Chemical and Biological Hazards Prevention

Studies and Research Projects

REPORT **R-834**

Thermal Stress and Chemicals

Knowledge Review and the Highest Risk Occupations in Québec

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Legal Deposit
Bibliothèque et Archives nationales du Québec
2014
ISBN: 978-2-89631-746-2 (PDF)
ISSN: 0820-8395

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This study was funded by the IRSST. The conclusions and recommendations are solely those of the authors.
This publication is a translation of the French original; only the original version (R-799) is authoritative.

PEER REVIEW

In compliance with IRSST policy, the research results published in this document have been peer-reviewed.

ACKNOWLEDGEMENTS

The authors wish to thank Daniel Drolet for his contribution in the selection of the experts as well as in the development of the Excel file used in the consultation. The authors also thank the 13 consulted experts for their collaboration in the occupation ranking.

SUMMARY

Cold or heat exposure triggers a series of compensatory physiological responses that enable the human body to maintain its internal temperature despite thermal stress. These thermoregulatory mechanisms are well documented, and the physiological changes that they involve can modify the functions of several organs related to the absorption and metabolism of chemicals. Pharmacological and epidemiological studies have reported an increase in the absorption and effects of certain medications as well as in the human mortality rate associated with air pollution, during simultaneous exposure to heat and xenobiotics. By extrapolating these data to occupational health, it is reasonable to conclude that simultaneous exposure to thermal stress and chemicals is likely to increase the absorption of certain xenobiotics as well as their effects.

The first objective of this study was to find all of the data published in the recent scientific literature. The second objective was to identify those chemical-exposed Québec workers who could be most affected by thermal stress. Particular attention was paid to the presence of chemicals likely to affect thermoregulatory mechanisms.

The literature review was carried out by querying the Medline, Toxline and Chemical Abstracts bibliographic databases for the January 1990 to June 2012 period in order to document the physiological changes associated with thermal stress, concomitant exposures to thermal stress and chemicals as well as their effects, those chemical-exposed workers most likely to be affected by thermal stress, and the chemicals that can affect thermoregulatory mechanisms. A process relying on professional judgement was subsequently used to identify Québec workplaces where thermal stress exposure was likely to lead to a change in the toxicokinetics of the chemicals. Hence, 13 experts in the thermal stress field or industrial hygiene were individually consulted to rank the 136 chosen occupations in relation to the importance of the studied problem.

The collected data show that the impact of cold exposure on the toxicokinetics and effects of chemicals has not been extensively studied. The few studies identified have reported that exposure to cold thermal stress generally leads to a reduction in the toxicity of chemicals. Heat exposure, however, is associated with an increase in the pulmonary and skin absorption of xenobiotics, with this often being linked to an increase in their toxicity and concentration in biological fluids. Biological exposure monitoring can be used to show the increase in pulmonary or skin absorption with heat exposure. The degree of the increase depends on the intensity of the thermal stress, the exposure levels, and the physicochemical characteristics of the chemicals.

Of the occupations most affected by this problem in Québec, 20 are in the non-metallic mineral manufacturing/primary metal manufacturing/fabricated metal product manufacturing sector, as well as roofers and firefighters. These work environments should be given priority in future studies aiming to better characterize the risk associated with simultaneous exposure to thermal stress and chemicals. More specifically, exposure to certain contaminants can affect thermoregulatory mechanisms and thus reduce workers' capacity to adapt to heat. The workers primarily affected by this problem are those exposed to lead and its inorganic compounds (dusts and fumes), to certain pesticides (organophosphorus compounds and carbamates), and to metal oxide fumes (zinc, aluminum, antimony, cadmium, copper, magnesium, manganese, tin).

This review will provide occupational health practitioners with a guide in their risk assessment procedures for situations of simultaneous exposure to thermal stress and chemicals, mainly by having identified certain higher risk occupations. The data compiled in this report can also be used to develop toxicokinetic models for a better risk assessment. Workplace studies could also be conducted to document, in a real situation, the impact of heat exposure on the absorption and toxicokinetics of chemicals, with biological monitoring being a tool of choice in studying this problem.

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1. INTRODUCTION

Heat exposure can lead to health problems, from sunstroke to heatstroke, with the latter causing possible death following thermoregulatory failure. In Québec between 1983 and 2003, heat caused the death of nine workers involved in activities such as reforestation, manual tree felling, construction, and agricultural work (Schreiber et al., 2004). Work in the cold can also lead to health problems, but this is of much less concern, at least in Québec, where workers generally have effective means of protection (Schreiber et al., 2004).

Exposure to cold or heat triggers a series of compensatory physiological responses that enable the human body to maintain its internal temperature despite thermal stress. These thermoregulatory mechanisms are well documented, and the physiological changes that they involve, mainly in the redistribution of blood flows, can alter the functions of several organs related to the absorption and metabolism of chemicals (Mairiaux and Malchaire, 1990). Also, certain substances, including pesticides, can affect thermoregulatory mechanisms, potentially reducing the workers' capacity to adapt to thermal stress (Johnson Rowsey et al., 2003).

Pharmacological studies have reported an increase in the absorption and effects of certain medications when they are administered simultaneously with heat exposure (Sidhu et al., 2011; Vanakoski and Seppäla, 1998). Also, epidemiological studies on the impact of simultaneous exposure to thermal stress and air pollution have shown a significant effect of this combination of stressors on the human mortality rate (Katsouyanni et al., 1993; Rainham and Smoyer-Tomic, 2003). The extrapolation of population data in an occupational health environment suggests that concomitant exposure to heat stress and chemicals is likely to increase the absorption and effects of certain xenobiotics. Few data are currently available on this subject, and hence the interest in identifying, analyzing and integrating the published results. In doing so, the impact of thermal stress on the evaluation of the risk associated with occupational exposure to chemicals could be discussed, particularly from the standpoint of its impact on biological monitoring.

2. OBJECTIVES

2.1 General objective

The objective of this study was to analyze and consolidate all of the data published in the recent scientific literature in order to document the effect of thermal stress on the kinetics and toxicity of chemicals in the context of occupational health, and on biological monitoring. The results could primarily be used to identify certain higher-risk occupations in the context of work related to the issue of climate change.

2.2 Specific objectives

More specifically, the objectives of the study were of three types:

- To identify, by means of a literature review, studies on
  - physiological changes associated with thermal stress;
  - concomitant exposure to thermal stress and chemicals as well as their effects;
  - chemical-exposed workers (including air pollution) most likely to be affected by thermal stress;
  - chemicals that can alter workers' thermoregulatory mechanisms.

- To identify those chemical-exposed workers who could be most affected by thermal stress by paying particular attention to the presence of chemical species likely to affect workers' thermoregulatory mechanisms.

- To discuss the impact of concomitant exposure to thermal stress and chemicals on the absorption, metabolism, interpretation of biological monitoring data, and toxicity of chemicals (including, when relevant, air pollution for outdoor workers).

3. METHOD

3.1 Literature review

The literature review was carried out by querying the Medline, Toxline and Chemical Abstracts bibliographic databases for the January 1990 to June 2012 period. Combinations of different key words were used: *hot temperature*, *heat stress*, *thermal stress*, *hypothermia*, *hyperthermia*, *cold temperature*, *cold stress*, *body temperature*, *thermoregulation and physiological response*, *chemical*, *toxic response*, *toxicant*, *xenobiotic*, *health effect*, and *work environment*. Publications prior to 1990 were considered on the basis of their relevance, regardless of the date of publication.

3.2 Identification of workers simultaneously exposed to thermal stress and chemicals

Workers likely to be simultaneously exposed to thermal stress and chemicals were identified, initially, by means of the literature review as described in point 3.1. Then, a process involving the judgement of professionals working in occupational hygiene was used to identify Québec workplaces where exposure to thermal stress was likely to produce a change in the kinetics and toxicity of chemicals.

This process, described in the following paragraphs, was carried out in two steps. In the first step, our research group identified a list of occupations in which the workers could be potentially significantly exposed to thermal stress and chemicals. In the second step, this list was submitted to a group of professionals to assess and rank the importance of this double exposure for each occupation.

3.2.1 Assessment of thermal stress factors and measurement criteria

Thermal stress corresponds to all of the thermal loads imposed on the human body resulting from the metabolic load (energy expended during work) and the heat exchanged with the general environment. Heat exchanges between the environment and the human body can be expressed by the thermal balance (see section 4.1.1) which is the expression for the change in the body's temperature.

The basic parameters. As summarized by Malchaire (2004), six parameters directly affect heat exchanges in work environments, namely 1) air temperature (dry temperature), 2) air humidity, 3) air velocity, 4) temperature of the surrounding surfaces (radiant temperature), 5) clothing or clothing insulation, and finally, 6) energy expenditure (work metabolism). While all these factors can be measured quantitatively (dry temperature, natural humid temperature, air velocity, black globe temperature, body temperature, etc.), the last two essentially depend on the requirements related to the rules and production processes as well as the tasks performed by the person at his workstation.

When addressing the evaluation aspects of the basic parameters of thermal stress, it is important to describe the indexes for predicting the related conditions. In fact, observation (from experience or knowledge about the workplaces) makes it possible to examine the factors that are responsible for a satisfactory work situation (meaning a thermal comfort situation—without risk) or a unsatisfactory situation (meaning a stress situation—with risk). Of the six parameters mentioned above, only four were retained to determine the occupations with a risk of hot or cold thermal stress. They are the four following thermal stress factors: temperature, relative humidity, radiant energy, and energy expenditure or workload. From the standpoint of this study, the air velocity, the wearing of personal protective equipment, and clothing insulation are factors that were not taken into consideration because their use requires that the workers be observed in real time in their specific work situation. The same is true for intense cold and heat wave episodes, which were not taken into consideration in the evaluation of thermal stress for outdoor occupations. Also, when the two types of stresses (hot and cold) were present at the same workstation, heat stress was given priority because it is more likely than cold thermal stress to lead to physiological changes that modify the toxicokinetics of chemicals.

Energy expenditure or workload: *a very important parameter*. Of the four thermal stress factors retained, energy expenditure (or workload) is of critical importance. Very often, because a worker cannot do anything about the nature of his occupation (meaning that it is imperatively imposed by the process of his work), he will be considered at risk for thermal stress. For example, the roofer occupation requires that the person doing it will work mainly in the summer, when the weather is good and sometimes very hot, with an unusual work schedule, by exerting great physical effort due to the heavy loads that he must handle at heights and the different body positions that he must adopt, most often in trying to maintain a precarious balance. The same is true for numerous construction professions, as well as for different occupations in such fields as agriculture and forestry. Energy expenditure is one of the important parameters to be considered in evaluating thermal stress risk. This is why a list of the coded tasks for work-related physical activity from the *Compendium of Physical Activities* of Ainsworth at Arizona State University was used (Ainsworth et al., 2011). This Compendium, which classifies physical activity by rate of energy expenditure, was developed to make it easier to compare results from different studies. It uses a 5-digit code and classifies more than 800 human physical activities under major headings (for example, occupational, sports, household activities, etc.) by their energy intensity defined as the ratio of the metabolic rate for a specific activity to the resting metabolic rate. The data in the Compendium were obtained from studies on adults using models measuring the energy expenditure for certain daily physical activities in different living environments.

Determining and applying judgement criteria for each thermal stress factor. Work-situation judgement criteria were therefore developed for each retained factor and are presented in Table 1. Except for a few differences, they correspond to those presented by Malchaire (2004). The primary differences are in the grouping of the "very high" and "extreme" temperature categories into a single "very high" category. In the same way, the last two categories for "very hot" and "extreme" radiation were grouped in our study into a single "very hot" category. While these judgement criteria are defined in a rather broad way, they are nevertheless guidelines for assessing the importance of each of the thermal stress factors for a given occupation.

Table 1: Thermal stress factors and judgement criteria

Factors	*Criteria*	*Judgement*
Temperature	Cool, cold or freezing temperature	Low
	Generally between 15 and 27°C	Normal
	From 28 to 35°C	High
	Above 35°C	Very high
Humidity	Dry throat, nose, and/or eyes after 2–3 hours (<20% RH[1])	Low
	Same as outside (between 30 and 60/70% RH)	Normal
	Clammy skin (60–80% RH)	High
	Wet skin (>80% RH)	Very high
Radiation	Cold sensation on hands/face after 2–3 minutes	Cold
	No perceptible thermal radiation	Normal
	Hot sensation on hands/face after 2–3 minutes	Hot
	Impossible to keep hands/face exposed for more than 2 min	Very hot
Workload	Work seated, requiring slight exertion (< 1.6 MET)	Light
	Work seated or standing with greater exertion (1.6 and 3.0 MET)	Average
	Intense physical exertion (3.1 and 6.0 MET)	Heavy
	Very intense sustained physical exertion (> 6.0 MET)	Very heavy

[1] RH: Relative humidity
Adapted from Malchaire (2004)

A list of the occupations distributed in numerous activity sectors was developed by our research group from employment data originating from different sources: the sector labour committees on the website of *Métiers-Québec* (Commission de la construction du Québec, 2011), Statistics Canada (2007) for the North American Industry Classification System (NAICS), and Human Resources and Skills Development Canada (2006) for the National Occupational Classification (NOC). The list of identified occupations is presented according to NAICS. The four thermal stress factors were then evaluated by our research group for each occupation in relation to the judgement criteria in Table 1.

Thermal stress risk rating matrix. To help interpret the hazard level resulting from all of the criteria associated with the four thermal stress factors, our research team constructed a risk rating matrix. A probability scale was created. It provided the probability of presence (frequency) of thermal stress for a worker in a specific occupation. The proposed scale has four probability levels: low, average, high and very high. A work-situation severity scale (low, average, high, very high) was also developed. Severity reflects the degree of thermal stress to which a worker in a specific occupation is exposed. The severity level associated with each occupation was determined in relation to the importance attributed to each of the four thermal stress factors based on the professional judgement of the team members.

Finally, the combination of the probability and severity scales allowed for the development of a 16-box risk-rating matrix, as presented in Table 2. This table refers to an occupation-exposure matrix frequently used in risk analysis, with an approach similar to the one described by

Mulhausen et al. (2006). Based on judgement founded on experience and the scientific literature, four risk values were used: negligible, tolerable, significant, and critical. For the purpose of this study, only those occupations whose risk of thermal stress was judged significant or critical were retained.

Table 2: Thermal stress risk rating matrix

Probability	Severity: Low	Average	High	Very high
Low	Negligible	Tolerable	Significant	Significant
Average	Negligible	Tolerable	Significant	Critical
High	Negligible	Tolerable	Significant	Critical
Very high	Tolerable	Significant	Significant	Critical

List of occupations with a thermal stress risk in Québec. Briefly, the procedure presented in the previous paragraphs was carried out in four steps. For each occupation, our research group i) made a judgement about the temperature, humidity, radiation and workload conditions using the criteria presented in Table 1; ii) evaluated the probability (frequency) of the presence of thermal stress; iii) assessed the severity of the work situation in relation to the importance assigned to each of the four thermal stress factors; and iv) determined the risk rating by using the matrix presented in Table 2 for the determined probability and severity. A table was developed containing the list of the main occupations identified by activity sector and including the judgement criteria associated with the four retained factors, the assigned probability and severity, as well as the risk rating for each occupation. An example of this table is in Appendix 1.

3.2.2 Evaluation of chemical exposure

Chemical exposure was then evaluated for the occupations retained as being *critical* or *significant* as to thermal stress risk, by considering eight classes of products: 1) solvents, 2) dusts, 3) pesticides, 4) polycyclic aromatic hydrocarbons, 5) toxic gases, 6) heavy metals, 7) asbestos/silica, and 8) reagents/other chemicals.

Each of these product classes is not exclusive. Hence, a heavy metal can be found in the composition of a pesticide or even in the composition of dusts. Nevertheless, this classification of products gives a good indication of workers' exposures to the contaminants found in workplaces. One should note, however, that in the absence of quantitative probative data on workers' exposure and the wearing of personal protective equipment for all of the listed occupations, the occupations will be evaluated based on the known and documented presence of chemicals in the work environment.

The information that was used to complete the data comes from the National Occupational Exposure Survey (NOES) database between 1981 and 1983 (NIOSH, 1990), and from the results of the analyses of chemicals produced at the IRSST for the 2001–2005 period (Ostiguy et al., 2007a, and Ostiguy et al., 2007b).

This information, as well as literature searches on the use, handling and production of chemicals enabled the research team to make a qualitative assessment of the quantity and diversity of the chemicals to which workers in different occupations are likely to be exposed. Based on professional judgement and by considering the importance of the exposure to chemicals (quantity and diversity) and the thermal risk rating (significant or critical), the research team then assigned a priority rating between 1 and 5 to each occupation retained, with rating 1 corresponding to the occupations with the highest risk for concomitant exposure to chemicals and thermal stress. Appendix 2 presents an example of an evaluation of the chemical exposure for a few occupations most at risk for thermal stress. Only those occupations that obtained rating 1 or 2 were retained for the subsequent steps.

3.2.3 Number of potentially exposed workers

The number of workers associated with the occupations retained in the previous step was estimated from the number of paid workers in the 2006 Canadian population census. From monthly data from the Statistics Canada Survey of Employment, Payroll and Hours, the census data were adjusted to take into account the monthly variations in the numbers of individuals for each industrial group during the 2005–2007 period. These data do not include self-employed workers in unincorporated companies.

3.2.4 Consultation of experts and final occupation ranking

As described in sections 3.2.1 and 3.2.2, our research group did an initial occupation ranking. The list submitted to the experts corresponded to occupations that obtained rating "1" or "2" for simultaneous exposure to thermal stress and chemicals. The group of 13 experts in the field of thermal stress or industrial hygiene was consulted to rank and complete this list of occupations as needed. Using a rating from 1 to 10, the experts were asked to rank the 136 occupations presented in Appendix 3 in relation to the degree of the risk, with ranking 1 being associated with occupations considered by the experts as having a very high simultaneous exposure to thermal stress and chemicals. The experts' responses were collated, and the means and standard deviations of the ratings assigned to each occupation were calculated.

4. RESULTS

This section presents, first, the main information collected in the scientific literature review, and then the occupations that were identified as having the highest risk by considering thermal stress and chemical exposure.

4.1 Literature review

4.1.1 Thermal considerations

Humans are endothermic beings, meaning that they depend on the internal production of heat to control their body temperature (Tb). Humans maintain their Tb at around 37°C. This stability implies that there is a balance between heat production (basal metabolism, thermogenesis, physical activity) and heat losses by radiation, convection, conduction and evaporation. The term thermal balance is used to designate the sum of these gains and losses of body heat (Schreiber et al., 2004; Mairiaux and Malchaire, 1990):

$$M = Cres + Eres + K + C + R + E$$

According to this equation, the production of internal body heat (M) is compensated by respiratory tract heat exchange by convection (Cres) and evaporation (Eres), as well as by skin heat exchange by conduction (K), convection (C), radiation (R) and evaporation (E).

To maintain homeothermy, the human body uses two methods of control: behavioural control and control based on the autonomic nervous system. Behavioural responses involve changing clothing, moving away from the source of heat or cold, changing the level of physical activity, or even consuming hot or cold beverages and meals (Mairiaux and Malchaire, 1990). The most obvious reflex manifestations of thermal control are sweating and an increase in skin blood flow in hot environments as well as a reduction in skin blood flow and shivers or thermogenesis in cold environments. When the thermoregulatory mechanisms based on the autonomic nervous system come into play, they result in several physiological changes likely to have an impact on the absorption, metabolism and toxicity of chemicals (Gordon, 2005).

The factors listed in the next two sections are likely to affect the thermoregulatory mechanism activation threshold, or even the extent of the physiological changes associated with them, which can have an impact on the kinetics and toxicity of chemicals.

4.1.1.1 Individual factors affecting the body's tolerance to thermal stress

Several individual factors can affect the body's tolerance to thermal stress. A summary is presented below. For more details, the reader can consult two articles of Ganem et al. (2004, 2006).

Aging. Aging leads to a reduction in heat tolerance, even for healthy individuals. The factors responsible for this situation are a gradual reduction in maximum aerobic power (VO_2max), in stroke volume and cardiac output, in cutaneous vasodilation, as well as an increase in the sweating threshold accompanied by a reduction in sweat excretion (Gordon, 2005). However, according to Pandolf (1991), the reduced heat tolerance threshold in older people depends more on their physical condition than their age. An aging body also has more difficulty adapting to cold due to a reduced ability to decrease its blood flow and increase its heat production (Gordon, 2005; Stocks et al., 2004). Elderly people would therefore be at higher risk of suffering from hypothermia or hyperthermia (Slevinski, 2007).

Sex. Due to morphological and functional dissimilarities between the sexes, differences can be observed during exposure to thermal stress. In a hot and dry environment, women are slower to start sweating, and have higher body and skin temperatures and a higher heart rate (Mairiaux and Malchaire, 1990), which would make them more vulnerable than men when exposed to dry heat (Pandolf, 1991). However, this difference between the sexes disappears when the individuals are acclimatized to heat (Mairiaux and Malchaire, 1990). In a hot and humid environment, women's tolerance of heat is equivalent to that of men, even though the total amount of secreted sweat is lower in women. Heat tolerance does not seem to be affected by the menstrual cycle (Mairiaux and Malchaire, 1990), while pregnancy reduces heat resistance (Semenza et al., 1996). In cold exposure, there is a sex-related difference in vasoconstrictive response, with a lower skin-environment temperature gradient having been shown in women than in men (Japke Claessens, 2008).

Obesity. Obesity and poor physical condition are factors that reduce the body's ability to deal with heat. The subcutaneous fat mass limits heat transfer by conduction (Leon and Gordon, 2011). Also, for two individuals of the same weight, the thinner individual will have a considerably higher body water mass than the other. Hence, a water deficit due to heat exposure and deficient hydration can have major consequences on obese subjects (Kenefick and Sawka, 2007). A higher body fat mass reduces heat losses and allows a better resistance to cold (Stocks et al., 2004).

Diseases, medications, alcohol and other factors. Chronic diseases and medications that disrupt thermoregulation are factors that can induce increased sensitivity to heat (Albert et al., 2006). Certain medications against hypertension can reduce sweating and therefore the body's capacity to eliminate heat. The consumption of alcohol and certain illegal drugs can also promote disorders associated with heat exposure (Slevinski, 2007). All factors hindering heat production, contributing to heat losses, or interfering with the body's ability to maintain its Tb can promote hypothermia. These factors include the state of health, nutritional state, dehydration, mental status, medication, and alcohol consumption (Slevinski, 2007). Coffee and ethanol produce a vasodilatory effect (loss of heat), and their consumption must ideally be avoided during exposure to cold (Slevinski, 2007).

4.1.1.2 Factors in the work environment that can affect the interaction between thermal stress and chemical exposure

Several factors linked to working conditions or the work environment must be considered in evaluating the potential risk resulting from the interaction between thermal stress and exposure to chemicals.

Protective clothing and equipment. Personal protective clothing and the different types of personal protective equipment are important factors to be considered in evaluating thermal stress due to their weight or the skin insulation that they provide, which limits heat exchanges with the environment. Workers likely to be affected by this problem include pesticide spreaders, firefighters and race car drivers (Leon and Gordon, 2011). Abundant perspiration can sometimes affect the integrity of clothing fabrics, thus increasing the probability that the contaminants in the work environment would pass through them and be deposited on the skin and possibly be absorbed (Wester et al., 1996). Heat can also cause workers to remove their protective clothing or equipment, thus increasing the concomitant exposure to heat and chemicals (Leon, 2008). The wearing of a protective mask makes the consumption of fluids more difficult and may consequently result in the dehydration of heat-exposed workers (Kenefick and Sawka, 2007).

Physical activity. Physical activity helps raise the Tb, which increases the demand on the thermoregulatory mechanisms. Intense activity carried out in a hot environment leads to competition in the cardiovascular system so that the active muscles and the skin system can be simultaneously provided a suitable blood flow to evacuate the heat. When maximum cardiovascular capacity is reached, the blood flow to the muscles is maintained, to the detriment of the thermoregulatory mechanisms (Johnson, 2010).

Conditions of the outdoor environment. Solar radiation, wind and humidity are factors that can affect the concentrations and distribution of chemicals present in the work environment. A high temperature promotes the dispersion of chemicals in the air. The higher the ambient temperature, the more the volatile substances will tend to be present in vapour form, thus increasing the levels of exposure via the respiratory tract. Humidity and wind velocity are the most important factors related to heat losses by evaporation. Low humidity coupled with wind promotes the evaporation of perspiration from the skin surface, making this mechanism more effective. Wind can also promote heat losses by convection.

4.1.2 Thermoregulatory mechanisms

Thermoregulatory mechanisms, which enable the human body to maintain its internal temperature in response to thermal stress, are described in the following paragraphs, particularly relating to the physiological changes that are likely to result in a change in the kinetics and toxicity of chemicals. For more details on thermoregulatory mechanisms, the reader can consult Mairiaux and Malchaire (1990) as well as Gordon (2005).

Thermoregulation is achieved due to the existence of thermosensitive nerve structures that continuously detect the temperature of peripheral tissues as well as the Tb. The sympathetic nervous system plays an important role in the thermoregulatory mechanisms. These thermal signals are integrated in the hypothalamus. The perception of thermal discomfort can lead to behavioural responses (e.g., stopping physical activity, ingesting cold liquid) or trigger, by reflex nerve pathways, one or more compensatory physiological responses. In this latter case, this is *forced* hypothermia or hyperthermia, meaning that the body tends to bring its Tb back to a level equivalent to its usual body temperature (Tset). Under other circumstances, for example with an infection, the body programs an increase in its temperature. This is *regulated* hyperthermia. This distinction is important in understanding the action mechanisms involved during exposure to certain chemicals acting on the body's thermoregulatory system. If exposure to a chemical agent leads to a change in the Tset, this means that this substance necessarily acts on the central nervous system, which is not inevitably the case for exposures to substances leading to a forced hypothermia or hyperthermia response (Gordon, 2005).

4.1.3 Heat exposure and physiological changes

Heat exposure triggers a series of compensatory physiological responses that enable the human body to maintain its internal temperature at around 37°C. These thermoregulatory mechanisms are well documented and involve physiological changes. They include an increase and redistribution of cardiac output, an acceleration of respiratory flow and pulmonary ventilation, an increase in peripheral blood flow, and an increase in sweat secretion. These physiological changes are described in the paragraphs below.

Evaporation is the main heat dissipation mechanism in humans. Sweat excretion is controlled by the sympathetic nervous system. Sweat is produced by the eccrine and apocrine glands, with the former being mainly responsible for thermoregulation in humans. The density, secretion rate and activation threshold of sweat glands are determinant factors for the sweat volume produced (Leon and Gordon, 2011; Ramphal, 2000). Sweat rate is a function of thermal balance, which is strongly affected by the intensity of the physical effort. Energy is required to evaporate sweat at the skin's surface, with this energy translating into a loss of heat (Japke Claessens, 2008). The state of hydration of the skin's surface can modify sweat excretion. In fact, the gradual reduction in sweat excretion in subjects exposed to a humid environment would be due to the gradual hydration of the outer layers of the skin.

The need for heat transfer to the environment is also translated into a significant increase in skin blood flow (vasodilation). Humans can present a wide range of skin blood flows, going from 150–200 mL/min in a cool environment, to 2000 mL/min in a hot environment (Gordon, 2005). Skin blood flow increases by 3 L/min/°C rectal temperature, which can lead to 10-fold increases, and sometimes even higher, depending on the individual and the thermal environment (Leon and Gordon, 2011; Vanakoski and Seppäla, 1998). For example, skin blood flow increases by 400% with heat exposure producing a heart rate of 140 beats/min (Sidhu et al., 2011). While these results cannot be generalized to all heat exposure situations, they nevertheless show that heat exposure is likely to cause a significant increase in skin blood flow.

To respond to the increase in skin blood flow, the cardiovascular system uses adaptation mechanisms comparable to those used during muscular exercise (Mairiaux and Malchaire, 1990; Rowell, 1986). However, differences are noted for blood flows in the skin and muscles. Blood flow in the muscles increases significantly during physical activity, whereas it decreases with heat exposure. Skin blood flow represents more than 50% of the cardiac output with heat exposure, compared to 10% during physical exercise (Sidhu et al., 2011).

The cardiovascular system reacts by increasing cardiac output mainly by elevating the heart rate (HR), whereas the systolic ejection volume remains stable or decreases. Cardiac output can thus increase from 75 to 100% (Vanakoski and Seppäla, 1998; Mairiaux and Malchaire, 1990). It has been shown for workers in Soderberg potrooms that heat exposure alone represented an additional load on the cardiovascular system in the order of 20–25 beats/min (Rodahl, 2003). Respiratory surfaces can contribute to heat exchanges with the environment by promoting the evaporation of liquid (Japke Claessens, 2008). In fact, humans present an increase in respiratory frequency and minute ventilation, which contributes modestly to the evaporation of water (Ingram and Mount, 1975; Leon and Gordon, 2011).

Haldane (1905) was the first researcher to report an increase in pulmonary ventilation associated with hyperthermia in humans. Also, Cabanac and White (1995) showed an increase in pulmonary ventilation in subjects exposed to heat while resting. This increase occurred when the tympanic and oesophageal temperatures (T_{oes}) of individuals respectively reached 38.1 and 38.5°C. In this study, volunteers were seated in a water bath at 41°C. Fujii et al. (2008) noted an elevation in pulmonary ventilation beginning with T_{oes} of 37.8±0.5°C in individuals immersed in a 35°C water bath.

Also observed is a redistribution of some of the blood flow irrigating the inactive regions, mainly the abdominal organs (splanchnic network) and the kidneys, towards subcutaneous tissues. Sidhu et al. (2011) reported a reduction in blood flow in the kidneys, intestines, stomach, spleen and pancreas during heat exposure. This reduction varies with the intensity of the thermal stress and its impact on the heart rate. Under extreme conditions, corresponding to skin temperatures in the order of 40–41°C, Vanakoski and Seppäla (1998) reported a 30–35% reduction in blood flow in the viscera, which can lead to gastrointestinal tract ischemia and increase vascular permeability (Leon, 2008).

In a subject performing muscular exercise in a hot environment, vasodilation increases even more, leading to an additional reduction in splanchnic and renal blood flows, which increases skin blood flow. The HR increases to avoid a significant drop in cardiac output and blood pressure. The pressure control system then produces, via a reflex nerve pathway, an increase in vasoconstrictor tone to reduce skin blood flow. Hence, a competition exists between Tb control (vasodilation—increase in skin blood flow) and blood pressure control (maintaining muscular and cardiac blood flows) (Mairiaux and Malchaire, 1990).

An individual exposed repeatedly to heat develops adaptation mechanisms. These mechanisms are mainly translated into a reduction in the rise in Tb and a reduction in HR. This thermal balance is obtained due to increased vasodilation and sweating efficiency, and a decrease in the response threshold (Mairiaux and Malchaire, 1990).

The different methods for evaluating the thermal stress index (e.g., the Wet Bulb Globe Temperature (WBGT), a composite temperature index used for estimating the effects of temperature, humidity and solar radiation on humans) are applied in order to maintain the Tb below 38°C (38.5°C for heat-adapted workers). Compliance with thermal stress regulations should enable most workers to maintain their Tb below limits beyond which the thermoregulatory mechanisms are activated (WHO, 1969; ROHS, 2007; ACGIH, 2009).

4.1.4 Cold exposure and physiological changes

As described in the article of Stocks et al. (2004), numerous physiological changes are associated with cold exposure. With cold exposure, skin blood flow decreases through vasoconstriction of the peripheral and muscular blood vessels (Slevinski, 2007). This is translated into a reduction in the transfer of central body heat towards the skin, and consequently leads to a reduction in heat losses from the skin towards the environment (Japke Claessens, 2008). Cold exposure also triggers a process of thermogenesis from the energy stored in the body, which leads to an increase in metabolism. If the cold exposure continues, shivers start, which helps increase the production of heat (Japke Claessens, 2008). The thermoregulatory mechanisms that come into play with cold exposure are energy-consuming and can produce an increase in cardiac output and pulmonary ventilation (Japke Claessens, 2008; Ballard, 1974). When cold exposure continues and the rectal temperature reaches 35°C, the metabolic rate decreases (Ballard, 1974). Following the initial increase in the respiratory and heart rates, they decrease in proportion to the drop in Tb. Blood flows to the kidneys and liver are also reduced (Ballard, 1974). Also seen are a reduction in plasma volume in the order of 7% and an increase in urinary flow (Stocks et al., 2004; Ballard, 1974). The sympathetic nervous system exerts its effect through catecholamines, namely norepinephrine and epinephrine, which can bond to the α and β adrenoreceptors. In general, stimulation of the β receptors increases thermogenesis, while stimulation of the α receptors increases vasoconstriction (Stocks et al., 2004). Hypothermia corresponds to Tb < 35°C (Slevinski, 2007).

4.1.5 Effect of concomitant exposure to thermal stress on the toxicokinetics and toxicity of chemicals

As mentioned in the previous sections, exposure to thermal stress triggers a series of compensatory physiological responses that are likely to modify the absorption, distribution, biotransformation and excretion of chemicals (Gordon et al., 2008). These physiological changes can ultimately be responsible for a change in the tissue levels reached and the toxicity of xenobiotics (Leon, 2008). Several studies on laboratory animals clearly show that a link exists between temperature and the toxicity of xenobiotics. However, due to major differences between laboratory animals and humans in internal temperature control, the extrapolation of the results of animal studies to humans carries some uncertainty (Leon, 2008). As a result, the present literature review will primarily consider the human data obtained.

4.1.5.1 Chemicals and heat exposure

Absorption
The quantities of xenobiotics absorbed via the pulmonary and cutaneous routes during work in a hot environment can significantly increase due to the elevation in pulmonary ventilation and skin blood flow (vasodilation) (Gordon et al., 2008; Leon, 2008). The impact on gastrointestinal absorption seems negligible (Vanakoski and Seppäla, 1998).

Cutaneous absorption. The increase in skin temperature and skin blood flow as well as the presence of sweat on the skin surface can promote the cutaneous absorption of chemicals during concomitant exposure to heat (Vanakoski and Seppäla, 1998; Wester et al., 1996; Gordon, 2005). The size of this increase is a function of the substance's physicochemical properties, the exposed surface, and the intensity of the thermal stress (Leon, 2008; Riviere and Williams, 1992). In fact, in the field of pharmacology, studies have shown that the skin absorption of several medications increased in hot environments (Lenz, 2011).

Vanakoski and Seppäla (1998) reported an increase in the cutaneous absorption of insulin (subcutaneous administration), nitroglycerin, methyl salicylate, and nicotine (smears or patches) with short-term exposures of approximately 30 minutes to heat, in saunas or at an ambient temperature of 40°C. An increase of 50 to 150% was noted in the plasma concentrations of these substances following heat exposure. Using these results as a basis, the authors concluded that ambient temperatures above 30°C can have a significant impact on the cutaneous absorption of several substances. Funckes et al. (1963) showed an increase in the skin absorption of parathion (in powder form) as a function of temperature with volunteers. These authors reported a 25% increase in the urinary excretion of p-nitrophenol (metabolite of parathion) between exposures at 14°C and 21°C, 17% between 21°C and 28°C, and 180% between 28°C and 40.5°C. Since the sweat glands are activated by cholinergic stimulation, parathion, like other cholinesterase-inhibiting pesticides, could directly promote the production of sweat and the skin absorption of these substances (Gordon, 2005). According to Gordon (2005), sufficient literature data exist to conclude that heat and physical exercise (together or separately) promote the skin absorption of pesticides in humans.

These data suggest that heat exposure will probably increase the skin absorption of chemicals present in the workplace. This situation is likely to relate even more to those substances for which the cutaneous route already contributes to the overall exposure of workers in a thermoneutral environment. For these substances, the threshold limit values proposed by several organizations are often accompanied by the "percutaneous" designation. For example, according to the American Conference of Governmental Industrial Hygienists (ACGIH® [2012]), the Québec *Regulation respecting occupational health and safety* (ROHS, 2007), and the Institut national de recherche en sécurité (INRS France, 2008), 14 chemicals appearing in the IRSST's *Guide de surveillance biologique de l'exposition* have a significant potential for cutaneous absorption, namely benzene, ethylene glycol monoethyl ether, ethylglycol acetate, ethylbenzene, n-hexane, mercury (vapour and inorganic compounds), methanol, methylethyl ketone, organophosphorus compounds, pentachlorophenol, phenol, styrene, toluene and xylenes (Truchon et al., 2012). The cutaneous absorption of these substances could therefore be significantly higher during concomitant exposure to heat.

Pulmonary absorption. No information could be found relating to the effect of heat exposure on the pulmonary absorption of medications or chemicals present in the workplace. However, since heat exposure, like physical exercise, leads to an increase in pulmonary ventilation, this suggests that the absorption of chemicals will increase in individuals exposed to heat (Mautz, 2003). In fact, the significance of the contribution of physical activity on pulmonary absorption has already been demonstrated. The absorption of organic solvents depends mainly on their solubility in the blood, meaning their blood-air partition coefficient ($P_{blood:air}$). According to Csanády and Filser (2001), an increase in pulmonary ventilation will increase the absorption of organic solvents with a $P_{blood:air}$ greater than six. Table 3 presents the $P_{blood:air}$ values corresponding to the organic substances appearing in the IRSST's *Guide de surveillance biologique de l'exposition* (Truchon et al., 2012). Thus, exposure to sufficiently intense heat to trigger thermoregulatory mechanisms would therefore likely lead to an increase in the absorption of 12 of the 14 organic substances listed in this table. However, the degree of this increase must be documented.

The results of the study of Tardif et al. (2008), conducted on volunteers exposed to five solvents, demonstrated that the increase in pulmonary ventilation associated with physical activity could lead to an increase in the order of 200% in the concentration of the biological exposure indicators for the most blood-soluble solvents (e.g., toluene, acetone, trichloroethylene, styrene).

Concentrations of n-hexane, a substance less soluble in the blood, were not greatly affected. Considering the similarities in the physiological changes associated with physical activity or exposure to hot thermal stress, it is reasonable to conclude that simultaneous exposure to heat and chemicals will increase the biological monitoring data values when the substance is blood-soluble.

Table 3: Expected influence of workload or heat exposure on the pulmonary absorption of different organic substances in relation to their $P_{blood:air}$ value

Substances whose absorption is affected by pulmonary ventilation $P_{blood:air} > 6$	***Substances whose absorption is not or is only slightly affected by pulmonary ventilation*** $P_{blood:air} < 6$
Acetone	n-Hexane
Benzene	1,1,1-Trichloroethane
Ethylene glycol monoethyl ether	
Ethylbenzene	
Methanol	
Methylethyl ketone	
Methylisobutyl ketone	
Styrene	
Tetrachloroethylene	
Toluene	
Trichloroethylene	
Xylenes	

An increase in pulmonary ventilation also affects particle deposition in the different regions of the respiratory tract. Pulmonary deposition depends on the different properties of the particles, mainly their diameter and the type of respiration (oral or nasal) (Bennett et al., 1985; ICRP, 1995). Compared to organic substances, few validated quantitative data are available relating to the impact of an increase in pulmonary ventilation on the absorption of xenobiotics in particulate form. Two studies have reported that the total number of deposited particles can increase up to a factor of 4.5 during moderate exercise (Daigle et al., 2003; Löndahl et al., 2007). Since heat exposure leads to an increase in pulmonary ventilation, an increase can also be expected in the pulmonary absorption of contaminants present in particulate form.

Gastrointestinal absorption. In a journal article, Vanakoski and Seppäla (1998) reported that short-term heat exposures (15 to 60 min), producing skin temperatures in the order of 39°C, have a minor impact on the gastrointestinal absorption, bioavailability and elimination of several medications (midazolam, ephedrine, propanolol, tetracycline). According to the literature review by Sidhu et al. (2011), intestinal transit time would be unchanged during heat exposure, whereas the data available on gastric emptying allow no probative conclusion.

Distribution

The redistribution of blood flow during thermal stress can have an impact on the distribution and accumulation of chemicals in the body (Gordon, 2005). Hence, heat exposure increases the retention of xenobiotics in the soft tissues due to a reduction in urinary excretion (Leon, 2008). The volume of distribution of xenobiotics can drop following dehydration. This situation affects substances that are not highly lipid-soluble even more, which have a small distribution volume corresponding, for example, to the blood volume (Vanakoski and Seppäla, 1998). However, short-term heat exposure (< 1 h) would have a negligible effect on the distribution volume (Vanakoski and Seppäla, 1998). Binding with proteins can theoretically increase due to dehydration and an increase in the plasma concentrations of proteins. This can modify the distribution of substances strongly bound to proteins (Lenz, 2011). However, like Sidhu et al. (2011), we did not find any study confirming this effect. Overall, according to the literature review by Vanakoski and Seppäla (1998), heat exposure would have a negligible effect on the distribution of most xenobiotics.

Biotransformation

The biotransformation of chemicals is a complex process that depends mainly on their physicochemical properties, blood flow, and enzymatic activity (Lenz, 2011). The biotransformation of substances with a high hepatic extraction rate depends to a great extent on hepatic blood flow. Since heat exposure reduces hepatic blood flow, this should lead to reduced hepatic clearance (Vanakoski and Seppäla, 1998). The clearance of indocyanine green, a substance used, among others, for evaluating hepatic flow, is reduced by close to 30% during heat exposure (41°C, 3 h, resting) (Swartz et al., 1974). The half-life of several substances can therefore increase during simultaneous exposure to heat (Schlaeffer et al., 1984). Short-term heat exposure (< 1 h) has a negligible effect on hepatic blood flow, and the clearance of xenobiotics is therefore usually unchanged under these conditions (Vanakoski and Seppäla, 1998; Lenz, 2011).

The clearance of xenobiotics more weakly extracted (< 20%) from the liver will not be greatly affected by a change in hepatic blood flow during heat exposure. The biotransformation of these substances essentially depends on enzymatic activity and the free fraction (not bound to proteins) present in the plasma (Lenz, 2011). However, heat exposure is likely to lead to an increase in enzymatic activity and protein binding, two factors that can theoretically modify the toxicokinetics of these xenobiotics (Lenz, 2011), but no data confirming these possible effects were found.

Excretion

With heat exposure, the renal excretion of xenobiotics can decrease due to dehydration and a reduction in renal blood flow (Gordon, 2005; Vanakoski and Seppäla, 1998). The substances most affected are those that are eliminated unchanged in the urine and those whose elimination depends on renal function (Lenz, 2011). According to pharmacokinetic studies, the urinary excretion of several medications is reduced or delayed when renal blood flow is reduced. This is expressed in some cases by an increase in the plasma concentrations of medications (Vanakoski and Seppäla, 1998; Lenz, 2011).

Furthermore, an increase in sweating during heat exposure can increase the excretion of substances eliminated via this route. Heavy metals and trace metals such as iron, aluminum, cobalt, copper, lead, manganese, mercury, molybdenum, nickel, tin and zinc (Hohnadel et al., 1973), and volatile organic substances such as acetone, ether, ethanol and toluene, are excreted in sweat (Naitoh et al., 2002).

Urinary excretion of creatinine. In the context of occupational biological exposure monitoring activities, creatinine correction is used to adjust the urinary concentrations of the different biological parameters when spot sampling is done. Creatinine correction is based on the hypothesis that its excretion is constant, regardless of urinary flow, which is questioned by some authors (Boeniger et al., 1993). Since work in a hot environment leads to an increase in water losses by sweating, this can result in reduced urinary flow. Since reduced urinary flow often corresponds to reduced creatinine excretion, this method of correction can be less precise under these circumstances (Boeniger et al., 1993).

Toxicity

As shown mainly in animal studies, an increase in Tb is accompanied by an increase in several biological processes (rate of enzymatic reactions, binding to receptors, lipid peroxidation, oxidative phosphorylation, etc.), which is likely to lead to an increase in the intensity of the effects of medications or chemicals (Leon, 2008).

Only a few human studies on the impact of heat exposure on the toxicity of chemicals were identified. Walker et al. (2001) studied the effect of combined exposure to heat and carbon monoxide with race car drivers. Their study showed that this exposure led to a greater reduction in psychomotor performances than exposure to carbon monoxide or heat alone. Wei et al. (1988) also reported the increased toxicity of carbon monoxide when workers are simultaneously exposed to CO and heat. A study by Attia et al. (1988) reported that heat stress increases the likelihood of lead poisoning. The World Health Organization (WHO, 1981) reported that combined exposure to heat and solvents can be responsible for an increase in the health effects reported by workers. The heat/chemical interaction would be significant only when exposure levels were close to permissible concentrations (TLVs), and the effects would be less significant in acclimated workers (Freundt, 1990). According to Freundt (1990), other studies are necessary to confirm these results. Studies on the impact of simultaneous exposure to heat and air pollution have shown a significant effect on the human mortality rate and on cardiovascular effects (Rainham and Smoyer-Tomic, 2003; Qian et al., 2010; Ren et al., 2011).

In the pharmacology field, an increase in the clinical effects of several medications has been reported with heat exposure. This increase seems to be associated with a higher dose since the cutaneous absorption of several medications is increased (Vanakoski and Seppäla, 1998; Sidhu et al., 2011).

Finally, according to Gordon (2005), a worker exposed to an environment that forces him to actively dissipate heat (thermoregulatory mechanisms activated) is likely to show toxicities to lower doses than when he works in a thermoneutral environment, mainly because of a potentially increased absorption of chemicals via the respiratory and cutaneous routes.

4.1.5.2 Chemicals and cold exposure

The impact of cold exposure on the kinetics and effects of chemicals has been much less investigated than that of heat exposure. The little information collected is summarized in the following paragraphs.

Absorption
The increased demand for heat production with cold exposure results in an elevation in respiratory rate, which can lead to the increased absorption of contaminants via the respiratory route (Gordon, 2005). However, this situation is likely to occur only under conditions rarely encountered in workplaces, and no study could be found that quantified this theoretical impact.

Distribution, metabolism and elimination
Since cold exposure produces a slowing of the different metabolic processes, it is usually accompanied by a reduction in the biotransformation and excretion of xenobiotics, thus prolonging their residence time in the body (Gordon et al., 2008). However, this slowing of metabolic activities is encountered only in cases of severe hypothermia, which are very unlikely in the workplace.

Toxicity
A drop in Tb can reduce the toxicity of numerous chemicals since the biochemical reactions leading to cellular damage (such as the formation of reactive oxygen species, lipid peroxidation, or the production of toxic metabolites) are slowed as the Tb drops (Gordon et al., 2008; Leon, 2008). Leon (2008) reported a case of severe carbon monoxide poisoning in which the individual was saved by inducing hypothermia. These conclusions seem to apply to most chemical agents except DDT and pyrethroids, insecticides that specifically affect the sodium channels involved in membrane polarization (Gordon, 2005). These chemical agents block entry to these channels by keeping them in an open position, which leads to prolonged depolarization of the membranes. This process is accentuated when the temperature drops (Gordon, 2005).

Despite the fact that cold can lead to increased absorption of chemical agents via the respiratory tract and a reduction in their biotransformation and excretion, the final result seems to be a reduction in the toxicity of numerous chemicals (Gordon, 2005).

4.1.6 Effect of chemicals on thermoregulatory mechanisms

When exposure to a chemical leads to hypothermia or hyperthermia, this means that the body's thermosensitive nerve structures, and therefore thermoregulatory mechanisms (metabolic thermogenesis, water evaporation, peripheral vasomotricity), are affected (Leon, 2008; Gordon, 2005). While very common in laboratory animals, this type of response is more rarely encountered in humans (Gordon et al., 2008). However, cases of accidental poisonings by certain xenobiotics have shown this type of response in humans. Hence, certain chemical agents can affect thermoregulatory mechanisms, which could reduce workers' capacity to adapt to thermal stress (Johnson Rowsey et al., 2003).

4.1.6.1 Vasoconstricting substances

Vasoconstricting substances are likely to inhibit the body's capacity to dissipate heat through vasodilation of the skin blood vessels (Leon, 2008). Among the substances mentioned in the ROHS, only lead and its inorganic compounds (dusts and fumes) have been identified as being vasoconstricting substances (Vyskocil et al., 2005). A vasoconstrictor will have little effect on Tb in a cold environment, because there is already peripheral vasoconstriction. However, in a hot environment, skin blood flow is usually elevated to promote heat loss. Under such circumstances, blood vessel vasoconstriction can hinder heat dissipation (Gordon, 2005).

4.1.6.2 Vasodilating substances

Substances producing a vasodilating effect promote heat loss. Exposure to such chemical agents can therefore promote hypothermia (Slevinski, 2007). Among the substances mentioned in the ROHS, propylene glycol dinitrate, ethylene glycol dinitrate, enflurane, halothane, normal propyl nitrate, nitroglycerin and sodium azide have been identified as being vasodilating substances (Vyskocil et al., 2005). Ethanol has already been identified in cases of accidental death by hypothermia in individuals exposed to cold (Leon, 2008). Ethanol exposure leads to an increase in skin blood flow, which can produce a hypothermic effect. However, this effect is usually minor or negligible in workplaces (Gordon, 2005).

4.1.6.3 Organophosphorus compounds and carbamates

The action mechanism associated with the toxicity of organophosphorus compounds and carbamates is acetylcholinesterase inhibition. This enzyme's function is to degrade acetylcholine, which binds to central nervous system receptors. The effect of this binding is to modify a variety of responses associated with maintaining Tb, such as skin blood flow, heart rate, respiration, and sweat secretion (Leon, 2008). The human data available were primarily obtained in emergency situations following cases of acute poisoning by parathion and methylparathion. In cases of severe poisoning, hypothermia is observed in the first hours, followed by hyperthermia that can last up to one week (Gordon, 2005). The hypothermia observed in the first hours is due to stimulation of the muscarinic cholinergic pathway, which leads to increased sweating and peripheral vasodilation (Gordon, 2005; Gordon et al., 2005). The subsequent fever is attributed to the mechanisms established by the thermosensitive nerve structures, in order to reduce heat losses and increase Tb (Gordon, 2005).

4.1.6.4 Metals

In humans, metal fumes can be the origin of toxicities characterized by such things as fever (Fine et al., 1997). Exposure to the metal oxides present in welding fumes, foundries, or emitted during galvanization operations can lead to a series of symptoms including fever. Zinc oxide seems to be the most toxic. According to Fine et al. (1997), 2-hour worker exposure to zinc oxide at a concentration of 5 mg/m^3 via the pulmonary route led to an increase in Tb 11 hours after exposure. Other metal oxides that produce the same effect are aluminum, antimony, cadmium, copper, magnesium, manganese and tin (Gordon, 2005).

4.1.6.5 Pentachlorophenol

Pentachlorophenol (PCP), like other uncoupling agents in oxidative phosphorylation, leads to an increased metabolism. Significant and prolonged increases in Tb as well as significant sweating have been noted following a worker's acute exposure to PCP (Gordon, 2005).

4.1.6.6 Arsenic

A case of human hyperthermia (39°C) was reported following acute exposure to arsine (Wilkinson et al., 1975). Arsenic exposure is associated with the development of Raynaud's syndrome, which is characterized by a reduction in peripheral blood flow. Since cold exposure also leads to a reduction in peripheral blood flow, it may promote the development of this syndrome. Smelter workers are a group of workers at risk for this problem during acute or chronic exposure to arsenic at temperatures ≤ 10–15°C (Lagerkvist et al., 1986, 1988).

4.1.6.7 Other substances

Studies have reported that exposure to plastic pyrolysis products is responsible for "polymer fever" (Kuntz and McCord, 1974; Williams et al., 1974). Hyperthermia has been observed in humans following exposure to chlordane and neonicotinoid insecticides. However, the action mechanism is not known (Gordon, 2005).

4.2 Identification of workers simultaneously exposed to thermal stress and chemicals

Very few studies have addressed the simultaneous occupational exposure to thermal stress and chemicals. The few data identified are described in the following paragraphs, targeting certain occupations.

Farmers and pesticide spreaders. Farmers and workers applying pesticides (substances often absorbed significantly through the skin) often have to work in a hot environment. Also, the literature has frequently reported that these workers stop wearing their protective equipment due to their discomfort in a hot environment, thus promoting the absorption of chemicals (Gordon, 2005).

Firefighters. These workers are exposed to thermal stress not only because they work close to fire, but also because they occasionally work in confined spaces and wear clothing or equipment that is sometimes very restrictive. They are simultaneously exposed to the different chemicals found on sites where they have to work: carbon monoxide, benzene, particulates, asbestos, cyanides, hydrogen chloride, polycyclic aromatic hydrocarbons, fumes, stored products, products used to control fires, etc. (Melius, 2001; Leon, 2008).

Race car drivers. These drivers are often exposed to carbon monoxide (CO) concentrations as high as 200 ppm, simultaneously with heat stress, since the temperature inside race cars can easily reach 50°C (Gordon, 2005; Leon, 2008). The protective clothing worn by drivers can also help to increase heat stress by reducing heat elimination. Walker et al. (2001) clearly demonstrated that concomitant exposure to heat and CO increased the number of errors. CO seems to exacerbate the response to thermal stress. However, the mechanism involved has not yet been elucidated. According to recent data obtained from animal experiments, CO could play a mediator role in the initiation of fever. Compared to animal data, few human data are available related to the effect of CO on the control of Tb for exposure to low concentrations (Gordon, 2005).

Ceramics artists. These workers can be simultaneously exposed to heat, metals (e.g., lead), fibrogenic dusts (e.g., silica), and other toxic emissions from ovens (Dorevitch and Babin, 2001).

Plastics industry workers. According to WHO (1981), combined exposure to heat and the chemicals used in plastics production can be responsible for an increase in several health effects, including objective changes to neurological, cardiovascular, or hematological function parameters.

As a complement to the literature data, a second component of this study was to identify the Québec workers exposed significantly to thermal stress and chemicals. The potential for exposure to thermal stress was documented for 1010 occupations distributed in more than 35 NAICS economic activity sectors or subsectors. Only eight of these 1010 occupations presented a potential for cold exposure. For these, the risk rating assigned for thermal stress was negligible or tolerable.

The risk of thermal stress due to heat was evaluated as critical or significant for 257 occupations. The forestry and logging, construction, primary metal manufacturing, pulp and paper, plastics processing, mining, quarries, oil and gas, utilities, agriculture, animal production, and fishing sectors are those with the highest risk of thermal stress. In these sectors, the targeted occupations are most often related to production, handling and maintenance work. Of these 257 occupations, 136 were retained because of the significant potential for concomitant exposure to chemicals. These occupations and the related numbers of workers are presented in Appendix 3. The numbers of workers presented are those associated with NOC occupations by using the four-digit code (NOC-4) that corresponded most appropriately to the priority occupation titles identified by our research group. It is important to note that these numbers correspond to all of the occupations associated with an NOC-4 code and not specifically to the priority occupation titles retained, which are often only a subset of these different classes of occupations, thus resulting, in most cases, in an overestimation of the real numbers.

The mean of the ratings assigned by each expert was calculated for these 136 occupations. A risk rating equal to 1 is associated with occupations for which simultaneous exposure to thermal stress and chemicals is assessed as very high. All of the calculated mean ratings were between 2.1 and 7.5 (Appendix 3). Table 4 presents the 22 occupations for which the mean rating assigned by the experts was below 3, and therefore the most likely to put the workers in a situation of simultaneous exposure to heat stress and chemicals.

Table 4: Occupations prioritized by the experts in relation to their potential risk resulting from concomitant exposure to chemicals and thermal stresses

Occupations	Rating				n[4]
	Mean	S.D.	Min	Max	
Gold caster[1]	2.1	1.5	1	6	11
Roofer[2]	2.2	1.1	1	4	13
Caster[1]	2.3	1.5	1	6	13
Smelter operator[1]	2.3	1.6	1	5	13
Forge helper[1]	2.4	1.0	1	5	13
Firefighter[3]	2.4	1.8	1	7	12
Metal processing labourers[1]	2.5	1.1	1	5	13
Firing kiln labourer[1]	2.5	1.3	1	5	13
Smelting furnace helper[1]	2.5	1.3	1	5	13
Foundry labourer[1]	2.5	1,3	1	5	13
Casting helper[1]	2.5	0.9	2	5	13
Moulder[1]	2.5	1.3	1	6	13
Oven operator[1]	2.5	1.6	1	6	13
Ceramic kiln operator[1]	2.6	1.4	1	5	12
Brick kiln operator[1]	2.7	1.4	1	5	12
Metal fabricating machine operator[1]	2.7	1.6	1	6	13
Furnace operator[1]	2.7	1.7	1	6	13
Steel hardener[1]	2.8	1.5	1	6	13
Extruder[1]	2.8	1.6	1	6	12
Smelting furnace operator[1]	2.9	1.6	1	6	13
Die-casting machine operator[1]	2.9	1.6	1	6	12
Boilermaker[1]	2.9	1.5	1	5	12

[1] Non-metallic mineral product manufacturing/primary metal manufacturing/fabricated metal product manufacturing sector
[2] Construction sector
[3] Utilities/Public administration sector
[4] Number of experts who assigned a rating

This process showed that occupations in the non-metallic mineral product manufacturing/primary metal manufacturing/fabricated metal product manufacturing sector are those where the potential risk is highest for workers simultaneously exposed to heat stress and chemicals. In this sector, gold casters, casters, smelter operators, and forge helpers are at the top of the list with positions 1, 3, 4 and 5, respectively, while roofers rank 2nd.

5. DISCUSSION

5.1 Literature review

One of the objectives of this study was to do a literature review in order to document the impact of thermal stress exposure on the absorption, distribution, biotransformation, excretion and toxicity of chemicals in the workplace. Despite extensive theoretical information, very little quantitative data has been published on this subject. However, by integrating the published information, mainly in the pharmacology and toxicology fields, a review could be produced on the expected changes in the kinetics and toxicity of chemicals following the physiological responses triggered by cold or heat exposure.

The impact of cold exposure on the kinetics and toxicity of chemicals would be negligible. Cold exposure can, in theory, increase the absorption of xenobiotics via the pulmonary route due to the increased respiratory rate associated with the higher demand for heat production (Gordon, 2005). In theory, it can also lead to a reduction in their biotransformation and excretion (Gordon et al., 2008). However, these changes occur in cases of severe hypothermia, which are rather unlikely in a work environment.

In fact, most of the identified studies addressed the potential effects of heat exposure on the kinetics and toxicity of chemicals. Generally, one can conclude that heat exposure increases the absorption and toxicity of most chemicals. In most cases, this increased toxicity is associated with an increase in the absorption of contaminants via the pulmonary and cutaneous routes, but it can also be due to an increase in the ambient concentrations of more volatile substances, often associated with a rise in temperature (WHO, 1981). Also, since heat leads to a significant increase in skin blood flow, priority must be given to chemicals whose threshold limit values are accompanied by the "percutaneous" designation because they are recognized as easily passing through the skin.

Like physical activity, heat exposure produces an increase in pulmonary ventilation, which is likely to increase the pulmonary absorption of xenobiotics. In fact, a study addressing the effect of physical activity on the toxicokinetics of five solvents showed that an increase in pulmonary ventilation resulted in an increase in the absorption of substances with the highest blood solubility. The biological concentrations of these substances could increase by a factor of 2 (Tardif et al., 2008). Thus, exposure to sufficiently intense heat to trigger thermoregulatory mechanisms and result in increased pulmonary ventilation could lead to an increase in the absorption of chemicals via this route. The absorption of the most soluble chemicals in the blood ($P_{blood:air} > 6$) would be even more affected (Csanády and Filser, 2001). The rise in pulmonary ventilation is also likely to increase the pulmonary deposition of chemical contaminants present in particulate form (Daigle et al., 2003; Löndhal et al., 2007).

Heat exposure seems to have little impact on the distribution of chemicals. However, it can delay their excretion or slow the biotransformation of substances strongly eliminated by the liver due to the reduction in renal and hepatic blood flows that it produces (Vanakoski and Seppäla, 1998). These latter two factors can contribute to increased blood concentrations (Vanakoski and Seppäla, 1998; Lenz, 2011).

As previously mentioned, the overall impact of heat exposure is expressed in most cases by an increase in the concentration of xenobiotics in biological fluids. This increase is associated mainly with an increased absorption of xenobiotics, but also to a lesser extent, with slower elimination (Vanakoski and Seppäla, 1998). Since the "internal dose" of a contaminant is increased, more health effects may be reported by the workers (WHO, 1981). The chemical/heat interaction would have a significant impact on the toxicity of the contaminants, mainly when the exposure levels are close to the permissible concentrations (Freundt, 1990). Similarly, compliance with thermal stress regulations should enable most workers to maintain their Tb below the thresholds leading to activation of thermoregulatory mechanisms (ACGIH, 2009). However, it is important to note that certain factors associated with individuals (section 4.1.1.1) or the work environment (section 4.1.1.2) can affect a worker's threshold or physiological response. Also, an individual exposed repeatedly to heat will develop adaptation mechanisms that will make him more resistant to hot temperatures. Exposure to certain chemicals can also disrupt thermoregulatory mechanisms, which could reduce the worker's capacity to adapt to thermal stress (section 4.1.6). All of these factors sometimes make it difficult to predict the physiological impact of co-exposure to heat and chemicals on an individual.

Biological exposure monitoring can be used to show, for a given ambient concentration of contaminant, an increase in absorption due to simultaneous heat exposure. Since changes observed in the toxicokinetics of chemicals are generally of short duration and occur simultaneously with the compensatory physiological responses induced by heat exposure, this approach will be useful mainly when reliable indicators varying rapidly with time are documented. In fact, for xenobiotics with longer half-lives (such as metals), the impact on the measurement of biological indicators will be significant only if the simultaneous exposure to these two stressors continues over time. Hence, heat exposure will primarily affect the acute toxicity of chemicals.

Currently available quantitative data indicate that the amount of contaminant absorbed could increase by a factor of 2, depending on the intensity of the physiological response associated with the thermal stress and the physicochemical characteristics of the substance (Vanakoski and Seppäla, 1998; Tardif et al., 2008; Funckes et al., 1963). However, the quantitative impact of these changes must be further documented. Studies specifically quantifying the thermal stress and physiological responses are necessary to better predict the consequences of heat exposure on the kinetics and toxicity of chemicals as well as on biological monitoring data. Environmental surveillance, namely the measurement of the contaminant's ambient concentration in the work environment, cannot be used to determine the potential increase in workers' internal exposure. Under these circumstances, biological monitoring is the approach to be favoured. However, it is important to consider that heat, in the same way as the workload or the anatomical, physiological and biochemical characteristics of individuals, is only one of the many factors that can affect biological monitoring data.

5.2 Identification of occupations

The second objective of this study was to identify occupations where workers could be potentially concomitantly exposed to thermal stress and chemicals. Since few data have been published in this field, we used an approach similar to the Delphi method, based on the judgement of experts (Cuhls et al., 2002). The principle of this method is that predictions made by a group of experts are reliable. However, while the Delphi method can make use of successive consultations, in this study the group of experts was consulted only once. In fact, from the initial consultation, occupations could be clearly identified that involved more risk for exposure to thermal stress and chemicals. There is always some subjectivity in an approach based on professional judgement. However, the use of risk matrices for this study provided a more systematic dimension to the evaluation of thermal stress parameters. In addition, the data presented in Table 4 show that there can be significant differences in the ratings assigned by the experts for the same occupation. For this reason, no subtle comparison was made between the mean calculated ratings. Instead, we chose to present as priority occupations all of the occupations with a mean rating below 3.

The 22 prioritized occupations are listed in Table 4. They include 20 occupations in the metal manufacturing sector, as well as roofers and firefighters. It is difficult to estimate the real numbers related to the priority occupations in the metal manufacturing sector because other occupations are also associated with the same NOC-4. Hence, more than 14,000 workers would be associated with the NOC-4 occupations, including the occupation titles appearing in Appendix 3, for this activity sector. While the real number of workers simultaneously exposed to thermal stress and chemicals is less than this number, it is reasonable to estimate at a few thousand the number of Québec workers working in the metal manufacturing sector who would be involved. Added to these are the 3,000 roofers and shinglers, as well as the 4,900 firefighters.

Wearing personal protective equipment may help to increase workers' thermal stress, but on the other hand, it often reduces or even eliminates exposure to chemicals. Also, the impact of intense cold and heat wave episodes was not considered in evaluating the thermal stress of workers associated with occupations performed outdoors. This constitutes a limitation in the present study since many of the 136 occupations appearing in the list submitted to the experts are performed outdoors (e.g., agriculture, forestry, construction). These factors are involved, sometimes significantly, in the level of thermal stress. Hence, some workers working outdoors or wearing personal protective equipment and not among this study's prioritized occupations may also be at risk. Since the occupation ranking is based on a theoretical approach, without observations or measurements, this ranking could have been different following workplace interventions involving objective measurements of the different stressors affecting the workers. In fact, the wearing of personal protective equipment, clothing insulation, acclimatization of workers or not, their state of health and their physical condition, cold or heat wave episodes, as well as air velocity are factors to be considered in evaluating thermal stress, which are all likely to influence the body's response in a real work situation.

As previously mentioned, exposure to certain chemicals can affect the thermoregulatory mechanisms and thus reduce a worker's capacity to adapt to heat. Ceramic artists can be exposed to lead, farmers and pesticide spreaders to organophosphorus compounds and carbamates, and workers in the 20 prioritized occupations in the metal manufacturing sector to metal oxide fumes, substances that can affect the thermoregulatory mechanisms. For exposure levels close to permissible ambient concentrations, workers exposed to these chemicals could have more difficulty adapting to heat.

6. CONCLUSION, APPLICABILITY OF RESULTS, AND POTENTIAL BENEFITS

On the completion of this study, simultaneous exposure to cold and chemicals seems generally to be associated with a reduced toxicity of xenobiotics. However, concomitant exposure to heat and chemicals leads to an increase in the pulmonary and cutaneous absorption of xenobiotics, which translates into an increase in the concentration of the different biological exposure monitoring and toxicity parameters. The degree of these increases depends on the intensity of the thermal stress, the exposure levels, and the physicochemical characteristics of the chemicals. Since the data found in the literature correspond in many cases to situations of intense exposure to thermal stress, toxicokinetic models should be developed and validated to assess the weight of each of these factors by taking into account temperature and chemical exposure conditions as encountered in workplaces. Workplace studies could also be carried out to document, in real situations, the impact of heat exposure on the absorption and toxicokinetics of chemicals, with biological monitoring being a tool of choice in studying this problem.

Based on the results of this study, the occupations and workers most affected in Québec by this problem are those in the non-metallic mineral product manufacturing/primary metal manufacturing/fabricated metal product manufacturing sector, roofers, and firefighters. Furthermore, these sectors should be given priority in future research aiming to better characterize the risk.

This review should provide occupational health practitioners with a guide in their risk evaluation procedures for situations of simultaneous exposure to thermal stress and chemicals, mainly by having identified some higher-risk occupations.

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APPENDIX 1: EXAMPLE OF THERMAL RISK RATING

ACTIVITY SECTOR (NAICS) 111-112-114: AGRICULTURE, ANIMAL PRODUCTION AND FISHING							
OCCUPATIONS	TEMPERATURE	HUMIDITY	RADIATION	WORKLOAD	PROBABILITY	SEVERITY	RISK RATING
Beekeeper/Apiculturist/Apiarist	normal	normal	normal	light	average	low	negligible
Farm hand (unskilled worker)	high	high	hot	heavy	very high	very high	critical
Aquaculturist	normal	high	normal	average	low	low	negligible
Tree surgeon (urban area)	high	high	hot	average	high	average	important
Sugar bush worker	low	high	cold	heavy	average	average	tolerable
Sugar bush worker/maple tapping worker	low	high	cold	heavy	average	average	tolerable
Aquaculture support worker	normal	high	normal	heavy	average	low	negligible
Semiskilled grain farm worker	high	high	very hot	very heavy	very high	very high	critical
Semiskilled cattle production worker	high	high	hot	heavy	high	high	important
Cattle production helper	high	high	hot	heavy	high	high	important
Semiskilled horticulture worker	high	normal	hot	heavy	high	high	important
Semiskilled dairy production worker	high	high	hot	heavy	high	high	important
Dairy farm helper	high	high	hot	heavy	high	high	important
Semiskilled fish farm worker	normal	high	normal	average	average	low	negligible
Semiskilled pig production worker	high	high	hot	heavy	high	high	important
Pig production helper	high	high	hot	heavy	high	high	important
Poultry farm worker	high	normal	hot	heavy	high	average	tolerable
Poultry production helper	high	normal	hot	heavy	high	average	tolerable
Ovine production worker	high	high	very hot	heavy	very high	very high	critical
Ovine production helper	high	high	very hot	heavy	very high	very high	critical
Greenhouse helper	high	high	hot	heavy	very high	average	important
Farmer	high	normal	hot	heavy	high	high	important
Grower	high	normal	hot	heavy	high	high	important
Vineyard worker	high	normal	hot	heavy	high	high	important
Mariculture technician	normal	normal	hot	heavy	average	high	important

APPENDIX 2: EXAMPLE OF ASSESSMENT OF CONCOMITANT EXPOSURE TO CHEMICALS AND THERMAL STRESSES USING PRIORITY RATINGS

ACTIVITY SECTORS (NAICS)	OCCUPATION GROUPS MOST RISK FOR THERMAL STRESS	PRESENCE OF CHEMICALS								PRIORITY RATING
		SOLVENTS	DUSTS	PESTICIDES	PAH[1]	GASES	HEAVY METALS	ASBESTOS /SILICA	REAGENTS/ OTHER SUBSTANCES	
AGRICULTURE, ANIMAL PRODUCTION AND FISHING	Farm hand (unskilled worker)	✓	✓	✓	✓	✓			✓	1
	Tree surgeon (urban area)			✓			✓			5
	Semiskilled grain farm worker	✓	✓	✓	✓	✓			✓	1
	Semiskilled cattle production worker		✓	✓					✓	5
	Cattle production helper		✓	✓					✓	5
	Semiskilled horticulture worker		✓	✓			✓		✓	4
	Semiskilled dairy production worker	✓							✓	2
	Dairy farm helper	✓							✓	2
	Semiskilled pig production worker					✓				3
	Pig production helper			✓		✓				3
	Ovine production worker		✓	✓						1
	Ovine production helper		✓	✓						1
	Greenhouse helper			✓			✓		✓	3
	Farmer	✓	✓	✓	✓	✓			✓	1
	Grower	✓	✓	✓	✓	✓			✓	1
	Vineyard worker		✓	✓						3
	Mariculture technician								✓	4

[1]PAH: Polycyclic aromatic hydrocarbons
[2] Rating 1: highest – rating 5: lowest

APPENDIX 3: PRIORITIZATION OF OCCUPATIONS IN RELATION TO THEIR POTENTIAL RISK RESULTING FROM CONCOMITANT EXPOSURE TO CHEMICALS AND THERMAL STRESSES

<table>
<tr><th rowspan="2">#</th><th rowspan="2">NAICS Description</th><th rowspan="2">NOC-4[1] Description</th><th rowspan="2">Priority occupations</th><th colspan="5">Priority rating</th><th></th></tr>
<tr><th>Mean</th><th>S.D.</th><th>Min</th><th>Max</th><th>Range</th><th>n[2]</th></tr>
<tr><td>1</td><td rowspan="8">Agriculture, forestry, fishing and hunting (except for support activities)</td><td rowspan="6">Agricultural labourers (n=12,780)</td><td>Farm hand (unskilled worker)</td><td>5.0</td><td>2.7</td><td>1</td><td>10</td><td>9</td><td>13</td></tr>
<tr><td>2</td><td>Ovine production worker</td><td>4.6</td><td>1.9</td><td>1</td><td>8</td><td>7</td><td>13</td></tr>
<tr><td>3</td><td>Ovine production helper</td><td>4.4</td><td>1.9</td><td>1</td><td>8</td><td>7</td><td>13</td></tr>
<tr><td>4</td><td>Semiskilled grain and fodder production worker</td><td>4.9</td><td>2.2</td><td>1</td><td>10</td><td>9</td><td>13</td></tr>
<tr><td>5</td><td>Semiskilled dairy production worker</td><td>5.2</td><td>2.0</td><td>1</td><td>8</td><td>7</td><td>13</td></tr>
<tr><td>6</td><td>Dairy farm helper</td><td>5.1</td><td>2.0</td><td>1</td><td>8</td><td>7</td><td>13</td></tr>
<tr><td>7</td><td rowspan="2">Farmers and farm managers (n=15 861)</td><td>Farmer</td><td>5.9</td><td>2.3</td><td>1</td><td>10</td><td>9</td><td>13</td></tr>
<tr><td>8</td><td>Grower</td><td>5.9</td><td>2.3</td><td>1</td><td>10</td><td>9</td><td>13</td></tr>
<tr><td>9</td><td rowspan="2">Food, beverage and tobacco product manufacturing</td><td>Hand workers (n=1,927)</td><td>Day labourer (reception of goods)</td><td>7.0</td><td>2.2</td><td>1</td><td>10</td><td>9</td><td>13</td></tr>
<tr><td>10</td><td>Food, beverage and tobacco processing workers (n=14,300)</td><td>Food processing labourer</td><td>7.3</td><td>1.9</td><td>3</td><td>10</td><td>7</td><td>13</td></tr>
<tr><td>11</td><td rowspan="8">Construction</td><td rowspan="2">Construction trades helpers and labourers (n=15,135)</td><td>Day labourer</td><td>4.9</td><td>1.6</td><td>2</td><td>8</td><td>6</td><td>13</td></tr>
<tr><td>12</td><td>Civil engineering site labourer</td><td>4.7</td><td>1.7</td><td>2</td><td>8</td><td>6</td><td>13</td></tr>
<tr><td>13</td><td>Roofers and shinglers (n=3,007)</td><td>Roofer</td><td>2.2</td><td>1.1</td><td>1</td><td>4</td><td>3</td><td>13</td></tr>
<tr><td>14</td><td>Heavy equipment operators (except crane) (n=5,687)</td><td>Heavy equipment operator (excavator, grader, backhoe, etc.)</td><td>5.9</td><td>2.2</td><td>2</td><td>9</td><td>7</td><td>13</td></tr>
<tr><td>15</td><td>Bricklayer-masons (n=2,900)</td><td>Bricklayer-mason</td><td>4.6</td><td>2.3</td><td>1</td><td>10</td><td>9</td><td>13</td></tr>
<tr><td>16</td><td>Concrete finishers (n=1,250)</td><td>Cement finisher</td><td>4.4</td><td>1.7</td><td>1</td><td>7</td><td>6</td><td>13</td></tr>
<tr><td>17</td><td>Ironworkers (n=805)</td><td>Reinforcing rod workers</td><td>5.1</td><td>2.2</td><td>2</td><td>8</td><td>6</td><td>13</td></tr>
<tr><td>18</td><td>Boilermakers (n=180)</td><td>Boilermaker (tower crane, tank, boiler assembly)</td><td>3.7</td><td>2.2</td><td>2</td><td>8</td><td>6</td><td>13</td></tr>
<tr><td>19</td><td>Repair and maintenance</td><td>Material handlers (n=89)</td><td>Material handler (warehouse, yard, etc.)</td><td>6.8</td><td>1.9</td><td>2</td><td>9</td><td>7</td><td>13</td></tr>
</table>

#	NAICS Description	NOC-4[1] Description	Priority occupations	Priority rating Mean	S.D.	Min	Max	Range	n[2]
20		Motor vehicle body repairers (n=4,496)	Body repairer	5.7	1.4	4	8	4	13
21			Body repairer helper	5.6	1.6	3	8	5	13
22			Automobile polisher-sander	5.6	1.8	3	9	6	13
23	Machinery manufacturing	Heavy or light metalworking machine operators (n=75)	Metalworking machine operator	5.3	1.7	3	8	5	13
24			Industrial machine operator	5.5	1.7	2	8	6	13
25		Other labourers in processing, manufacturing and utilities (n=328)	Operator-helper labourer	5.3	1.6	2	7	5	12
26		Material handlers (n=323)	Material handler (warehouse)	6.6	2.1	2	10	8	13
27		Machine adjusters (n=478)	Machine adjuster	5.8	1.8	2	9	7	12
28	Forestry and Logging and Support activities for forestry	Logging and forestry labourers (n=1,145)	Swamper	4.4	1.8	2	8	6	13
29			Forest development worker	4.6	2.1	2	8	6	13
30			Seasonal tree planter	4.9	2.5	2	10	8	13
31		Silviculture and forestry workers (n=2,466)	Forest management worker	5.0	1.9	2	8	6	13
32			Silviculture worker	5.2	1.8	3	8	5	13
33			Forester	4.9	2.0	2	8	6	13
34		Logging machinery operators (n=1,547)	Skidder operator	4.9	2.0	2	8	6	13
35		Chainsaw and skidder operators (n=1,406)	Feller	4.3	1.9	2	8	6	13
36		Construction millwrights and industrial mechanics (except textile) (n=347)	Site equipment mechanic	5.2	1.6	2	7	5	13
37		Labourers in wood, pulp and paper processing (n=66)	Sawmill labourer	4.9	1.9	2	8	6	13
38	Transportation equipment manufacturing	Light and heavy metalworking machine operators (n=236)	Metalworking machine operator	5.4	1.9	2	8	6	13
39		Plastics processing machine operators (n=118)	Plastics processing machine operator (vehicle parts)	4.9	1.5	3	8	5	13

#	NAICS Description	NOC-4[1] Description	Priority occupations	Priority rating					
				Mean	S.D.	Min	Max	Range	n[2]
40		Other labourers in processing, manufacturing and utilities (n=393)	Production day labourer	5.9	1.3	4	8	4	12
41		Material handlers (n=505)	Material handler (storeroom-warehouse)	7.5	2.4	2	10	8	13
42	Furniture and related product manufacturing	Material handlers (n=2,239)	Material handler (warehouse, yard, etc.)	6.5	1.9	2	9	7	13
43		Other labourers in processing, manufacturing and utilities (n=4,131)	Wood product manufacturing shop labourer	5.9	1.7	3	8	5	13
44	Mining, quarrying, and oil and gas extraction	Underground production and development miners (n=1,609)	Miner	3.9	1.9	1	7	6	12
45			Underground miner	4.0	2.0	1	7	6	12
46		Machine operators, mineral and metal processing (n=244)	Machine operator, mineral processing	4.4	2.2	1	7	6	12
47		Mine labourers (n=346)	Rock splitter	4.4	2.3	1	8	7	12
48		Oil and gas well drillers, servicers, testers and related workers (n=226)	Directional drilling operator	4.7	2.0	2	7	5	13
49		Construction millwrights and industrial mechanics (except textile) (n=489)	Mechanic	5.2	1.7	3	7	4	13
50		Material handlers (n=180)	Material handler (warehouse, yard, etc.)	6.1	2.2	2	9	7	13
51	Paper manufacturing	Papermaking and coating control operators (n=811)	Operator, pulp and paper production unit	4.0	1.73	2	8	6	13
52		Pulping control operators (n=246)	Bleacher operator	3.5	1.7	2	8	6	12
53			Paper-pulp preparer	3.9	1.8	2	8	6	13
54		Labourers in wood, pulp and paper processing (n=4,372)	Labourer	3.5	1.1	2	5	3	13
55		Pulp mill machine operators (n=973)	De-inking machine operator	3.6	0.7	3	5	2	11
56			Operator, chemical products	3.5	0.9	3	6	3	11
57			De-inking shop operator	3.6	0.9	2	5	3	11

#	NAICS Description	NOC-4[1] Description	Priority occupations	Priority rating					
				Mean	S.D.	Min	Max	Range	n[2]
58		Material handlers (n=926)	Material handler in pulp and paper (manufacture)	4.6	1.3	3	7	4	13
59			Warehouseman	5.5	2.2	2	9	7	13
60			Loader	5.3	2.0	2	8	6	13
61	Plastics and Rubber Products Manufacturing	Plastics processing machine operators (n=2,829)	Machine operator	5.0	1.2	3	7	4	12
62			Sprayer operator	4.5	1.2	3	7	4	12
63			Calender operator	4.7	1.4	2	7	5	13
64			Extruding machine operator	4.4	1.5	2	7	5	13
65			Moulding machine operator	4.2	1.6	2	7	5	13
66		Labourers in rubber and plastics products manufacturing (n=4,965)	Operator helper	4.6	1.7	2	7	5	13
67		Plastic products assemblers, finishers and inspectors (n=2,610)	Finisher-inspector	5.1	1.6	2	8	6	12
68		Supervisors, plastic and rubber products manufacturing (n=1,743)	Team leader	6.0	1.6	3	8	5	13
69		Construction millwrights and industrial mechanics (except textile) (n=689)	Millwright	5.0	1.6	3	8	5	13
70		Shippers and receivers (n=771)	Warehouse person	6.7	1.9	2	9	7	13
71	Non-Metallic Mineral Product Manufacturing / Primary metal manufacturing / Fabricated Metal Product Manufacturing	Boilermakers (n=248)	Boilermaker	2.9	1.5	1	5	4	12
72		Foundry workers (n=1,489)	Melter	2.3	1.6	1	5	4	13
73			Caster	2.3	1.5	1	6	5	13
74			Gold caster	2.1	1.5	1	6	5	11
75			Furnaceman	2.5	1.6	1	6	5	13
76			Furnace operator	2.7	1.7	1	6	5	13
77			Casting machine operator	2.9	1.6	1	6	5	12
78			Moulder	2.5	1.3	1	6	5	13

#	NAICS Description	NOC-4[1] Description	Priority occupations	Priority rating					
				Mean	S.D.	Min	Max	Range	n[2]
79		Machine operators, mineral and metal processing (n=3,010)	Smelting furnace operator	2.9	1.6	1	6	5	13
80			Metal fabricating machine operator	2.7	1.6	1	6	5	13
81			Steel hardener	2.8	1.5	1	6	5	13
82			Extruder	2.8	1.6	1	6	5	12
83		Labourers in mineral and metal processing (n=3,862)	Foundry labourer	2.5	1.3	1	5	4	13
84			Operator helper, smelting furnace	2.5	1.3	1	5	4	13
85			Baking furnace labourer	2.5	1.3	1	5	4	13
86		Labourers in metal fabrication (n=2,237)	Forge helper	2.4	1.0	1	5	4	13
87			Metal processing labourer	2.5	1.1	1	5	4	13
88			Moulder helper	2.5	0.9	2	5	3	13
89		Material handlers (n=2 070)	Warehouse material handler	5.2	2.2	2	8	6	13
90		Concrete, clay and stone forming operators (n=1,341)	Brick kiln operator	2.7	1.4	1	5	4	12
91			Ceramic oven operator	2.6	1.4	1	5	4	12
92			Cement making machine operator	3.0	1.0	2	5	3	12
93			Concrete block production worker	3.0	1.3	2	6	4	12
94	Petroleum and coal product / chemical manufacturing	Boilermakers (n=76)	Boilermaker	3.2	1.3	1	5	4	12
95		Material handlers (n=694)	Material handler	4.2	1.7	2	7	5	11
96		Labourers in chemical processing and utilities (n=1,251)	Labourer (maintenance)	4.0	1.1	2	5	3	11
97			Production labourer	4.4	1.4	2	6	4	11
98		Chemical plant machine operators (n=4,311)	Chemical processor	4.1	1.3	3	7	4	11
99			Chemical processing machine operator	4.4	1.4	3	7	4	11
100			Distiller operator	4.3	2.1	1	8	7	11

#	NAICS Description	NOC-4[1] Description	Priority occupations	Priority rating					
				Mean	S.D.	Min	Max	Range	n[2]
101	Utilities / Public administration	Silviculture and forestry workers (n=199)	Tree pruner	5.5	2.4	2	10	8	13
102		Firefighters (n=4,903)	Firefighter	2.4	1.8	1	7	6	12
103		Landscaping and grounds maintenance labourers (n=1 064)	Grounds maintenance labourer	5.1	1.7	3	8	5	13
104		Public works and maintenance labourers (n=8,507)	Park maintenance worker	5.8	1.6	3	8	5	13
105			Labourer (maintenance and public works)	5.5	2.0	3	9	6	13
106			Road worker (street repair and maintenance)	4.2	1.9	2	8	6	13
107		Heavy equipment operators (except crane) (n=1,306)	Power shovel operator	6.2	2.3	2	10	8	13
108		Landscape and horticultural technicians and specialists (n=786)	Landscape gardener	4.8	1.6	3	8	5	13
109		Electrical power line and cable workers (n=2,200)	Lineman	6.1	2.4	2	10	8	13
110			Transmission lineman	6.1	2.4	2	10	8	13
111			Repairman (lines)	6.3	2.6	2	10	8	13
112		Public works maintenance equipment operators (n=344)	Motorized equipment operator (maintenance and public works)	6.3	2.1	2	10	8	13
113		Material handlers (n=269)	Material handler (municipal warehouse)	6.7	2.1	2	9	7	13
114	Textile and textile product mills / leather and allied product manufacturing	Textile dyeing and finishing machine operators (n=1,122)	Bleacher	3.8	1.5	1	6	5	13
115			Calender operator	4.3	1.6	2	8	6	12
116		Textile fibre and yarn preparation machine operators (n=1,225)	Textile fibre preparation machine operator	4.2	1.6	2	7	5	12
117		Hide and pelt processing workers (n=47)	Leather garment manufacturing worker	4.8	2.1	1	8	7	12
118		Material handlers (n=807)	Warehouse material handler	7.0	2.6	2	10	8	12
119	Transportation and warehousing	Material handlers (n=4,930)	Merchandise material handler	6.9	2.2	2	10	8	13

#	NAICS Description	NOC-4[1] Description	Priority occupations	Priority rating					
				Mean	S.D.	Min	Max	Range	n[2]
120			Storageman	7.2	2.3	2	10	8	13
121		Engine room crew, water transport (n=40)	Engine-room crew	4.3	3.0	1	10	9	13
122	Accommodation and food services	Cooks (n=37,934)	Cook	4.9	1.9	3	8	5	13
123			Kitchen helper	5.0	2.0	3	8	5	13
124		Food counter attendants, kitchen helpers and related occupations (n=44,498)	Dishwasher	5.2	2.5	2	10	8	13
125	Health care and social assistance	Cooks (n=7,952)	Cook	5.3	1.8	3	8	5	13
126			Kitchen helper	5.4	1.9	3	8	5	13
127		Food counter attendants, kitchen helpers and related occupations (n=8,553)	Dishwasher	5.9	2.7	2	10	8	13
128	Food and beverage stores	Bakers (n=3,200)	Baker	4.5	1.7	2	8	6	13
129			Pastry cook	4.9	1.5	3	8	5	13
130	All NAICS	Dry cleaning and laundry occupations (n=4,246)	Presser-cleaner	3.5	1.6	1	6	5	13
131			Laundry attendant	3.9	1.7	1	7	6	13
132		Ironing, pressing and finishing occupations (n=2,638)	Presser-cleaner	3.4	1.6	1	6	5	13
133			Laundry attendant	4.3	1.7	2	7	5	13
134		Landscaping and groundskeeping managers and contractors (n=528)	Grounds maintenance landscaper	5.3	1.8	3	8	5	13
135		Landscaping and grounds maintenance labourers (n=13,082)	Grounds maintenance worker	4.8	1.8	2	8	6	13
136		Occupations unique to the Armed Forces (n=11,428)	Military - soldier	4.8	1.2	2	6	4	12

[1] The numbers of workers (n) presented are related to the NOC-4 and NAICS to which they were linked, and not only to the occupation titles that were judged as priority. Thus, the various NOC-4 professions retained, and their respective number of workers, often include, in addition to the priority occupation titles, other occupation titles not retained as priority in this study. To obtain a more complete description of all the professions and occupation titles covered by an NOC code, the reader can consult the following site: http://www.statcan.gc.ca/subjects-sujets/standard-norme/soc-cnp/2006/noc2006-cnp2006-menu-eng.htm (consulted March 2014).

[2] Number of experts that assigned a rating