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Toxicity Test Requirements and Performance Criteria for Passenger Railcar Materials

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14. ABSTRACT

Currently, there is no standard for regulating the toxic gas emission in National Fire Protection Association (NFPA) 130 or Title 49 Code of Federal Regulations (CFR) § 238.103. The International Maritime Organization (IMO) Fire Test Procedure (FTP) Annex 1: Part 2 toxicity standard with the 25 kW/m^2 non-piloted and piloted exposure was determined in this research to be the most appropriate standard for adoption for use in the U.S. railcar industry. Jensen Hughes, Inc. performed testing on railcar materials with American Society for Testing and Materials (ASTM) E662 and International Standards Organization (ISO) 5659-2. Researchers used the experimental and literature data to compare measurement methods, sampling times, test exposure, and performance criteria. The IMO FTP performance criteria are similar to the 20-minute scaled ERPG-3 criteria and are appropriate for evaluating material fire gas toxicity.

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1 cup (c) = 0.24 liter (l)	1 liter (l) = 0.26 gallon (gal)
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1 quart (qt) = 0.96 liter (l)	
1 gallon (gal) = 3.8 liters (l)	
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)	1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
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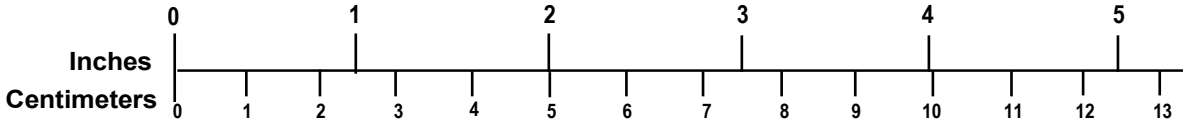

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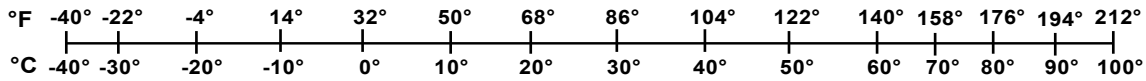

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Executive Summary

The Federal Railroad Administration funded research to investigate toxic gas emission from passenger rail materials in standard toxicity tests. Jensen Hughes, Inc. conducted this work from October 1, 2019, to September 15, 2020. The focus of this effort was to establish limits on the toxicity of passenger rail car materials through the selection of a test method, measurement method, and appropriate criteria.

Jensen Hughes conducted testing to evaluate four main research questions: 1) what smoke test chamber and exposure should be used for toxicity testing; 2) what is the impact of the measurement method on the measured toxic gas concentrations; 3) when should gases be sampled from the smoke chamber for toxic gas analysis, and 4) which method and criteria should be used to evaluate material toxicity performance. Testing of four materials at three different test labs, Govmark (Farmingdale, NY), Southwest Research Institute (SwRI [San Antonio, TX]), and Intertek (Middleton, WI), obtained smoke density and toxic gas emission results. The tests occurred in two different smoke test chambers, American Society for Testing and Materials (ASTM) E662 and International Standards Organization (ISO) 5659-2. Three exposures from these were compared, 25 kW/m^2 piloted mode in both smoke chambers, and 50 kW/m^2 non-piloted exposure in ISO 5659-2. The authors used Legacy and Fourier Transfer Infrared Spectroscopy (FTIR)-based measurement methods to obtain toxic gas concentrations and determine if a higher precision, but higher cost technique, is necessary. The sampling of gases took place at 4, 8, and 20 minutes or continuously depending on the measurement method.

This research found the ISO 5659-2 test at 50 kW/m^2 to be the most severe of all considered tests in generating toxic gas emissions from the materials, but perhaps overly conservative since during the test no pilot flame is used which results in mostly smoldering combustion. The most appropriate exposure was ASTM E662 in the piloted mode, and is currently used in the U.S. to report material toxicity performance. The ISO 5659-2 at 25 kW/m^2 in the piloted mode was comparable to the ASTM E662 test for most materials. Each measurement method provided a similar precision; however, for some irritant gases FTIR-based methods may be more convenient and have less interference from spurious gas compounds. Gas concentrations were generally found to be maximum at 20 minutes for all test standards.

Researchers compared the criteria from current transportation industry toxicity tests to various toxic gas limits and dosage models. The Emergency Response Planning Guidelines-3 (ERPG-3) limit criteria scaled to a 20-minute egress time exposure were deemed to be appropriate. These limits were found to be more conservative than the ISO 13571 Fractional Effective Dosage (FED) and Fractional Effective Concentration (FEC) models for the 20-minute exposure for preventing incapacitation.

This research determined that the most appropriate existing toxicity standard for the U.S. rail industry is International Maritime Organization (IMO) Fire Test Procedures (FTP) Annex 1: Part 2, which is currently used in the naval industry. Toxic gases are measured using the current state-of-the-art FTIR measurement method at the end of the exposure duration. The IMO FTP performance criteria are higher but comparable to the ERPG-3 scaled limit criteria, thus providing a conservative assessment of material toxicity. This standard uses the ISO 5659-2 smoke box test apparatus, which was found to provide similar results to the ASTM E662 test apparatus currently used for evaluating material toxicity through industry-based standards

(Boeing Specification Support Standard [BSS] 7239 or SMP [Bombardier toxicity specification] 800C). Material toxicity evaluation testing is recommended at a 25 kW/m^2 exposure in both non-piloted and piloted mode, which is consistent with historic toxicity reporting and smoke generation testing.

1. Introduction

Combustible linings installed in passenger rail cars in the United States must pass flame spread and smoke generation requirements. Currently, no toxicity testing of materials is required in Title 49 Code of Federal Regulations (CFR) § 238.103, Appendix B [1] by the Federal Railroad Administration (FRA) or National Fire Protection Association (NFPA) 130 [2]. Jensen Hughes, Inc. performed research to assess existing toxicity methods and performance criteria and provided a recommended material toxicity test requirement.

1.1 Background

The terms 'standard,' 'test method,' and 'specification' in this document refer to different published documents from various organizations and are defined here for clarity. 'Standard' refers to actual standards published by volunteer committee organizations such as American Society for Testing and Materials (ASTM), International Standards Organization (ISO), International Maritime Organization (IMO), European Committee for Standardization (CEN), and NFPA. 'Specification' refers to a commercial company's requirement for testing materials, such as Boeing Specification Support Standard (BSS) 7239, which is the method for toxicity testing for Boeing. A specification will refer to a specific test method but is not regarded as a standard since it is not published publicly by a standards organization. 'Test method' refers to a technique provided in a standard or specification for measuring toxic gas generation from materials, and it is used in this report to refer to the technique to measure toxicity by standards such as European Norm (EN) 45545-2 Annex C as well as specifications such as BSS 7239.

There are several toxicity standards and specifications that currently exist for materials used in transportation and building applications. These include BSS 7239 [3], SMP 800C [4], International Maritime Organization (IMO) Fire Test Procedure (FTP) Annex 1: Part 2 [5], EN 45545-2 [6], and ISO 13344 [7]. The BSS 7239 specification is published by Boeing and is commonly included in rail car acquisition requirements, although it is not a formal requirement in 49 CFR § 238.103, Appendix B or NFPA 130. At the last NFPA 130 rule-making meeting, there was considerable interest in including a toxicity test requirement for materials. However, no appropriate standard was proposed and demonstrated for inclusion in NFPA 130. In addition, the use of toxicity methods developed by industry (specifications BSS 7239 by Boeing and SMP 800C by Bombardier) was considered to be inappropriate for inclusion in the NFPA 130 standard. Instead, researchers preferred standards developed by volunteer committee organizations (e.g., ISO 13344, IMO FTP Annex 1: Part 2, EN 45545-2).

An additional standard considered in this work for evaluating toxicity levels for materials is ISO 13571 [8]. ISO 13571 does not prescribe test requirements but provides criteria for evaluating incapacitation of humans due to toxic gas levels in a space. The method can thus be used to evaluate both materials and requirement levels to ensure safe egress from a location with a fire.

1.2 Scope

The goal of the current work was to provide the basis for a toxicity test standard and evaluation criteria for materials to limit the impact of toxic gases on passengers during egress from a railcar in the event of a fire. In this evaluation, a review of test standards and existing regulations in the transportation industry took place. Jensen Hughes conducted the tests to assess the difference between various test methods on material toxic gas emissions. Although BSS 7239 would not be

recommended since it is developed by industry, while testing was in general accordance with BSS 7239 since it is currently used by the railcar industry and it provides a benchmark for material performance with other standards. Researchers performed other tests according to EN 45545-2 and IMO FTP Annex 1: Part 2 standards. The testing conducted in this study was on four different materials that are currently used inside of a railcar. In addition, the research team constructed a database of transportation toxicity tests to better understand the broader impact of the selected methodology on the rail industry. The use of test data collected in this study and the assembled database led to evaluating existing toxicity test standards and performance criteria to identify a recommended standard for the U.S. rail industry.

1.3 Overall Approach

The existing toxicity standards prescribe the material testing and performance criteria differently. These differences include the sample exposure and orientation, how and when the toxic gases are measured, and the method and criteria used to evaluate material performance. The testing conducted in this research assessed the impact of these different variations and results to recommend the appropriate standard for railcar applications.

1.4 Objectives

The objectives of this study were to evaluate various transportation toxicity tests and to determine an appropriate existing toxicity standard for use by the U.S. rail industry. The toxicity testing of materials and the analysis of data answered the following key questions:

1. What smoke test chamber and exposure should be used for toxicity testing?
2. What is the impact of the measurement method on the measured toxic gas concentrations?
3. When should gases be sampled from the smoke chamber for toxic gas analysis?
4. Which method and criteria should be used to evaluate material toxicity performance?

1.5 Organization of the Report

This report is divided into seven main sections describing the technical work. Section 1 introduces the work and testing conducted, including the steps taken to identify recommendations. Section 2 provides an overview of the existing toxicity test standards and evaluation criteria for materials. Section 3 summarizes the gas measurement methods used in the test. Section 4 contains the material descriptions and test matrix. Sections 5 and 6 contain the results from the test program and findings from the study, and Section 7 summarizes the research conclusions, and provides recommendations for further research and a suggested regulatory standard for railcar materials. Appendix A describes the overall methods used in this study to measure toxic gas effluents from burning materials in ASTM E662 and ISO 5659-2 smoke tests. Appendix B discusses the four sources considered in this work for evaluating the combined effect of toxic gases on humans. Appendix C shows the materials data from the current study.

2. Overview of Standards and Criteria

Researchers selected several existing toxicity standards and specifications for this study based on a prior literature review [9] and current review of toxicity standards. These include BSS 7239, SMP 800C, IMO FTP part 2, EN 45545-2, ISO 13344, and ISO 13571. BSS 7239 is a specification published by Boeing which is commonly used in rail acquisition to evaluate material toxicity. This is similar to SMP 800C, which is also used to evaluate railcar material toxicity in the United States. IMO FTP part 2 is a toxicity standard for marine vessels. EN 45545-2 is the European Norm standard for railcar materials, and Annex C contains a standard method for assessing toxic gas generation.

Two standards which are published by ISO provide methods for evaluating material toxic gas hazard. ISO 13344 is a test standard that can be used for any application. ISO 13344 is different from other standards in that it does not specify a test apparatus or specific experimental approach for generating the smoke for toxic gas measurement, so either an ASTM E662 [10] or ISO 5659-2 [11] smoke chamber may be used and meet the intent of the standard. An additional standard used for the analysis of toxicity data is ISO 13571 [8]. This is similar to ISO 13344 in the sense that it provides a method for calculating a dose based on toxicity data. The purpose of ISO 13571 is to provide a method for calculating time to incapacitation or incapacitation dosage for a certain toxic gas or heat exposure.

2.1 Smoke Chamber Used in Toxicity Tests

All the standards considered in this research use either ASTM E662 [10] or ISO 5659-2 [11] smoke test chambers to generate smoke for toxic gas sampling. Table 2-1 shows characteristics of these tests. Both test chambers are also used to measure the smoke density of materials exposed to an electrical radiant heat source. The smoke generation is assessed by measuring the change in light intensity through a vertical path along the chamber height when a 3 inches by 3 inches (75 mm by 75 mm) sample is exposed to a 25 or 50 kW/m^2 exposure. A pilot flame is also provided to ignite the sample in some tests (piloted). The chamber used for both standards measures 36 inches x 24 inches by 36 inches (914 mm x 610 mm x 914 mm) and is shown in Figure 2-1. The main difference between the two standards is the sample configuration and magnitude of exposure. ASTM E662 uses a radiant furnace which exposes a vertically-mounted sample to 25 kW/m^2. In the ISO 5659-2 apparatus, a cone heater exposes a horizontally oriented sample to 25 or 50 kW/m^2. Appendix B contains a more complete description of the dosage-based toxicity models.

Table 2-1: Standard tests for measuring smoke optical density of materials

	Exposures	Specimen Orientation	Specimen Size	Chamber Size
ASTM E662	25 kW/m^2 piloted & non-piloted	Vertical	3 inches x 3 inches (75 mm x 75 mm)	36 inches x 24 inches x 36 inches (914 mm x 610 mm x 914 mm)
ISO 5659-2	25 kW/m^2 piloted & non-piloted, 50 kW/m^2 non-piloted	Horizontal	3inches x 3 inches	36 inches x 24 inches x 36 inches

	Exposures	Specimen Orientation	Specimen Size	Chamber Size
			(75 mm x 75 mm)	(914 mm x 610 mm x 914 mm)

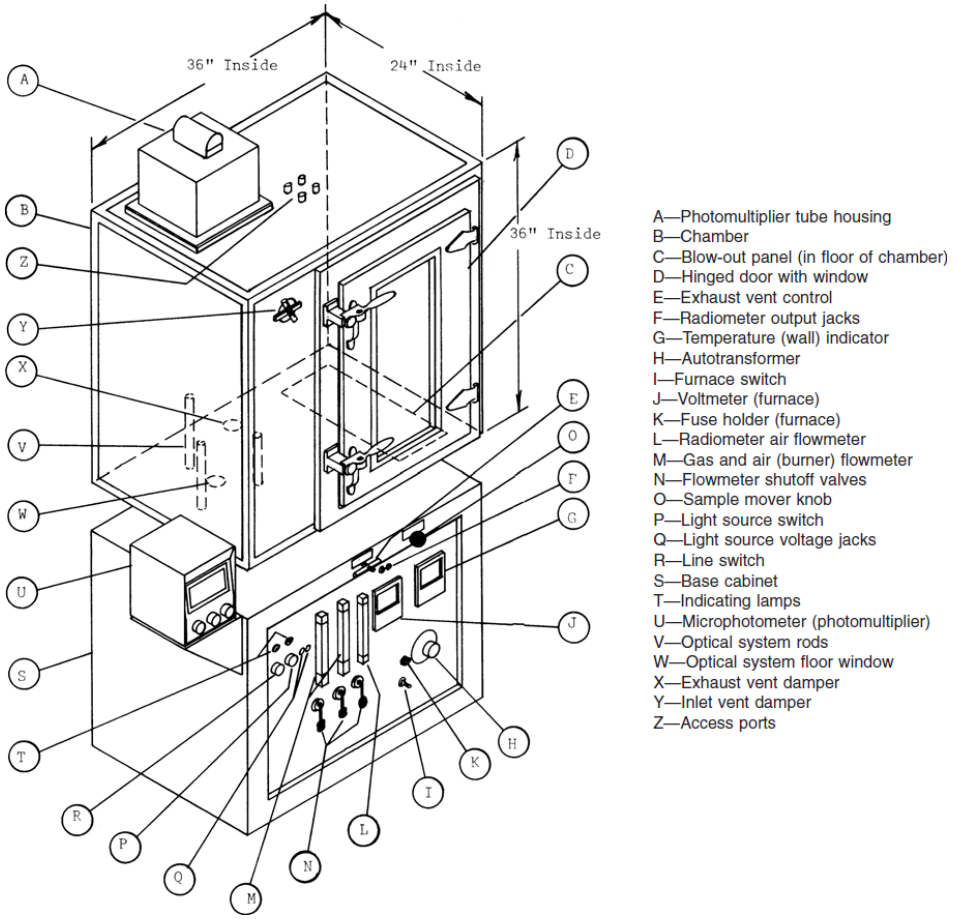

Figure 2-1: Schematic of National Bureau of Standards (NBS) smoke chamber used in ASTM E662

2.2 BSS 7239 and SMP 800C

BSS 7239 “Test Method for Toxic Gas Generation by Materials on Combustion” [3] is a specification published by Boeing and is used to evaluate material toxicity. The test may be done simultaneously with ASTM E662 in the NBS smoke chamber, which is shown in Figure 2-1. The specimens are tested in both flaming (pilot) and non-flaming (without pilot) modes with a 25 kW/m^2 heat exposure. The gas concentrations of carbon monoxide (CO), hydrogen cyanide (HCN), sulphur dioxide (SO_2), nitrous oxides (NO_X), hydrogen fluoride (HF), and hydrogen chloride (HCl) are measured. Dräger tubes are used to measure the gas concentrations. Additionally, the specification permits other methods, such as nondispersive infrared (NDIR) instruments, for measuring the concentrations of certain gases. BSS 7239 specifies gas extraction 4 minutes after the start of the test and requires that gases must be sampled within 2.5 minutes. Table 2-2 provide limits on the measured gas concentrations.

SMP 800C is a similar specification that is published by Bombardier. The main difference between the specifications is the addition of CO_2 and hydrogen bromide (HBr) as the gases to evaluate. In addition, glass detector tubes are not permitted as a method to measure toxic gases in SMP 800C [4]. To enable a comparison of the test data with this standard and others, CO_2, and in some cases HBr, was measured during the BSS 7239 tests.

2.3 IMO FTP Annex 1: Part 2

A common toxicity test for material used in the maritime industry is IMO FTP Annex 1: Part 2, Appendix 2, "Fire test procedures for toxic gas generation" [5]. This test uses the ISO 5659-2 standard with modifications for measuring toxicity. Three exposures are required for a full evaluation of a material: 25 kW/m^2 with pilot, 25 kW/m^2 without pilot, and 50 kW/m^2 without pilot. During the first sample for each exposure, only smoke data is recorded. This test is analyzed and the time of the maximum smoke density is recorded. This time of maximum smoke density is then used as the time to sample toxic gases in the subsequent two tests. The gases are extracted from the chamber and analyzed with a Fourier Transform Infrared (FTIR) spectroscopy system as described in ISO 19702 [12]. Seven gases are measured in this test: CO, HCN, HCl, SO_2, NO_X, HF, and HBr. Table 2-2 provides the toxic gas limits set by the standard.

Table 2-2: Gas concentration limits for transportation toxicity standards

	Gas Concentration Limit (ppm)							
Standard	CO	CO_2	HCN	HCl	SO_2	NO_X	HF	HBr
BSS 7239	3500	-	150	500	100	100	200	-
SMP 800 C	3500	90000	100	500	100	100[1]	100	100
IMO FTP Part 2	1450	-	140	600	120	350	600	600

[1]NO_2 limit

2.4 EN 45545-2

EN 45545-2 Annex C "Testing methods for determination of toxic gases from railway products" [6] contains test methods for assessing toxicity of materials for the rail industry developed by the European Union. There are two standards detailed in EN 45545-2 that can be used for determining the composition of gases and fumes generated by the combustion of specified railway products: ISO 5659-2 and NF X70-100-2 [13]. Method 1 is the ISO 5659-2 test, where the specimens are tested in a smoke box at 50 kW/m^2 without a pilot flame or 25 kW/m^2 with a pilot flame. The gases are sampled and analyzed at 4 and 8 minutes using the FTIR technique. Method 2 is the NF X70-100-2 test, in which specimens are thermally decomposed in a tube furnace and the effluent is collected throughout a 40-minute test. Method 2 is only done for small parts in the railcar and does not apply to large materials such as seats, wall linings, ceiling panels, and partitions. Thus, in this study, researchers only considered Method 1.

The toxic gas concentrations from either the 4 or 8-minute measurement are used to calculate the Conventional Index of Toxicity (CIT). CIT is a dimensionless weighted summation, representing the overall toxicity of the gases analyzed. In Method 1, CIT is defined as $CIT_G = 0.0805 \times \sum_{i=1}^{8} \frac{c_i}{C_i}$, where c_i is the concentration measured in mg/m^3 of the i^{th} gas in the smoke chamber and C_i is the

reference concentration of the i^{th} gas [6]. Table 2-3 lists the reference concentrations of the toxic gases. In EN 45545-2, CIT performance criteria values range from 0.75 to 1.8 depending on the function of the material and the hazard level (HL) of the railcar. A nominal incapacitating level is CIT = 1.0.

Table 2-3: Reference concentrations for dosage-based standards EN 45545-2

	Reference Concentration							
Standard	CO	CO_2	HCN	HCl	SO_2	NO_X	HF	HBr
EN 45545-2 Annex C Method 1 (mg/m3)	1380	72000	55	75	262	38	25	99

2.5 ISO 13344

ISO 13344 "Estimation of the lethal toxic potency of fire effluents" is a standard for assessing the toxicity of materials according to the 30-minute exposure of rats. The standard provides a method to determine LC_{50} and fractional effective dose (FED) levels for the material. Appendix B contains the complete method for calculating the FED of a material. Two different formulas are provided to calculate the gas toxicity and researchers considered both in the analysis of the data. A specific fire test is not prescribed by the standard; rather, the standard recommends a relevant test to be chosen for the application (termed a physical fire model). CO, CO_2, and O_2 must be continuously sampled, and HCN, HCl, HBr, NO_X, SO_2, acrolein, and formaldehyde may be sampled at specific times as appropriate. Similar to the calculation of CIT, the calculation of FED is performed by summing the ratios of each gas with their reference concentration. The physical fire models used in this research were the ASTM E662 25 kW/m^2 piloted exposure, ISO 5659-2 25 kW/m^2 piloted exposure, and ISO 5659-2 50 kW/m^2 non-piloted mode exposure. Measurements of CO, CO_2, HCl, HCN, HF, HBr, SO_2, and NO_X were obtained for these tests using different measurement methods.

2.6 ISO 13571

ISO 13571 "Life-threatening components of fire – Guidelines for the estimation of time to compromised tenability in fires" provides a methodology to determine the tenability of humans in fires due to multiple factors. These factors include smoke toxicity exposure, heat exposure, and smoke obscuration. The toxic gas model in this standard provides equations to estimate the time to tenability from exposure to asphyxiant gases and irritant gases. The equations are intended to be used in a full-scale fire scenario where people are exposed to toxic fire effluents. Asphyxiant gases CO, CO_2, and HCN are included in the fractional effective dose (FED) equation. A fractional effective concentration (FEC) equation is calculated at each discrete time step, and includes irritant gases HCl, HBr, HF, NO_2, and SO_2. The FEC is only dependent on the combined concentration of the irritant gases, not on the dosage, because at high concentrations irritant incapacitating effects occur over a short amount of time [8]. This standard was considered in this study as a potential criteria method for evaluating the material toxicity performance. Appendix B explains the calculation of the FED and FEC values.

3. Toxicity Measurement Methods

Three methods were used for measuring toxic gases in ASTM E662 and ISO 5659-2 tests. Appendix A provides a full detailed explanation of these methods. An overview of each method is given in this section, along with the standard or specification with which the method is normally used. The experiments performed used each of these methods in either ASTM E662 or ISO 5659-2 tests.

3.1 Method A – Dräger/Electrochemical Cell/NDIR/Wet Chemistry

Method A used four techniques to measure the toxic gases in the smoke chamber. Dräger tubes were used to measure the gases hydrogen chloride (HCl), hydrogen bromide (HBr), and hydrogen cyanide (HCN). Electrochemical cells were used to measure carbon monoxide (CO), nitrogen oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). Non-dispersive Infrared (NDIR) was used to measure carbon dioxide (CO_2) concentrations. Finally, a wet chemistry method was used to determine the concentration of hydrogen fluoride (HF).

Method A is commonly used for measuring gas concentrations in BSS 7239 toxicity tests. Some techniques in Method A (i.e., Electrochemical cells, NDIR, and wet chemistry) may also be used for measuring gas concentrations in SMP 800C. Most of the techniques in this method can only be performed one time per smoke test; thus, a separate test must be performed to determine gas concentrations at a different time interval. For BSS 7239, gases are sampled at 4 minutes for 2.5 minutes. For SMP 800C, gases are sampled at 4 minutes for 16 minutes. For these manufacturer specifications, no additional time intervals are required.

In this experimental study, Method A was used in conjunction with the ASTM E662 test in the flaming (or piloted) mode to measure toxic gas concentrations for the four materials. Concentrations were obtained at 20 minutes for all materials, and also obtained at 4 and 8 minutes for Sample 1 and Sample 5 tests. CO, CO_2, NO, NO_2, and SO_2 concentrations were recorded semi-continuously for Sample 2 and Sample 6.

3.2 Method B – Continuous FTIR

Method B uses Fourier-Transform Infrared (FTIR) spectroscopy to determine gas concentrations simultaneously. This method complies with the requirements of EN 45545-2 Annex C for sampling gas concentrations continuously during the test. This method may also be used to sample gases according to IMO FTP Annex 1: Part 2. Table 3-1 provides an overview of which methods may be used with the different toxicity standards. All gas concentrations are determined simultaneously from an analysis of the absorption spectra for a scan or scans of a gas cell which is filled with gas from the smoke box. The time interval between spectra is 15–20 seconds.

This method was used with ASTM E662 flaming mode, ISO 5659-2 with 25 kW/m^2 piloted mode, and ISO 5659-2 with 50 kW/m^2 non-piloted mode for testing Sample 1 and Sample 5. This method was not used for testing Sample 2 or Sample 6.

3.3 Method C – Incremental/Semi-Continuous FTIR

Method C also uses an FTIR spectroscopy system for measuring gas concentrations. The performance of this technique and analysis are similar to Method B. However, this method uses a larger gas cell and more scans per time interval, thus the time interval between spectra is 90–120

seconds. This method is more discontinuous but still provides all gas concentrations at multiple time intervals for the same test. This method complies with the requirements of IMO FTP Annex 1: Part 2, Appendix 2 toxicity test. Method C was used with ISO 5659-2 at 50 kW/m^2 for testing Sample 2 and Sample 6.

Table 3-1: Measurement methods used by toxicity standards

Toxicity Standard	Measurement Method	Test Standard
BSS 7239	Method A	ASTM E662
EN 45545-2 Annex C	Method B	ISO 5659-2
IMO FTP Annex 1: Part 2	Method B, Method C	ISO 5659-2

3.4 Accuracy of Measurement Methods

Table 3-2 shows the accuracy of the gas concentrations measured using different measurement methods. All methods have similar uncertainties. A significant benefit to Method B and Method C is that all gas concentration levels are determined simultaneously, from one single sampling source from the smoke box. Method A uses various techniques to assess the gas concentrations, and these occur over different time intervals (e.g., HCl and HBr are sampled within 20 seconds using the Dräger tube pump, but HF takes 300 seconds for the entire sample to be obtained for wet chemistry.)

The accuracy of Method B and Method C was assumed to be similar to existing FTIR spectroscopy systems. FTIR systems have been reported to have uncertainties of 5–15 percent [14,15]. Method A uses multiple techniques, and uncertainties range from 5–20 percent for all gases. Appendix A provides a full description of the measurement methods. Testing performed on the passenger rail car materials enabled a comparison of the different measurement methods.

Table 3-2: Accuracy of measurement methods for different gases

Gas	Method A	Method B	Method C
CO	5–10 percent	5–15 percent	5–15 percent
CO_2	10–20 percent	5–15 percent	5–15 percent
NO	5–10 percent	5–15 percent	5–15 percent
NO_2	5 percent	5–15 percent	5–15 percent
SO_2	5–10 percent	5–15 percent	5–15 percent
HCl	10–15 percent	5–15 percent	5–15 percent
HF	-	5–15 percent	5–15 percent
HBr	10–15 percent	5–15 percent	5–15 percent
HCN	10–15 percent	5–15 percent	5–15 percent

4. Evaluation Matrix

Researchers performed testing of toxic gases on four materials to compare the smoke test, exposure, and measurement method. Table 4-1 contains the test matrix for this experimental study. The smoke tests ASTM E662 and ISO 5659-2 are commonly used in the rail car industry to test smoke obscuration properties of materials. ASTM E662 is currently used in regulation for smoke generation of materials in the U.S. railcar industry and provides one exposure level, 25 kW/m^2, at two modes, flaming and non-flaming. ISO 5659-2 provides two exposure types: 50 kW/m^2 non-piloted, and 25 kW/m^2, at two modes, piloted and non-piloted. In this work, the gases produced by testing in the piloted modes of ASTM E662 and ISO 5659-2 at 25 kW/m^2 are compared to the ISO 5659-2 50 kW/m^2 non-piloted exposure. In addition to differences in smoke chamber and exposure, a comparison of measurement method of toxic gases was also performed. Methods B and C are based on FTIR spectroscopy systems. Method A is a combination of electrochemical cell detectors, NDIR, detector tubes, and wet chemistry methods. The testing of this method was only in the ASTM E662 smoke test, as no toxicity standards using ISO 5659-2 uses these techniques.

The four materials tested for this work were Sample 1, Sample 2, Sample 5, and Sample 6, and prior work describes it fully [15]. Samples 1 and 5 were thermoplastic materials and are typically used for seatbacks, window masks, and other parts of passenger railcars. Sample 6 was a fiberglass reinforced plastic (FRP) and is used as wall and ceiling linings in railcars. In this work, Sample 6 was procured at a thickness of 0.118 in (3.0 mm). Sample 2 was an aluminum-faced plywood sandwich panel and is used for walls and partitions in railcars. Table 4-2 summarizes a description of the four subject materials.

Table 4-1: Test matrix for four materials tested in this study

Smoke Box	Exposure Level (kW/m^2)	Toxic Gas Measurement	Sample 1 Thermoplastic	Sample 5 Thermoplastic	Sample 6 FRP	Sample 2 Sandwich Panel
ASTM E662	25, Pilot	Method A	X	X	X	X
ASTM E662	25, Pilot	Method B	X	X		
ISO 5659-2	25, Pilot	Method B	X	X		
ISO 5659-2	50, Non-Pilot	Method B	X	X		
ISO 5659-2	50, Non-Pilot	Method C			X	X

*For each toxicity measurement, conducting a corresponding smoke test took place to evaluate smoke optical density and time to peak optical density for the material.

Table 4-2: Description of materials tested in experimental work

ID	Description	Thickness (in [mm])	Component on Railcar
Sample 1	Acrylic/PVC based thermoplastic	0.154 [3.9]	Seatback, window mask, shrouds
Sample 2	Aluminum faced plywood sandwich composite	0.496 [12.6]	Partition, doors

ID	Description	Thickness (in [mm])	Component on Railcar
Sample 5	Polycarbonate based thermoplastic	0.150 [3.8]	Seatback, window mask, shrouds
Sample 6	Vinyl ester resin glass composite	0.118 [3.0]	Wall/ceiling lining, partition, window mask

5. Results

Researchers acquired smoke and toxicity data from railcar and other transportation-grade materials from testing, literature, and the database generated in the prior work [9]. The experiments on four materials took place at three recognized test labs for BSS 7239, IMO FTP Annex 1: Part 2, and EN 45545-2 smoke toxicity testing. Both smoke obscuration and toxic gas concentrations were obtained from the testing. These tests were performed to provide a comparison of exposures, measurement methods, and smoke test chamber. Appendix C provides the data from testing. Additionally, researchers compiled a database of toxic gas concentrations from materials tested using BSS 7239, SMP 800C, IMO FTP Annex 1: Part 2, and ISO 5659-2 with FTIR for use in evaluating test methods and performance criteria.

5.1 Smoke Optical Density

Specific optical density was measured for each material to assess the time of maximum smoke obscuration. For each of the materials the average is plotted for ASTM E662 at 25 kW/m^2 piloted, ISO 5659-2 at 25 kW/m^2 piloted, and ISO 5659-2 at 50 kW/m^2 non-piloted smoke tests. For some ISO 5656-2 tests only 10 minutes of smoke data was obtained per the standard. All ASTM E662 tests and the remaining ISO 5659-2 tests were conducted for a full 20 minutes.

Sample 1 had a maximum smoke density at the end of the test for each mode. Figure 5-1 shows the results for the average of three tests. For this material, the ISO 5659-2 at 50 kW/m^2 had the greatest smoke optical density over the entire test duration. The ISO 5659-2 at 25 kW/m^2 piloted test had the lowest smoke density and was less than the 50 kW/m^2 and ASTM E662 tests up to 10 minutes.

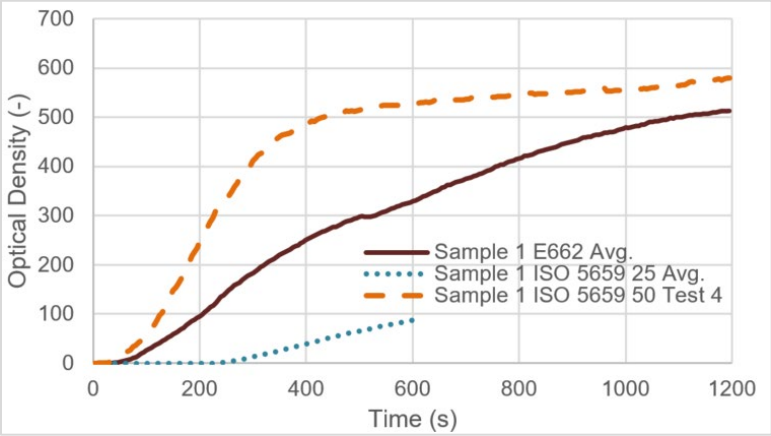

Figure 5-1: Sample 1 thermoplastic smoke density results for each test chamber

Sample 5 also had maximum smoke density at the end of the test for each mode. Figure 5-2 shows the results from testing Sample 5 in different smoke tests. In the ISO 5659-2 at 50 kW/m^2 test, the smoke optical density was significantly greater over the 10-minute test duration. Testing the optical density in this condition proved to be problematic, and for four out of five tests the signal for light transmission was lost during the test due to excessive smoke production. Thus, in the test plotted in Figure 5-2, only one curve from the fifth test is plotted, not an average of three or four tests as done for the other conditions. The ISO 5659-2 at 25 kW/m^2 piloted test and the

ASTM E662 tests had similar overall smoke density of over 10 minutes, and both were less than the 50 kW/m^2 condition.

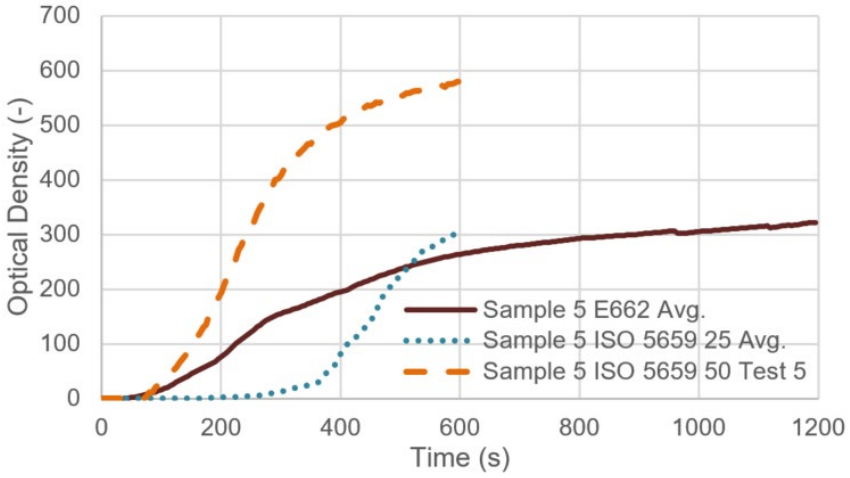

Figure 5-2: Sample 5 thermoplastic smoke density results for each test chamber

Sample 6 was a 0.118 in (3.0 mm) thick FRP material. Figure 5-3 shows the smoke density results for tests in the ASTM E662 and ISO 5659-2 at 50 kW/m^2 tests. Maximum smoke density averaged roughly 800 seconds for ISO 5659-2 and 1,200 seconds for ASTM E662. Smoke density was higher for the higher exposure ISO 5659-2 test.

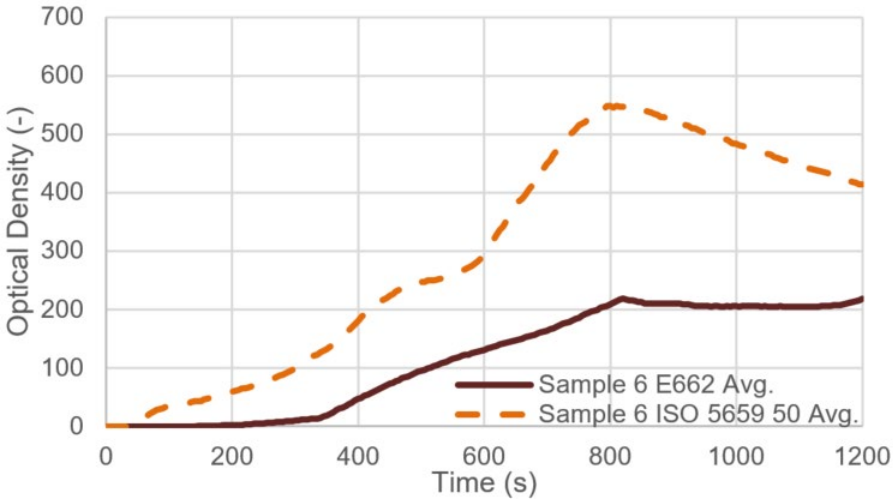

Figure 5-3: Sample 6 FRP smoke density results for ASTM E662 and ISO 5659-2 at 50 kW/m^2

Figure 5-4 shows the results for Sample 2 material tested with ASTM E662 and ISO 5659-2 at 50 kW/m^2. Smoke density was larger for the ASTM E662 test. The ISO 5659-2 test maximum smoke density occurred at 358 seconds. This duration is substantially shorter than all other materials. The ASTM E662 maximum smoke density occurred at 890 seconds.

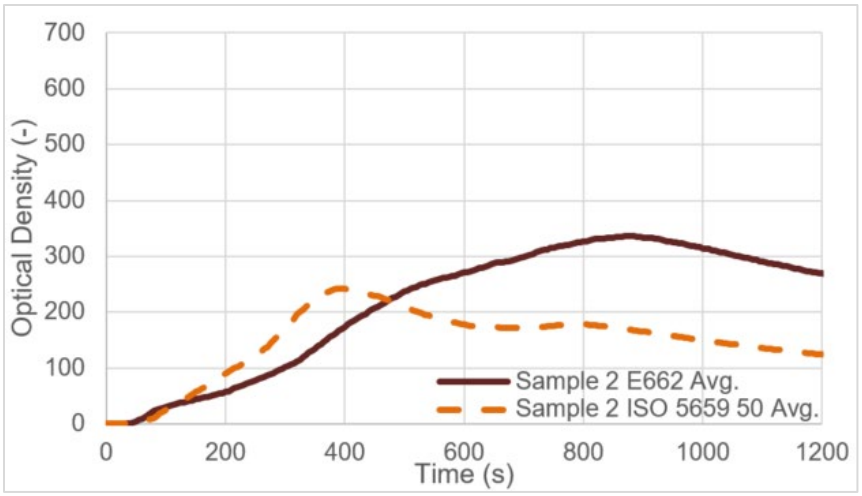

Figure 5-4: Sample 2 aluminum-faced plywood sandwich composite smoke density results for ASTM E662 and ISO 5659-2 at 50 kW/m^2

Table 5-1 summarizes the smoke density tests conducted on the materials. For most materials, smoke density was the highest at the end of the test. Sample 2 and Sample 6 ISO 5659-2 were exceptions. For Sample 1 and Sample 5, some conditions were only tested up to 600 seconds. For these tests, the maximum smoke density recorded was at 600 seconds. All materials pass the NFPA 130 smoke density requirement of <100 at 1.5 minutes and <200 at 4 minutes in the ASTM E662 test.

Table 5-1: Smoke optical density results for all test conditions and materials

Material	Test	Ds (1.5 min)	Ds (4 min)	Ds (20 min)	Ds, max	tDs, max (s)
Sample 1	ASTM E662	19	135	518	518	1200
	ISO 5659-2 25 p	0	1	–	88	600*
	ISO 5659-2 50	12	247	580	580	1,195
Sample 5	ASTM E662	13	114	322	322	1,200
	ISO 5659-2 25 p	0	5	–	303	600*
	ISO 5659-2 50	12	299	–	579	600*
Sample 6	ASTM E662	27	5	220	220	1200
	ISO 5659-2 50	37	78	413	578	784
Sample 2	ASTM E662	0	4	270	337	890
	ISO 5659-2 50	18	116	124	256	358

*Test conducted for 10-minute duration

5.2 Toxicity Levels

Toxic gas concentrations were measured for each part of the test matrix in Table 4-1. Depending on the measurement method, the measurement of concentrations were taken continuously, semi-

continuously, or at discrete intervals. The maximum time for the test exposure was 20 minutes. The following sub-sections present the results for each material.

5.2.1 Sample 1

Experiments measuring toxic gases generated by testing Sample 1 were performed using ASTM E662 flaming exposure, ISO 5659-2 at 50 kW/m^2 exposure, and ISO 5659-2 at 25 kW/m^2 piloted exposure. The two measurement methods used were Method A (ASTM E662 exposure) and Method B (each exposure). For this material, regardless of exposure type, only CO and CO_2 were detected in significant concentrations. The test detected a small amount of NO_X while using Method A in the ASTM E662 test; at 20 minutes the value averaged 7 ppm for two experiments.

Figure 5-5 shows a comparison of CO and CO_2 gases generated in the ASTM E662 test for both Method A and Method B. CO concentrations at 20 minutes for Method A and Method B were 870 and 590 ppm, respectively. CO_2 concentrations were significantly different at 20 minutes for both methods. While CO and CO_2 concentrations increased in the chamber between 8 and 20 minutes in the Method A test, after 10 minutes the concentrations declined for the Method B test. This is attributed to the variation in sample combustion and testing conditions. For the ASTM E662 tests with Method B a wire grid was used to contain the intumescing polymer; a wire grid was not used for the Method A test and this could explain some difference in the result. Uncertainty for the ASTM E662 CO concentration at 20 minutes is estimated as ±5 percent (or ±44 ppm) based on the 95 percent confidence level for standard deviation of the mean of 2 specimens. Polymer samples may warp, drip, fall out of the sample holder, or intumesce during testing and this can increase variability.

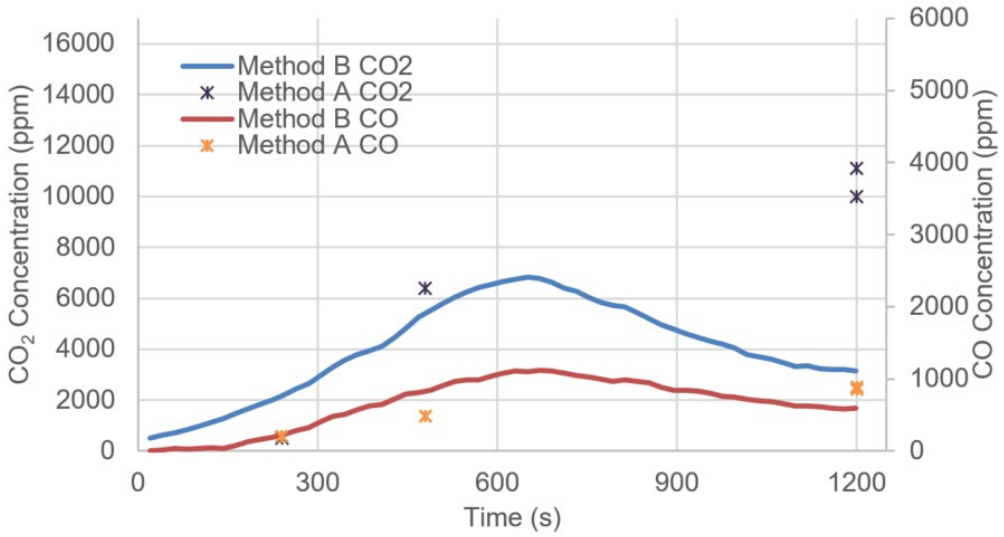

Figure 5-5: Sample 1 CO and CO_2 concentrations for ASTM E662 exposure using measurement Method A and Method B

Figure 5-6 contains CO and CO_2 concentrations measured in Sample 1 tests with measurement Method B, for all exposure types. For measurement Method B ISO 5659-2 tests, a wire grid was used, an identical setup to the ASTM E662 Method B tests. CO and CO_2 were the only concentrations detected using this measurement method. The ISO 5659-2 at 50 kW/m^2 test had the highest CO concentrations of all the test exposure conditions. Both ASTM E662 and ISO 5659-2 at 25 kW/m^2 piloted tests had significantly larger CO_2 concentrations over the 20 minute

test period, which was attributed to more flaming in these tests. For each test except the ASTM E662 with Method B, the peak gas concentrations occurred at 20 minutes, which also was the time of maximum smoke density. Table 5-2 tabulates the gas concentrations measured at 20 minutes. The 50 kW/m^2 exposure is the most severe exposure for this material, with CO reaching 3,017 ppm at 20 minutes. For the 25 kW/m^2 exposures, CO concentrations at 20 minutes ranged from 495 ppm to 870 ppm.

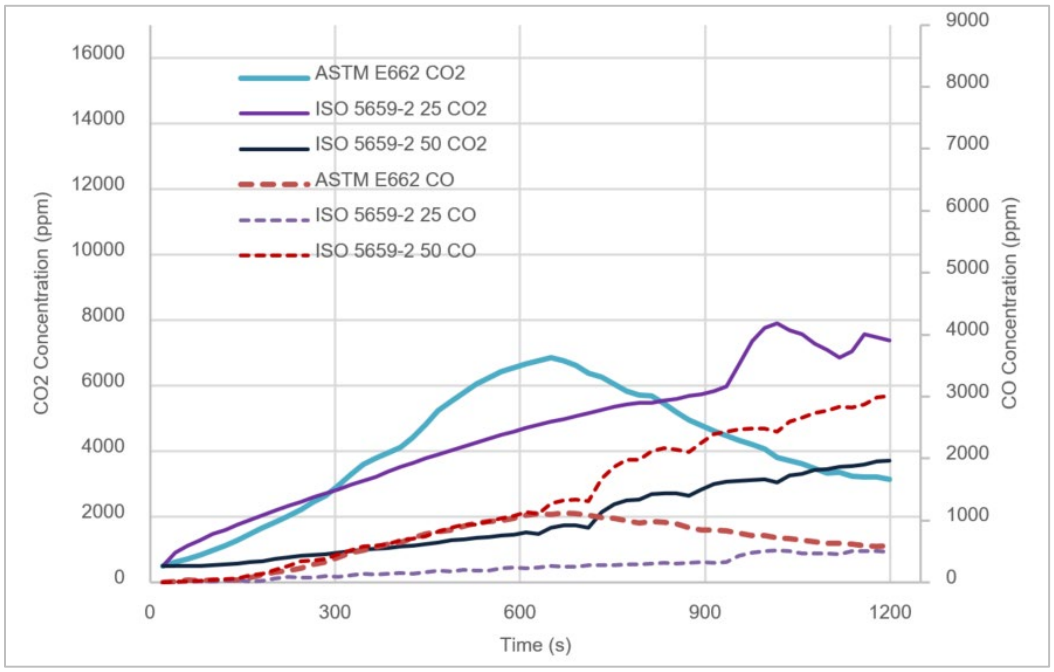

Figure 5-6: Sample 1 CO and CO_2 concentrations for ASTM E662, ISO 5659-2 50 kW/m^2, and ISO 5659-2 25 kW/m^2 tests using measurement Method B

Table 5-2: Sample 1 gas concentrations at 20 minutes

Exposure	Measurement	CO	CO_2	HCl	HCN	HF	HBr	SO_2	NO_X
ASTM E662	Method A	870	10,550	n.d.	n.d.	n.d.	n.d.	n.d.	7
ASTM E662	Method B	590	3,151	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ISO 5659-2 25	Method B	495	7,370	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ISO 5659-2 50	Method B	3,017	3,707	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. = not detected

5.2.2 Sample 5

The same tests run with Sample 1 were ran with the Sample 5 material. Figure 5-7 shows a comparison of measurement Methods A and B. The test was in the ASTM E662 smoke chamber with a flaming mode 25 kW/m^2 exposure. CO and CO_2 concentrations developed were significantly different between the two methods, with 20 minutes CO concentrations of 1,070 and 2,803 ppm for Method A and Method B, respectively. While researchers did perform a repeat test for Method A, this was not done for the Method B test. As the method was estimated to be below 20 percent for the gas concentrations themselves, the difference is not attributed to the measurement method but to test variability. For the ASTM E662 tests with Method B a wire

grid was used to contain the intumescing polymer; the Method A test did not use a wire grid and this could explain some difference in the result. Uncertainty for the ASTM E662 CO concentration at 20 minutes is estimated as ±36 percent (or ±380 ppm) based on the 95 percent confidence level for standard deviation of the mean of two specimens. Sample 5 had a high variation in the smoke box optical density tests.

The only significant concentrations developed in the Sample 5 tests were CO and CO_2. The Method A ASTM E662 tests detected a small amount of NO_X, and at 20 minutes the concentration averaged 7 ppm.

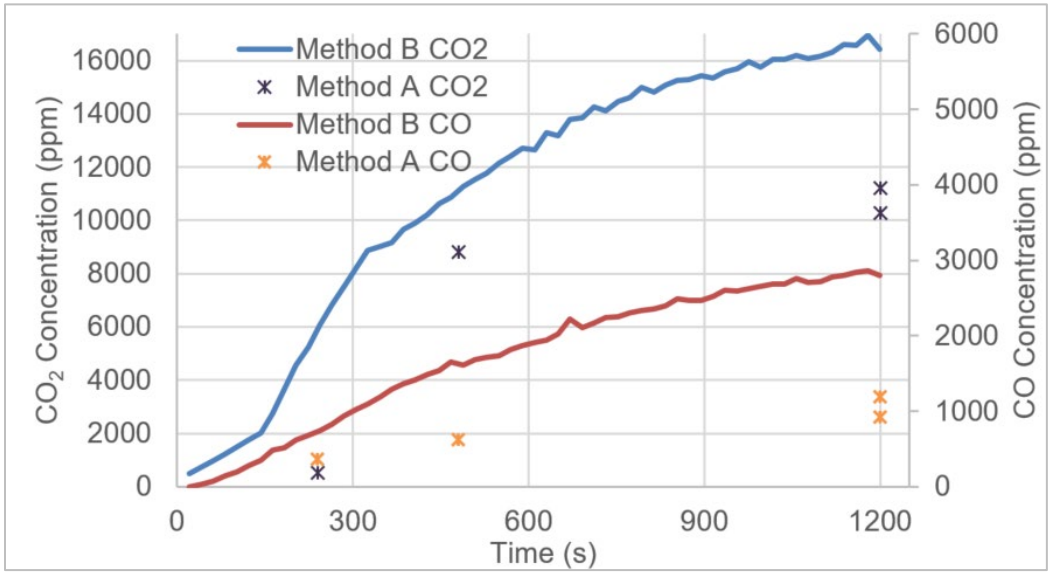

Figure 5-7: Sample 5 CO and CO_2 concentrations for ASTM E662 exposure using measurement Method A and Method B

Figure 5-8 shows the comparison of CO and CO_2 for different test exposures with measurement Method B. For all tests, the maximum CO and CO_2 concentrations occurred at 20 minutes. Discontinuities in the ISO 5659-2 at 50 kW/m^2 exposure were not considered to reflect the actual concentrations as the data points deviate from the overall trend. Although the ASTM E662 test with Method B used the wire grid, the ISO 5659-2 test did not. The ISO 5659-2 at 50 kW/m^2 had the largest CO concentration by a factor of 2 and was again the most severe exposure. The other exposures had larger CO_2 concentrations. Both ASTM E662 and ISO 5659-2 at 25 kW/m^2 include a pilot flame for ignition, which provides pre-mixed propane and air. This contributes somewhat to the CO_2 level in the box but does not account for the difference between the 50 kW/m^2 and 25 kW/m^2 exposure, which is attributed to a difference in burning behavior of the material.

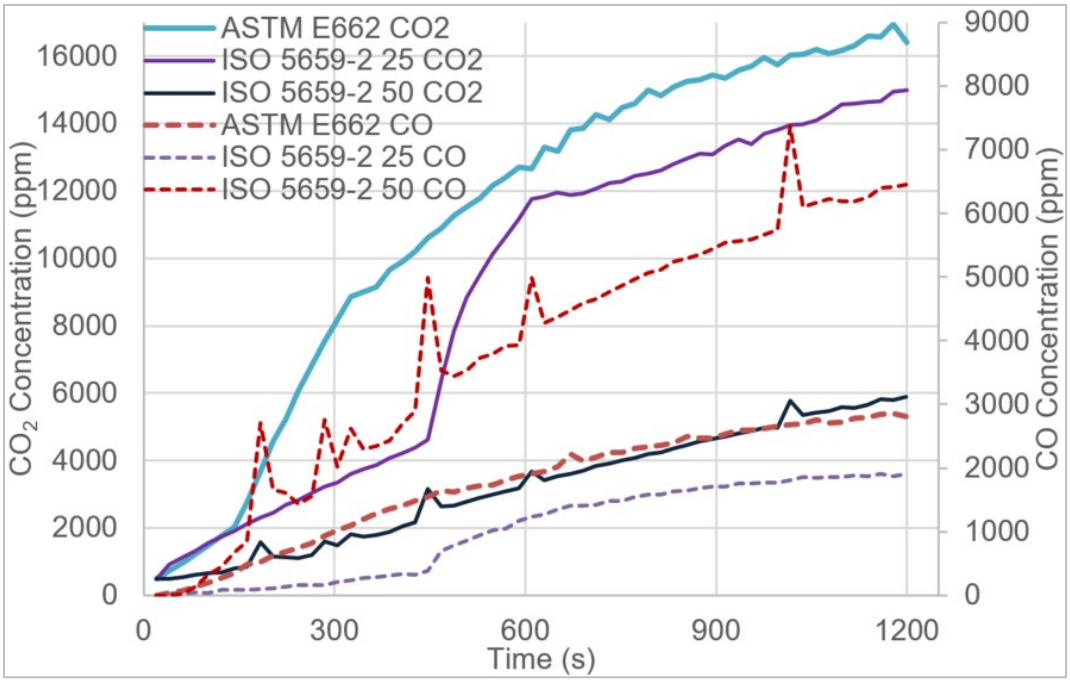

Figure 5-8: Sample 5 CO and CO_2 concentrations for ASTM E662, ISO 5659-2 50 kW/m^2, and ISO 5659-2 25 kW/m^2 tests using measurement Method B

Table 5-3: Sample 5 gas concentrations at 20 minutes

Exposure	Measurement	CO	CO_2	HCl	HCN	HF	HBr	SO_2	NO_X
ASTM E662	Method A	1,060	10,740	n.d.	n.d.	n.d.	n.d.	n.d.	7
ASTM E662	Method B	2,804	16,412	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ISO 5659-2 25	Method B	1,909	14,991	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ISO 5659-2 50	Method B	6,450	5,892	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. = not detected

5.2.3 Sample 6

Researchers tested the Sample 6 materials with ASTM E662 with Method A and ISO 5659-2 at 50 kW/m^2 with Method C. For the ASTM E662 with measurement Method A, the CO, CO_2, NO, NO_2, and SO_2 concentrations were measured at every 60 seconds interval with NDIR and electrochemical cells. Measurement Method C involved measuring the gas concentrations every 90 s with a FTIR spectroscopy system. Figure 5-9 shows the time-varying CO and CO_2 concentration for the average of two tests for both ASTM E662 and ISO 5659-2. For Sample 6, ASTM E662 and ISO 5659-2 CO concentrations were similar. The average ASTM E662 CO concentration at 20 minutes was slightly higher at 825 ±195 ppm; for ISO 5659-2 at 50 kW/m^2 the average concentration was 636 ±155 ppm. For this test, the more severe toxicity test exposure is ASTM E662 with the piloted mode. Peak CO concentrations for each test exposure was measured at 20 minutes.

For Sample 6 ASTM E662 test, a NO_2 concentration of 103 ppm and an HCN concentration of 7.5 ppm were detected at 20 minutes. Other concentrations were negligible. For the ISO 5659-2

test only CO and CO_2 were detected. The lower detectable limit for Method C of NO, NO_2, and HCN concentrations is 67.2 ppm, 14.8 ppm, and 21.7 ppm, respectively. CO_2 concentrations were larger for the ISO 5659-2 tests. Note that there was no CO_2 detected in the ASTM E662 tests with Method A until the concentration was greater than 5,000 ppm.

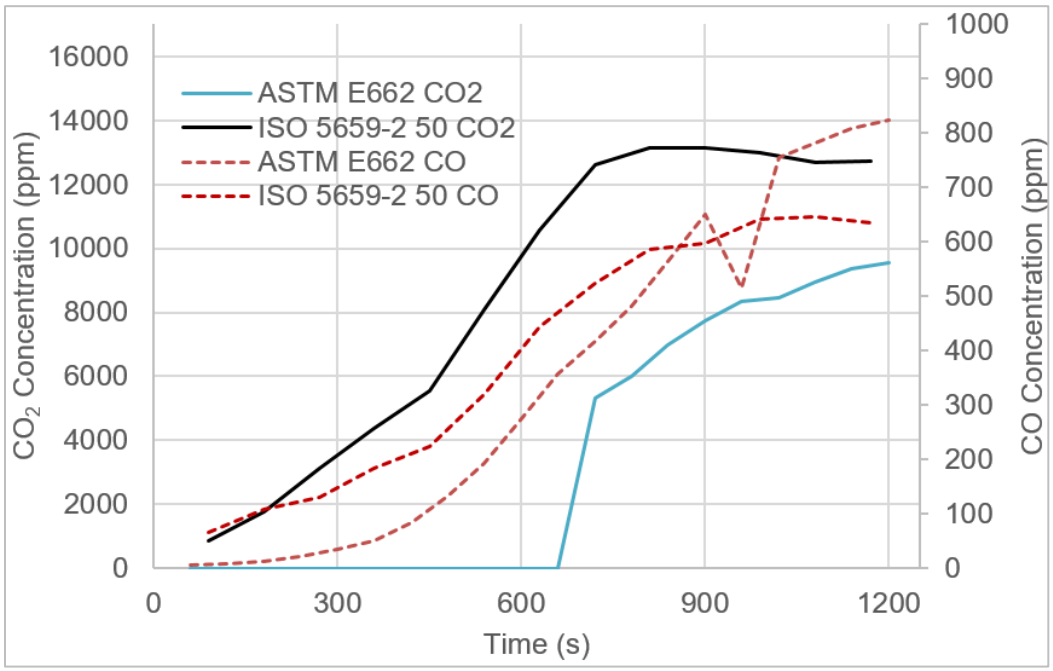

Figure 5-9: Sample 6 CO and CO_2 concentrations for ASTM E662 with Method A and ISO 5659-2 50 kW/m² tests with Method C. Results are the average of two tests

Table 5-4: Sample 6 gas concentrations at 20 minutes

Exposure	Measurement	CO	CO_2	HCl	HCN	HF	HBr	SO_2	NO_2
ASTM E662	Method A	825	9,550	n.d.	7.5	2.8	n.d.	n.d.	103
ISO 5659-2 50	Method C	636	12,728	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. = not detected

5.2.4 Sample 2

Researchers tested the Sample 2 materials with ASTM E662 with Method A and ISO 5659-2 at 50 kW/m² with Method C. The process for measuring gases was the same as for Sample 6. Figure 5-10 shows the time-varying CO and CO_2 concentration for the average of two tests for both ASTM E662 and ISO 5659-2. For Sample 2, both test exposures had maximum CO concentrations at 20 minutes; however, the CO concentrations were much higher for the ISO 5659-2 test, with the peak concentration of 809 ppm. This is 10 times the amount measured in the ASTM E662. CO_2 concentrations were high in the ISO 5659-2 test, reaching over 2.5 percent. The ASTM E662 test determined no measurable CO_2.

The critical heat flux for Sample 2 was measured as 23.5 kW/m² [15] in cone calorimeter tests. This material's aluminum face sheet can tend to delaminate in the cone calorimeter testing which can reduce the heat transfer to the combustible plywood core. The ASTM E662 test produced a low amount of CO and CO_2 due to the low exposure of 25 kW/m².

The Sample 2 ASTM E662 test detected a NO_X concentration of 0.9 ppm and an HCN concentration of 2.5 ppm at 20 minutes. A HF concentration of 3.8 ppm was also determined at 20 minutes. Other concentrations were negligible or not detected. The ISO 5659-2 test detected CO and CO_2 concentrations for each time increment.

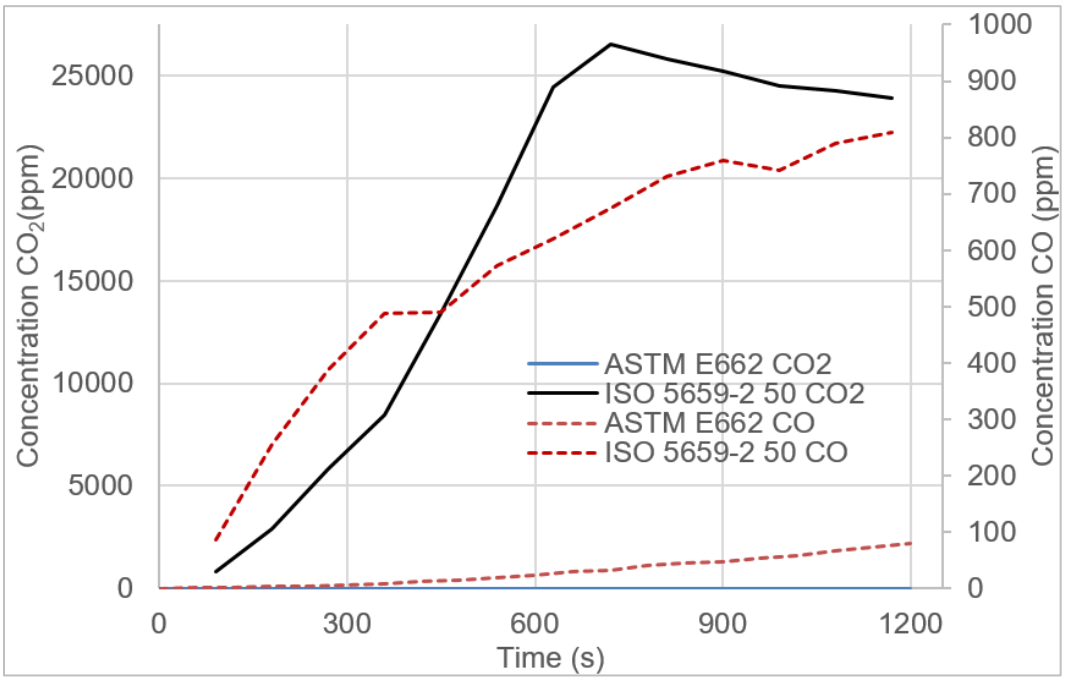

Figure 5-10: Sample 2 CO and CO_2 concentrations for ASTM E662 with Method A and ISO 5659-2 50 kW/m^2 tests with Method C. Results are the average of two tests

Table 5-5: Sample 2 gas concentrations at 20 minutes

Exposure	Measurement	CO	CO_2	HCl	HCN	HF	HBr	SO_2	NO_2
ASTM E662	Method A	80	n.d.	n.d.	2.5	3.8	n.d.	n.d.	0.9
ISO 5659-2 50	Method C	809	23,890	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. = not detected

5.2.5 Toxicity Testing Summary

For all materials tested, researchers measured the highest CO concentrations in the ISO 5659-2 50 kW/m^2 test exposure. Most of the tests had the highest toxicant gas concentrations at 20 minutes. The only toxicants measured in significant concentrations for these materials are CO and NO_X. Researchers did not measure concentration above 10 ppm for any other toxicant or irritant. ASTM E662 CO concentrations at 20 minutes were lower by 50 percent to 90 percent of those measured in ISO 5659-2 at 50 kW/m^2 for three out of four samples. Sample 6 was the exception, it had a higher CO concentration for the ASTM E662 test.

The Method B Sample 1 and Sample 5 ASTM E662 and ISO 5659-2 at 25 kW/m^2 results were compared to determine which test is more conservative. Peak CO concentrations were lower for the ISO 5659-2 test by 55 percent and 31 percent for Sample 1 and Sample 5, respectively. Burning in the ISO 5659-2 may have been inhibited more than in the ASTM E662 test. Polymers may burn differently when exposed in the horizontal configuration (ISO 5659-2) rather than the

vertical configuration (ASTM E662) if they are prone to drip, sag, or intumesce. Both Sample 1 and Sample 5 intumesced during the testing. For rigid materials such as FRP and sandwich composite materials, the difference in peak concentration is expected to be lower.

All measurement methods have similar accuracy. Researchers also compared measurement Method A (i.e., Drager tubes, NDIR, electrochemical cell) and Method B (i.e., FTIR with shorter time between spectra) using ASTM E662 tests with Sample 1 and Sample 5. CO concentrations for Method B were about 50–60 percent lower or higher than Method A at the 20-minute duration and this difference is attributed to test-to-test variability as well as some differences in how the research team conducted the test (e.g., use of wire mesh). FTIR based methods (Methods B and C) provided concentrations with time for all gases.

In addition, tests using Method A and Method C were more economical than Method B. Method B obtains gas concentrations at a higher rate for compliance with EN 45545-2 Annex C, and this more specialized system raises testing costs. Method C is optimized for the IMO FTP Annex 1: Part 2 toxicity test and has higher detectable limits than the other methods as well as a longer duration between gas measurements.

5.3 Other Literature Data

A database was compiled including U.S. and European railcar materials, tested using BSS 7239, SMP 800C, and ISO 5659-2 with FTIR. Additional test results from materials used in the naval industry were also compiled; these materials were tested with IMO FTP Annex 1: Part 2 and BSS 7239. Researchers used the data during the assessment of the performance criteria and models.

BSS 7239 and SMP 800C data were acquired from rail car material qualification tests. Figure 5-11 through Figure 5-16 contain boxplots showing the range of concentrations for CO, CO_2, HCl, HCN, NO_2, and HF for different types of materials used for large items and linings of the railcar. Most materials do not have significant amounts of irritant gases or HCN. Thermoplastics and FRP materials are more likely to have some amount of HCl, HF, and HBr (not shown) than sandwich composite materials.

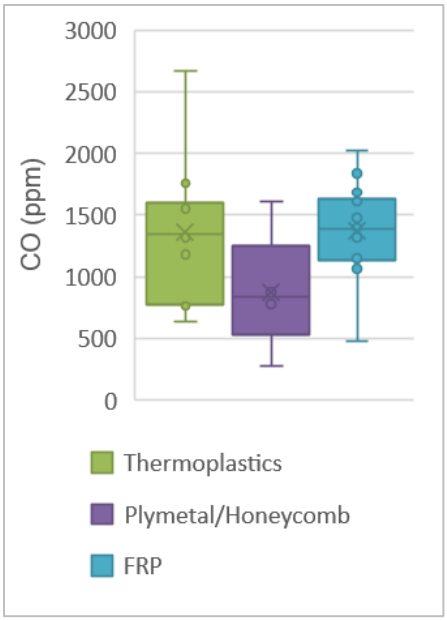

Figure 5-11: SMP 800C railcar database CO concentrations

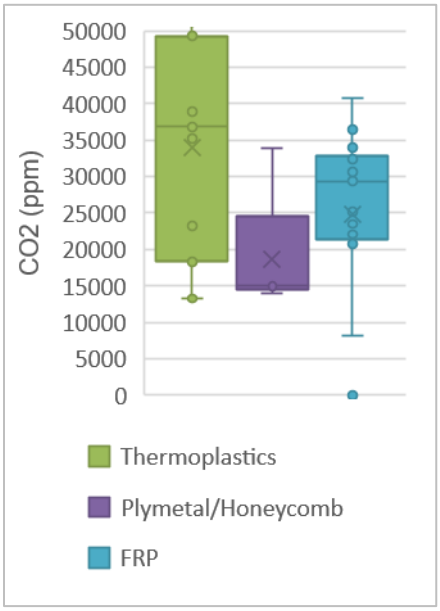

Figure 5-12: SMP 800C railcar database CO_2 concentrations

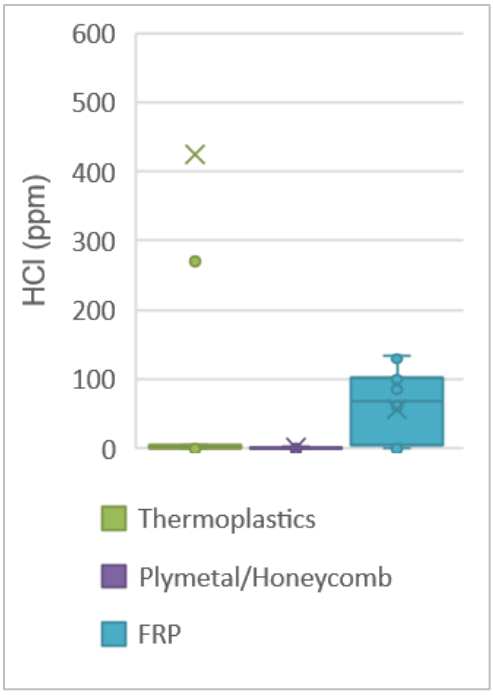

Figure 5-13: SMP 800C railcar database HCl concentrations

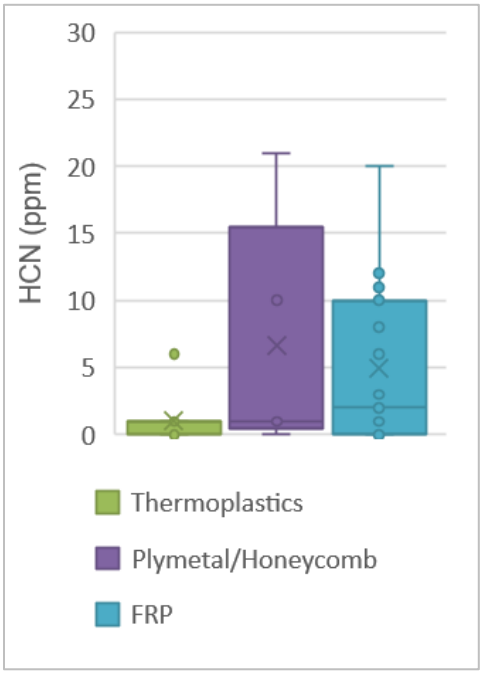

Figure 5-14: SMP 800C railcar database HCN concentrations

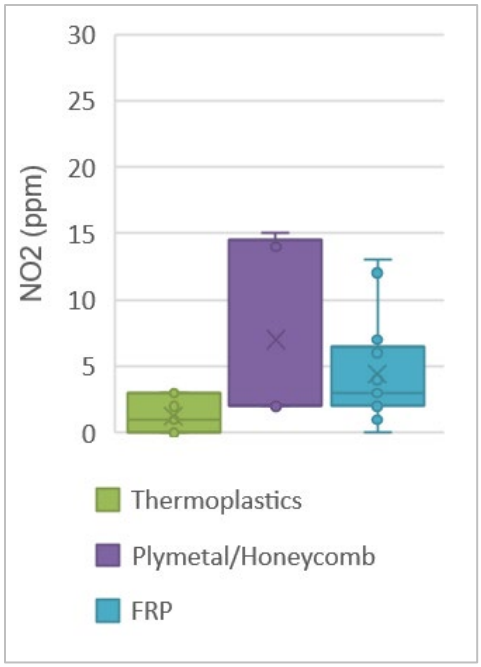

Figure 5-15: SMP 800C railcar database NO_2 concentrations

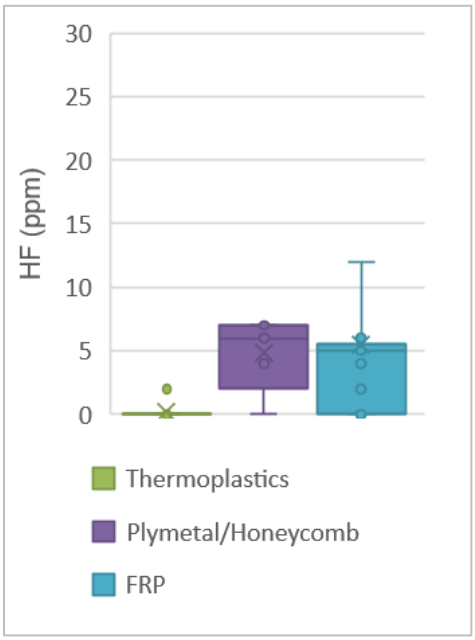

Figure 5-16: SMP 800C railcar database HF concentrations

Research Institute of Sweden (RISE)/SP published a dataset of European railcar materials which were tested using ISO 5659-2 with FTIR [16]. This data included concentrations from tests performed at 25 kW/m^2 piloted and 50 kW/m^2 non-piloted mode. In general, testing these materials used in large surfaces of the railcar consisted of wall linings, seatbacks, and partitions at the 50 kW/m^2 exposure level. Figure 5-17 to Figure 5-22 show boxplots for the 50 kW/m^2 ISO 5659-2 data for CO, HCN, NO_2, HCl, HBr, and SO_2. Researchers selected concentrations at 20 minutes for this comparison. In general, HCN and NO_2 concentrations are greatest for plymetal

and honeycomb panels. Acid gases such as HCl and HBr are more likely to occur in thermoplastic and FRP materials. HF was not detected for the materials in this dataset. A few of the materials also had significant levels of acrolein and formaldehyde.

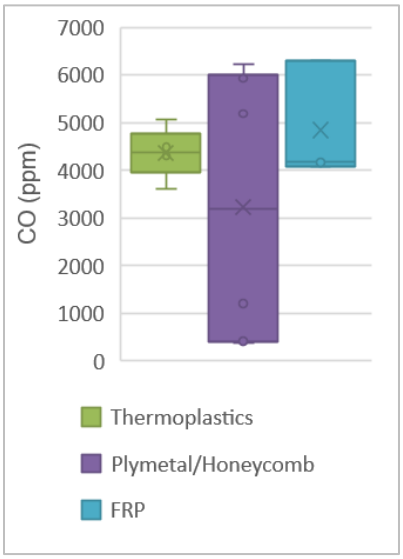

Figure 5-17: ISO 5659-2 50 kW/m^2 railcar database CO concentrations at 20 minutes

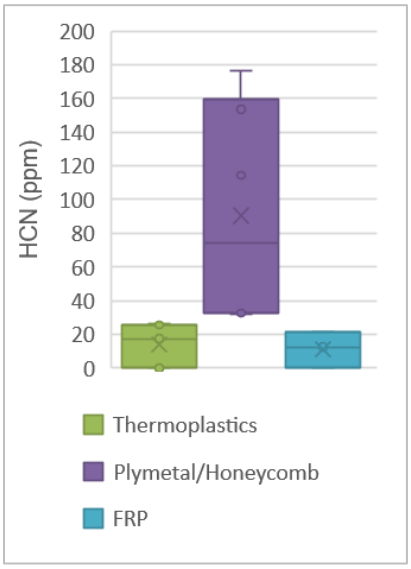

Figure 5-18: ISO 5659-2 50 kW/m^2 railcar database HCN concentrations at 20 minutes

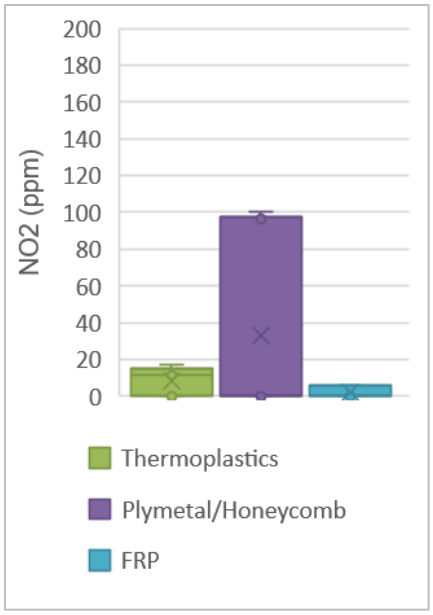

Figure 5-19: ISO 5659-2 50 kW/m^2 railcar database NO_2 concentrations at 20 minutes

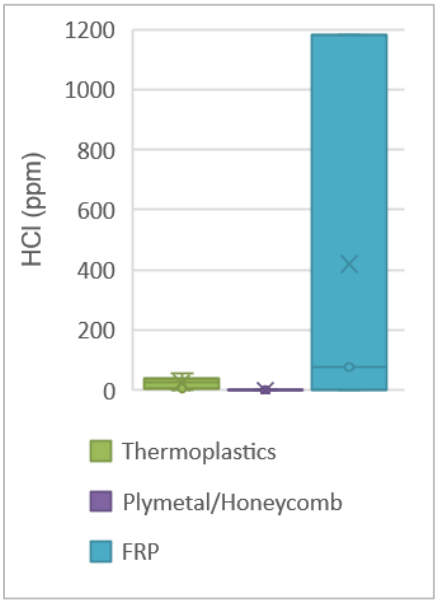

Figure 5-20: ISO 5659-2 50 kW/m^2 railcar database HCl concentrations at 20 minutes

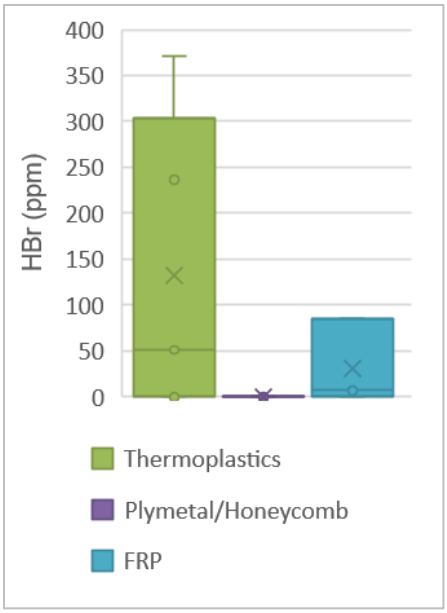

Figure 5-21: ISO 5659-2 50 kW/m^2 railcar database HBr concentrations at 20 minutes

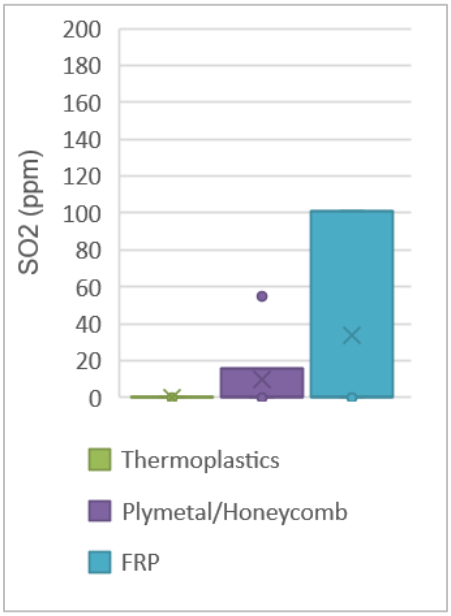

Figure 5-22: ISO 5659-2 50 kW/m^2 railcar database SO_2 concentrations at 20 minutes

Typically, the peak concentrations for the ISO 5659-2 FTIR tests at 50 kW/m^2 occurred between 18 and 20 minutes. Figure 5-24 shows the proportion of materials which have gas peak concentration between 10 and 20 minutes and between 18 and 20 minutes. For CO, 14 out of 15 total materials had peak concentrations between 18 and 20 minutes. For irritant gases such as NO_X, HCl, HBr, and SO_2, peak concentrations are usually between 10 and 20 minutes. Although the actual peak concentration may be at different time intervals for each gas, once the material generates a certain concentration usually the concentration is maintained at some level. An example is a wood-panel type material tested in the study, which had toxic emission of CO, HCN, and NO_X gases, shown in Figure 5-25. Although peak concentrations for CO, HCN, and

NO_X were measured at 510, 675, and 885 s, respectively, the concentration at 20 minutes is within 18 ppm to the peak concentration. Smoke density for the same materials at the same exposure occurred anywhere from 3 to 20 minutes and does not match the time of maximum gas concentrations. Over half of the materials had maximum smoke density occurring at or after 10 minutes.

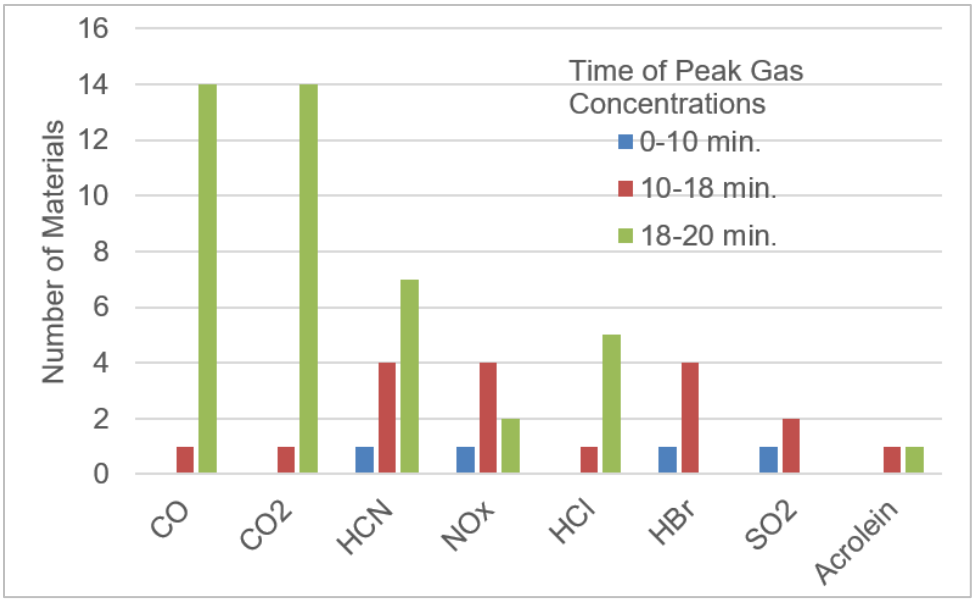

Figure 5-23: ISO 5659-2 50 kW/m^2 FTIR tests time of peak concentration

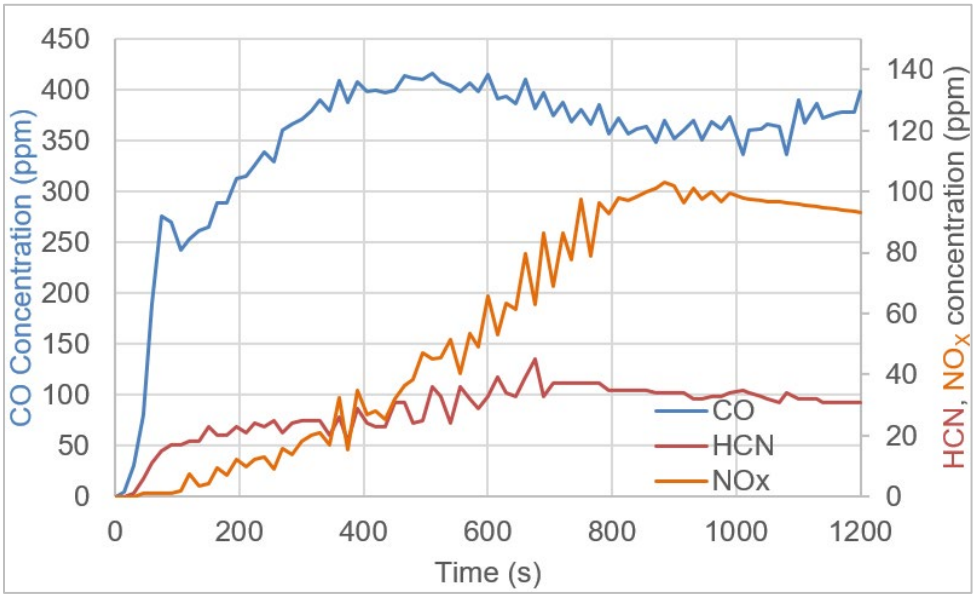

Figure 5-24: ISO 5659-2 50 kW/m^2 gas concentrations from wood panel rail car material test

ISO 5659-2 FTIR data for the 25 kW/m^2 piloted exposure was also published by RISE/SP, for a different set of materials. Materials tested at 25 kW/m^2 include upward-facing surfaces such as flooring, upholstery materials, as well as cable thermoplastics. Figure 5-25 through Figure 5-29

shows boxplots which display the concentration levels for these types of materials when tested in the 25 kW/m^2 test. CO concentrations measured were significantly less than for the materials set tested using the 50 kW/m^2. NO_2 and SO_2 concentrations were higher for the cable thermoplastics than the thermoplastics tested at 50 kW/m^2, which were materials used in larger size components such as window masks and seatbacks.

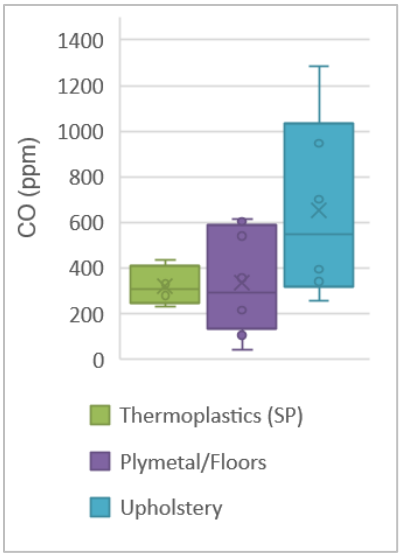

Figure 5-25: ISO 5659-2 25 kW/m^2 railcar database CO concentrations at 20 minutes

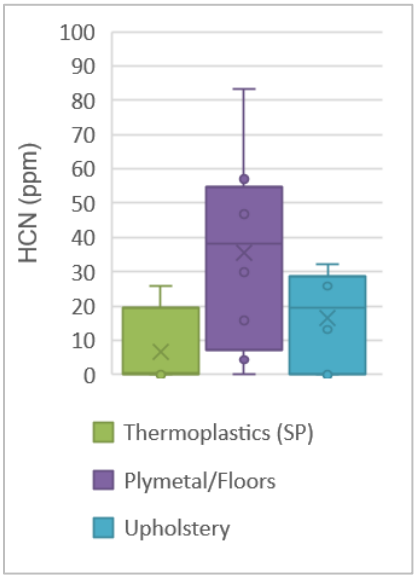

Figure 5-26: ISO 5659-2 25 kW/m^2 railcar database HCN concentrations at 20 minutes

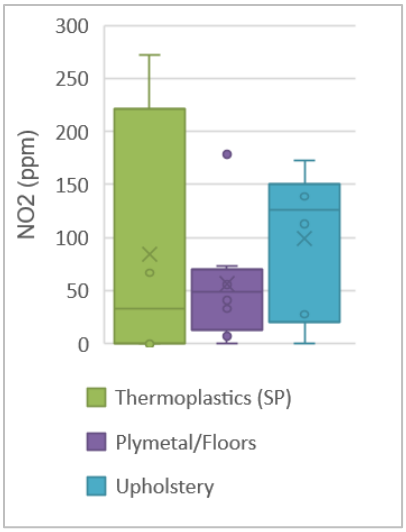

Figure 5-27: ISO 5659-2 25 kW/m^2 railcar database NO_2 concentrations at 20 minutes

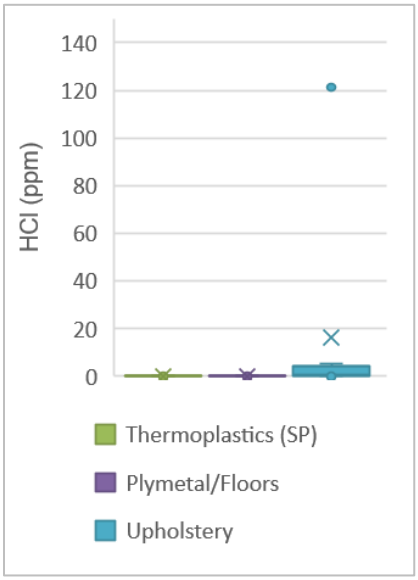

Figure 5-28: ISO 5659-2 25 kW/m^2 railcar database HCl concentrations at 20 minutes

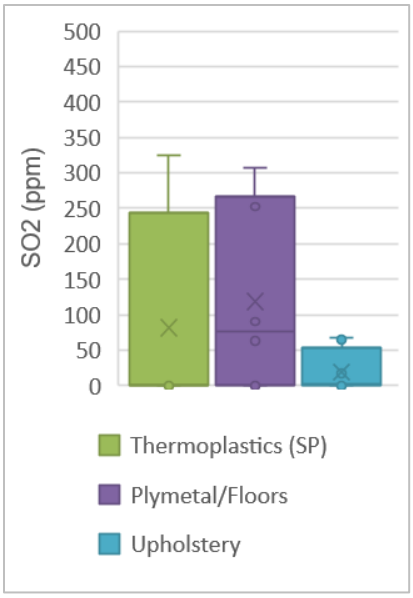

Figure 5-29: ISO 5659-2 25 kW/m^2 railcar database SO_2 concentrations at 20 minutes

Other published data includes that of Morchat [17] and Janssens [18]. Both reports include results from smoke and toxicity tests of glass fiber reinforced polymers for naval watercraft. Morchat [17] used ASTM E662 and BSS 7239 to measure concentrations at various intervals. Table 5-6 contains peak gas concentrations for the tests conducted on samples using a variety of polymer resins with and without a fire retardant, alumina trihydrate (ATH). Morchat measured CO, HCN, NO_X, HBr, HCl, HF, and SO_2 in the BSS 7239 tests. Only CO, HCl, and HBr were measured in significant concentrations.

Table 5-6: Morchat BSS 7239 peak gas concentrations [17]

Description	Type	CO (ppm)	HCl (ppm)	HBr (ppm)
Derakane 510A	FRP	3,056	60	62
Derakane 510A 25 phr	FRP	2,640	83	163
Hetron 197AT	FRP	3,328	450	28
Hetron 197AT 25 phr	FRP	2,605	280	7
Hetron 27196	FRP	1,760	870	7
Hetron 27196 25 phr	FRP	2,375	1,580	3
Hetron 692TP25	FRP	2,545	150	16
Hetron 692TP25 25 phr	FRP	2,513	16	34
Epon 813	FRP	870	26	4

Description	Type	CO (ppm)	HCl (ppm)	HBr (ppm)
Epon 813 25 phr	FRP	1,100	6	2

Janssens [18] performed an experimental study on composites used in high-speed craft in U.S. Coast Guard applications. The research team performed ISO 5659-2 smoke and toxicity tests according to the IMO FTP Annex 1: Part 2 procedure which prescribes detection of gas concentrations at the time of maximum smoke density using an FTIR spectroscopy system. Table 5-7 and Table 5-8 contain the toxic gas concentrations measured in this study. Only CO, HCN, HCl, and SO_2 were measured; other gases did not attain a detectable concentration. In this study, the 50 kW/m^2 non-piloted exposure had the highest gas concentrations for most of the materials. One exception was the FR modified acrylic material, which had 802 ppm CO for the 25 kW/m^2 piloted condition but only 507 ppm CO for the 50 kW/m^2 non-piloted condition. The 25 kW/m^2 non-piloted exposure had higher SO_2 concentrations and lower CO concentrations than the 25 kW/m^2 piloted exposure. This study also reported smoke data for these materials, and for most materials, the time to maximum smoke density was between 10 and 20 minutes. This is the case regardless of the exposure.

Table 5-7: U.S. Coast Guard (USCG) IMO FTP part 2 toxic gas concentrations in ppm for CO and HCN

	CO			HCN		
	50 np	25 np	25 p	50 np	25 np	25 p
FR phenolic	501	288	342	0	0	0
Fire restricting material	3,452	183	161	59	0	0
FR polyester	4,780	359	2,572	0	0	0
FR vinyl ester	5,330	377	1,836	0	0	0
FR epoxy	1,363	288	215	0	0	0
Coated FR epoxy	320	25	105	32	0	0
Wall covering	828	236	272	0	0	0
Polyester	2,018	364	1,157	0	0	0
FR modified acrylic	507	370	802	0	0	0

np=non-piloted, p=piloted

Table 5-8: USCG IMO FTP part 2 toxic gas concentrations in ppm for HCl and SO_2

	HCl			SO_2		
	50 np	25 np	25 p	50 np	25 np	25 p
FR phenolic	15	0	0	0	20	0
Fire restricting material	0	0	0	102	49	42
FR polyester	0	0	46	120	96	30

	HCl			SO_2		
FR vinyl ester	74	0	33	109	21	18
FR epoxy	34	0	0	109	40	36
Coated FR epoxy	15	11	12	28	14	0
Wall covering	0	0	0	22	12	0
Polyester	12	0	0	22	97	0
FR modified acrylic	16	0	13	0	0	0

np=non-piloted, p=piloted

6. Discussion

The application of small-scale toxicity test results to limit the railcar materials' toxic gas emission in the end use condition requires the selection of a representative test and evaluation parameters. The heat exposure, sample orientation, and the time of gas sampling must be representative of a fire scenario in the railcar. The gas concentration measurement method must be sufficiently precise and accurate to record the transient toxic emission of the material. Another factor in determining an appropriate standard is defining the limiting criteria used to accept the material test results. Different models and approaches to estimate the overall hazard of multiple toxic gases have been developed. Each of these aspects of setting a standard are evaluated in this section to provide a basis for railcar material toxicity requirements.

6.1 Smoke Box Test Type

The smoke optical density generated in the two tests is generally correlated to toxic gas levels developed in the chamber. Typically, toxicity tests for qualifying transportation grade materials use the same test apparatus as for the smoke density. The two tests considered in this work are ASTM E662 and ISO 5659-2 which are common smoke density tests for many industries and are used in the U.S. and European regulations. ASTM E662 prescribes a 25 kW/m^2 exposure in both piloted and non-piloted mode. ISO 5659-2 uses a cone heater for both 25 and 50 kW/m^2 exposures in the piloted or non-piloted modes. The 50kW/m^2 exposure is normally only performed in non-piloted mode. This work compared the ISO 5659-2 50 kW/m^2 non-piloted and 25 kW/m^2 piloted exposures to the ASTM E662 25 kW/m^2 piloted exposure.

In this testing, the ISO 5659-2 test at 50 kW/m^2 in non-piloted mode was generally the most severe condition for all materials for both smoke density and toxic gas emission, with two exceptions. For Sample 2, smoke density at 20 minutes was lower for ISO 5659-2 at 50 kW/m^2. However, the toxic gases generated were up to 10 times those generated in the ASTM E662 test. Sample 2 was an aluminum-faced plywood-core sandwich composite with very good fire performance at lower heat exposures. Sample 6, vinyl-ester-based glass-reinforced polymer, had comparable concentrations between the ISO 5659-2 at 50 kW/m^2 (636 ±195 ppm) and ASTM E662 (825 ±155 ppm). Sample 6 also had 103 ppm NO_2 in ASTM E662, but no detectable concentration in ISO 5659-2 at 50 kW/m^2. This may be due to the presence of a pilot flame in ASTM E662.

Although the ISO 5659-2 with the 50 kW/m^2 non-piloted exposure generally causes the highest CO concentrations, this mode may not represent fire conditions expected for a representative initiating fire in a rail car. Generally, an initiating fire will consist of a flaming ignition source. Thus, the non-piloted 50 kW/m^2 exposure may cause higher CO concentrations than would occur in a real-scale fire. Marsh et al. [20] found that for polyurethane foam, CO concentrations were six times smaller for the piloted 50 kW/m^2 exposure than for the non-piloted 50 kW/m^2 ISO 5659-2 test. Marsh et al. [20] also points out that the presence of a flame enhances the oxidation of the CO into CO_2.

The experimental data from Sample 1 and Sample 5 using measurement Method B (see Figure 5-6 and Figure 5-8) indicate that ASTM E662 results in higher toxicity levels than ISO 5659-2 at 25 kW/m^2. The difference can be attributed to the burning behavior of the thermoplastic material in the vertical and horizontal configurations. As the heat exposure is similar, for many materials

it is expected that these two tests would yield a similar result unless the materials tested are prone to drip, intumesce, or experience other volatile and unpredictable behavior.

6.2 Gas Concentration Measurement Method

The measurement method used was not observed to have a significant impact on the measured gas concentrations. Method A has lower detectable limits for gas concentrations than Method B and Method C. There are several different detection techniques used in Method A. One of these is the colorimetric glass detector tubes, which have low limits of detection, as these have been developed for detecting workplace contaminants. However, glass detector tubes may have significant interference with other fire gas compounds, particularly HCN and halogens. The main benefit to Method B and Method C, based on FTIR spectroscopy systems, is that all subject gas concentrations are measured simultaneously from the absorption of the IR spectrum by the different gas components. The detectable limits are higher due to the need to determine a characteristic absorption profile in the spectrum. Accuracy is quite good and interference between gases is generally similar or lower than the Method A techniques.

The major source of variation between measurement methods in the experimental study is the test-to-test variation. Some additional error is introduced by the difference in sample time since each method has a different delay. Transportation materials generally have fire retardant additives, which can lead to higher test-to-test variability. The Sample 5 smoke and toxicity tests exhibited such variability..

The main benefit of FTIR spectroscopy systems for use in toxicity tests is the ability to measure multiple gas concentrations for a single time interval, with low effect on the smoke density or gases in the chamber. A disadvantage of the Method A colorimetric tube technique is interference of a tube with other gases. For example, the HCl detector tube has some sensitivity to NO_2 and chlorine [20]. This leads to higher measurement uncertainties which are difficult to quantify.

In defining a test and measurement method for U.S. railcar lining materials, it is desirable to have a standardized approach that limits variability between test labs. Method A includes several techniques that have different equipment requirements and sampling durations. For this reason, it is recommended that toxicity tests be performed with Method B or Method C, which use a FTIR spectroscopy system for all gas concentrations.

6.3 Gas Sampling Time

For the experiments performed in this study, all but one test had maximum gas concentrations at or near 20 minutes. Maximum smoke density for each material was also near the end of the test. An exception was the smoke density for Sample 2, which was an aluminum-faced sandwich composite material. This material had lower smoke density overall than other materials and for the ISO 5659-2 at 50 kW/m^2 had maximum smoke density at 358 seconds. The IMO FTP code specifies sampling the gas concentrations at the time of maximum smoke density. This time is often significantly different from the time of peak gas concentrations. The RISE/SP database contains both smoke density and toxic gas concentration results for several materials tested in ISO 5659-2 at 50 kW/m^2, and for most of the materials, the maximum concentration was at 20 minutes, while the maximum smoke density occurred anywhere from 3 to 20 minutes for the same set of materials. There was also a significant amount of test-to-test variation that would also make it difficult to select a time at which the peak gas concentrations would be expected. As

a result, gases should be sampled at the end of the test (20 minutes) rather than at the time of peak smoke density.

6.4 Performance Criteria

Each toxicity standard and specification considered in this work has a different method for evaluating material toxicity performance. Some, like BSS 7239, SMP 800C, and IMO FTP Annex 1: Part 2, use simple concentration limits. The idea behind these standards is that for the time duration of interest, the concentration in the space will not exceed a certain level which would cause incapacitation or death due to toxic gases. Other methods use dosage-based calculations to determine the overall toxicity of the gas composition as described below, which requires a more continuous measurement of gas concentrations for accurate calculation.

The EN 45545-2 standard uses a summation term to aggregate the effects of the different toxicants and irritants in the railcar. The CIT is a single calculated value, which represents the particular hazard in the railcar. This evaluation method assumes the interaction between the toxic gases is additive. CIT value uses concentration values at 4 and 8 minutes from the toxicity test and normalizes them by reference concentrations, which are based on the National Institute for Occupational Safety and Health's (NIOSH) Immediately Dangerous to Life of Health (IDLH) levels for toxic gases. The IDLH levels are based on gas concentrations which would inhibit the escape of workers from a contaminated environment. Appendix B provides the method of calculation of the CIT parameter according to EN 45545-2. Although EN 45545-2 uses the IDLH levels as the basis for calculating the CIT, the precursor term enables the nominal allowable concentrations in the smoke box to be over 12 times that of the reference IDLH concentrations. The precursor term represents the ratio between the expected burning surface area and the railcar volume to the smoke box material sample area and the smoke box volume. In the precursor term calculation, the expected burning surface area in the railcar is 1.08 ft^2 (0.1 m^2), which is only about 11 percent of the area expected from a representative initiating fire such as NFPA 286. Even though the smoke box volume scaling in EN 45545 is appropriate, the lower expected burning surface area makes this methodology non-conservative. Therefore, the CIT method as in EN 45545-2 is not recommended.

The ISO 13344 and ISO 13571 standards use a FED approach. For ISO 13344 the dosage is based on the median lethal concentration (LC_{50}) for rats for both asphyxiant gases CO and HCN, as well as irritant gases. For ISO 13571 the FED is calculated only for asphyxiant gases such as CO and HCN; a FEC is calculated for irritant gases. The FEC is the summation of each irritant gas normalized by its critical concentration. Disabling effects of these gases are from eye and respiratory tract irritation and is assumed to be instantaneous upon the critical concentration being reached [8]. The equations in ISO 13344 for calculation of a tenability time are more convenient, but they are less useful than the approach provided by ISO 13571. The ISO 13344 equations provide a less conservative result than the ISO 13571 FED/FEC approach as they are based on rat lethality data instead of human incapacitation.

Table 6-1 compares the BSS 7239, SMP 800C, IMO FTP Annex 1: Part 2, and IDLH concentrations. In addition to these, the Emergency Release Prevention Guideline (ERPG) concentrations are also included for comparison. The ERPGs are developed to ensure the safety of people from a release of toxic chemicals for 60 minutes. ERPGs have been developed to assist organizations in emergency planning and response to a release of toxic chemicals. These levels are developed considering the effects of chemicals on the general population. ERPG-3, included

in Table 6-1, is the level above which nearly all individuals would not experience life-threatening effects after a 60-minute exposure to the gas concentration. SMP 800C criteria also include CO_2 limit of 90,000 ppm. Although CO_2 can enhance the effect of other toxicants, this is usually not a significant factor unless the CO_2 level is higher than 3 percent [21].

Table 6-1: Gas concentration limit criteria for BSS 7239, SMP 800C, IMO FTP part 2, IDLH, and ERPG-3

	BSS 7239	SMP 800C	IMO FTP part 2	IDLH	ERPG-3	ERPG-3 scaled*
CO	3,500	3,500	1,450	1,200	500	1,500
HCN	150	100	140	50	25	75
NO_2	100	100	350	13	30	90
HCl	500	500	600	50	150	450
HF	200	100	600	30	50	150
HBr	-	100	600	30	150	450
SO_2	100	100	120	100	25	75
Acrolein	-	-	-	2	1.5	4.5
Formaldehyde	-	-	-	20	40	120

*scaled from 60-minute values to a 20-minute value

The one-time emergency hazard prevention basis of the ERPGs is highly applicable to the focus of this study, which is the safe evacuation of passengers from a railcar during a fire. Based on floor fire resistance requirements in NFPA 130, it is assumed that railcar evacuation can occur within 15–30 minutes. Thus, the maximum allowable concentration in a railcar compartment may be larger than the 60-minute ERPG-3 level and was scaled to a 20-minute time to be in the range of railcar egress times and consistent with the range of toxicity test times. Concentrations were scaled using the ten-Berge equations, $C^n \times t = K$, where K is a constant, t is the time duration, C is the concentration, and n is the dose-time relationship parameter [22]. For simplicity, $n = 1$ for this study. As seen in Table 6-1, the scaled ERPG-3 levels are very similar to the IMO FTP Annex 1: Part 2 criteria. For the remainder figures and plots that follow, ERPG-3 refers to the scaled concentrations, as these are applicable for the 20-minute exposure of occupants in a railcar fire scenario.

Of the existing toxicity standards, the IMO FTP Annex 1: Part 2 is the most conservative in limits on asphyxiant gases CO and HCN and has similar levels to the ERPG-3 scaled limits. BSS 7239 and SMP 800C have lower limits on the irritant gas criteria, but these specifications indicate that gases will be sampled beginning at 4 minutes. This particular sampling time interval does not capture the highest level of toxic gases. Also, egress of occupants from the railcar may take 15–30 minutes, and only sampling at 4 minutes does not provide a conservative assessment of material toxicity. The IMO FTP Annex 1: Part 2 is conducted for 20 minutes, which is in the range of the expected egress time.

Figure 6-1 and Figure 6-2 show a comparison of railcar material toxicity results with the scaled ERPG-3 levels and ISO 13571 FED/FEC. Figure 6-1 contains materials tested in ASTM E662 test or SMP 800C with concentrations reported at 20 minutes. SMP 800C toxic gas

concentrations are measured between 4 and 20 minutes, and the data here is assumed to reflect concentrations at 20 minutes. The FED and FEC were computed according to ISO 13571 with concentrations at 20 minutes. Most of the U.S. railcar materials pass both ERPG-3 scaled levels and the ISO 13571 FED/FEC criteria. Data plotted is from railcar material database [9] as well as the current experimental study.

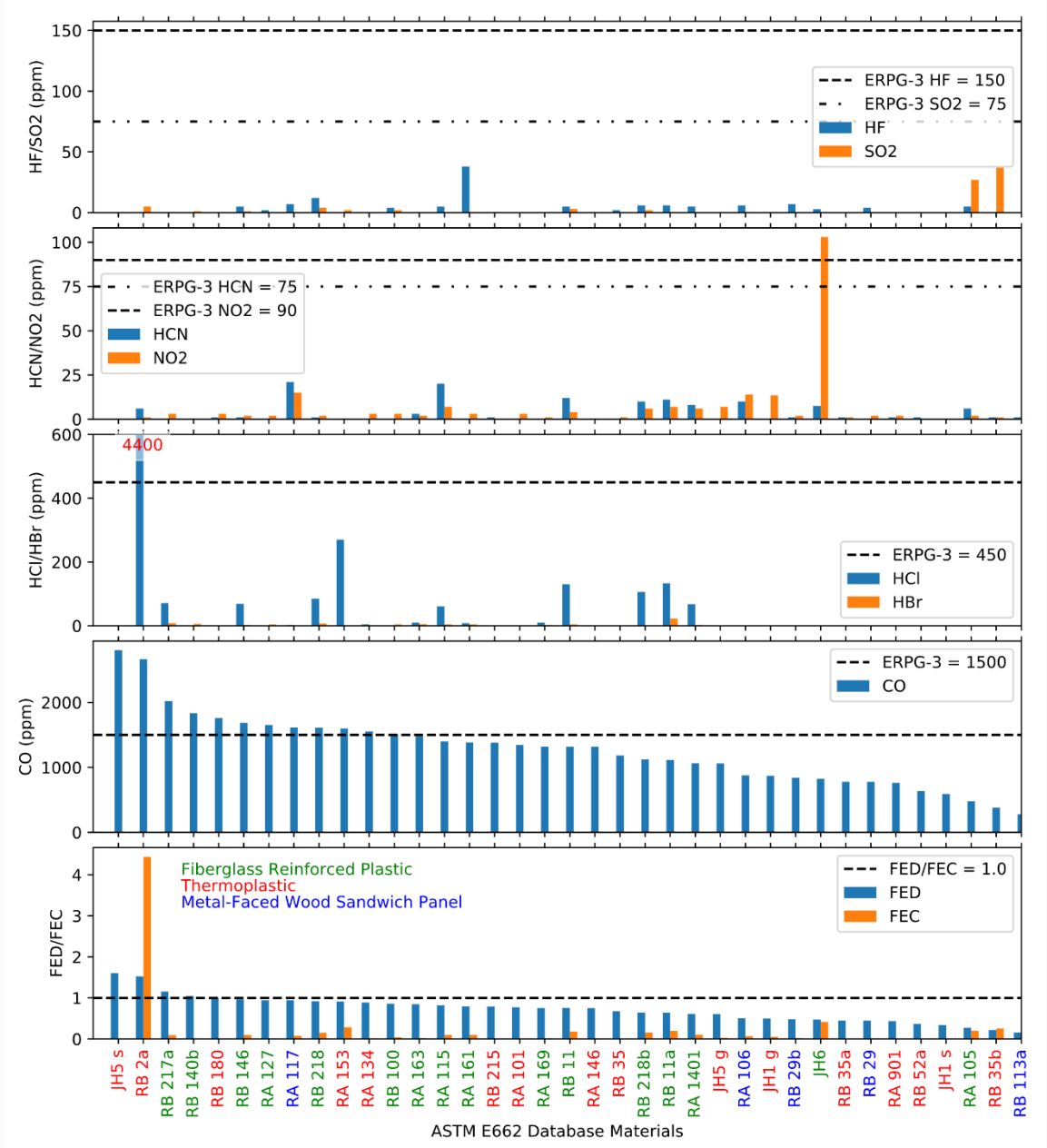

Figure 6-1: U.S. railcar material toxicity, tested with ASTM E662, compared with ERPG-3 scaled concentration and FED/FEC model

Figure 6-2 contains concentrations at 20 minutes for ISO 5659-2 50 kW/m^2 FTIR tests on railcar materials. Most do not pass either ERPG-3 scaled or the FED/FEC criteria. All but five materials fail the CO criterion ERPG-3 scaled < 1,500 ppm. All but three materials fail the FED < 1.0

criteria. Data included in Figure 6-2 is from the RISE/SP database [16] as well as from current experimental work. As mentioned in Section 6.1, the 50 kW/m^2 non-piloted exposure is likely overly conservative and not consistent with the current testing approach for other incomplete combustion products (smoke) on materials that use an exposure of 25 kW/m^2 piloted and non-piloted. The data does show that both methods do screen out similar materials, indicating they are equally adequate performance criteria.

Figure 6-3 contains a similar comparison of material toxic gases for 25 kW/m^2 piloted exposure. Concentrations at 20 minutes are plotted and used to calculate the FED and FEC. Toxic gas levels for materials from the RISE/SP database and the current experimental work are compared to the ERPG-3 scaled criteria and FED/FEC. Most of the RISE/SP materials tested at 25 kW/m^2 piloted exposure are not as applicable as they include upholstery items, cable thermoplastics, and other small parts. Although these items are present in the railcar, the larger surface area materials such as wall linings, seatbacks, and partitions are expected to contribute more significantly to development of toxic gases. Figure 6-3 shows that either set of performance criteria screens out poorly performing materials tested with this exposure.

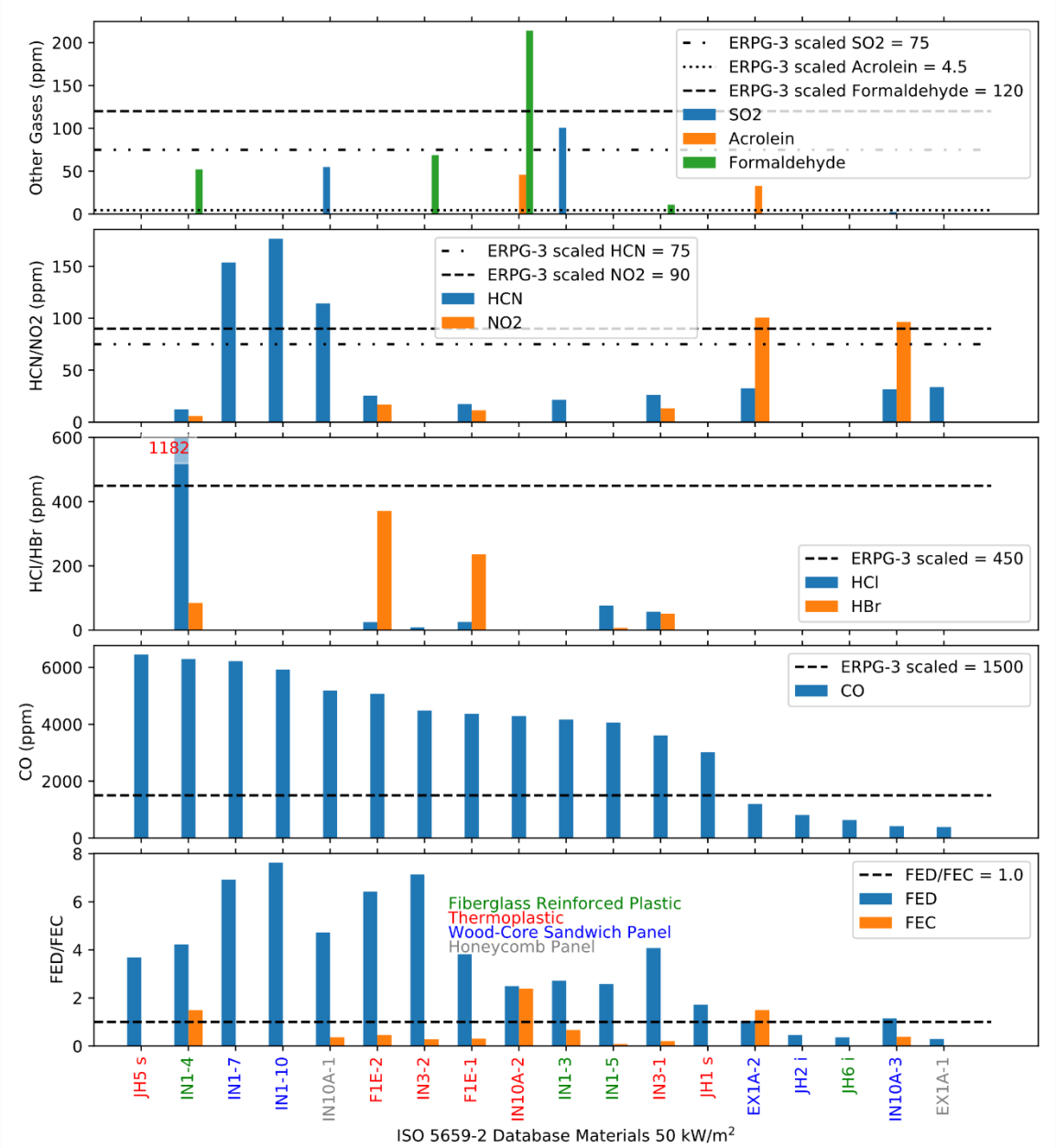

Figure 6-2: European and U.S. railcar material toxicity, tested with ISO 5659-2 at 50 kW/m^2 and FTIR, compared with ERPG-3 scaled concentration and FED/FEC model

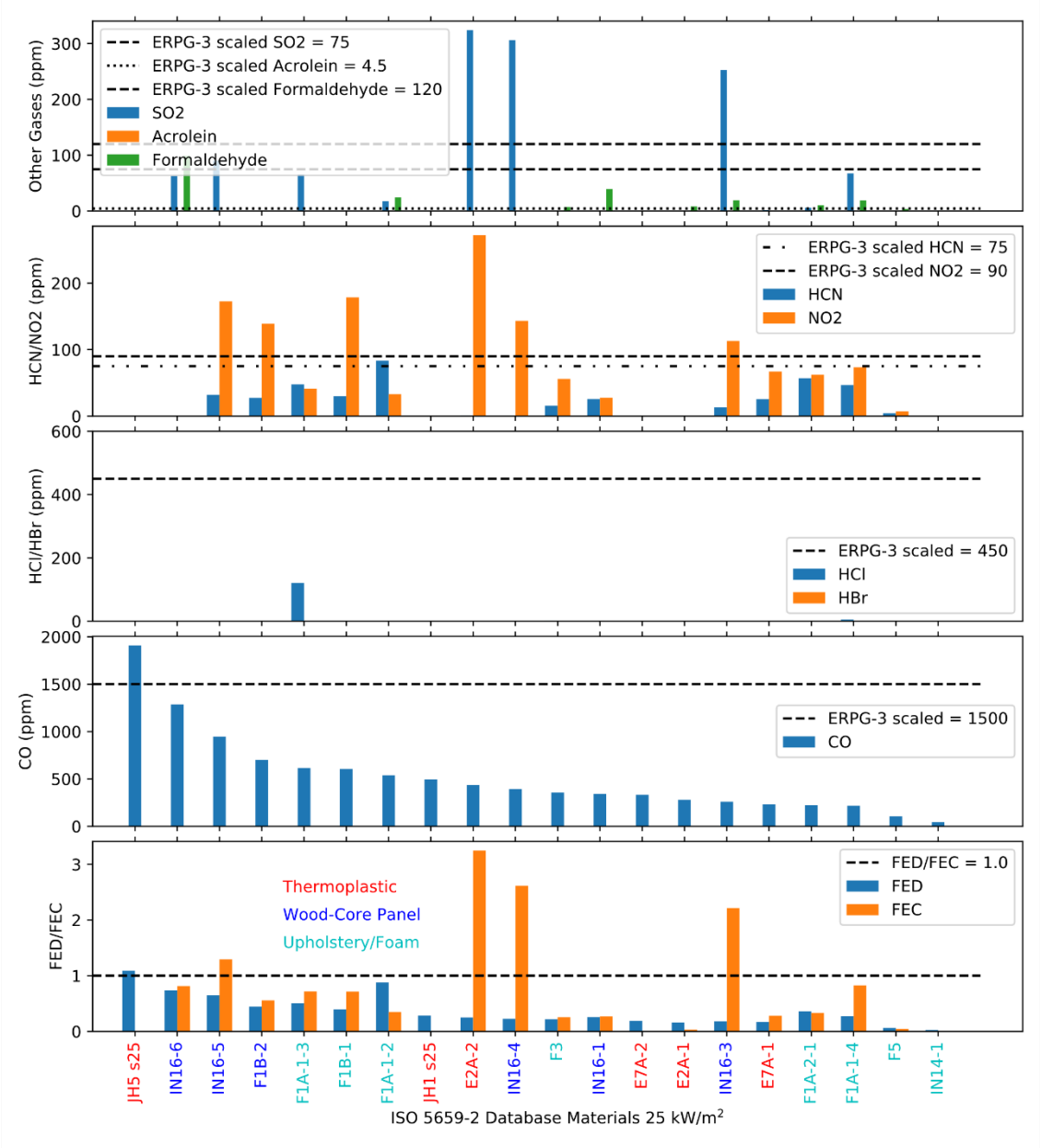

Figure 6-3: European and U.S. railcar material toxicity, tested with ISO 5659-2 at 25 kW/m² and FTIR, compared with ERPG-3 scaled concentration and FED/FEC model

A comparison of FED/FEC and maximum concentration was also performed for naval industry materials. Calculating the FED consisted of using either the reported maximum concentration or the concentration measured at peak smoke density for a 20-minute duration. Results are shown for FRP composites tested with BSS 7239 [17] in Figure 6-4. Most of these materials fail both CO < 1,500 ppm and FED < 1.0. Note that with these materials the only irritant measured in significant concentrations was HCl. Both criteria methods screen out similar materials. Figure 6-5, Figure 6-6, and Figure 6-7 contain results for materials tested in IMO FTP Annex 1: Part 2. For these materials, four out of nine fail FED > 1 and CO > 1,500 ppm at the 50 kW/m² non-piloted exposure, while only two fail these criteria for 25 kW/m² piloted. Both criteria

screened out similar materials with the toxicity limits screening slightly more samples than the FED/FEC model.

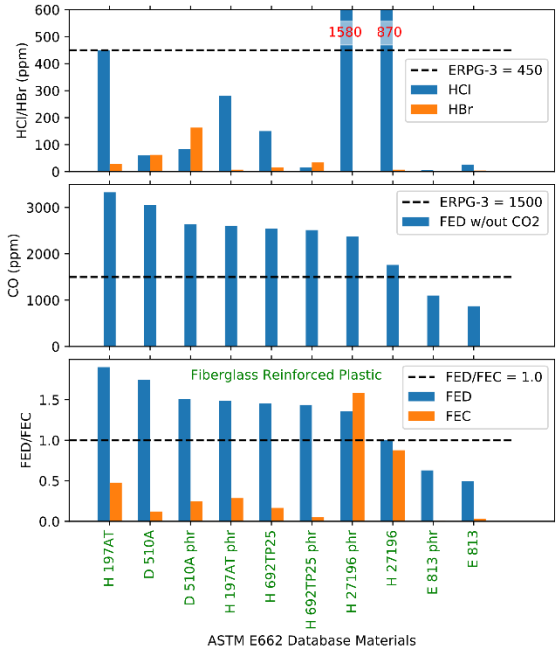

Figure 6-4: BSS 7239 maximum concentration and FED/FEC for composite materials with and without fire retardant

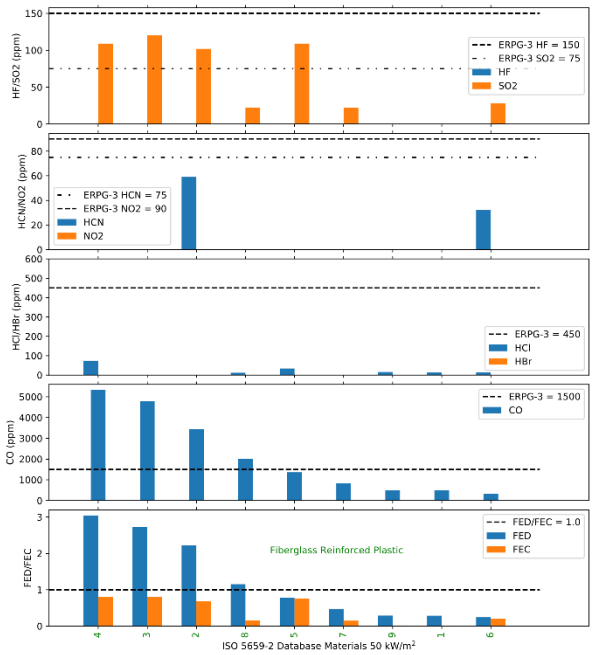

Figure 6-5: USCG materials IMO FTP part 2 at 50 kW/m^2 non-piloted mode, concentrations and FED/FEC

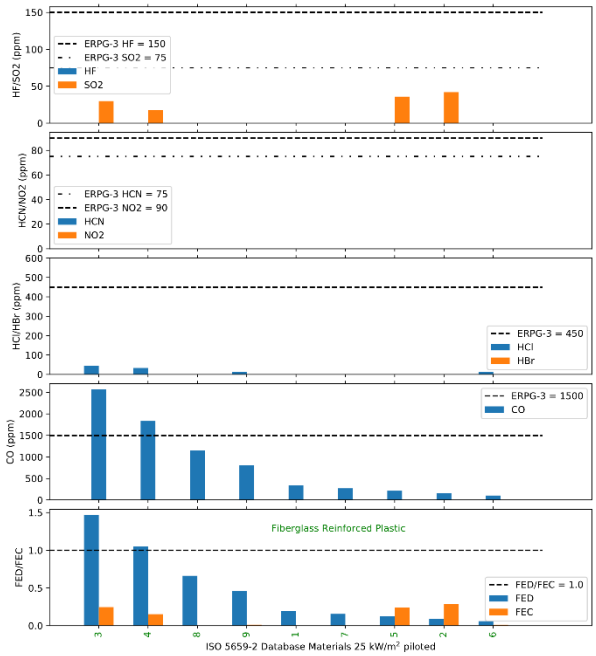

Figure 6-6: USCG materials IMO FTP part 2 at 25 kW/m^2 piloted mode, concentrations and FED/FEC

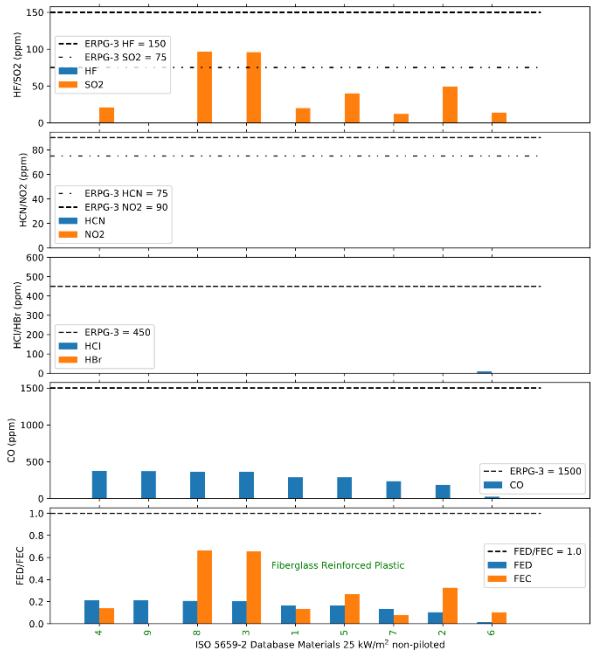

Figure 6-7: USCG materials IMO FTP part 2 at 25 kW/m^2 non-piloted mode, concentrations and FED/FEC

Figure 6-8 contains a comparison of the screening performance of the IMO FTP Annex 1: Part 2 approach and the ERPG-3 scaled criteria. Gas concentrations for IMO FTP Annex 1: Part 2 were taken at the point of maximum smoke density. Gas concentrations for the ERPG-3 scaled criteria

evaluation were taken at 20 minutes. For the USCG data, the two screening methodologies produced similar results. For the RISE/SP data, the ERPG-3 scaled criteria approach was more conservative. This was due to selecting the concentrations at 20 minutes and the lower concentration limit for NO_2. Four materials tested with ISO 5659-2 at 50 kW/m^2 in the RISE/SP dataset had significantly larger CO concentrations at 20 minutes than at the time of maximum smoke density. NO_2 concentrations were similar, but the IMO criterion for NO_2 is 350 ppm while the ERPG-3 is 90 ppm.

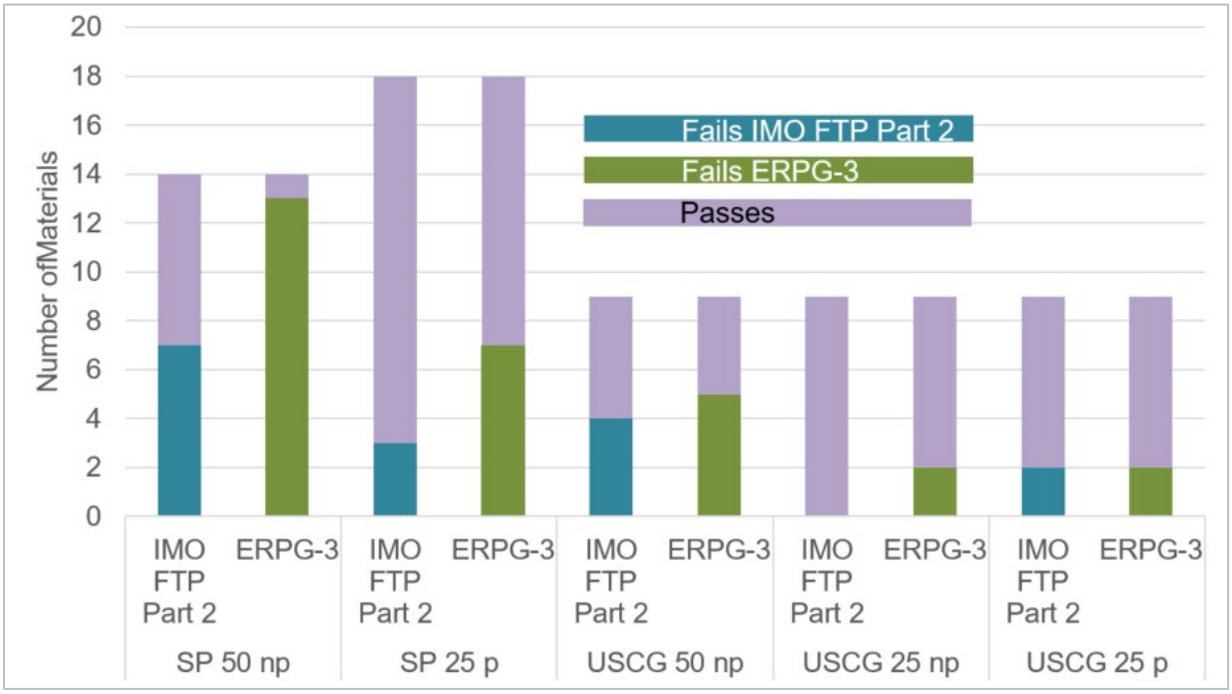

Figure 6-8: Comparison of screening performance of IMO FTP Part 2 criteria and ERPG-3 scaled criteria on database materials tested with ISO 5659-2 with FTIR

The ERPG-3 scaled criteria represent limits where a concentration could be present for a 20-minute exposure period and would not cause life-threatening effects. From the analysis of the toxicity data shown in Figure 6-8, this is more conservative than the ISO 13571 FED/FEC criteria, which provides a method to predict whether an exposure dosage or irritant gas combination will cause incapacitation. The ERPG-3 scaled concentrations are also lower than IMO FTP Annex 1: Part 2 limit criteria. The exception is the CO concentration, which is limited to 1,500 ppm for the ERPG and 1,450 ppm for IMO FTP Part 2. Other concentration limits, for HCN and irritant gases, are larger for IMO FTP Annex 1: Part 2 than for ERPG-3 scaled. In most cases, CO will govern the overall gas toxicity. Therefore, the IMO performance criterion is recommended since it is already part of an existing standard.

6.5 Recommended Toxicity Standard

The IMO FTP Annex 1: Part 2 toxicity test standard with testing at exposures of 25 kW/m^2 piloted and non-piloted is recommended for U.S. rail applications. IMO FTP part 2 specifies requirements for sampling gas concentrations with a FTIR spectroscopy system similar to Method C, which is more cost effective than Method B used in EN 45545-2. IMO concentration limits, while higher than ERPG-3 scaled concentrations, do screen out poor performing

materials. This is primarily due to the CO concentration limit, which primarily controls the overall toxicity, being similar for both IMO and ERPG-3. The higher exposure of 50 kW/m^2 non-piloted mode should not be used since it screens out most railcar materials, has an exposure not likely to occur, and is inconsistent with the evaluation of other incomplete combustion products (smoke) for materials.

7. Conclusion

It is important to ensure that the materials used in passenger rail cars do not have excessive emission of toxic gases which can cause incapacitation to occupants during egress from the train in a fire scenario. This investigation into toxicity standards and specifications was performed to determine an appropriate standard for inclusion in NFPA 130 [2] to limit toxicity due to rail car construction materials. Currently, only flame spread and smoke emission are regulated by NFPA 130 and 49 CFR § 238.103 [1]. During this work, Jensen Hughes performed toxicity tests on four railcar materials to evaluate test methods and measurement methods. In addition to this data, a database of rail car and other transportation materials was collected to determine criteria for limiting material toxicity.

7.1 Findings

Of the three measurement methods evaluated in the test program, each provided an appropriate level of precision for use. The FTIR-based Method C has higher detectable limits than do the techniques in Method A. Method A includes glass detector tubes, which can have problems with gas compound interferences. Method B or Method C are appropriate for testing materials as they obtain a sampling at the same time and with minimal interference with other gas compounds. Method C was selected since it is more cost-effective than Method B.

Most toxicity tests use either the ASTM E662 or the ISO 5659-2 chamber and exposure for generating the toxic gases. Both of these provide a 25 kW/m^2 piloted and non-piloted exposure. ASTM E662 orients the material vertically rather than horizontally for ISO 5659-2. ISO 5659-2 includes 50 kW/m^2 non-piloted exposure which was the most severe in both smoke and CO emission. This exposure may be overly conservative due to the absence of a pilot flame to provide flaming combustion. Of the ASTM E662 and ISO 5659-2 at 25 kW/m^2 piloted exposure, the vertical orientation ASTM E662 test caused more CO emission for each of the two polymers tested, Sample 1 and Sample 5. ASTM E662 is already used for rail car smoke density tests and some operators and manufacturers use BSS 7239 or SMP 800C, which uses the same test, to assess material toxicity. Analysis of literature data reveals that both ASTM E662 and ISO 5659-2 at 25 kW/m^2 piloted can provide an appropriate screening of materials that have excessive toxic gas emission.

For the toxicity tests, the gas sampling time was also evaluated. For almost all tests, the measurement of maximum concentrations was at 20 minutes. The expectation of egress from a railcar is within 15–30 minutes, thus, sampling at 20 minutes is the most conservative approach. Sampling at the time of maximum smoke density, as specified by IMO FTP part 2, is not recommended since the test to test variability is high and the maximum smoke density does not necessarily correspond to the maximum toxic gas levels.

The ERPG-3 concentrations scaled to a 20-minute exposure period to align with railcar egress times provided a similar screening of material performance compared with the more sophisticated FED toxicity and FEC irritant models. Also, the scaled ERPG-3 were similar to the IMO FTP Annex 1: Part 2 performance concentration limits except for some of the irritants. Since the overall toxicity in most cases is governed by CO, researchers recommend the IMO limits that are already in a standard.

7.2 Recommendation and Future Work

Based on this research, the research team recommended the IMO FTP Annex 1: Part 2 test with the 25 kW/m^2 piloted and non-piloted exposures for use in the U.S. rail industry. This includes a cost-effective FTIR measurement method and toxic gas performance criteria that adequately screen poor-performing materials. Although there are some database materials which were tested with ISO 5659-2 at 25 kW/m^2 piloted exposure, these materials are generally from smaller parts and not the larger surfaces of the railcar. It is recommended that an additional test program be performed to test additional materials with IMO test protocol. The additional materials to test with the recommended test method should be larger surfaces in the railcar. These may include materials such as the following:

1. Phenolic based composite used for wall/floor panels
2. Translucent polycarbonate used for window or windscreen
3. Seat cushion
4. Seat backshell (FRP based)
5. Table (wood or FRP based)
6. Curtains or other window covering material

Testing and evaluation of these materials will confirm the selection of the IMO FTP Annex 1: Part 2 test and criteria as the appropriate standard for limiting toxicity of materials in the U.S. rail industry.

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Appendix A.
Toxicity Measurement Details

This study used three overall methods to measure toxic gas effluents from burning materials in ASTM E662 and ISO 5659-2 smoke tests. Generally, each test lab has different capabilities to assess each toxicant or irritant. As some standards require specific methods for an assessment of gases, each lab can only provide official test results according to their capabilities.

Method A – Dräger, Electrochemical Cells, NDIR, and Wet Chemistry

Method A includes a combination of detection methods, and measurement details for each gas is contained in Table A-1. Researchers measured CO, CO_2, NO, NO_2, and SO_2 using a Testo 350. This device uses separate electrochemical cells to detect CO, NO, NO_2, and SO_2, and an NDIR sensor to detect CO_2. The research team used colorimetric glass tubes, or Dräger tubes to detect HCl, HBr, and HCN. HF is detected using a wet chemistry method, where determining the gas concentration took place using an ion-specific electrode in a solution made from sampling the smoke gases in an impinger bottle. The impinger bottle contains an absorption solution which is then used to prepare the aqueous solution from which ions are detected using the electronic instrument, the Fisher Scientific Orion Dual Star PH/ISE meter.

The Testo 350 device has a response time of 10–40 seconds, after which the gases can be continuously measured. The device has a sampling rate of 1 liter (l)/min. For this study, a sample was taken after 60 seconds of gas sampling from the smoke box at the particular time interval of interest.

To measure gases using Dräger tubes, researchers used a hand pump to draw a sample of the smoke gases from the chamber. The pumping is repeated a specific number of times according to the specification and is usually completed within 10–20 seconds. The substrate in the tubes changes color when exposed to a gas and the advancement of the color change across the tube is measured to determine the gas concentration.

The wet chemistry or ion-specific electrode method is a multi-step measurement method. First, an impinger bottle to sample gases from the chamber into an absorption solution. The solution is then used to create an aqueous solution using specific chemical reagents. An ion-specific electrode, in this case, the Fisher Scientific Orion Dual Star PH/ISE meter is used to determine the ion concentration in the solution. The actual gas concentration is determined using an equation provided in the Airbus method [23].

Table A-1: Measurement details for gases determined using measurement Method A

Gas	Measurement Type/Device	Response Time (s)	Lower Detection Limit (ppm)	Number of Samples per Test
CO	Electrochemical Cell	40	1	1–20
CO_2	NDIR	10	1	1–20
NO	Electrochemical Cell	40	1	1–20
NO_2	Electrochemical Cell	40	1	1–20
SO_2	Electrochemical Cell	30	1	1–20

Gas	Measurement Type/Device	Response Time (s)	Lower Detection Limit (ppm)	Number of Samples per Test
HCl	Dräger	10	1	1
HF	Ion specific electrode	300	2	1
HBr	Dräger	10–20	2	1
HCN	Dräger	10–20	0.5	1

Generally, the accuracy of gases measured using electrochemical cells is within +/- 10 percent of the measured value. The accuracy of the CO_2 measurement using NDIR is generally within +/- 0.5 percent of the full range (50 percent) plus 1.5 percent of the measured value. Thus, the maximum uncertainty is 2 percent of the full 50 percent range. The Dräger tube devices themselves typically have an uncertainty between 10 and 20 percent. Sampling irregularities or tubes which are not fresh or were exposed to non-ideal storage conditions may cause additional uncertainty.

Accuracy of the Fisher Scientific Orion Dual Star PH/ISE meter for ion detection is ±0.2 mV or ±0.05 percent of the reading, whichever is greater. Ultimately, the overall uncertainty of the method will depend on this accuracy as well as the calibration solution and sample preparation method. Uncertainty is expected to be very low, but has not been determined.

Method B – Continuous FTIR

Method B involves an FTIR spectroscopy system which is capable of continuous measurement of gases, and measurement details are contained in Table A-2. All gases are measured simultaneously from a scan of the extracted gases in the gas cell. An analysis of the absorption of each spectrum is done at each time interval to determine the gas concentrations in parts per million (ppm) present in the gas mixture.

This method complies with the requirements of EN 45545-2 Annex C, which specifies that the FTIR spectrometer must have a scan-interval of ≤ 3 seconds and an interval between spectra of ≤ 15 seconds. Generally, at least four scans are performed per spectra. Minimum detection limits must be less than 300 ppm for CO_2 and less than 15 ppm for all other gases. For this work, the time interval between spectra was set to a slightly larger 20 seconds.

Accuracy of FTIR spectrometers is very good and is generally less than 15 percent for the overall system.

Table A-2: Measurement details for gases determined using measurement Method B

Gas	Measurement Type/Device	Response time (s)	Lower Detection Limit (ppm)	Number of Samples per Test
CO	FTIR	20	1	60
CO_2	FTIR	20	1	60
NO	FTIR	20	1	60
NO_2	FTIR	20	1	60
SO_2	FTIR	20	1	60
HCl	FTIR	20	1	60

Gas	Measurement Type/Device	Response time (s)	Lower Detection Limit (ppm)	Number of Samples per Test
HF	FTIR	20	1	60
HBr	FTIR	20	1	60
HCN	FTIR	20	1	60

Method C – Semi-Continuous FTIR

Method C involves a FTIR spectroscopy system which is capable of semi-continuous measurement of gases, and measurement details are provided in Table A-3. All gases are measured simultaneously from a scan of the extracted gases in the gas cell. An analysis of the absorption of each spectrum is done at each time interval to determine the gas concentrations in ppm present in the gas mixture.

This method does not comply with the requirements of EN 45545-2 Annex C. The interval between spectra is between 90 and 120 seconds. A total of 10 scans are taken for each spectra. Lower detection limits are different for all gases and are provided in Table A-3. This system complies with the requirements of IMO FTP part 2 toxicity test.

Table A-3: Measurement details for gases determined using Measurement Method C

Gas	Measurement Type/Device	Response time (s)	Lower Detection Limit (ppm)	Number of Samples per Test
CO	FTIR	90	20.1	14
CO_2	FTIR	90	573	14
NO	FTIR	90	7.5	14
NO_2	FTIR	90	30.8	14
SO_2	FTIR	90	4.7	14
HCl	FTIR	90	40.7	14
HF	FTIR	90	77.9	14
HBr	FTIR	90	40.8	14
HCN	FTIR	90	28.9	14

Appendix B.
Gas Mixture Toxicity and Irritancy Models

Overview

Researchers considered models from four sources in this work for evaluating the combined effect of toxic gases on humans. These are the ISO 13571 FED and FEC models, the ISO 13344 FED model, the SFPE/Purser FED model, and the CIT_G model presented in EN 45545-2 and the TRANSFEU report. Here is an overview of the method, calculation approach, and summary of the technical basis of each model.

Fractional Effective Dosage (FED) models provide an estimation of an amount of burning material or duration of time which causes incapacitation or death due to the dosage of toxic gases. The nominal threshold FED = 1.0 is based on 50 percent of the population experiencing an incapacitating or lethal dosage.

ISO 13571 FED/FEC

ISO 13571 "Life-threatening components of fire – Guidelines for the estimation of time to compromised tenability in fires" presents methods to estimate time of impaired escape from a fire scenario based on incapacitating conditions for humans. This standard includes methods to estimate tenability due to exposure to toxic and irritant gases as well as exposure to heat and smoke.

The FED is calculated from the concentrations of asphyxiant gases CO and HCN. The FED is calculated using Equation 1 and tenability is assumed to be exceeded when FED > 1 ψ_{CO} and ψ_{HCN} are the average carbon monoxide (CO) and hydrogen cyanide (HCN) concentrations at h time increment. Other factors considered in other FED models are oxygen (O_2) depletion and carbon dioxide (CO_2) vitiation. The position of ISO 13571 is that O_2 depletion is not considered unless the concentration is less than 13 percent, and "All available evidence supports the working hypothesis that, in typical fire atmospheres, CO and HCN are the only asphyxiant combustion products that exert a significant effect on the time to compromised tenability [8]."

$$\boldsymbol{X_{FED} = \sum_{t_1}^{t_2} \frac{\psi_{CO}}{35000} \Delta t + \sum_{t_1}^{t_2} \frac{{\psi_{HCN}}^{2.36}}{1.2 \times 10^6} \Delta t} \quad (\mathbf{1})$$

Sometimes, for higher carbon dioxide (CO_2) concentrations the CO and HCN terms are multiplied by a frequency factor V_{CO2} which accounts for hyperventilation due to increase of CO_2 concentration in the air. This term is calculated with Equation 2.

$$\mathrm{V_{CO_2}} = \exp\left(\frac{[\mathrm{CO_2}]}{5}\right) \quad (2)$$

Irritant gases such as HCl cause incapacitating/lethal effects using a different mechanism in the human body than asphyxiant gases CO and HCN. Generally, these gases cause eye and respiratory irritation which causes short and long term inflammation of tissue depending on the level of concentration to which the subject is exposed. ISO 13571 includes a model for estimating the incapacitation due to elevated irritant gas concentrations. This model, the fractional effective

concentration (FEC) is calculated at each timestep for irritant gas concentrations. The gases considered in the model are hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). Other gases may also be included, such as acrolein and formaldehyde. The calculation of the FEC is contained in Equation 3 and tenability is assumed to have been exceeded when $X_{FEC} > 1$.

$$X_{FEC} = \frac{\Psi_{HCl}}{1000} + \frac{\Psi_{HBr}}{1000} + \frac{\Psi_{HF}}{500} + \frac{\Psi_{SO2}}{150} + \frac{\Psi_{NO2}}{250} \quad (3)$$

ISO 13344 FED

ISO 13344 "Estimation of the lethal toxic potency of fire effluent" presents a method to estimate lethal toxic potency of materials based on LC_{50} values of toxicants in fire effluents. LC_{50} is the lethal toxic potency for 30-minute exposure to a specific toxicant with evaluation of 14 days after, with 50 percent of the population of rats experiencing lethal effects in either the 30-minute exposure or the 14-day evaluation period.

The standard presented two equations, Method 1 (Equation 4) and Method 2 (Equation 5), which are both valid for estimating either the LC_{50} of the subject material or the FED of a fire effluent mixture. Equation 4 is based on CO and CO_2 interactions, O_2 depletion, and HCN, HCl, and HBr concentrations. The terms *m* and *b* are selected based on the CO_2 level. If $CO_2 \leq 5$ percent, $m = -18$ and $b = 122{,}000$ µl/l. If $CO_2 > 5$ percent, $m = 23$ and $b = -38{,}600$ µl/l. The contribution to FED for HCN, HCl, and HBr is linear based on critical concentrations.

$$L_{FED} = \frac{m[CO]}{[CO_2] - b} + \frac{21 - [O_2]}{(21 - 5.4)} + \frac{[HCN]}{150} + \frac{[HCl]}{3700} + \frac{[HBr]}{3000} \quad (4)$$

Method 2, shown in Equation 5, based on Purser's work, includes contribution from CO, HCN, HCl, HBr, HF, SO_2, NO_2, acrolein, and formaldehyde, and O_2 depletion based on a linear ratio of toxic effluent concentration to critical concentrations. For each of these toxicants and irritants, a multiplication factor to account for CO_2 driven hyperventilation, V_{CO2}, is used (see Equation 6). In addition to the hyperventilation effect, the acidosis, Z_A, due to CO_2 level is also included (see Equation 7).

$$L_{FED} = \left(\frac{[CO]}{5700} + \frac{[CN]}{165} + \frac{[HCl]}{3800} + \frac{[HBr]}{3800} + \frac{[HF]}{2900} + \frac{[SO_2]}{1400} + \frac{[NO_2]}{170}\right) \times V_{CO_2} + Z_A + \frac{21 - [O_2]}{21 - 5.4} \quad (5)$$

$$V_{CO_2} = 1 + \frac{\exp(0.14[CO_2]) - 1}{2} \quad (6)$$

$$Z_A = [CO_2] \times 0.05 \quad (7)$$

Purser FED (SFPE)

Purser's model is widely used in literature and in modeling software to predict incapacitation from a combination of toxic gases in fire effluents. The model is presented in SFPE handbook 5th ed. Chapter 63 [21]. FED = 1 indicates incapacitation of humans based on critical dosage levels of toxic gases. In the model, presented in Equation 8, CO, HCN, and O_2 components are

based on a fit to human data. Irritant concentrations such as NO_2, HCl, and HF are based on lethality dosages of rats.

$$\mathrm{FED(t)} = \left(\frac{3.317\mathrm{E}^{-5}[\mathrm{CO}]^{1.036}}{30/25}\mathrm{t} + \frac{[\mathrm{HCN}]^{2.36}}{1.2\mathrm{E}^{6}}\mathrm{t} + \frac{[\mathrm{NO_2}]}{1500}\mathrm{t} + \frac{[\mathrm{HCl}]}{114000}\mathrm{t} + \frac{[\mathrm{HF}]}{87000}\mathrm{t} + \ \ldots\right)\mathrm{V_{CO_2}} + \frac{1}{(\exp(8.13 - 0.54(20.9 - \%\mathrm{O_2}))}\mathrm{t} \quad (8)$$

EN 45545-2 CIT_G

Equation 9 presents the conventional Index of Toxicity (CIT), the parameter used for regulating toxic fumes in EN 45545-2. CIT_G is evaluated for general products on a railcar, which are materials used in larger surface area components such as seats, wall linings, and partitions. Gas concentrations from ISO 5659-2 tests at 25 kW/m^2 and 50 kW/m^2 are used to calculate CIT_G. Values are calculated for concentrations at 4 and 8 minutes and is the maximum value used for qualification. Table B-4 shows the gas concentrations used in the calculation. An alternative approach is provided in EN 45545-2 to calculate the CIT for non-listed products (CIT_{NLP}), which is for small parts in the railcar. This alternative approach uses the same calculation but the material is tested in a tube furnace. The tube furnace test was not evaluated in this study as it is generally not used to test larger materials' toxic gas emission in the transportation industry.

The CIT calculation is composed of two terms, the precursor term, and the summation term. The precursor term represents the system parameter, which is the ratio of the burning material surface area and the volume for the railcar and smoke box (Equation 10).

$$\mathrm{CIT_G} = \frac{0.51\mathrm{m}^3 \times 0.1\mathrm{m}^2}{150\mathrm{m}^3 \times 0.004225\mathrm{m}^2} \times \sum_{i=1}^{i=8} \frac{\mathrm{c_i}}{\mathrm{C_i}} \quad (9)$$

The summation term relates emission levels to reference concentrations. The concentration for each toxic effluent is normalized by a reference concentration, which is based on IDLH values published by NIOSH. Immediately Dangerous to Life and Health (IDLH) values are levels at which a 30-minute exposure for workforce population would lead to conditions impairing escape. The IDLH concentrations are converted to mass concentrations using pressure, P = 101,325 Pa and temperature, T = 25 °C.

According to the value of the precursor term as published by EN 45545-2, the concentrations in the smoke box may be 12.4 times allowable IDLH concentrations for a nominal environment, based on nominal values of burning surface area in the railcar and volume of an average railcar (see Table B-4).

Table B-4: CIT reference concentrations and IDLH concentrations

Gas	Reference mass concentration (mg/m3)	IDLH concentrations (ppm)
CO	1,380	1,200
CO_2	72,000	40,000
HCl	99	50

Gas	Reference mass concentration (mg/m_3)	IDLH concentrations (ppm)
HCN	55	50
HBr	75	30
HF	55	30
NO_X	38	20
SO_2	262	100

Appendix C. Materials Data from Current Study

Table C-1: Sample 1 of materials data

Test	Method	Time	Mass Loss	Ds	CO	CO_2	HCl	HCN	HF	HBr	SO_2	NO_X
ASTM E662	A	4 min	1.5	135	208	520	–	–	–	–	–	2
ASTM E662	B	4 min	–	73	232	2,209	–	–	–	–	–	–
ASTM E662	A	8 min	3.0	290	483	6,400	–	–	–	–	–	4
ASTM E662	B	8 min	–	286	846	5,516	–	–	–	–	–	–
ASTM E662	A	20 min	8.2	514	870	10,550	–	–	–	–	–	7
ASTM E662	B	20 min	5.0	368	590	3,151	–	–	–	–	–	–
ISO 5659-2 25	A	4 min	–	1	–	–	–	–	–	–	–	–
ISO 5659-2 25	B	4 min	–	7	76	2,453	–	–	–	–	–	–
ISO 5659-2 25	A	8 min	2.3	61	–	–	–	–	–	–	–	–
ISO 5659-2 25	B	8 min	–	55	180	4,013	–	–	–	–	–	–
ISO 5659-2 25	A	20 min	–	–	–	–	–	–	–	–	–	–
ISO 5659-2 25	B	20 min	3.6	263	495	7,370	–	–	–	–	–	–
ISO 5659-2 50	A	4 min	–	247	–	–	–	–	–	–	–	–
ISO 5659-2 50	B	4 min	–	312	338	811	–	–	–	–	–	–
ISO 5659-2 50	A	8 min	9.2	555	–	–	–	–	–	–	–	–
ISO 5659-2 50	B	8 min	–	–	885	1,280	–	–	–	–	–	–
ISO 5659-2 50	A	20 min	–	580	–	–	–	–	–	–	–	–
ISO 5659-2 50	B	20 min	13.4	–	3,017	3,707	–	–	–	–	–	–

Table C-2: Sample 5 of materials data

Test	Method	Time	Mass Loss	Ds	CO	CO_2	HCl	HCN	HF	HBr	SO_2	NO_X
ASTM E662	A	4 min	4.3	114	368	520	–	–	–	–	–	3
ASTM E662	B	4 min	–	146	744	6,083	–	–	–	–	–	–
ASTM E662	A	8 min	7.2	230	622	8,800	–	–	–	–	–	6
ASTM E662	B	8 min	–	345	1,614	11,269	–	–	–	–	–	–
ASTM E662	A	20 min	9.0	322	1,060	10,740	–	–	–	–	–	7
ASTM E662	B	20 min	9.9	–	2,804	16,412	–	–	–	–	–	–
ISO 5659-2 25	A	4 min	–	5	–	–	–	–	–	–	–	–
ISO 5659-2 25	B	4 min	–	11	162	2,831	–	–	–	–	–	–
ISO 5659-2 25	A	8 min	8.0	199	–	–	–	–	–	–	–	–

Test	Method	Time	Mass Loss	Ds	CO	CO_2	HCl	HCN	HF	HBr	SO_2	NO_X
ISO 5659-2 25	B	8 min	–	207	786	7,839	–	–	–	–	–	–
ISO 5659-2 25	A	20 min	–	–	–	–	–	–	–	–	–	–
ISO 5659-2 25	B	20 min	–	–	–	–	–	–	–	–	–	–
ISO 5659-2 50	A	4 min	–	338	–	–	–	–	–	–	–	–
ISO 5659-2 50	B	4 min	–	432	1,438	1,112	–	–	–	–	–	–
ISO 5659-2 50	A	8 min	14.6	526	–	–	–	–	–	–	–	–
ISO 5659-2 50	B	8 min	–	–	3,437	2,650	–	–	–	–	–	–
ISO 5659-2 50	A	20 min	–	–	–	–	–	–	–	–	–	–
ISO 5659-2 50	B	20 min	17.7	–	6,450	5,892	–	–	–	–	–	–

Table C-3: Sample 6 of materials data

Test	Method	Time	Mass Loss	Ds	CO	CO_2	HCl	HCN	HF	HBr	SO_2	NO_2
ASTM E662	A	4 min	–	5	22	–	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
ASTM E662	A	8 min	–	88	134	–	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
ASTM E662	A	20 min	9.5	220	825	9,550	–	8	3	–	–	104
ISO 5659-2 50	C	4 min	–	71	130	3,141	–	–	–	–	–	–
ISO 5659-2 50	C	8 min	–	243	224	5,543	–	–	–	–	–	–
ISO 5659-2 50	C	20 min	14.0	414	636	12,728	–	–	–	–	–	–

Table C-4: Sample 2 of materials data

Test	Method	Time	Mass Loss	Ds	CO	CO_2	HCl	HCN	HF	HBr	SO_2	NO_2
ASTM E662	A	4 min	–	74	4	–	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
ASTM E662	A	8 min	–	225	15	–	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
ASTM E662	A	20 min	23.2	270	80	–	–	3	4	–	–	1
ISO 5659-2 50	C	4 min	–	114	387	5,809	–	–	–	–	–	–
ISO 5659-2 50	C	8 min	–	219	489	13,392	–	–	–	–	–	–
ISO 5659-2 50	C	20 min	28.0	124	809	23,890	–	–	–	–	–	–

Table C-5: Sample 1 ASTM E662 piloted exposure Method A and Method B test results

Time (s)	Method B CO_2 ppm	Method B CO ppm	Time (s)	Method A CO_2 ppm	Method A CO ppm	NDIR NO_X ppm
20.46	500	0	240	520	208	1.5
40.78	619.397	18.2378	480	6,400	483	3.7
61.11	711.969	34.3402	1,200	10,000	886	5
81.43	843.34	23.7885	1,200	11,100	854	8.5
101.76	973.762	37.8119				
122.08	1,120.592	44.6345				
142.41	1,283.512	34.9962				
162.73	1,477.972	82.3069				
183.06	1,667.832	129.5945				
203.38	1,833.712	164.9943				
223.71	2,013.422	191.8728				
244.03	2,209.022	232.03				
264.36	2,452.962	289.683				
284.68	2,648.202	322.683				
305	2,962.642	405.661				
325.33	3,296.742	476.992				
345.65	3,590.542	516.94				
365.98	3,793.872	572.651				
386.3	3,954.592	623.97				
406.63	4,127.232	648.66				
426.95	4,435.792	715.487				
447.28	4,814.672	787.604				
467.6	5,248.852	815.86				
487.93	5,516.072	846.247				
508.25	5,792.652	909.564				
528.58	6,050.862	963.047				
548.9	6,244.332	985.468				
569.23	6,421.772	992.701				
589.56	6,550.872	1,039.418				
609.88	6,657.892	1,080.061				
630.21	6,765.782	1,107.307				
650.53	6,844.622	1,099.406				

Time (s)	Method B CO_2 ppm	Method B CO ppm	Time (s)	Method A CO_2 ppm	Method A CO ppm	NDIR NO_X ppm
670.86	6,766.942	1,116.239				
691.18	6,622.512	1,112.449				
711.51	6,386.382	1,084.501				
731.83	6,271.402	1,052.266				
752.16	6,048.262	1,034.026				
772.48	5,831.462	999.363				
792.81	5,716.412	963.487				
813.14	5,678.922	983.518				
833.46	5,447.522	967.276				
853.79	5,190.872	944.242				
874.11	4,953.772	883.185				
894.44	4,782.632	842.871				
914.76	4,628.622	839.817				
935.09	4,476.682	830.072				
955.41	4,323.712	798				
975.74	4,211.222	761.481				
996.06	4,064.152	752.714				
1,016.39	3,799.912	721.743				
1,036.71	3,716.612	703.035				
1,057.04	3,621.242	684.597				
1,077.36	3,482.722	656.927				
1,097.69	3,339.342	630.761				
1,118.01	3,367.712	626.284				
1,138.34	3,231.032	614.659				
1,158.66	3,214.342	592.108				
1,178.99	3,212.142	580.19				
1,199.31	3,151.232	590.428				

Table C-6: Sample 1 ISO 5659-2 25 kW/m^2 piloted and 50 kW/m^2 non-piloted exposure Method B test results

Time (s)	25 kW/m^2 CO_2 ppm	25 kW/m^2 CO ppm	Time (s)	50 kW/m^2 CO_2 ppm	50 kW/m^2 CO ppm
20.46	500	0	20.46	500	0
40.79	895.9203	5.513	40.79	507.9517	19.3794
61.12	1,125.637	19.291	61.11	507.2228	11.4638
81.45	1,280.766	19.12	81.44	512.7824	24.2182
101.77	1,470.451	9.912	101.76	526.7052	43.9908
122.1	1,599.821	25.5781	122.09	539.2703	48.5772
142.43	1,750.951	39.9613	142.41	570.4608	67.7417
162.76	1,910.991	15.034	162.74	615.3598	108.6365
183.08	2,051.691	30.7076	183.06	652.0868	138.5291
203.41	2,196.861	58.9197	203.39	706.2988	196.3918
223.74	2,326.201	83.815	223.71	760.2178	269.532
244.07	2,452.601	76.0112	244.04	811.2778	338.167
264.39	2,597.201	82.459	264.36	830.1278	357.783
284.72	2,708.371	102.7634	284.69	865.5008	383.947
305.05	2,825.891	92.4945	305.01	911.4688	456.953
325.38	2,975.301	110.9849	325.34	953.3708	517.435
345.7	3,100.121	133.9294	345.66	1,002.871	581.857
366.03	3,215.781	131.2824	365.98	1,024.3	594.868
386.36	3,371.051	139.6266	386.31	1,049.813	623.378
406.68	3,514.901	150.2521	406.63	1,085.008	676.467
427.01	3,633.221	140.5771	426.96	1,109.06	700.922
447.34	3,781.301	167.5501	447.29	1,171.267	740.349
467.67	3,898.001	191.0766	467.61	1,224.523	814.993
487.99	4,013.021	179.5394	487.94	1,280.379	884.77
508.32	4,139.721	197.6143	508.26	1,320.829	932.351
528.65	4,264.161	192.6335	528.59	1,351.882	936.418
548.97	4,372.441	195.9003	548.91	1,389.564	979.948
569.3	4,507.121	223.643	569.24	1,435.945	1,036.585
589.63	4,590.551	234.553	589.56	1,459.964	1,075.353
609.95	4,716.641	228.494	609.89	1,518.224	1,133.305
630.28	4,801.661	237.727	630.21	1,474.524	1,106.435

Time (s)	25 kW/m^2 CO_2 ppm	25 kW/m^2 CO ppm	Time (s)	50 kW/m^2 CO_2 ppm	50 kW/m^2 CO ppm
650.61	4,899.711	263.173	650.53	1,673.474	1,270.545
670.94	4,975.461	251.966	670.86	1,739.104	1,325.235
691.26	5,073.331	251.55	691.18	1,734.184	1,339.005
711.59	5,169.931	271.83	711.51	1,673.514	1,306.935
731.92	5,271.741	272.969	731.83	2,144.024	1,678.525
752.24	5,359.371	276.246	752.16	2,383.364	1,863.235
772.57	5,424.661	296.677	772.48	2,497.234	1,978.035
792.89	5,486.091	290.187	792.81	2,530.614	1,979.255
813.22	5,480.641	301.716	813.13	2,682.124	2,116.535
833.55	5,540.891	314.637	833.46	2,716.754	2,161.975
853.87	5,604.011	298.733	853.78	2,708.684	2,143.255
874.2	5,683.531	319.771	874.1	2,642.404	2,106.425
894.53	5,739.031	331.871	894.43	2,844.804	2,259.455
914.85	5,828.741	317.859	914.75	2,999.934	2,390.135
935.18	5,975.301	334.207	935.07	3,063.474	2,427.575
955.51	6,651.421	427.643	955.4	3,099.144	2,475.785
975.83	7,364.561	485.631	975.72	3,121.014	2,485.925
996.16	7,764.171	502.677	996.05	3,151.624	2,484.955
1,016.48	7,900.901	515.484	1,016.37	3,048.164	2,426.595
1,036.81	7,687.951	501.503	1,036.7	3,251.584	2,600.275
1,057.14	7,560.111	470.524	1,057.02	3,318.304	2,657.965
1,077.46	7,292.531	470.615	1,077.34	3,434.554	2,737.875
1,097.79	7,104.351	466.095	1,097.67	3,461.814	2,776.685
1,118.11	6,844.961	451.201	1,117.99	3,534.784	2,833.505
1,138.44	7,042.941	505.354	1,138.31	3,554.394	2,822.685
1,158.77	7,569.811	504.498	1,158.64	3,584.464	2,867.745
1,179.09	7,467.351	510.17	1,178.96	3,700.474	2,993.035
1,199.42	7,370.411	495.156	1,199.29	3,707.394	3,017.315

Table C-7: Sample 5 ASTM E662 piloted exposure Method A and Method B test results

Time (s)	Method B CO_2 ppm	Method B CO ppm	Time (s)	Method A CO_2 ppm	Method A CO ppm	NDIR NO_X ppm
20.46	500	0	240	520	368	3.1
40.79	721.076	30.8774	480	8,800	622	5.6

Time (s)	Method B CO_2 ppm	Method B CO ppm	Time (s)	Method A CO_2 ppm	Method A CO ppm	NDIR NO_X ppm
61.11	970.812	70.5594	1,200	10,280	923	7.5
81.44	1,220.677	141.2765	1,200	11,200	1,197	8.5
101.76	1,478.137	197.2093				
122.09	1,768.447	276.904				
142.42	2,019.187	347.077				
162.74	2,748.687	488.066				
183.07	3,671.817	519.19				
203.39	4,562.267	618.67				
223.72	5,238.497	679.264				
244.04	6,083.117	744.387				
264.37	6,832.447	826.441				
284.7	7,538.607	936.591				
305.02	8,184.367	1,024.708				
325.35	8,867.397	1,092.827				
345.68	9,009.267	1,191.339				
366	9,152.287	1,287.939				
386.33	9,657.517	1,359.619				
406.66	9,909.097	1,412.669				
426.98	10,216	1,485.759				
447.31	10,616.7	1,541.809				
467.64	10,877.3	1,649.009				
487.96	11,268.9	1,614.469				
508.29	1,1525.2	1,683.639				
528.61	11,776.7	1,719.049				
548.94	12,162.9	1,733.199				
569.27	12,402.5	1,813.889				
589.59	12,697.9	1,867.679				
609.92	12,654.6	1,908.119				
630.25	13,283.1	1,939.739				
650.57	13,171.6	2,024.799				
670.9	13,803.7	2,219.029				
691.23	13,851.5	2,108.259				
711.55	14,248	2,172.409				

Time (s)	Method B CO_2 ppm	Method B CO ppm	Time (s)	Method A CO_2 ppm	Method A CO ppm	NDIR NO_X ppm
731.88	14,114.9	2,246.139				
752.2	14,463	2,247.709				
772.53	14,598.8	2,303.859				
792.86	14,985.3	2,337.659				
813.18	14,828.3	2359.199				
833.51	15,080.2	2,392.329				
853.83	15,242.6	2,492.299				
874.16	15,286.3	2,465.599				
894.49	15,433.1	2,470.529				
914.81	15,342.5	2,525.629				
935.14	15,590.9	2,600.169				
955.46	15,687.7	2,594.519				
975.79	15,955.1	2,623.039				
996.12	15,754.7	2,659.759				
1,016.44	16,033.1	2,685.399				
1,036.77	16,055.5	2,691.089				
1,057.09	16,188.2	2,761.039				
1,077.42	16,082.5	2,705.939				
1,097.74	16,165.3	2,717.249				
1,118.07	16,316.4	2,775.939				
1,138.4	16,590.7	2,795.739				
1,158.72	16,575.7	2,837.869				
1,179.05	16,945.2	2,859.369				
1,199.37	16,412.2	2,803.639				

Table C-8: Sample 5 ISO 5659-2 25 kW/m^2 piloted and 50 kW/m^2 non-piloted exposure Method B test results

Time (s)	25 kW/m^2 CO_2 ppm	25 kW/m^2 CO ppm	Time (s)	50 kW/m^2 CO_2 ppm	50 kW/m^2 CO ppm
20.46	500	0	20.46	500	0
40.79	923.86	35.14	40.78	500	0
61.11	1,122.08	27.35	61.11	527.26	25.84
81.44	1,325.28	48.42	81.43	597.46	140.96
101.76	1,544.35	33.19	101.76	657.163	321.74
122.09	1,730.44	79.21	122.08	689.157	446.48
142.42	1,916.6	83.6	142.41	789.288	670.5
162.74	2,113.7	86.38	162.73	844.498	850.42
183.07	2,295.59	100.22	183.06	1,572.671	2,709.02
203.39	2,456.66	104.48	203.38	1,147.541	1,657.29
223.72	2,673.67	132.85	223.7	1,132.831	1,609.17
244.04	2,831.2	162.42	244.03	1,111.971	1,438.01
264.37	3,032.36	160.84	264.35	1,201.921	1,564.11
284.69	3,226.88	159.7	284.69	1,601.851	2,760.18
305.02	3,339.47	209.4	305.01	1,475.191	2,019.41
325.35	3,591.94	238.43	325.34	1,821.351	2,613.79
345.67	3,753.56	272.61	345.66	1,731.351	2,290.9
366	3,869.7	281.8	365.98	1,778.171	2,348.98
386.32	4,072.25	307.66	386.31	1,886.381	2,430.85
406.65	4,226.87	341.13	406.63	2,039.021	2,695.37
426.97	4,392.54	322.68	426.96	2,169.581	2,898.62
447.3	4,610.06	379.36	447.28	3,149.031	4,994.4
467.62	6,388.94	700.67	467.6	2,634.191	3,535.36
487.95	7,838.89	786.28	487.93	2,649.991	3,437.35
508.27	8,838.75	857.04	508.25	2,776.731	3,531.1
528.6	9,512.22	943.41	528.58	2,885.881	3,727.29
548.92	10,134.12	1,023.48	548.9	2,984.791	3,790.24
569.25	10,637.52	1,048.55	569.22	3,082.111	3,916.41
589.57	11,178.12	1,166.58	589.55	3,172.581	3,929.31
609.9	11,758.62	1,236.53	609.87	3,677.551	4,992.4
630.22	11,834.92	1,271.88	630.2	3,425.211	4,276.52

Time (s)	25 kW/m^2 CO_2 ppm	25 kW/m^2 CO ppm	Time (s)	50 kW/m^2 CO_2 ppm	50 kW/m^2 CO ppm
650.55	11,938.12	1,341.6	650.52	3,538.781	4,362.31
670.88	11,886.62	1,413.23	670.84	3,613.851	4,475.49
691.2	11,925.82	1,413.53	691.17	3,708.391	4,589.05
711.53	12,077.62	1,426.66	711.49	3,842.311	4,656.73
731.85	12,223.12	1,488.71	731.82	3,908.711	4,767.35
752.18	12,268.62	1,487.38	752.14	3,995.381	4,864.91
772.5	12,436.62	1,549.99	772.46	4,072.491	4,968.75
792.83	12,523.02	1,579.44	792.79	4,198.691	5,067.25
813.15	12,598.42	1,579.01	813.11	4,236.291	5,114.36
833.48	12,801.12	1,637.17	833.44	4,356.251	5,239.2
853.8	12,963.42	1,649.59	853.76	4,457.651	5,284.98
874.13	13,114.42	1,680.66	874.08	4,574.191	5,353.72
894.46	13,090.92	1,706.44	894.41	4,631.581	5,433.64
914.78	13,334.62	1,711.24	914.73	4,719.601	5,535.2
935.11	13,537.52	1,757.73	935.05	4,801.001	5,567.62
955.43	13,397.62	1,753.11	955.38	4,880.221	5,584.12
975.76	13,689.72	1,770.4	975.7	4,959.751	5,666.78
996.08	13,814.32	1,769.45	996.02	4,976.961	5,741.4
1,016.41	13,943.02	1,802.82	1,016.35	5,782.991	7,374.56
1,036.73	13,979.82	1,851.83	1,036.67	5,342.491	6,103.91
1,057.06	14,086.22	1,841.56	1,057	5,423.521	6,163.56
1,077.39	14,297.82	1,861.11	1,077.32	5,471.351	6,223.83
1,097.71	14,557.72	1,856.03	1,097.64	5,574.401	6,192.45
1,118.04	14,590.22	1,877.94	1,117.97	5,554.731	6,189.55
1,138.36	14,642.22	1,866.3	1,138.29	5,645.881	6,245.56
1,158.69	14,655.92	1,902.95	1,158.62	5,820.501	6,396.7
1,179.01	14,938.02	1,875.99	1,178.94	5,803.051	6,408.87
1,199.34	14,991.12	1,908.58	1,199.26	5,892.191	6,450.34

Table C-9: Sample 6 ASTM E662 piloted Method A test results

Time (s)	25 kW/m^2 CO_2 ppm #1	25 kW/m^2 CO_2 ppm #2	25 kW/m^2 CO ppm #1	25 kW/m^2 CO ppm #2
60	0	0	5	7
120	0	0	8	9
180	0	0	14	10
240	0	0	23	21
300	0	0	35	33
360	0	0	55	47
420	0	0	100	68
480	0	0	150	117
540	0	0	219	168
600	0	0	305	247
660	0	0	379	336
720	5,000	5,600	430	406
780	5,900	6,100	489	476
840	6,600	7,400	556	571
900	7,200	8,300	625	676
960	7,700	9,000	278	752
1,020	7,900	9,000	710	802
1,080	8,200	9,700	734	831
1,140	8,500	10,200	752	867
1,200	8,800	10,300	769	881

Table C-10: Sample 6 ISO 5659-2 50 kW/m^2 non-piloted Method C test results

Time (s)	50 kW/m^2 CO_2 ppm #1	50 kW/m^2 CO_2 ppm #2	50 kW/m^2 CO ppm #1	50 kW/m^2 CO ppm #2
90	719.5	1,024.1	14.1	118.6
180	1,406.7	2,155.2	65.5	150.1
270	1,947.7	4,334.9	59.8	200.5
360	2,701.8	6,038.7	168.9	199.9
450	3,438.5	7,649	183.6	265.4
540	5,692.8	10,441	303.2	333.9
630	8,177.2	13,000	420.3	467.2
720	1,1682	13,584	525	525

Time (s)	50 kW/m^2 CO_2 ppm #1	50 kW/m^2 CO_2 ppm #2	50 kW/m^2 CO ppm #1	50 kW/m^2 CO ppm #2
810	1,2597	13,661	622.9	548.2
900	12,658	13,608	680	514
990	12,346	13,619	684.9	599.1
1,080	12,343	13,020	711.9	579.6
1,170	12,197	13,260	706.7	566

Table C-11: Sample 2 ASTM E662 piloted Method A test results

Time (s)	25 kW/m^2 CO_2 ppm #1	25 kW/m^2 CO_2 ppm #2	25 kW/m^2 CO ppm #1	25 kW/m^2 CO ppm #2
0	0	0	0	0
60	0	0	2	2
120	0	0	2	2
180	0	0	3	3
240	0	0	4	4
300	0	0	5	6
360	0	0	8	8
420	0	0	11	12
480	0	0	13	17
540	0	0	16	21
600	0	0	20	25
660	0	0	30	28
720	0	0	34	31
780	0	0	36	43
840	0	0	50	38
900	0	0	55	39
960	0	0	64	44
1,020	0	0	69	48
1,080	0	0	79	52
1,140	0	0	87	58

Table C-12: Sample 2 ISO 5659-2 50 kW/m^2 non-piloted Method C test results

Time (s)	50 kW/m^2 CO_2 ppm #1	50 kW/m^2 CO_2 ppm #2	50 kW/m^2 CO ppm #1	50 kW/m^2 CO ppm #2	50 kW/m^2 CH4 ppm #1	50 kW/m^2 CH4 ppm #1
90	1,114.6	567.98	99.725	74.363	109	179
180	3,036.1	2,717.3	241.28	270.97	238	361
270	7,201.5	4,416.3	401.83	372.98	344	480
360	10,905	5,982.5	439.01	534.75	314	662
450	14,635	12,149	457.21	520.51	318	628
540	20,979	16,314	553.46	591.69	387	703
630	26,173	22,734	606.82	631.51	422	709
720	27,068	26,074	690.59	656.59	433	773
810	26,296	25,322	739.46	722.9	604	810
900	25,653	24,856	771.08	747.22	713	921
990	25,117	23,921	727.94	757.56	732	977
1,080	24,503	24,011	751.69	827.67	781	1,080
1,170	24,304	23,477	785.85	832.8	853	1,086

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
ATH	Alumina Trihydrate
ASTM	American Society of Testing Materials
NH_3	Ammonia
BSS	Boeing Specification Support Standard
CO_2	Carbon Dioxide
CO	Carbon Monoxide
CL	Chlorine
CFR	Code of Federal Regulations
CIT	Conventional Index of Toxicity
ERPG-3	Emergency Response Planning Guidelines-3
CEN	European Committee for Standardization
EN	European Norms
FRA	Federal Railroad Administration
FRP	Fiberglass Reinforced Plastic
FR	Fire Resistant
FTP	Fire Test Procedures
FTIR	Fourier Transform-Infrared
FEC	Fractional Effective Concentration
FED	Fractional Effective Dose
HL	Hazard Level
HRR	Heat Release Rate
HBr	Hydrogen Bromide
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HF	Hydrogen Fluoride
H_2S	Hydrogen Sulfide
IDLH	Immediately Dangerous to Life and Health
IMO	International Maritime Organization
ISO	International Standards Organization
LC_{50}	Median Lethal Concentration

ACRONYMS	EXPLANATION
NASFM	National Association of State Fire Marshals
NBS	National Bureau of Standards (NBS became the National Institute of Standards and Technology, or NIST, in 1988)
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxides
NDIR	Non-Dispersive Infrared
NF	Norme Française
ppm	Parts Per Million
P	Pressure
RISE	RISE Research Institutes of Sweden
SO_2	Sulfur Dioxide
SP	Swedish National Testing and Research Institute (merged with RISE in 2016)
T	Temperature
USCG	U.S. Coast Guard