAC). Air Pollution Control Rules. Part 2 Air Use Approval, R 336.1201 - 336.1299. Air Quality Division, Department of Environmental Quality. Lansing, MI.

Mizohata, A. and T. Mamuro. 1979. Chemical Element Balances in Aerosols Over Sakai, Osaka. *Annual Report of the Radiation Centre of Osaka Prefecture* 20: 55-69.

National Institute for Occupational Safety and Health (NIOSH). 1994. *NIOSH Manual of Sampling and Analytical Methods – 4th Edition, Issue 2, Elements by ICP - Method 7300.* US Department of Health, Education, and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Physical Sciences and Engineering, Cincinnati, OH, August 1994.

New Hampshire Administrative Rule. Chapter Env-A 1400. Regulated Toxic Air Pollutants. New Hampshire Department of Environmental Services. Concord, NH.

New Jersey Administrative Code (NJAC). Title 7, Chapter 27, Subchapter 8. Permits and Certificates for Minor Facilities (and Major Facilities without an Operating Permit). New Jersey Department of Environmental Protection. Trenton, NJ.

New Jersey Department of Environmental Protection. 1994. Technical Manual 1003. Guidance on Preparing a Risk Assessment for Air Contaminant Emissions. Air Quality Permitting Program, Bureau of Air Quality Evaluation, New Jersey Department of Environmental Protection. Trenton, NJ. Revised December 1994.

New Zealand Ministry for the Environment and Ministry of Health (New Zealand). 2000. Proposals for Revised and New Ambient Air Quality Guidelines. Discussion Document. Air Quality Technical Report No 16. Prepared by the Ministry for the Environment and the Ministry of Health. December 2000. 79 pp.

North Carolina Administrative Code (NCAC). North Carolina Air Quality Rules 15A NCAC 2D.1100 – Air Pollution Control Requirements (Control of Toxic Air Pollutants). North Carolina Department of Environment and Natural Resources. Raleigh, NC.

North Carolina Administrative Code (NCAC). North Carolina Air Quality Rules 15A NCAC 2Q.0700 – Air Quality Permit Procedures (Toxic Air Pollutant Procedures). North Carolina Department of Environment and Natural Resources. Raleigh, NC.

Occupational Safety and Health Administration (OSHA). 2002a. *OSHA Sampling and Analytical Methods, Metal and Metalloid Particulates (Atomic Absorption) – Method ID 121*. Inorganic Methods Evaluation Branch, Occupational Safety and Health Administration, US Department of Labor, OSHA Salt Lake Technical Center, Salt Lake City, UT. February 2002.

Occupational Safety and Health Administration (OSHA). 2002b. *OSHA Sampling and Analytical Methods, Metal and Metalloid Particulates (ICP) – Method ID 125G*. Inorganic Methods Evaluation Branch, Occupational Safety and Health Administration, US Department of Labor, OSHA Salt Lake Technical Center, Salt Lake City, UT. September 2002.

Ohio Environmental Protection Agency (EPA). 2003. Review of New Sources of Toxic Emissions. Air Toxics Unit, Division of Air Pollution Control, Ohio EPA. Columbus, OH. 11 pp (available at: http://www.epa.state.oh.us/dapc/atu/atu.html, accessed 22 January 2003).

Ohio Environmental Protection Agency (Ohio EPA). 1994. Review of New Sources of Air Toxic Emissions. Proposed for Public Comment. Division of Air Pollution Control, Ohio EPA. Columbus, OH. January 1994. 31 pp.

Oklahoma Administrative Code (OAC). Title 252. Chapter 100. Air Pollution Control. 100:252-41 - Control of Emission of Hazardous and Toxic Air Contaminants. Oklahoma Department of Environmental Quality. Oklahoma City, OK.

Oklahoma Department of Environmental Quality (DEQ). 2002. Air Toxics Partial Listing [maximum acceptable ambient concentrations (MAAC) for air toxics]. Oklahoma City, OK. Available at: http://www.deq.state.ok.us/AQDNew/toxics/listings/pollutant_query_1.html (accessed 23 January 2003).

Olmez, I.. 1989. Instrumental Neutron Activation Analysis of Atmospheric Particulate Matter. In: Methods of Air Sampling and Analysis, 3rd Edition. Lodge Jr., J.P. (ed.), Lewis Publishers, Chelsea, MI, pp. 143-150.

Ontario Ministry of the Environment (MOE). 1999. Summary of Point Of Impingement Standards, Point Of Impingement Guidelines, and Ambient Air Quality Criteria (AAQC). Standards Development Branch, Ontario Ministry of the Environment, Toronto, ON. November 1999. 12 pp.

Post, J.E. and P.R. Buseck. 1984. Characterization of Individual particles in the Phoenix Urban Aerosol Using Electron Beam Instruments. *Env. Sci. Tech.* 18: 35-42.

Price, J.H., V.C. Anselmo, S.L. Dantter, J.M. Jenks, and S. Mgebroff. 1982. *Cost Effective Measurement of Elemental Concentrations in Aerosol in Texas by X-Ray Fluorescence Analysis*. Paper No. 82-39.5. Air Pollution Control Association, Pittsburgh, PA, 16 pp.

Rhode Island Department of Environmental Management. 1992. Air Pollution Control Regulation No. 22. Division of Air and Hazardous Materials, Rhode Island Department of Environmental Management. Providence, RI. Amended 19 November 1992.

RIVM (Rijksinstituut Voor Volksgezondheid en Milieu). 2001. *Re-Evaluation of Human-Toxicological Maximum Permissible Risk Levels.* Baars, A.J., R.M. Theelen, P.J. Janssen, J.M. Hesse, M.E. van Apeldoorn, M.C. Meijerink, L. Verdam and M.J. Zeilmaker. National Institute of Public Health and the Environment. The Netherlands, RIVM Report 711701 025. www.rivm.nl

Rizzio, E., G. Giaveri, and M. Gallorini. 2000. Some Analytical Problems Encountered for Trace Elements Determination in the Airborne Particulate Matter of Urban and Rural Areas. *Sci. Total Env.* 256: 11-22.

Rizzio, E., G. Giaveri, D. Arginelli, L. Gini, A. Profumo, and M. Gallorini. 1999. Trace Elements Total Content and Particle Sizes Distribution in the Air Particulate Matter of a Rural-Residential Area in North Italy Investigated by Instrumental Neutron Activation Analysis. *Sci. Total Env.* 226: 47-56.

Rojas, C.M., P. Artaxo, and R. Van Grieken. 1990. Aerosols in Santiago De Chile: a Study Using Receptor Modeling with X-Ray Fluorescence and Single Particle Analysis. *Atmos. Env.* 24B: 227-241.

Royal Society of Chemistry (RSC). 1999. *Dictionary of Substances and Their Effects Database*. Royal Society of Chemistry, Cambridge, UK, on-line database.

Salma, I. and E. Zemplen-Papp. 1999. Instrumental Neutron Activation Analysis for Studying Size-Fractionated Aerosols. *Nuclear Instruments and Methods in Physics Research A* 435: 462-474.

Saucy, D.A., J.R. Anderson, and P.R. Buseck. 1987. Cluster Analysis Applied to Atmospheric Aerosol Samples from the Norwegian Arctic. *Atmos. Env.* 21: 1649-1657.

Schmeling, M., R. Klockenkamper, and D. Klockow. 1997. Application of Total-Reflection X-Ray Fluorescence Spectrometry to the Analysis of Airborne Particulate Matter. *Spectrochimica Acta Part B* 52: 985-994.

Schwar, M. J. R. 1998. Nuisance dust deposition and soiling rate measurements. *Environ. Technol*. 19: 223-229.

Shaw, G.E. 1983. X-Ray Spectrometry of Polar Aerosols. *Atmos. Env.* 17(2): 329-339.

Texas Natural Resource Conservation Commission (TNRCC). 2001. Toxicology & Risk Assessment (TARA) Section Effects Screening Levels. http://www.tnrcc.state.tx.us/permitting/tox/index.html (accessed 23 January 2003).

The Netherlands National Institute of Public Health and the Environment (RIVM). 2001. Re-evaluation of human-toxicological maximum permissible risk levels. RIVN Report 711701 025. RIVN, Bilthoven, The Netherlands. March 2001. 297 pp.

Tropp, R.J., K. Jones, G. Kuhn, and N.J. Berg. 1998. *Comparison of* $PM_{2.5}$ *Saturation Samplers with Prototype* $PM_{2.5}$ *Federal Reference Method Samplers*. Presented at the Air and Waste Management Association Speciality Conference on $PM_{2.5}$: A Fine Particle Standard. Long Beach, CA, USA, January 1998.

U.S. EPA (U.S. Environmental Protection Agency). 1994. *Guidelines for* PM_{10} *Sampling and Analysis Applicable to Receptor Modelling*. Office of Air and Radiation and Office of Air Quality Planning and Standards, Research Triangle Park, N.C., March 1994, EPA Report No. EPA/452/R-94/009.

U.S. EPA (U.S. Environmental Protection Agency). 1999a. *Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air*. Office of Research and Development, Washington, D.C., June 1999, EPA Report No. EPA/625/R-96/010a.

U.S. EPA (U.S. Environmental Protection Agency). 1999b. *Particulate Matter* ($PM_{2.5}$) *Speciation Guidance – Final Draft, Edition 1*. Monitoring and Quality Assurance Group, Emissions, Monitoring, and Analysis Division. Office of Air Quality Planning and Standards, Research Triangle Park, N.C., October 7, 1999.

US Environmental Protection Agency (EPA). 2003. Integrated Risk Information System. http://www.epa.gov/iris/ (accessed 22 January 2003).

Van Borm, W.A., F.C. Adams, and W. Maenhaut. 1989. Characterization of Individual Particles in the Antwerp Aerosol. *Atmos. Env.* 23: 1130-1151.

Van Borm, W.A., F.C. Adams, and W. Maenhaut. 1990. Receptor Modelling of the Antwerp Aerosol. *Atmos. Env.* 24B: 419-434.

Vermont Air Pollution Control Regulations. 2001. State of Vermont Agency of Natural Resources. Air Pollution Control Division. Waterbury, VT. 29 November 2001. 187 pp.

Washington Administrative Code (WAC). Chapter 173-460 WAC. Controls For New Sources Of Toxic Air Pollutants. Washington State Department of Ecology. Olympia, WA.

WBK & Associates Inc. (WBK). 2003. Assessment Report on Developing Ambient Air Quality Guidelines for Metals in Alberta: Identification and Prioritization of Candidate Metals. Report prepared for Alberta Environment, Edmonton, AB. March 2003. 32 pp.

Wisconsin Administrative Code (WAC). Air Pollution Control Rules. Chapter NR 445. Control of Hazardous Pollutants. Wisconsin Department of Natural Resources. Madison WI.

World Health Organization (WHO). 2000. Air Quality Guidelines for Europe, 2nd Edition. WHO Regional Publications, European Series, No. 91. WHO Regional Office for Europe, Copenhagen. 273 pp.

Xhoffer, C., P. Bernard, R. Van Grieken, and L. Van der Auwera. 1991. Chemical Characterization and Source Apportionment of Individual Aerosol Particles Over the North Sea and the English Channel Using Multivariate Techniques. *Env. Sci. Tech.* 25: 1470-1478.

Zoller, W.H. and G.E. Gordon. 1970. Instrumental Activation Analysis of Atmospheric Pollutants Utilizing Ge (Li) X-Ray Detectors. *Anal. Chem.* 42: 257-265.

APPENDIX A

Table A-1 Emissions of Nickel and its Compounds According to NPRI (NPRI, 2002)

NPRI ID	Company	City	Province	Emissions of Nickel and Its Compounds (tonnes)				
				Air	Water	Land	Underground	Total
1465	Inco Limited	Copper Cliff	ON	1.237	194.558	0.000	0.000	195.795
2537	Safety-Kleen Ltd.	Corunna	ON	0.120	0.000	73.000	0.000	73.120
0444	Inco Limited	Copper Cliff	ON	64.187	0.000	0.000	0.000	64.187
4000	Nova Scotia Power Inc.	Point Aconi	NS	0.000	0.000	46.400	0.000	46.400
1861	Ontario Power Generation Inc	Nanticoke	ON	0.925	0.000	45.471	0.000	46.396
1809	Ontario Power Generation Inc	Courtright	ON	0.261	0.010	42.473	0.000	42.744
3992	Nova Scotia Power Inc.	New Waterford	NS	0.000	0.000	36.500	0.000	36.500
1696	New Brunswick Power	Saint John	NB	15.309	0.028	20.526	0.000	35.863
3704	Imperial Oil	Sarnia	ON	30.334	0.000	0.000	0.000	30.334
4882	Newfoundland and Labrador Hydro	Holyrood	NL	22.300	0.000	4.000	0.000	26.300
2284	TransAlta Corporation	Duffield	AB	0.389	0.000	21.170	0.000	21.559
1471	Inco Limited	Port Colborne	ON	0.566	0.550	13.173	0.000	14.289
4316	North Atlantic Refining Ltd.	Come by Chance	NL	13.800	0.000	0.000	0.000	13.800
1036	Sheerness Generating Station	Hanna	AB	0.000	0.000	12.581	0.000	12.581
1467	Inco Limited	Walden	ON	12.420	0.000	0.000	0.000	12.420
1236	Falconbridge Limited	Falconbridge	ON	11.028	0.770	0.012	0.000	11.810
1712	New Brunswick Power	Dalhousie	NB	7.900	0.105	0.000	0.000	8.005
3962	Shell Canada Products	Corunna	ON	6.971	0.000	0.105	0.000	7.076
1233	Falconbridge limited	Onaping	ON	0.556	2.582	0.000	0.000	3.138
3623	Noranda Inc	Rouyn-Noranda	QC	1.710	0.392	0.000	0.000	2.102
2230	Suncor Energy Inc.	Fort McMurray	AB	1.277	0.628	0.000	0.000	1.905
3897	Petro-Canada	Montreal	QC	1.474	0.034	0.000	0.000	1.508
4327	Métachimie Canada Ltee	Granby	QC	0.000	0.000	1.500	0.000	1.500
2274	Syncrude Canada Ltd.	Fort McMurray	AB	1.298	0.000	0.000	0.000	1.298
1944	Bayer Inc.	Sarnia	ON	0.006	0.000	1.260	0.000	1.266

Table A-1 Emissions of Nickel and its Compounds According to NPRI (NPRI, 2002) (continued)

NPRI ID	Company	City	Province	Emissions of Nickel and Its Compounds (tonnes)				
				Air	Water	Land	Underground	Total
3385	NORANDA INC.	Murdochville	QC	0.820	0.321	0.000	0.000	1.141
1656	Motor Coach Industries Limited	Winnipeg	MB	1.050	0.000	0.000	0.000	1.050
3158	Slater Stainless Corp.	Welland	ON	0.819	0.050	0.000	0.000	0.869
1106	AltaSteel Ltd.	Edmonton	AB	0.406	0.001	0.432	0.000	0.839
5848	Turbomachinery Products	Mississauga	ON	0.664	0.000	0.000	0.000	0.664
2815	Falconbridge Ltd-Kidd Metallurgical Div.	Timmins/District of Cochrane	ON	0.278	0.231	0.000	0.000	0.509
1469	Inco Limited	Copper Cliff	ON	0.500	0.000	0.000	0.000	0.500
2984	Stelco Inc.	Hamilton	ON	0.000	0.000	0.000	0.000	0.483
3953	Slater Stainless Corp.	Sorel-Tracy	QC	0.310	0.170	0.000	0.000	0.480
0267	Edmonton Power Inc.	Warburg	AB	0.468	0.000	0.000	0.000	0.468
7154	Deloro Stellite Inc.	Belleville	ON	0.426	0.000	0.000	0.000	0.426
5448	Falconbridge Limité	Rouyn-Noranda	QC	0.100	0.280	0.000	0.000	0.380
7041	Bruce Power Limited Partnership	Municipality of Kincardine	ON	0.360	0.000	0.000	0.000	0.360
3901	Petro-Canada	Oakville	ON	0.339	0.000	0.007	0.000	0.346
1785	NOVA Chemicals (Canada) Ltd.	Sarnia	ON	0.000	0.000	0.000	0.000	0.334
4101	Irving Oil Limited	Saint John	NB	0.325	0.000	0.000	0.000	0.325
1547	Metal Technologies-Woodstock Ltd.	Woodstock	ON	0.308	0.000	0.000	0.000	0.308
3197	Williams Operating Corporation	Marathon	ON	0.057	0.196	0.000	0.000	0.253
2548	Miramar Con Mine Ltd.	Yellowknife	NT	0.000	0.232	0.000	0.000	0.232
1400	Newmont Canada Limited	Marathon	ON	0.004	0.200	0.000	0.000	0.204
1653	Motor Coach Industries	Winnipeg	MB	0.000	0.000	0.000	0.000	0.200
5721	Reko International Group Inc.	Oldcastle	ON	0.000	0.000	0.200	0.000	0.200
4650	Criterion Catalysts & Technologies Canada Inc.	Medicine Hat	AB	0.196	0.000	0.000	0.000	0.196

Table A-1 Emissions of Nickel and its Compounds According to NPRI (NPRI, 2002) (continued)

NPRI ID	Company	City	Province	Emissions of Nickel and Its Compounds (tonnes)				
				Air	Water	Land	Underground	Total
3120	A.G.Simpson Co Ltd.	Oshawa	ON	0.190	0.000	0.000	0.000	0.190
0280	Dow Chemical Canada Incorporated	Fort Saskatchewan	AB	0.000	0.000	0.186	0.000	0.186
3916	Noranda inc.	Montréal-Est	QC	0.167	0.000	0.000	0.000	0.167
4874	Agrium Products Inc.	Fort Saskatchewan	AB	0.000	0.000	0.000	0.150	0.150
7001	Robertson Building Systems Ltd	Hamilton	ON	0.147	0.000	0.000	0.000	0.147
1568	Kinross Gold Corporation	Kirkland Lake	ON	0.000	0.145	0.000	0.000	0.145
5761	Johnson Matthey Limited	St. Catharines	ON	0.000	0.000	0.000	0.000	0.123
1143	Cambior Inc	Amos	QC	0.000	0.119	0.000	0.000	0.119
3855	Lake Erie Steel Company	Nanticoke	ON	0.109	0.007	0.000	0.000	0.116
4819	Norcast Castings company	Mont-Joli	QC	0.099	0.015	0.000	0.000	0.114
0870	Q3 Aluminum Technologies Inc.	Long-Sault	ON	0.100	0.000	0.000	0.000	0.100
3949	Karmax Heavy Stamping	Milton	ON	0.000	0.000	0.100	0.000	0.100
5293	All Brite Metal Finishing Ltd.	Edmonton	AB	0.000	0.000	0.000	0.000	0.093
3713	Dofasco Inc.	Hamilton	ON	0.088	0.000	0.000	0.000	0.088
5253	Cutler-Hammer	Airdrie	AB	0.080	0.000	0.000	0.000	0.080
5400	Ressources Breakwater	Cléricy	QC	0.000	0.080	0.000	0.000	0.080
0455	Ingot Metal Company Limited	Weston	ON	0.000	0.000	0.000	0.000	0.070
7108	Columbus McKinnon Limited	Cobourg	ON	0.070	0.000	0.000	0.000	0.070
1520	Ivaco Rolling Mills Limited Partnership	L'Orignal	ON	0.000	0.000	0.000	0.000	0.065
2496	Amcan Castings Limited	Hamilton	ON	0.000	0.000	0.000	0.000	0.062
2312	Tuyaux Wolverine (Canada) inc.	Montréal-Est	QC	0.060	0.000	0.000	0.000	0.060
2161	Slater Steels Inc.	Hamilton	ON	0.049	0.000	0.000	0.000	0.049
3824	Co-Steel Lasco	Whitby	ON	0.005	0.043	0.000	0.000	0.048
7150	Techform Products Limited	Penetanguishene	ON	0.000	0.000	0.000	0.000	0.047
5474	Lafarge Canada inc.	Saint-Constant	QC	0.043	0.000	0.000	0.000	0.043

Table A-1 Emissions of Nickel and its Compounds According to NPRI (NPRI, 2002) (continued)

NPRI ID	Company	City	Province	Emissions of Nickel and Its Compounds (tonnes)				
				Air	Water	Land	Underground	Total
0701	Kubota Metal Corporation	Orillia	ON	0.041	0.000	0.000	0.000	0.041
2844	Ontario Power Generation Inc.	Mississauga	ON	0.040	0.001	0.000	0.000	0.041
2595	Toral Cast	Concord	ON	0.000	0.000	0.000	0.000	0.040
4756	Long Manufacturing Ltd.	Oakville	ON	0.038	0.000	0.000	0.000	0.038
1698	New Brunswick Power	Belledune	NB	0.012	0.025	0.000	0.000	0.037
5600	Babcock & Wilcox Canada	Cambridge	ON	0.000	0.000	0.000	0.000	0.037
0057	Bombardier Transport	La Pocatière	QC	0.034	0.000	0.000	0.000	0.034
3903	Petro-Canada	Edmonton	AB	0.029	0.000	0.005	0.000	0.034
2134	Agrium Products Inc.	Redwater/Municipal Didtrict of	AB	0.000	0.020	0.000	0.013	0.033
5727	Dana Canada Corporation	Mount Forest	ON	0.000	0.000	0.000	0.000	0.032
5745	Westcast Industries	Stratford	ON	0.032	0.000	0.000	0.000	0.032
3419	Ford Motor Company	Oakville	ON	0.031	0.000	0.000	0.000	0.031
4440	Specialty Cast Metals Limited	Niagara Falls	ON	0.000	0.000	0.000	0.000	0.031
0108	Barrick Gold Corporation	Kirland Lake	ON	0.009	0.021	0.000	0.000	0.030
3977	Akzo Nobel Chemicals Ltd.	Saskatoon	SK	0.000	0.000	0.000	0.000	0.028
5964	EMIRFI Shield Plating Inc.	Scarborough	ON	0.028	0.000	0.000	0.000	0.028
4820	Royal Canadian Mint	Winnipeg	MB	0.026	0.000	0.000	0.000	0.026
0315	ESCO Limited	Port Hope	ON	0.012	0.000	0.013	0.000	0.025
4419	Timminco Limited	Haley	ON	0.000	0.000	0.000	0.000	0.023
5672	Tenneco Automotive	Cambridge	ON	0.000	0.000	0.000	0.000	0.023
1461	GKN Sinter Metals	St. Thomas	ON	0.021	0.000	0.000	0.000	0.021
3227	General Motors of Canada Limited	St. Catharines	ON	0.018	0.003	0.000	0.000	0.021
5313	Foothills Steel Foundry Ltd.	Calgary	AB	0.000	0.000	0.000	0.000	0.018
4797	Les Forges de Sorel Inc.	St-Joseph-de-Sorel	QC	0.017	0.000	0.000	0.000	0.017

Table A-1 Emissions of Nickel and its Compounds According to NPRI (NPRI, 2002) (continued)

NPRI ID	Company	City	Province	Emissions of Nickel and Its Compounds (tonnes)				
				Air	Water	Land	Underground	Total
4868	The Cobalt Refinery Company Inc.	Fort Saskatchewan	AB	0.013	0.000	0.004	0.000	0.017
1464	Imperial Oil	Sarnia	ON	0.015	0.000	0.000	0.000	0.015
4781	Ford of Canada	Windsor/Essex	ON	0.015	0.000	0.000	0.000	0.015
1779	NOVA Chemicals Corporation	Red Deer	AB	0.000	0.014	0.000	0.000	0.014
3655	Ispat Sidbec Inc.	Contrecoeur	QC	0.000	0.013	0.000	0.000	0.013
4048	Consumers' Co-operative Refineries Ltd./NewGrade Energy Inc.	Regina	SK	0.010	0.000	0.000	0.000	0.010
4205	A.H. Tallman Bronze Co. Ltd.	Burlington	ON	0.010	0.000	0.000	0.000	0.010
5947	Pacific Plating Ltd.	Weston	ON	0.010	0.000	0.000	0.000	0.010
7107	Ks Centoco Wheel Corporation	Tilbury	ON	0.009	0.000	0.000	0.000	0.009
2963	Shell Chemicals Canada Ltd.	Fort Saskatchewan	AB	0.001	0.006	0.000	0.000	0.007
4368	Prévost Car Inc.	Ste-Claire	QC	0.000	0.000	0.000	0.000	0.007
3190	TRW Canada Ltd., OSS	Midland	ON	0.006	0.000	0.000	0.000	0.006
0231	Delhi Industries Inc	Delhi	ON	0.005	0.000	0.000	0.000	0.005
1070	Algoma Steel Inc	Sault Ste. Marie	ON	0.000	0.000	0.000	0.000	0.005
2683	Presstran Industries	St Thomas	ON	0.000	0.000	0.000	0.000	0.005
4980	Zalev Brothers Co.	Windsor	ON	0.004	0.000	0.000	0.000	0.004
5636	Babcock & Wilcox Canada	Melville	SK	0.000	0.000	0.000	0.000	0.004
1269	Nemak of Canada Corporation	Windsor	ON	0.003	0.000	0.000	0.000	0.003
2960	Shell Canada Products	Fort Saskatchewan	AB	0.000	0.003	0.000	0.000	0.003
3149	Oxford Automotive Canda Ltd.	Chatham	ON	0.003	0.000	0.000	0.000	0.003
3254	GE Canada	Bromont	QC	0.003	0.000	0.000	0.000	0.003
5825	Massiv Die-Form	Brampton	ON	0.003	0.000	0.000	0.000	0.003
7096	Archie McCoy Hamilton Ltd	Troy	ON	0.000	0.000	0.000	0.000	0.003
2499	Microprecision Die Casting Inc.	Burlington	ON	0.000	0.000	0.000	0.000	0.002

Table A-1 Emissions of Nickel and its Compounds According to NPRI (NPRI, 2002) (continued)

NPRI ID	Company	City	Province	Emissions of Nickel and Its Compounds (tonnes)				
				Air	Water	Land	Underground	Total
3395	Les Poudres Metalliques du Quebec Ltee	Sorel-Tracy	QC	0.000	0.000	0.000	0.000	0.002
4912	TKA Fabco Corp	Dresden	ON	0.002	0.000	0.000	0.000	0.002
5602	Royal Canadian Mint	Ottawa	ON	0.002	0.000	0.000	0.000	0.002
5630	Mytox	Woodbridge	ON	0.000	0.000	0.000	0.000	0.002
7072	Energy Plus 2000 Limited	Ajax	ON	0.000	0.000	0.000	0.000	0.002
1401	Henkel Canada Corporation	Toronto	ON	0.001	0.000	0.000	0.000	0.001
1958	Pratt & Whitney Canadan Cie	Halifax County	NS	0.001	0.000	0.000	0.000	0.001
1964	Pratt & Whitney Canada Cie	Longueuil	QC	0.001	0.000	0.000	0.000	0.001
3152	Oxford Automotive Canada Ltd.	Wallaceburg	ON	0.001	0.000	0.000	0.000	0.001
3747	Cominco Mining Partnership	Polaris	NU	0.000	0.001	0.000	0.000	0.001
3766	General Motors of Canada Limited	London	ON	0.001	0.000	0.000	0.000	0.001
4907	Budd Canada Inc.	Kitchener	ON	0.001	0.000	0.000	0.000	0.001
5153	Lafarge Canada Inc.	Kamloops	BC	0.001	0.000	0.000	0.000	0.001
5601	Bombardier Transportation	Thunder Bay	ON	0.001	0.000	0.000	0.000	0.001
5606	Multichair Inc.	Mississauga	ON	0.001	0.000	0.000	0.000	0.001
5663	Bombardier Transportation	Millhaven	ON	0.001	0.000	0.000	0.000	0.001
5681	russel metals inc	lachine	QC	0.001	0.000	0.000	0.000	0.001
5793	Stanley Manufacturing Company Inc.	Toronto	ON	0.001	0.000	0.000	0.000	0.001
5827	Ontario Engineered Suspensions Ltd.	Blenheim	ON	0.001	0.000	0.000	0.000	0.001
5918	Multichair Inc.	Mississauga	ON	0.001	0.000	0.000	0.000	0.001
5969	Nelson Industrial Inc	Pickering	ON	0.000	0.000	0.000	0.000	0.001
7123	Orion Bus Industries	Mississauga	ON	0.001	0.000	0.000	0.000	0.001