RATIONALE FOR THE DEVELOPMENT OF ONTARIO AIR STANDARDS FOR SULPHUR DIOXIDE (SO_2)

May 2017

Standards Development Branch
Ministry of the Environment
and Climate Change

Executive Summary

This document provides the scientific rationale used by the Ontario Ministry of the Environment and Climate Change (the Ministry) in proposing updated Ambient Air Quality Criteria (AAQCs) and air standards for sulphur dioxide (SO_2) (CAS # 7446-09-5). This document builds upon the *Science Discussion Document on the Development of Air Standards for Sulphur Dioxide (SO_2)*, which describes the science reviewed (MOECC, 2016).

In preparing this document, the Ministry considered the available toxicological evidence, human health risk assessments from other jurisdictions, and the science-related stakeholder questions and comments gleaned from pre-consultation on the Science Discussion Document. There was a general consensus from the pre-consultation stage that a short-term (acute) AAQC and air standard would be supported based on human health effects, in addition to a long-term (chronic) AAQC and air standard based on phytotoxic effects.

The Ministry relied primarily on the recent health risk assessment carried out by Health Canada (2016) to inform the development of the Canadian Ambient Air Quality Standards (CAAQS) for SO_2. This assessment also reflects information obtained from the U.S. EPA (2008) and the World Health Organization (WHO, 2005). The Ministry used these assessments to identify the most sensitive adverse effect associated with ambient air exposure of SO_2, and concurs with world-wide jurisdictions that respiratory morbidity is the critical adverse health endpoint for acute SO_2 exposure.

Considering the fact that asthma sufferers are prone to the health effects of bronchoconstriction, combined with the asthma prevalence rates in the Ontario population, asthmatics are considered a significant susceptible group in establishing a health-based AAQC and air standard for SO_2. Specifically, the Ministry proposes that an acute AAQC and air standard for SO_2 be based on bronchoconstriction as observed by the quantitative evaluation of detriments in lung function in exercising asthmatics in controlled chamber studies. Bronchoconstriction is a well-supported mode of action in SO_2 respiratory morbidity, via stimulation of chemosensitive receptors initiating reflexive contraction of smooth muscles in the bronchial airways. This mode of action is also supported by the semi-quantitative information from relevant epidemiological studies.

Based on the U.S. EPA and Health Canada meta-analyses of chamber studies of exercising asthmatics, the Ministry considers 67 ppb (180 $\mu g/m^3$) as an appropriate proposed value for deriving an acute AAQC, in order to protect the general population and sensitive individuals against the health effects associated with a 10-minute exposure to SO_2. From this, AAQCs and air standards with appropriate averaging times are proposed to support evaluation of ambient air monitoring and compliance under Ontario Regulation 419: Air Pollution – Local Air Quality (O. Reg. 419/05), respectively.

Concurrently, the Ministry considers the direct effect of SO_2 on vegetation, including foliar injury, decreased photosynthesis, and decreased growth, as the critical adverse endpoint for chronic SO_2 exposure, and considers lichens as the susceptible species in studying the chronic effects of SO_2 on the environment. Based on work performed by the WHO, the Ministry considers 4 ppb (10 µg/m^3) as appropriate proposed value for both a chronic AAQC and air standard for SO_2, in order to protect ecological impacts, with an annual averaging time being the most toxicologically-relevant.

Together, based a quantitative analysis of human clinical studies under controlled conditions of exercising asthmatics experiencing respiratory morbidity, the Ministry proposes the following health-based acute AAQC for SO_2:

Proposed 10-minute AAQC for SO_2:

> **Ten-minute (10-minute) Ambient Air Quality Criterion (AAQC) of 180 µg/m^3 (micrograms per cubic metre of air) for SO_2 (67 ppb), based on respiratory morbidity in exposed sensitive populations**

AAQCs may be converted to different averaging times to support implementing O. Reg. 419/05 compliance purposes. The Ministry utilizes conversion factors derived from an exponential equation based on empirical monitoring data, ratios of concentrations observed for different averaging times, and meteorological considerations, referenced in Section 17 of O. Reg. 419/05. Thus, using the preceding health-based 10-minute AAQC as a foundation, the following AAQC and air standard are proposed:

Proposed One-hour AAQC for SO_2:

> **One-hour (1-hour) Ambient Air Quality Criterion (AAQC) of 100 µg/m^3 (micrograms per cubic metre of air) for SO_2 (40 ppb), based on respiratory morbidity in exposed sensitive populations**

For Ontario Regulation 419: Air Pollution – Local Air Quality compliance purposes, the Ministry proposes the following air standard for SO_2:

Proposed One-hour Standard for SO_2:

> **One-hour (1-hour) air standard of 100 µg/m^3 (micrograms per cubic metre of air) for SO_2 (40 ppb), based on respiratory morbidity in exposed sensitive populations**

Based on the observable effects on lichen abundance and biodiversity with environmental chronic exposures to SO_2, and the assessment of the WHO, the Ministry proposes the following ecologically-based chronic AAQC for SO_2:

Proposed Annual AAQC for SO_2:

- **Annual Ambient Air Quality Criterion (AAQC) of 10 μg/m^3 (micrograms per cubic metre of air) for SO_2 (4 ppb), based on vegetation damage in exposed sensitive species**

Additionally, for Ontario Regulation 419: Air Pollution – Local Air Quality compliance purposes, the Ministry proposes the following air standard for SO_2:

Proposed Annual Air Standard for SO_2:

- **Annual air standard of 10 μg/m^3 (micrograms per cubic metre of air) for SO_2 (4 ppb), based on vegetation damage in exposed sensitive species**

These standards are proposed to be incorporated into Ontario Regulation 419/05: Air Pollution – Local Air Quality (O. Reg. 419/05).

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1.0 Introduction

1.1 Background

The Ontario Ministry of Environment and Climate Change (the Ministry) has identified the need to develop and/or update air standards for priority contaminants. The Ministry's Standards Plan, which was released in October, 1996 and revised in November, 1999 (MOE 1996; MOE 1999), identified candidate substances for which current air standards will be reviewed or new standards developed. Sulphur dioxide (CAS # 7446-09-5) was identified as a high priority candidate for air standard development based on its release pattern in Ontario, identification as a priority by federal and national committees, and recent toxicological information that was published subsequent to the development of the existing standard in 1974, and retained in 2005.

The purpose of the document is to provide the rationale for the proposed Ambient Air Quality Criteria (AAQCs) and air standards for sulphur dioxide (SO_2). This document builds upon the *Science Discussion Document on the Development of Air Standards for Sulphur Dioxide (SO_2)*, prepared by the Ministry of Environment and Climate Change (MOECC, 2016).

1.2 Overview of the AAQC/Standard Setting Process

AAQCs and air standards are set at concentrations that are protective against adverse effects. They are based solely on science, informed by such factors as the substance's physical and chemical properties, its environmental fate, its environmental effects, its toxicology and human health effects, and the scientific analyses underlying the approaches taken by other jurisdictions in setting effects-based criteria.

The Ministry first develops an AAQC, which is used to evaluate air quality that results from all sources of a contaminant to air. Air standards are based on AAQCs and set under Ontario Regulation 419: Air Pollution – Local Air Quality (O. Reg. 419/05). Air standards may sometimes be numerically the same as an AAQC, but are tools that contribute to the management of local air quality. Under the regulation, air standards are used to assess the contributions of a contaminant to air by a regulated facility.

The current process for setting AAQCs and air standards was established in 2008, through consultation with stakeholders. The first step is for the Ministry to prepare a Science Discussion Document and to invite interested stakeholders to discuss the science in a "pre-consultation" meeting; during the current update of the SO_2 air standard, this occurred on May 11, 2016, in Toronto. After giving consideration to outstanding issues which may arise from the pre-consultation phase, a regulatory proposal is made through a Rationale Document (i.e., this document), which undergoes formal public consultation by posting on the Ontario Environmental Registry (i.e., the "consultation" step). The posting of the Rationale Document provides an opportunity for input from stakeholders regarding the proposed AAQCs and air standards. Meetings with stakeholders may also be held during this step. The Ministry considers comments received during the consultation to inform its decisions on the proposed AAQCs and air standards. A Decision Document is prepared, which includes key comments from stakeholders and the responses provided by the Ministry. The air standards are added to O. Reg. 419/05 and the final decisions are posted on the Environmental Registry.

2.0 Background

In preparing the rationale for developing AAQCs and air standards for SO_2 that are protective of human health and the environment, the Ministry considers the available toxicological evidence, human health risk assessments from other jurisdictions, and the science-related stakeholder comments gleaned from pre-consultation of the Science Discussion Document. For comparison purposes, 1 ppb SO_2 = 2.66 µg/m^3 (at 20.0^{o}C and 1 atm).

2.1 Summary of the Science Discussion Document

A summary of the finalized *Science Discussion Document on the Development of Air Standards for Sulphur Dioxide (SO_2)* (MOECC, 2016) is presented here by repeating its Executive Summary:

> Sulphur dioxide is a colourless gas at room temperature and typical environmental conditions. As it is heavier than air, it may accumulate at ground level under some ambient conditions. SO_2 is released from natural sources (e.g., forest fires, wildfires), and from anthropogenic sources in quantities that may substantially affect local air quality. Major anthropogenic sources in Ontario include non-ferrous smelting and refining, petroleum refining, iron and steel industry, transportation sources (e.g., air and marine transportation), incinerators, and other industrial sources (e.g. cement plants, pulp and paper mills, chemical industry). The odour of SO_2 has been described as irritating and pungent (U.S. National Library of Medicine, 2016), with a consensus odour threshold value of 500 ppb (1300 µg/m^3) (Health Canada, 2016).
>
> SO_2 can affect elements of ecosystems via direct impact on plants through soil uptake or direct adsorption of SO_2 from air, and indirectly through the deposition and retention in soils of other sulphur-containing compounds such as sulphuric acid and sulphate particles. Acute and chronic exposures to SO_2 have phytotoxic effects on vegetation which include foliar injury, decreased photosynthesis, and decreased growth. Lichens are among the first species affected by acidifying deposition and have been used as early warning indicators of air pollution, particularly acidifying sulphur pollutants.
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> In humans, inhaled SO_2 is rapidly solubilized in the upper respiratory tract and may be absorbed across nasal mucosa and the mucosal cells of the trachea (ATSDR, 1998; Arts et al., 2006). With increasing physical activity, the shift from nasal to oronasal breathing results in greater SO_2 penetration into the bronchial region of the respiratory tract. SO_2 is not likely to reach the lungs. Once absorbed across mucosal cells, hydrated SO_2 transforms to sulphite/bisulphite at

physiologic pH. However, sulphite levels in the body are predominately influenced by endogenous production and by ingestion of sulphites in food.

Inhaled SO_2 stimulates bronchial epithelial irritant receptors in the tracheobronchial tree. This initiates a reflexive contraction of smooth muscles in the bronchial airways associated with bronchial constriction. It is this bronchial constriction that is associated with respiratory morbidity. Using a weight of evidence approach, Health Canada and the United States Environmental Protection Agency (U.S. EPA, 2008; 2015; Health Canada, 2016) concluded that the strongest causal relationship exists between short-term SO_2 exposure and respiratory effects. These adverse effects include bronchoconstriction, changes in lung function, airway inflammation, airway hyper-responsiveness, and emergency room hospital visits. Respiratory morbidity can be considered the underlying critical effect for the formation of a SO_2 AAQC. However, exposure estimates are considered to be more accurate in human clinical studies under controlled conditions (i.e., chamber studies) compared to epidemiological data, and thus are typically relied upon for quantitative evaluation by various jurisdictions.

The U.S. EPA amassed data from a series of chamber studies and performed a meta-analysis, demonstrating dose response findings in respiratory function and percent of affected asthmatics These studies formed the basis of the consensus benchmarks in the development of the U.S. EPA National Ambient Air Quality Standards (NAAQS). Health effect consensus benchmark concentrations of 200 ppb and 400 ppb were used to perform a quantitative exposure and risk assessment on two proposed 1-hour values at 50 ppb and 100 ppb, in order to predict the frequency in days of 5 minute exceedences of the benchmark concentration. From this, the U.S. EPA inferred that at a 75 ppb 1-hour limit, there is potential for a few daily 5 minute exceedences of the health effects benchmark concentrations of 200 and 400 ppb over a year. Thus, the 75 ppb (200 $\mu g/m^3$) 1-hour average NAAQS for SO_2 was established to be protective of public health, with an adequate margin of safety.

Health Canada (2016) developed a SO_2 reference concentration (RfC) from the statistically significant lowest observed adverse effect concentration (LOAEC) of 400 ppb, resulting in lung function decrements from controlled human exposure studies of asthmatics exposed for 5-10-minutes at increased ventilation (WHO, 2005; U.S. EPA, 2008; Johns and Linn, 2011). To account for the uncertainties in the controlled human exposure dataset, and to consider the supporting evidence from epidemiology, a combined uncertainty factor (UF) of 6 was applied. This resulted in a 10-minute inhalation RfC of 67 ppb (180 $\mu g/m^3$), which was converted to a 1-hour limit of 40 ppb (100 $\mu g/m^3$) in consideration of the stability of the metric. The RfC of 67 ppb (180 μg/m^3) was used to inform the CAAQS management levels.

In attempting to identify a key study for AAQC development, the Ministry's will focus on data that will allow for protection to all individuals in the general population, including those who are likely to be susceptible to developing the critical effect. Specific life-stages or groups thought to be at risk for increased susceptibility to SO_2-mediated adverse health effects include asthmatics. Estimates of exposure are considered to be more accurate in chamber studies, and thus will be relied upon for quantitative evaluation. The Ministry proposes to utilize these studies as a group, to be representative of the 'key study' for AAQC and air standard development. In consideration of the U.S. EPA (2008) analysis of a number of chamber studies, consensus benchmarks concentrations of 200 ppb (525 μg/m^3) and 400 ppb (1050 μg/m^3) are noted, and as used by Health Canada (2016) in developing the 10-minute RfC of 67 ppb (180 μg/m^3).

A review of the mode of action and controlled human studies support intermittent spikes in the 5-10-minute range as being the most health-relevant. Thus, a short averaging time is appropriate. The selection of the appropriate averaging time, however, needs to be balanced with monitoring practicalities, modelling capabilities, jurisdictional consistency, and other implementation considerations.

In addition, a chronic AAQC and air standard aimed to protect vegetation from direct SO_2 effects will be considered by the Ministry, based on the WHO vegetation effects range of 4 ppb (10 μg/m^3) to 8 ppb (20 μg/m^3) on an annual basis.

2.2 Summary of the Pre-consultation Meeting and Comments

In April 2016, as part of the Standards Plan for air standards development (MOE, 1996; MOE, 1999), the Ministry distributed the Science Discussion Document for SO_2 to interested stakeholders (MOECC, 2016). The Ministry requested scientific input regarding the toxicological information examined by the Ministry, and comments on the strengths and weaknesses of the possible paths towards the development of the AAQCs and air standards for SO_2. On May 11, 2016, the Ministry hosted a Pre-consultation Science Meeting at 40 St. Clair Avenue West, Toronto, with interested stakeholders and invited participants to provide any additional comments in writing, following the meeting. The Ministry received oral and written comments and information from members of some First Nation communities as well as from stakeholders representing industry, public health, environmental groups and consulting firms.

A summary of the key questions and comments received on the draft Science Discussion Document is provided below.

1) *Does the Ministry consider asthmatics as the most sensitive group on which to base the standard or does the ministry consider other groups to be more sensitive?*

The Ministry considers asthmatics to be the most sensitive group, and would not propose a more stringent standard based on another more sensitive population. However, the acknowledgment of the variation within the asthmatic population remains.

2) *Does the Ministry have details regarding the contribution of SO_2 to air from various sources? Setting an air standard under the regulation does not address unregulated sources and this should be considered if the goal is improvement in air quality*.

The local air quality regulation is intended to address Ontario point sources of air contaminants and is one of the many tools used by Ontario to manage air quality.

3) *Will the Ministry endorse the (then-proposed) Canadian Council of Ministers of the Environment (CCME) Canadian Ambient Air Quality Standard (CAAQS) for SO_2 (i.e., will the CAAQS process influence the development of the Ontario air standards)?*

As a part of the continuing implementation of the federal Air Quality Management System, on October 3, 2016, CCME announced new Canadian Ambient Air Quality Standards (CAAQS) for sulphur dioxide. Ontario has been an active participant with other provinces and territories in the development of the CAAQS, which are non-regulatory targets intended to drive improvements in ambient air quality. Health Canada's health risk assessment of SO_2 has informed the setting of both the CAAQS and Ontario proposed air standards. However, CAAQS are established at concentrations that are achievable, whereas Ontario's air standards are based solely on effects information. Specifically, the non-regulatory CAAQS ranges represent ambient air targets developed in consideration of not only health and environmental impacts, but also current standard levels, trends and projections in ambient concentrations, and elements of achievability; these latter considerations are not considered in Ontario's AAQC and air standard development process. In Ontario, achievability and economic issues are addressed through technology-based standards under O. Reg. 419/05.

4) *While it is understood that the clinical studies provide the quantitative estimate of exposure and effects, will the Ministry consider how to give more weight to epidemiological studies?*

Epidemiological studies have shown relationships between SO_2 exposure and effects at any air concentration. However, at low concentrations of SO_2 in ambient air, it is difficult to separate the SO_2 effects from other co-occurring pollutants like PM and NO_2.

5) *The effects on respiration were seen after 5-10-minutes of exposure. This effect does not become more severe if exposure is continued for an hour. Therefore the ministry should use the Health Canada 10-minute reference concentration (RfC) as a 1-hour value without adjustment.*

It is reasonable to assume that a 10-minute RfC of 67 ppb is biologically equivalent to a 1-hour RfC of 67 ppb; that is, the health risks associated with a 10-minute or 1-hour exposure at a *constant level* of 67 ppb are indistinguishable from each other. This is because biological responses to SO_2 inhalation exposure occur very rapidly, within the first few minutes from commencement of inhalation; continuing the exposure further does not increase the effects.

However, under the O.Reg. 419/05 modelling compliance structure, meeting a 1-hour air standard (or RfC) at 67 ppb, would not take into consideration meteorological variation and may allow for peak periods much higher than 67 ppb. As a result, measurements of hourly average concentrations may not be representative of short duration (e.g., 10-minute) “peak" concentrations within the hour, because such peaks (and “valleys”) are smoothed out in the course of meeting a 67 ppb 1-hour compliance point. To reduce the possible occurrences of such peaks, O.Reg. 419/05 conversion factors are utilized in AAQC and air standard setting to convert health-based RfC averaging times (i.e., 10-min) to different averaging times to support ambient air monitoring and O.Reg. 419/05 compliance purposes (i.e., 1-hour), respectively.

6) *The ministry included uncertainty factors for the Health Canada reference concentration in its draft science document. Where does that information come from because Health Canada does not provide it in its own SO_2 science document?*

The ministry received this information directly from Health Canada, and has included this in the finalized Science Discussion Document.

The above discussion informed the finalization of the Science Discussion Document (included in the current posting) and the regulatory proposal described in this document. Moving forward, the Ministry will invite input on this Rationale Document from all interested parties (see Section 6.0).

2.3 Strategies in the Development of SO_2 AAQCs

The Ministry relied primarily on the recent health risk assessment carried out by Health Canada (2016). This assessment included information obtained from the U.S. EPA (2008) and the World Health Organization (WHO, 2005). The strategy employed was to utilize these assessments to identify the most sensitive adverse effect associated with ambient air exposure to SO_2. In this document, the rationale underlying the selection of this endpoint, the key study(s), and most appropriate health-protective point of departures are presented, followed by a discussion of the science policy considerations in the application of uncertainty factors and averaging times.

During the process to identify a critical effect, data for a number of effects are reviewed. The Ministry sets a single AAQC and air standard from a single critical effect; if another effect is of concern, then a second AAQC will be considered for development. Based on the review of the science, the Ministry considered it appropriate to develop a short-term (acute) AAQC based on human health effects (Section 3.0) as well as a long-term (chronic) AAQC based on phytotoxic effects (Section 4.0).

It should be noted that the CCME non-regulatory CAAQS for SO_2 (Table 2.1) are also informed by the 2016 Health Canada risk assessment, but include additional considerations such as current standard levels, trends and projections in ambient concentrations, and elements of achievability; these latter considerations are not considered in the present Ontario AAQC and air standard development process. Notable, during the CAAQS development process, Health Canada described the then-proposed range for the 1-hour CAAQS to be 40 to 70 ppb as follows:

- If the 1-hour CAAQS were set at 40 ppb, all members of the population, including sensitive subgroups such as individuals with asthma, would be expected to be protected if 40 ppb were not exceeded.

- If the 1-hour CAAQS were set at 70 ppb, the general population would be expected to be protected but there would be times when sensitive subgroups such as individuals with asthma may not be protected, even if the 70 ppb were not exceeded.

As the 2020 CAAQS of 70 ppb is not considered to be protective of susceptible individuals, and represents a non-regulatory limit which takes into account current standard levels, implementation issues, projections in ambient concentrations, and elements of achievability, it is not considered applicable to the development of an SO_2 AAQC, and will not be discussed further.

In contrast, the health-based 40 ppb lower bound is considered to be protective of susceptible individuals, as it represents a 1-hour conversion of the health-based Health

Canada 10-minute RfC of 67 ppm, it is thus considered applicable to the development of an SO_2 AAQC and air standard.

Table 2.1. As a part of the federal Air Quality Management System, on October 3, 2016, the Canadian Council of the Ministers of the Environment (CCME) announced new Canadian Ambient Air Quality Standards (CAAQS) for sulphur dioxide that are intended to drive the improvement of air quality across the country. The CAAQS values and management levels for the 1-hour CAAQS are listed in the tables below (CCME, 2017).

Management level and action	Management levels for the 1-hour CAAQS for SO_2 (ppb)	
	Effective 2020	Effective 2025
Red To ensure that CAAQS are not exceeded through advanced air management actions	> 70 ppb (CAAQS)	> 65 ppb (CAAQS)
Orange To improve air quality through active air management and prevent exceedance of the CAAQS	>50 to ≤70 ppb	> 50 to ≤ 65 ppb
Yellow To improve air quality using early and ongoing actions for continuous improvement	> 30 to ≤ 50 ppb	
Green To maintain good air quality through proactive air management measures to keep clean areas clean	≤ 30 ppb	

Averaging time	Numerical Value in parts per billion (ppb)		Statistical form of the standards (metric)
	Effective 2020	Effective 2025	
1-hour	70	65	The 3-year average of the annual 99th percentile of the SO_2 daily maximum 1-hour average concentrations.

3.0 Development of an Acute AAQC for SO_2

3.1 Critical Effect

As outlined in the Science Discussion Document for SO_2 (MOECC, 2016), the foundation for the Ministry's rationale for a proposed acute AAQC and air standard for SO_2 is based on the recent health assessments of Health Canada and the United States Environmental Protection Agency (U.S. EPA, 2008; 2015; Health Canada, 2016).

Briefly, the information from controlled human exposure, epidemiologic data, and toxicological studies has been integrated by these agencies to form conclusions about the causal nature of relationships between SO_2 exposure and health effects. Both assessments examined the available scientific evidence using established considerations for assigning causal determination (U.S. EPA, 2008), and took into consideration the Bradford Hill criteria, which are succinctly summarized by Health Canada (2016) (italics in original):

> "the *strength* of the associations, including the magnitude and precision of the risk estimates and their statistical significance
>
> the *robustness* of the associations to model specifications and adjustment for potential confounders such as weather, temporal trends, and co-occurring pollutants
>
> the *consistency* of reported associations across studies and study designs conducted by different researchers in different locations and times
>
> the *biological plausibility* of the associations in light of what is known about the effects of this chemical, referencing data from experimental studies or other sources demonstrating plausible biological mechanisms
>
> the *coherence* of the relationship between exposure to the chemical and related endpoints within and across animal toxicology, controlled human exposure, and various types of epidemiological studies"

Using a weight of evidence approach, both agency health assessments concluded that the strongest causal relationship exists between short-term SO_2 exposure and respiratory morbidity.

The Ministry supported the above selection of the critical adverse effect endpoint based on the use of the Bradford Hill criteria and unequivocal evidence from multiple high quality studies. The selected critical effect is a product of the use of the most certain and predictive, rather than most conservative, information. That is, while epidemiological studies describe adverse effects at exposure to SO_2 concentrations *lower* than those observed in chamber studies, there remain concerns regarding the accuracy of exposure estimates from ambient measurements typical of epidemiologic studies. Thus, while there is consistency among evidence from epidemiologic and toxicological studies, and biological plausibility for effects specifically related to respiratory morbidity, estimates of exposure are considered to be *more accurate* in human clinical studies under controlled conditions (i.e., chamber studies), and thus will be relied upon for quantitative evaluation.

> **MINISTRY RATIONALE:** The Ministry will consider respiratory morbidity as the critical adverse health endpoint for short-term SO_2 exposure.

3.2 Susceptible Population and Selection of Key Study

An appropriate key study selection is essential for the goal of establishing an AAQC protective for all individuals, including those who are likely to be susceptible to developing the critical effect (e.g., children, pregnant women, elderly), when data are available. In this case, the evidence clearly identifies asthmatics as a susceptible population of note.

Briefly, as discussed in the Science Discussion Document (MOECC, 2016), respiratory morbidity manifested as bronchoconstriction is the most commonly observed adverse effects following SO_2 inhalation exposure. This is observed not only in the controlled human exposure literature, but also in the epidemiological literature. Stimulation of chemosensitive receptors in tracheobronchial tree followed by the initiation of reflexive contraction of smooth muscles in the bronchial airways is considered a mode of action in SO_2 respiratory morbidity. Thus, it is reasonable to consider asthmatics as a susceptible population. It is noted that asthma is characterized by inflammation and airway hyperresponsiveness, which manifests as excessive bronchoconstriction to contractile stimuli (Barnes, 1996; Buels and Fryer, 2012). Indeed, there is significant evidence to demonstrate that asthmatics are at increased risk for SO_2-mediated health effects. This is especially notable, as it is estimated that asthma affects approximately 3 million Canadians, representing about 9% of the population. Of particular note, there are higher prevalence rates in children between the ages of 4 and 11, and among certain ethnic or racial groups, including First Nations communities (Fenton et al., 2012; Asthma Society of Canada, 2016).

In their tabulation of key evidence underlying the causal determinations for SO_2, the U.S. EPA (2015) noted consistent evidence from multiple, high quality epidemiologic studies at relevant SO_2 concentrations showing an increase in asthma-related hospital admissions in studies of all age groups (e.g., children, older adults). The U.S. EPA further stated that the evidence from epidemiologic studies describing long-term SO_2

exposure is generally supportive but not entirely consistent for increases in asthma incidence and prevalence. Furthermore, the evidence from epidemiological studies is coherent with limited animal toxicological evidence of allergic sensitization, airway remodeling, and enhanced airway responsiveness, which are key events (or endpoints) in the mode of action for the development of asthma-like symptoms. Additionally, there is some supporting epidemiologic evidence of associations with respiratory symptoms among children with asthma. Finally, as described in Section 5.7 of the Science Discussion Document (MOECC, 2016), the U.S. EPA (2008) performed a meta-analysis on the evidence from multiple human clinical studies of exercising asthmatics, which demonstrated clinically observable decrements in lung function, following as little as 5-10-minutes of exposure.

Taken together, considering asthmatics are prone to the health effects of bronchoconstriction, the data show that respiratory effects experienced by asthmatics following SO_2 exposure appear to be more severe than among non-asthmatics. Combined with the significant asthma prevalence rates in the Ontario population, asthmatics are considered a significant susceptible group in establishing a health-based AAQC for SO_2.

MINISTRY RATIONALE: Asthmatics are considered a susceptible population in studying the effects of SO_2 associated with bronchoconstriction.

Respiratory morbidity epidemiological and controlled human chamber studies are relied upon by various jurisdictions in establishing ambient air limits for SO_2 (WHO, 2005; U.S. EPA, 2010; CCME, 2016). Despite such a strong causal relationship, key uncertainties and limitations remain in utilizing epidemiological data for the development of AAQCs for SO_2 (MOECC, 2016). Briefly, measurement error in averaging ambient exposure, co-pollutant confounding, concurrent peak exposures within long-term average exposures, and other etiological factors (e.g., underlying disease state, life-stage) are such limitations. As uncertainty remains in quantifying the concentration-response relationship in epidemiological studies, estimates of exposure are considered to be more accurate in chamber studies.

While there is consistency among evidence from epidemiologic and toxicological studies, and biological plausibility for effects specifically related to respiratory morbidity, there remain concerns regarding the exposure estimates from epidemiologic studies in their applicability of representing an individual's SO_2 exposure associated with the generation of an episode of respiratory morbidity; that is, average estimates of SO_2 exposure may not represent peak exposures, which are the key determinant of acute effects. In contrast with epidemiological studies, controlled human clinical studies feature direct exposure to SO_2 at known levels for specific short durations, without the interference of other pollutants, and allow for the recording of symptomatic and asymptomatic measurements of lung function.

Estimates of exposure are considered to be more accurate in human clinical studies under controlled conditions (i.e., chamber studies), and more relevant to the mode of action of short-term peak exposure and respiratory morbidity. Thus, the Ministry proposes that these chamber studies, together, lend themselves to the quantitative dose-response effects seen with SO_2 exposure among exercising asthmatics, and are, in fact, used by various jurisdictions in establishing their limits. Such a selection is supported by the semi-quantitative data gleaned from epidemiological studies.

MINISTRY RATIONALE: The development of an acute AAQC for SO_2 is better served by the quantitative evaluation of lung function as observed in exercising asthmatics under controlled conditions (i.e., chamber studies), supported by semi-quantitative information from relevant epidemiological studies.

Thus, similar to Health Canada, the Ministry will utilize the U.S. EPA meta-analyses of multiple chamber studies of exercising asthmatics, in place of the selection of a single ‘key study’.

3.3 Proposed AAQC Derivation

The scientific basis for short-term limits from the following jurisdictions were considered: WHO (2005), the Office of Environmental Health Hazard Assessment (OEHHA) of the California Environmental Protection Agency (CalEPA, 2008), the U.S. EPA (2010), and Health Canada (2016). The SO_2 air quality criteria of the various jurisdictions identified, while valuable in providing some context, may have different stated mandates and may have different implementation criteria relative to the Ontario context (Table 3.1).

Pulmonary resistance to airflow is the hallmark pathophysiology of bronchoconstriction, and can either be measured by an increase in specific airway resistance (sRaw) or a decrease in forced expiratory volume in 1 second (FEV_1). sRaw is measures changes in volume within an organ or whole body; FEV_1 is the volume of air that can forcibly be blown out in one second, after full inspiration. For quantitative evaluations, agencies have consistently relied upon these lung measurements, taken from subjects that are typically young adults with mild-to-moderate controlled asthma and not receiving medication, while performing moderate levels of physical activity (e.g., stationary bicycle). Due to ethical reasons, children and those with severe or uncontrolled asthma are typically excluded.

In the Ministry's initial step of analysis, it was noted that the basis of the point of departure (POD) used by different agencies varied. For example, WHO (2005) and CalEPA (2008) appear to have considered asthmatics *as a group* and the "clinical significance" or "discomfort level" of effects in adopting the POD, rather than decrements in lung function *for an individual*, as performed by U.S. EPA, and adopted by Health Canada (discussed further, below). Common to both WHO and CalEPA ambient air limits is the fact that *no uncertainty factors were utilized in their development*. This is concerning, as measurable adverse effects have been observed in some individuals in studies featuring similar exposure levels. The Ministry interprets this by suggesting that the WHO and CalEPA limits would not be protective for some sensitive individuals (e.g., children and those with severe or uncontrolled asthma), if either were to be adopted as an AAQC. Thus, the WHO and CalEPA guidelines were not further considered by the Ministry.

In contrast, the more recent and comprehensive assessment by US EPA (2010) –also utilized by Health Canada (2016) – considered both the individual and group response rates of asthmatics, as well as the degree of the lung function detriments, as being associated with either asymptomatic or symptomatic health effects. This analysis led to the identification of the 200 and 400 ppb Health Effects Benchmark Concentrations, for 5 minute exposures (Table 3.2). These benchmarks are based on a quantitative relationship between exposure and effects and are considered supportable by the Ministry for the development of a health-based AAQC and air standard. Specifically, with regard to the 200 ppb Health Effects Consensus Benchmark Concentrations:

- 200 - 300 ppb (525 - 800 µg/m^3) for 5-10-minutes represents the lowest concentration range in free-breathing controlled human exposure studies where some individuals have moderate or greater decrement in lung function.
- Approximately 5-30% exercising asthmatics experience moderate or greater decreases in lung function (i.e., ≥ 100% increase in sRaw, and/or a ≥ 15% decrease in FEV_1).
- Group mean levels of lung function changes were not statistically different.

With regard to the 400 - 600 ppb Health Effects Consensus Benchmark Concentrations:

- 400 - 600 ppb (1050 - 1600 µg/m^3) for 5-10-minutes represents the lowest concentration range in free-breathing controlled human exposure studies where moderate or greater decrements in lung function occurred and were frequently accompanied by respiratory symptoms.
- A greater percentage (20-60%) of exercising asthmatics experiences moderate or greater decrease in lung function (i.e., ≥ 200% increase sRaw, and/or a ≥ 20% decrease in FEV_1), and is increasingly associated with respiratory symptoms (e.g., wheezing, chest tightness).
- At ≥ 400 ppb, group mean levels of lung function changes were statistically different.

Table 3.1 Short-Term SO_2 Jurisdictional Limits of Agencies Considered by the Ministry

Agency	Year	Limit	Value	Averaging Time	Description	Basis
World Health Organization (WHO)	2005	Air Quality Guideline (AQG)	500 μg/m^3 (190 ppb)	10 min	AQG value considers minimum concentrations associated with adverse effects in the most extreme circumstances (i.e. exercising asthmatics).	• 200 ppb – associated with small changes in baseline FEV1 after short-term exposure (i.e 10 min) regarded as not being clinically significant. • Dose-response relationship of increased detriments in lung function was observed; ranged from 200 to 600 ppb.
California Environmental Protection Agency (CalEPA)	2008	California Ambient Air Quality Standard (CalAAQS)	660 μg/m^3 (250 ppb)	1 hr	CalAAQS represents value that would not result in discomfort in respiratory effects in sensitive individual for a period of 1 hr. Limit aims to protect sensitive individuals (i.e., exercising asthmatics) from respiratory effects of acute exposure.	• 250 ppb – NOAEL consensus value from multiple studies of adverse respiratory effects associated with bronchoconstriction • NOAEL Range 200 to 250 ppb for 60-75 min • LOAELs were identified from 400 to 500 ppb for 5 to 75 minutes. • Total application of an Uncertainty Factor of 1.
United States Environmental Protection Agency (U.S. EPA)	2010	National Ambient Air Quality Standards (NAAQS)	200 μg/m^3 (75 ppb)	1 hr	NAAQS (primary) are set according to the Clean Air Act which does not require the U.S. EPA to establish primary NAAQS at zero-risk, but rather at a level that reduces risk sufficiently so as to protect public health with an adequate margin of safety.	• 200 and 400 ppb Health Effects Benchmark Concentrations (5 minutes) were identified and reasonably judged to be important from a public health perspective. • The predicted number of days of exceedence of these benchmarks based on proposed 1-hour average values at 50 ppb and 100 ppb was used as part of a quantitative exposure and risk assessment. • A NAAQS set at 75 ppb would result in minimal predicted exceedences of the benchmarks.
Health Canada 2016	2016	Reference Concentration (RfC)	180 μg/m^3 (67 ppb)	10 min	RfC (inhalation) is an estimate of the level of continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of adverse non-cancer health effects over a lifetime.	• 400 ppb was used as the statistically significant LOAEC, which resulted in lung function decrements from controlled human exposure studies of asthmatics exposed for 5-10-minutes at increased ventilation (WHO, 2006; U.S. EPA, 2008; Johns and Linn, 2011). • To account for the uncertainties in the controlled human exposure dataset, and considering the supporting evidence from the epidemiology, a combined uncertainty factor (UF) of 6 was applied resulting in an inhalation RfC of 67 ppb SO_2

Table 3.2 Health Canada SO_2 Health Effects Summary.

Health Effect Consensus Benchmark Concentrations (> 5 minute)	**≥ 200 ppb**	**≥ 400 ppb**
Measurable Effects on Lung Function*	✓	✓✓
Group mean levels of statistically significant lung function changes	x	✓
Respiratory Symptoms**	No symptoms	Symptoms

* Lung Function: Bronchoconstriction and respiratory symptoms that are often followed by rapid shallow breathing.
** Respiratory Symptoms: Include mild (perceptible wheeze or chest tightness) to severe (breathing distress requiring the use of a bronchodilator).

The Ministry finds the U.S. EPA approach for identifying an adverse effect following SO_2 inhalation as noteworthy. Briefly, the U.S. EPA (2010) position was based on consideration of an American Thoracic Society (ATS) publication titled *"What Constitutes an Adverse Health Effect of Air Pollution?"* (ATS, 2000). The U.S. EPA (2008) summarized their findings in the following statement:

> *"In their official statement, the ATS concluded that an air pollution-induced shift in a population distribution of a given health-related endpoint (e.g., lung function in asthmatic children) should be considered adverse, even if this shift does not result in the immediate occurrence of illness in any one individual in the population. The ATS also recommended that transient loss in lung function with accompanying respiratory symptoms attributable to air pollution should be considered adverse. However, it is important to note that symptom perception is highly variable among asthmatics even during severe episodes of asthmatic bronchoconstriction. An asymptomatic decrease in lung function may pose a significant health risk to asthmatic individuals as it is less likely that these individuals will seek treatment (Eckert et al., 2004; Fritz et al., 2007). Therefore, whereas the conclusions in the 1994 Supplement were based on SO_2 exposure concentrations which resulted in large decrements in lung function along with moderate to severe respiratory symptoms, the current review of data from human clinical studies focused on moderate to large SO_2-induced decrements in lung function along with respiratory symptoms ranging from mild (perceptible wheeze or chest tightness) to severe (breathing distress requiring the use of a bronchodilator)."*

The U.S. EPA's 2010 acknowledgement that decrements in lung function for an individual may have a significant impact on not only individual susceptibility, but also on population susceptibility, and represents a shift in regulatory approach towards SO_2-induced decrements in lung function. Further, the appreciation of transient changes in respiratory function as being significant, and the use of the ATS (2000) definition of adverse effects based on an individual, are supported by the Ministry.

The risk assessment approach taken by the U.S. EPA in estimating the potential impact of a 1-hour limit (based on the 3-year average of the annual 99th percentile of 1-hour daily maximum concentrations) is not considered applicable to AAQC development. Specifically, the implication of the U.S. EPA risk assessment approach is that it allows for a few daily 5-minute exceedences of 200 ppm and 400 ppm (i.e., Health Effects Consensus Benchmark Concentrations) over a year, with such exceedences associated with the potential to trigger adverse effects (discussed in MOECC, 2016; see Section 6.2.7). Additionally, although the U.S. EPA (2010) 75 ppb (200 µg/m^3) 1-hour average NAAQS for SO_2 is set according to the Clean Air Act, it does not require the EPA to establish a negligible-risk level (U.S. EPA, 2010). Specifically, the U.S. Federal Clean Air Act…

> "…*does not require* that primary NAAQS be set at a zero-risk level or *to protect the most susceptible individual*, but rather at a level that reduces risk sufficiently so as to protect the public health with an adequate margin of safety." (italics added)

Taken together, using the NAAQS of 75 ppb (200 µg/m^3) via this derivation approach for a proposed AAQC was not considered further.

In comparison, Health Canada (2016) developed an inhalation reference concentration (RfC) using 400 ppb a lowest observed adverse effect concentration (LOAEC) for a point of departure. The determination of the LOAEC considered the assessments of the health effects by both US EPA (2008) and WHO (2005), along with the recent analysis of Johns and Linn (2011).

To account for the uncertainties in the controlled human exposure dataset, and considering the supporting evidence from the epidemiology, a combined uncertainty factor (UF) of 6 was applied resulting in an inhalation RfC of 67 ppb (180 µg/m^3) SO_2. According to the Human Health Risk Assessment for Sulphur Dioxide (2016);

> *"Although the above studies exposed a susceptible subpopulation (i.e. asthmatics), further sensitivity was observed with some participants reacting at lower concentrations (e.g. as low as 0.2 ppm in chamber studies and 0.1 ppm in mouthpiece exposures (Johns and Linn, 2011)). A lower threshold has not been identified for asthmatics (Horstman et al., 1986, US EPA, 2008, Johns and Linn, 2011, WHO, 2005). Additionally, the studies are usually conducted at room temperature, while some increase in response has been noted when sulfur*

dioxide is administered in cold dry air (WHO, 2005). The studies generally have small sample sizes (e.g. 15 to 20 people) and participants are usually young adults who are otherwise healthy, therefore it is expected that further susceptibility in the population due to genetic factors or other factors like age and disease status may result in a lower level of response."

In addition, Health Canada cited the epidemiological data, which include much lower exposure levels compared to those used in the controlled human studies. These concentrations in air are relevant to Canadian exposure but have limited value in quantifying exposure-effects relationships, due to potential interaction among co-pollutants and differing degrees of measurement error.

According to earlier draft information from Health Canada, the UF of 6 is comprised of a UF of 2 for the use of a LOAEC versus a NOAEC, as the sensitive asthmatic subset response at 200 ppb was statistically non-significant (despite being approximately half of the value observed in healthy asthmatics), and a UF of 3 for intra-species conversion, given that the study is already in a sensitive subpopulation of humans (personal communication, June 1, 2016)

Health Canada's consideration of UFs was supported by the review of Johns and Linn (2011), and the accompanying critique by Johns et al. (2010) of controlled human exposure studies, wherein they considered 400 ppb as the LOAEL for asthmatics. This LOAEL was based upon consistent, coherent, statistically significant results from controlled human exposure studies, and took into account effects at concentrations of 200-300 ppb; these latter effects at 200-300 ppb support the concept that no NOAEL was established in the data set, thus suggesting a degree of intra-species sensitivity. This led to the development of an RfC of 67 ppb (180 μg/m^3), and represents a proposed approach for deriving an acute AAQC (Table 3.3).

Table 3.3 Proposed Approach #1: Health Canada RfC (2016)

Critical effect	Respiratory Morbidity (bronchoconstriction)
Key studies	Meta-analysis of clinical studies under controlled conditions (i.e., chamber studies) of exercising asthmatics (U.S. EPA, 2008, WHO 2005 and Johns and Linn, 2011)
Point of Departure	400 ppb (as a LOAEC)
Uncertainty Factor(s)	6 (2 for use of a LOAEC vs NOAEL; 3 for intra-species)
Proposed Acute AAQC	67 ppb

As an alternative approach to setting a health-based protective limit, the Ministry considers an Ontario-modification of the Health Canada RfC as a proposed derivation for a short-term AAQC (Proposed AAQC #2: Table 3.4). Here, the Ministry recommends rather than using the LOAEC of 400 ppb as the POD, the lower limit of 200 ppb be considered as the POD. This lower POD takes into consideration that there are detriments in lung function observed in some individuals, despite the lack of study group significance. As described by US EPA (2010),

> *"At 200 ppb, an appreciable percentage of exercising asthmatics exposed to SO_2 would be expected to have diminished reserve lung function and would be expected to be at greater risk if affected by another respiratory agent for example, viral infection."*

Thus, the Ministry considers 200 ppb as a more appropriate POD, akin to a benchmark dose (BMD) associated with a specified response level, based on the range of 200-300 ppb concomitant with an approximately 5 to 30% incidence of exercising asthmatics experiencing moderate or greater decreases in lung function (i.e., ≥ 100% increase in sRaw, and/or a ≥ 15% decrease in FEV_1) (US EPA 2010). Similar to the Health Canada approach, a UF of 3 to account for sensitive asthmatics is supported by the Ministry, with respect to several considerations cited by Health Canada (2016), including:

- Reactions were observed in chamber studies at lower concentrations in mouthpiece studies (as low as 100 ppb)
- A lower threshold (i.e., NOAEL) has not been identified for asthmatics
- Studies are conducted at room temperature while some increase in response was noted at colder dry air (WHO, 2005)
- That the studies generally had small sample size (e.g. 15 to 20 people)
- Participants were generally young who are otherwise healthy; therefore, it is expected that further susceptibility exists in the population, due to genetic factors or other factors like age and disease status
- More recent analysis by Linn et al. (2011) and the accompanying critique by John et al. (2010) identifies those asthmatic individuals that respond to higher concentrations (e.g., 600 ppb) also tend to respond at lower concentrations, raising the uncertainty related to intra-species sensitivity
- Epidemiological data may support respiratory effects at much lower levels of exposures relative to controlled human studies, though some uncertainty exists in interpretation due to measurement error, and co-pollutant exposure, and other factors noted in Section 3.2

Furthermore, the Ministry has also considered the application of an uncertainty factor for intra-species variability, additionally noting that:

- chamber studies relied upon by U.S. EPA (2008) and Health Canada (2016) included a larger set of studies than those conducted by Linn, all of which tended not to include severe asthmatics

- children were specifically not included in the chamber studies, although it was noted that subtle changes in lung function (as a measure of bronchial constriction) in an adult may be more pronounced in a child. Asthmatic children also have generally poorer outcomes due to a smaller airway, inferior asthma management, and other factors. A 15% or greater decline in FEV_1 may be a mild effect in normal adults, but may be regarded as more severe in children

In summary, the Ministry recognizes that the chamber studies that are relied upon for the quantitative analysis may not fully have characterized the asthmatic sensitive subpopulation, raising some uncertainty related to the intra-species variability. Therefore, an uncertainty factor is warranted to address intra-species variability, as previously discussed in the Science Discussion Document (MOECC, 2016; See Sections 7.3 and 7.4). However, a default UF of 10 may not be warranted and may be overly conservative, as it is acknowledged that the chamber studies are making observations in adult asthmatics under exercising conditions. As such, in taking into consideration a balance in the lines of evidence, and in agreement with Health Canada, an uncertainty factor of 3 for intra-species variability is supported.

Table 3.4 Proposed Approach #2: Ontario-modified Health Canada RfC (2016)

Critical effect	Respiratory Morbidity (bronchoconstriction)
Key studies	Meta-analysis of clinical studies under controlled conditions (i.e., chamber studies) of exercising asthmatics (U.S. EPA, 2008, WHO 2005 and Johns and Linn, 2011)
Point of Departure	200 ppb (akin to BMD)
Uncertainty Factor(s)	3 (for intra-species sensitivity)
Proposed Acute AAQC	67 ppb

In summary, the two proposed AAQC derivations (i.e., Health Canada and Ontario-modified Health Canada) are both supportable, and both result in 67 ppb (180 $\mu g/m^3$). Thus, the Ministry considers 67 ppb (180 $\mu g/m^3$) as an appropriate health-based value to protect the general population and sensitive individuals against the health effects associated with a 10-minute exposure to SO_2.

MINISTRY RATIONALE: Based on the U.S. EPA and Health Canada meta-analyses of chamber studies of exercising asthmatics, the Ministry considers 67 ppb (180 $\mu g/m^3$) an appropriate health-based value for an acute AAQC derivation, in order to protect the general population and sensitive individuals against the health effects associated with a 10-minute exposure to SO_2.

3.4 Consideration of Averaging Time

In general, averaging time selection is influenced by both the underlying toxicology of a substance, including exposure and effects (largely governed by science judgment), and implementation considerations, including modelling and monitoring (largely governed by science policy).

For acute exposure periods causing acute effects, the Ministry sets AAQCs and air standards that are protective in short-term exposures. Here, the general approach is to select averaging times based on the duration of exposure needed to cause these acute health effects, while balanced with implementation considerations through the use of a limited number of averaging times (e.g, 10-minutes, 1-hour, 8 hours).

As outlined in the Science Discussion Document (MOECC, 2016), a review of the SO_2 ambient monitoring data suggests that exposures associated with the incidence of acute effects are likely to be in the form of short-term intermittent spikes. A review of the mode of action and controlled human studies support intermittent spikes in the 5-10-minute range as being the most health-relevant, with regard to observed respiratory morbidity. Thus, a short averaging time is appropriate, and a 10-minute averaging time would be the most toxicologically relevant as an ambient air quality criteria. For this reason, 10-minutes is the most health-relevant averaging time for an acute AAQC for SO_2.

However, the selection of the appropriate averaging time for air standard compliance purposes needs to reflect standard monitoring practicalities, modelling capabilities, jurisdictional consistency, and other policy considerations. Typically, a 1-hour averaging time is assigned in the setting of acute ambient air limits by other jurisdictions.

During discussions of the science, some stakeholders recommended that the ministry use the 10-minute RfC of 67 ppb directly as a 1-hour air standard without conversion since the effects on respiration are observed after 5-10-minutes of exposure and do not become more severe if exposure is continued for an hour.

The maximum concentration observed in any 5-10-minute period is most critical because biological responses to SO_2 inhalation exposure occur very rapidly, within the first few minutes from commencement of inhalation. Continuing the exposure (at the same concentration) further does not increase the effects. However, in setting the air standard, consideration must be made of meteorological variation within an hour period that can result in concentrations of SO_2 above the 10-minute RfC.

As discussed in Section 2.2, Health Canada used extensive Canadian monitoring data to calculate 40 ppb as the 1-hour concentration that would ensure 67 ppb is not exceeded within any 10-minute period. The Ministry supports this calculation based on comparison to the equivalent 1-hour concentration calculated using the conversion factors referenced in Section 17 of O. Reg. 419/05 (MOECC, 2013). These conversion factors are derived from an exponential equation based on empirical monitoring data, ratios of concentrations observed for different averaging times, and meteorological considerations. Thus, using the health-based 10-minute AAQC as a foundation, a 1-hour AAQC and air standard equivalent to 40 ppb are proposed.

> **MINISTRY RATIONALE:** A 10-minute averaging time would be the most health-relevant for the proposed acute AAQC of 67 ppb (180 µg/m^3). Additionally, a 1-hour AAQC and 1-hour air standard of 40 ppb (100 µg/m^3) are proposed to support evaluation of ambient air monitoring and compliance under O. Reg. 419/05, respectively.

It should be noted that adverse effects are often reported in epidemiological studies at lower chronic exposures to SO_2 (i.e., relative to acute exposure mediating adverse health effects in chamber studies). However, it is generally understood that these long-term ambient air concentrations include concurrent peak concentrations, which are believed to be the key determinants of initiation of an adverse effect on human health. As such, a chronic AAQC/air standard based on human health will not be proposed by the Ministry. Rather, a chronic value based on protecting ecological impacts is proposed in Section 4.0.

4.0 Development of a Chronic AAQC and Air Standard for SO_2

4.1 Background

During the process to identify a critical effect, data for a number of effects were reviewed and found to be relevant to the setting of the AAQC and air standard. Upon review of the literature regarding ecological impacts of SO_2 releases to air, it became apparent that a chronic AAQC and air standard would be supported to address ecological impacts.

4.2 Critical Effect

SO_2 is an acidifying substance and corrosive agent in the environment (e.g., metal corrosion, deterioration of brick and stone, lake acidification, cracking and fading of exterior painted surfaces). In humid air and under fog conditions, SO_2 dissolves in the water molecules leading to the formation of a sulphuric acid mist, increasing potential of adverse effects on plants (i.e., acid deposition). While there are indirect effects on vegetation and soils, including deposition and retention of sulphuric acid and sulphate particles leading to increased acidification of ecosystems, it is the direct effects via soil uptake or directly through adsorption of SO_2 from air on vegetation that represent the path forward in setting a chronic air standard.

> **MINISTRY RATIONALE:** The Ministry considers the direct effect of SO_2 on vegetation, including foliar injury, decreased photosynthesis, and decreased growth, as the critical adverse endpoint for long-term SO_2 exposure.

Plants vary widely in their tolerance to SO_2. Due to their structure, lower plants such as lichens and mosses are among the most sensitive, and have been used as indicators of SO_2 pollution. Specifically, lichens are likely the most widely used biological metrics of long-term atmospheric pollution (CCME, 2014), and considered an early warning indicator of vegetative health (McCune, 2000).

Effects of SO_2 on lichens include reduced photosynthesis and respiration, damage to the algal component, leakage of electrolytes, inhibition of nitrogen fixation, reduced potassium absorption and structural changes. And as described in the Science Discussion Document (MOECC, 2016), acidifying deposition has an observable effect on lichen abundance and biodiversity within forest and urban communities. Indeed, lichen sensitivity to air quality stems from their reliance on airborne nutrients and water, as well as lack of protective structures such as cuticles found in vascular plants; trees and other vascular plants are affected by pollution, but are much slower to show impacts than lichens (Muir and McCune, 1988).

In Europe and the U.S., lichens are being used in assessing climate changes as a sensitive sentinel species (McCune, 2000; van Herk et al., 2002). Specifically, distributions of certain species are a response to regional moisture and temperature gradients. Mapping distribution of climate-sensitive species provides an indication of climatic conditions and monitoring over time reveals climate change effects.

Given the close relationship of lichens with other organisms, and their contribution to biodiversity, lichens provide an ideal group to monitor for changes in diversity in ecosystems. Lichens meet the criteria as useful indicators for assessing impacts of both air pollution and climate change.

MINISTRY RATIONALE: The Ministry considers lichens as the susceptible species in studying the chronic effects of SO_2 on the environment.

4.3 Proposed AAQC and Air Standard Derivation

As outlined in the Science Discussion Document for SO_2 (MOECC, 2016), the rationale for the development of a chronic AAQC and air standard is similar to the recommendations of the CAAQS Development and Review Working Group (CDRWG), which recommended specific values for the annual SO_2 CAAQS. For the annual SO_2 CAAQS, the values discussed are a range of 4 ppb (10 µg/m^3) to 8 ppb (20 µg/m^3). The CCME has since adopted 5 ppb (effective 2020) and 4 ppb (effective 2025) as the annual CAAQS (Table 2.1).

For the 8 ppb upper bound of the range, consideration was given to the chronic effects observed at concentrations of 8 ppb in the Sudbury area. This level is consistent with the European Union 8 ppb standard for the protection of vegetation, which was also adopted by Alberta. However, there is evidence to suggest that the more sensitive plant species (e.g., lichens) may not be fully protected at this level (WHO, 2000; WHO 2005).

The lower bound of the CCME range of values was set at 4 ppb, based on the WHO standard for the protection of lichens. Specifically, most of the studies suggesting acute sensitivity of lichens to SO_2 have involved correlation of field distributions of species with ambient concentrations. They indicate that winter or annual means of 30 µg/m^3 are sufficient to eradicate the most sensitive taxa. Community changes were observed at average concentrations below 10-11 µg/m^3 in one study around a newly established rural point source (Will-Wolf, 1981). Critical levels of 10-11 µg/m^3 (4 ppb) annual mean have been proposed by the WHO (2000), but it was noted that these levels may have to be further reduced as detailed information becomes available for other sensitive species. As lichens are the most widely used biological metrics of long-term atmospheric pollution, and considered an early warning indicator of vegetative health, the Ministry has confidence in this value as appropriate for the protection of the greater ecological health (i.e., crops and vegetation). Additionally, the lichen species referenced throughout the WHO document are generally found in both North America and Europe, and may be considered relevant to an Ontario AAQC and air standard. Taken together, it is this lower bound of the CCME range – 4 ppb – which represents an appropriate proposed value of chronic AAQC for SO_2, in order to protect vegetation.

MINISTRY RATIONALE: The Ministry considers the lower bound of the CCME range 4 ppb (10 $\mu g/m^3$) as appropriate proposed value for a chronic AAQC for SO_2, in order to protect against ecological impacts.

4.4 Consideration of Averaging Time

As noted in Section 3.4, averaging time selection is influenced by both the underlying toxicology of a substance, including exposure and effects (largely governed by science judgment), and implementation considerations, including modelling and monitoring (largely governed by science policy).

The Ministry considers toxicological and implementation issues in assigning an averaging time for effects due to chronic exposure. In general, an annual averaging time is believed to be appropriate when addressing chronic effects (i.e., effects observed after long-term exposure), where intermittent peak exposures are not considered likely to significantly influence the effect.

MINISTRY RATIONALE: An annual averaging time would be the most toxicologically-relevant for the chronic ecologically-based AAQC and air standard.

5.0 Recommendations

5.1 Recommended Acute AAQCs and Air Standards for SO_2

After an evaluation of the scientific rationale for SO_2 air guidelines and standards from environmental agencies, recent health assessments from Health Canada and the U.S. EPA, an examination of the current toxicology, and consideration of stakeholder comments, the Ministry considers the information of the U.S. EPA (2008; 2015) and Health Canada (2016) human health risk assessments as the basis for the proposed acute AAQC and air standards for SO_2, summarized in Table 5.1.

Specifically, based on a quantitative analysis of human clinical studies under controlled conditions of exercising asthmatics experiencing respiratory morbidity, the Ministry proposes the following health-based acute AAQC for SO_2:

Proposed 10-minute AAQC for SO_2:

> **Ten-minute (10 min) Ambient Air Quality Criterion (AAQC) of 180 µg/m^3 (micrograms per cubic metre of air) for SO_2 (67 ppb), based on respiratory morbidity in exposed sensitive populations**

AAQCs may be converted to a different averaging time to support ambient monitoring comparisons, and in air standard setting for Ontario Regulation 419: Air Pollution – Local Air Quality compliance purposes. The Ministry utilizes conversion factors derived from an exponential equation based on empirical monitoring data, ratios of concentrations observed for different averaging times, and meteorological considerations, referenced in Section 17 of Ontario Regulation 419: Air Pollution – Local Air Quality. Thus, using the preceding health-based 10-minute AAQC as a foundation, the following AAQC and air standard are proposed:

Proposed One-hour AAQC for SO_2:

> **One-hour (1 hr) Ambient Air Quality Criterion (AAQC) of 100 µg/m^3 (micrograms per cubic metre of air) for SO_2 (40 ppb), based on respiratory morbidity in exposed sensitive populations**

For Ontario Regulation 419: Air Pollution – Local Air Quality compliance purposes, the Ministry proposes the following air standard for SO_2**:**

Proposed One-hour Standard for SO_2:

> **One-hour (1 hr) air standard of 100 µg/m^3 (micrograms per cubic metre of air) for SO_2 (40 ppb), based on respiratory morbidity in exposed sensitive populations**

5.2 Recommended Chronic AAQC and Air Standard for SO_2

After an evaluation of the scientific rationale for SO_2 air guidelines and standards from environmental agencies, recent health and environmental assessments from Health Canada and the U.S. EPA, an examination of current toxicological research, and consideration of stakeholders' comments, the Ministry agrees with Health Canada and considers the WHO (2005) risk assessment approach to be the most appropriate for developing a chronic AAQC and air quality standard for SO_2. Specifically, considering the observable effects on lichen abundance and biodiversity with environmental chronic exposures to SO_2, the Ministry proposes the following ecologically-based chronic AAQC for SO_2:

Proposed Annual AAQC for SO_2:

- **Annual Ambient Air Quality Criterion (AAQC) of 10 µg/m^3 (micrograms per cubic metre of air) for SO_2 (4 ppb), based on vegetation damage in exposed sensitive species**

Additionally, for Ontario Regulation 419: Air Pollution – Local Air Quality compliance purposes, the Ministry proposes the following air standard for SO_2**:**

Proposed Annual Air Standard for SO_2:

- **Annual air standard of 10 µg/m^3 (micrograms per cubic metre of air) for SO_2 (4 ppb), based on vegetation damage in exposed sensitive species**

Table 5.1 Summary of proposed AAQCs and Air Standards for SO_2

Averaging Time	AAQC (µg/m^3)	Air Standard (µg/m^3)	Basis
10 min	180	–	Health (respiratory morbidity)
1-hr	100	100	Health (respiratory morbidity)
Annual	10	10	Vegetation (damage)

6.0 A Guide for Stakeholders Reviewing this Document

The Ministry welcomes written comments on this Rationale Document from all interested parties. Stakeholders are encouraged to provide comments which indicate whether they support or disagree with the above recommendations. It is also important that submissions include the rationale and reasoning supporting the stated positions so that the Ministry can make informed decisions on the proposed standard on the basis of clear, supportable arguments.

Comments on these and any other issues relevant to setting of air quality standards for sulphur dioxide can be sent to:

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8.0 Acronyms, Abbreviations, and Definitions

AAQC	ambient air quality criterion
AMC	Air Management Committee
ATS	American Thoracic Society
ATSDR	Agency for Toxic Substances and Disease Registry
BMD	benchmark dose
CAAQS	Canadian Ambient Air Quality Standard
C(al)AAQS	California Ambient Air Quality Standard
CalEPA	California Environmental Protection Agency
CAS	Chemical Abstracts Service
CCME	Canadian Council of Ministers of the Environment
CDRWG	CAAQS Development and Review Working Group
FEV_1	forced expiratory volume in 1 second
LOAEC	lowest observed adverse effect concentration
LOAEL	lowest observed adverse effect level
NAAQS	National Ambient Air Quality Standards
NOAEC	no observed adverse effect concentration
NOAEL	no observed adverse effect level
OEHHA	Office of Environmental Health Hazard Assessment
RfC	reference concentration
SO_2	sulphur dioxide
sRaw	specific airway resistance
UF	uncertainty factor
U.S. EPA	United States Environmental Protection Agency
WHO	World Health Organization

hr	hour
min	minute
ppb	part per billion
µg	a microgram, one millionth of a gram