Aerosol Transportation Risk Assessment

Final Report

prepared for

Pipeline and Hazardous Materials Safety Administration

prepared by

Cambridge Systematics, Inc.

with

HazMat Safety Consulting, LLC

ScienceSmith Consulting, Inc.

March 24, 2020

draft final report

Aerosol Transportation Risk Assessment

Final Report

prepared for

Pipeline and Hazardous Materials Safety Administration

prepared by

Cambridge Systematics, Inc.
3 Bethesda Metro Center
Bethesda, MD 20814

with

HazMat Safety Consulting, LLC
ScienceSmith Consulting, Inc.

date

March 24, 2020

Table of Contents

List of Tables

List of Figures

Abbreviations and Acronyms

3PL	Third-Party Logistics
ADR	European Agreement Concerning the International Carriage of Dangerous Goods by Road
ASQ	American Society for Quality
BLEVE	Boiling Liquid Expanding Vapor Explosion
CAA	Clean Air Act
CFR	Code of Federal Regulations
CFS	Commodity Flow Survey
COFC	Container on Flat Car
COSTHA	Council on the Safe Transportation of Hazardous Articles
CS Team	Cambridge Systematics Team
DOT	Department of Transportation
EPA	Environmental Protection Agency
EU	European Union
FAF	Freight Analysis Framework
FAF4.1	Freight Analysis Framework version
FEA	European Aerosol Federation
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FMEA	Failure modes and effects analysis
FTL	Full Truckload
GHS	Global Harmonization of Classification
HCPA	Household Consumer Products Association
HCS	Hazard Communication Standard
HFC	Hydrofluorocarbon
HHC	Highly Hazardous Chemicals
HHV	Higher Heating Value
HMR	Hazardous Material Regulations
HMTA	Hazardous Materials Transportation Act
HMTUSA	Hazardous Materials Transportation Uniform Safety Act
HOC	Heat of Combustion
In.	Inches
IATA DGR	IATA Dangerous Goods Regulations
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICAO TI	International Civil Aviation Organization Technical Instructions

IMDGC	International Maritime Dangerous Goods Code
kg	Kilograms
lbs.	Pounds
LFL	Lower Flammability Limit
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
LTL	Less-Than-Full Truckload
m^3	Cubic Meter
MJ	Megajoules
mL	Milliliters
mm	Millimeters
NFPA	National Fire Protection Association
NFPA 30B	The NFPA code for the manufacture and storage of aerosol products
NOM	Normas Officiales Mexicanas
OHMS	Office of Hazardous Materials Safety
ORM-D	A marking for mail or shipping in the United States that identifies other regulated materials for domestic transport only
OSHA	Occupational Safety and Health Administration
PG	Packing Group
PHMSA	Pipeline and Hazardous Materials Safety Administration
PSIG	Pounds Per Square in Gauge
PSM	Process Safety Management
RAGAGEP	Recognized and generally accepted good engineering practices
RMP	Risk Management Plan
RO/RO	Roll-On/Roll-Off
RPN	Risk Priority Number
SDS	Safety Data Sheets
SP	Special Permit
TDG	Transport of Dangerous Goods (Canada)
TOFC	Trailer on Flatcar
TQ	Threshold Quantity
U.S. DOT	United States Department of Transportation
UN	United Nations
UNMR	United Nations Model Regulations
UPS	United Parcel Service
VMT	Vehicle Miles Traveled

Executive Summary

The Pipeline and Hazardous Materials Safety Administration (PHMSA) Office of Hazardous Materials Safety (OHMS) contracted with the Cambridge Systematics Team (CS Team) to complete an Aerosol Risk Assessment. The purpose of this assessment was to determine if the United Nations Model Regulations' (UNMR) definition of aerosols maintain an equivalent level of safety to the Hazardous Material Regulations' (HMR) definition used in the United States.

For this study, stakeholder outreach included meetings with experts at PHMSA, and industry representatives from the Council on Safe Transportation of Hazardous Articles (COSTHA), and the Household & Commercial Products Association (HCPA). To evaluate the risks of harmonizing aerosol regulations, the CS Team prepared a risk assessment that compared the consequences of transporting aerosol containers containing "gas only" with those that contain a product and a propellant gas that is used to expel a liquid, powder or paste. The process included completing a failure modes and effects analysis (FMEA) and recommendations for risk mitigation. Based on the review of incident data and discussions with industry representatives with knowledge of aerosol incidents in both transportation and storage, the CS Team selected seven representative products and propellants for study. These products contain combinations of flammable and nonflammable products and propellants.

Based on a review of aerosol incidents, the CS Team developed transport scenarios that were most likely to lead to undesired consequences with root causes and effects. Root causes included (1) package dropped, (2) load shifts (3) external object crushes, (4) external object punctures, (5) defective container, and (6) vehicle accident. Effects included (1) personnel or equipment exposed, (2) leaked or released contents ignite (projectile created) and (4) violent release.

In order to evaluate different transport scenarios, the CS Team developed circumstances with storylines to illustrate situations under which the stated failures might occur. For each circumstance, the CS Team evaluated likely occurrences and mitigation strategies. The FMEA process included examining the potential effects of those failure modes by assigning occurrence, mitigation and severity ratings. Combining the results of these ratings enabled the CS Team to calculate a risk priority number (RPN) to rank representative products based on different scenarios. This was the process used to determine that the heat of combustion (HOC) values of the most flammable product and propellant (Vandal Mark Remover) were the same as the HOC for a gas-only container of butane fuel. Therefore, the CS Team concluded that transporting aerosol containers with a gas-only product represented the same level of risk as aerosols containing a gas propellant and other contents.

Based on the review of incident data and discussions with industry representatives with knowledge of aerosol incidents in both transportation and storage, the CS Team concluded that the risk of exposure to toxic or corrosive substances or the risk of asphyxiation is minimal because (1) there is a small quantity of gas in each aerosol container; and (2) there are air exchanges in transport vehicles, cargo vessels and aboard aircraft. For these reasons, the risk analysis focused mainly on the flammable hazards associated with the content of aerosol containers.

While the results of the FMEA suggest HOC was an important measure of flammability, aerosol testing should be conducted to corroborate the results of the risk assessment. This will provide actionable information and data to assist PHMSA in considering rulemaking required for proposed harmonization of the HMR and UNMR regulations pertaining to the transportation of aerosols.

1.0 Introduction

The CS Team compiled this Final Report to document the results of the Aerosol Risk Assessment, which includes highlights from the literature review and supply chain analysis. This report includes study findings and recommendations, including suggested aerosol tests to assist PHMSA in future rulemaking requirements.

2.0 Stakeholder Outreach

As part of the literature review, the CS Team worked with experts at PHMSA, COSTHA, and the HCPA to better understand aerosol production, storage, handling, and transportation. This included a visit to an aerosol production facility, webinars with aerosol industry representatives and attendance at industry meetings. As part of the industry outreach process, the CS Team presented the methodology for the aerosol FMEA and solicited input to corroborate the approach. This section describes outreach efforts with COSTHA, HCPA, industry experts, representatives from the European Federation of Aerosols (FEA) and British Aerosol Manufacturing Association (BAMA), and other aerosol subject matter experts.

2.1 COSTHA Survey

COSTHA surveyed its membership in February 2019, providing specific questions pertaining to the transportation of aerosols. Note that for this survey, the term “aerosols” referred to “filled aerosol dispensers transported from manufacturing locations to distribution centers and customers.” The survey contained 19 questions and it was distributed to all 170 members, of which 52 members responded to the survey for a return rate of 30.6 percent.[1] COSTHA membership includes a wide variety of companies, including transportation, packaging, suppliers, training, testing, and manufacturers. Companies that responded ship aerosols “daily, weekly, monthly, and rarely,” resulting in a broad cross-section of member responses.

2.1.1 Survey Results

Survey results suggest that members transport aerosols by multiple modes, including highway (86 percent), air (73 percent), vessel (39 percent), and by rail (18 percent). Generally, most respondents (80 percent) indicated that current regulations do not limit members’ ability to ship by a particular mode. Moreover, differences in domestic versus international regulations do not impact members’ ability to ship by a particular mode (85 percent). However, differences in domestic versus international aerosol classifications does result in labeling and placarding issues. Regarding international shipments, 33 percent of respondents ship by air, 21 percent by vessel, and 9 percent by highway. For domestic shipments, 82 percent of aerosols are transported by truck and 18 percent by air. Estimated volumes of aerosols transported yearly ranged widely per respondent from 400 ounces to 15 million units. The industry survey responses helped the CS Team better understand the complexities of the aerosol supply chain to inform the supply chain analysis. The results of the survey also provided insights into possible impacts of aerosol regulatory harmonization on different industries. While the survey results revealed the significance of the total aerosol transportation volumes, frequency, and modes of transport, they did not provide significant insights on the risks of aerosol transport.

1 Survey results confirmed by Tom Ferguson and Laurie Curry at COSHTA, June 20, 2019.

The COSTHA survey was focused on transportation and therefore helped mostly with the supply chain section.

2.2 HCPA Survey

Each year, HCPA conducts an Aerosol Survey to track trends in the aerosol market in the U.S. In addition to providing an overall aerosol industry snapshot, the survey helps members to guide product development and sales decisions. The HCPA Aerosol Products Division Survey Committee worked with an independent third-party firm, Association Research, Inc., to administer the survey, analyze the data and compile the results. The U.S. aerosol products industry remains strong and stable, according to the 67th annual HCPA Aerosol Pressurized Products Survey.

2.2.1 HCPA Survey Results

The HCPA survey included several questions pertaining to risk, such as when asked about any releases involving aerosols in transportation that have resulted in injuries, fires or significant property damage, HCPA members surveyed responded "no; aerosol products do not self-combust, and [we are] not aware of any transportation incidents involving aerosol products that resulted in injuries or significant property damage." When asked if there [was] a difference in risk related to shipping non-flammable aerosols and flammable aerosols, HCPA members surveyed responded "[It] depends on the definition of non-flammable aerosol product—under DOT, a non-flammable aerosol can still have combustion occur and feed in as fuel to an external fire whereas a truly non-flammable aerosol product composed of ingredients that cannot undergo combustion will not add into the fire. With that said, the amount that energy that would be added to a fire from a non-flammable aerosol capable of combustion would be very limited whereas a flammable aerosol product would very likely add more energy in the event of an external fire. Within products classified as flammable aerosol products, there is a range of how much energy it will add in the event of an external fire, so it would be more ingredient dependent than just based on the classification between flammable and non-flammable." HCPA staff provided the following overview of the aerosol market in the U.S. using survey results over the last five years, as displayed in Table 2.1 below.

Table 2.1 U.S. Aerosol Container Production
2013 to 2017

Year	Total Number of Aluminum Aerosol Containers	Total Number of Steel Aerosol Containers	Total Number of Aerosol Containers Produced in U.S.
2017	745,337,407	2,970,970,541	3,841,995,848
2016	810,822,088	3,019,937,902	3,754,415,533
2015	795,564,171	2,971,420,331	3,832,021,317
2014	837,993,673	2,894,461,704	3,796,782,274
2013	784,005,000	2,873,300,182	3,767,567,496

Source: HCPA.

The survey results indicate that steel exceeds aluminum aerosol container production by more than 3:1 and that aerosol container production volumes have not changed significantly over the past five years.

2.3 Stakeholder Interviews

In addition to the two industry surveys, the CS Team conducted stakeholder interviews with over 20 industry experts between June and October 2019. At the HCPA Midyear Meeting in Washington, DC on May 3, 2019, the CS Team met with the Committee on International Harmonization and asked questions pertaining to aerosol container handling and transport. At a COSTHA Meeting on October 14, the CS Team learned more about industry supply chain methods and trends to supplement the analysis. The interviews provided important insights on the aerosol supply chain and risks of transporting aerosols. The interviews confirmed that most aerosol manufacturers use similar methods of storing and transporting aerosols from manufacturing facilities to retailers and customers. The risks of transporting aerosols over the past 50 years have been reduced due to improvements in manufacturing techniques, automation and improved transportation and handling. A generalized summary of selected stakeholder interview notes can be found in Appendix B.

3.0 Aerosol Supply Chain

This section describes the aerosol supply chain analysis that was assembled with the help of two surveys, outreach with multiple stakeholders, and other industry resources. For the purposes of this study, the aerosol supply chain starts at the aerosol can filler. Aerosol cans are manufactured at other facilities and sent to aerosol fillers to be filled with products and propellants.

3.1 Aerosol Transportation

Aerosols are assembled and filled at manufacturing facilities. Once filled, aerosols are packaged into cases, which are assembled into pallets for truck shipments to nearby warehouses. This begins the aerosol supply chain described in this section, including transportation by truck, rail, air, and ship. This section describes aerosol transportation characteristics by overall frequency, distribution, geography, and mode of transport.

This generalized aerosol supply chain is depicted in Figure 3.1.

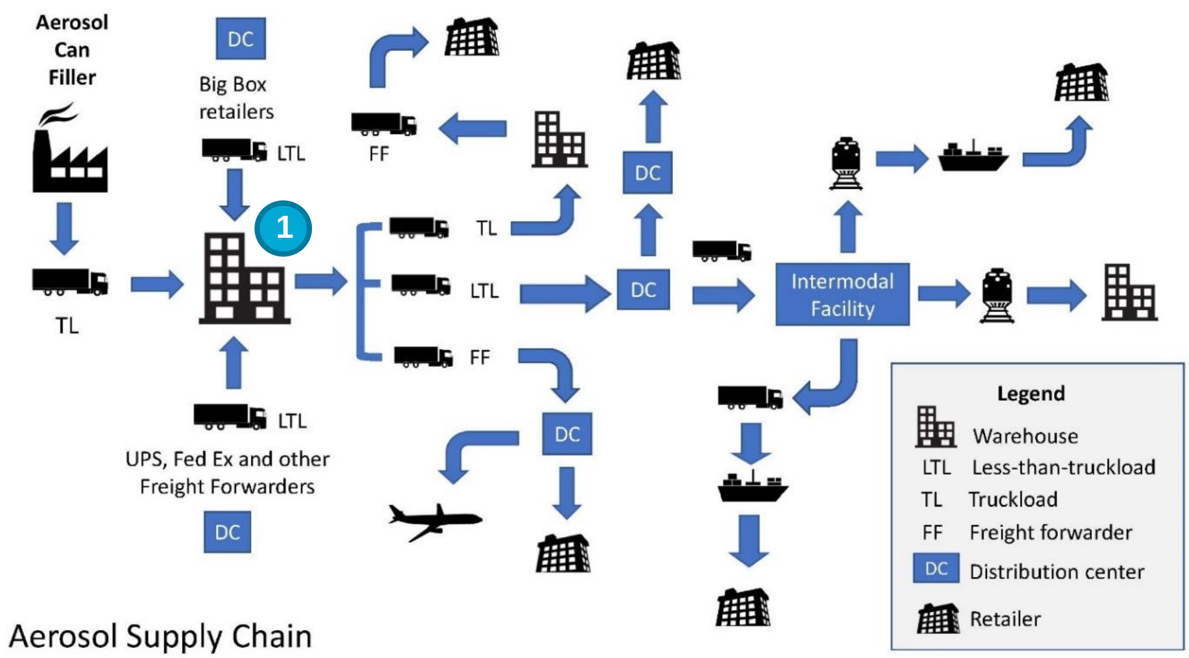


Figure 3.1 U.S. Aerosol Supply Chain

Source: Cambridge Systematics, interviews with aerosol manufacturers.

Transportation modes include truck, airline, rail, and vessel shipments. When deciding to ship by a particular mode, domestic movements have more options as they are typically shorter in distance than international shipments, and domestic movements have fewer customs and regulatory requirements. International aerosol transportation by air is limited both in terms of quantities and due to the higher costs. Several aerosol companies interviewed use vessels to transport containers to Asian, South American, and European markets.

3.2 Aerosol Commodity Flow Framework

3.2.1 Methodology

The CS Team developed a commodity flow framework was developed by scaling Government data on overall freight flows in the U.S. by the percent of freight flows that are hazmat and the percent of hazmat that are aerosols. Freight Analysis Framework version 4.1 (FAF4.1) 2012 data was used to develop a picture of aerosol transportation. The CS Team estimated national aerosol flows over the FAF4 network assuming that hazmat represents approximately 12 percent of all freight and aerosols represent less than one percent of all hazmat.

3.2.2 Analysis Results

Based on the methodology described above for deriving aerosol flow volumes, national, and metropolitan scale analyses were conducted to provide a “snapshot” of the aerosol supply chain from manufacturer to customer.

National Scale Analysis

At the national scale, aerosol flow volumes are assumed to be directly proportional to total freight volumes on the FAF network for trucks based on the methodology described above. As indicated from the COSTHA survey, 86 percent of aerosol manufacturers utilize highway modes for transport. Other modes include air (73 percent), vessel (39 percent) and rail (18 percent). Air transport of aerosols usually includes pharmaceuticals and specialty products requiring next day delivery. Aerosol truck volumes are highest in the eastern portion of the United States, particularly within the Midwest, eastern Texas, and Northeast regions. Key corridors with high levels of traffic include Interstate 95 between Washington D.C. and Boston (commonly referred to as the Northeast Corridor), Interstate 80 between New York and Chicago, and Interstates 78, 81, 40, and 30 which form connections between New York and Dallas and points west. Even though these totals are derived from total freight volumes, the data aligns well with the location of aerosol production facilities. Additional aerosol truck volumes can be viewed along the Interstate 5 corridor, particularly within the San Diego, Los Angeles, San Francisco, Portland, and Seattle areas due to the presence of larger population centers.

3.3 Aerosol Packaging

The U.S. HMR specifies that aerosols must be packed in strong outer packaging (§173.306). As defined in 49 CFR §171.8, a strong outer packaging means packaging that is “sturdy, durable, and constructed so that it will retain its contents under normal conditions of transportation.”

The UNMR has similar packaging requirements to the HMR, and requires the outer packaging to be “designed and constructed to prevent excessive movement of the aerosol and inadvertent discharge during normal conditions of transport.”

In both the UNMR and HMR, outer packages for aerosols that are not shipped as limited quantities must be subjected to a series of tests. First, they must be capable of withstanding a 3.9 feet (1.2 meters) drop test. Second, they must pass a stacking test, in which the test sample is subjected to a force applied to its top surface equivalent to the total weight of identical packages that might be stacked on top of it during transport. Third, outer packages are subjected to a vibration test, in which test packages are placed on a machine that causes the package to move up and down for one hour.

4.0 Aerosol Risk Assessment

The CS Team used the results of the literature review, stakeholder interviews, incident reports and compiled data collection to prepare the risk assessment comparing the potential consequences of transporting aerosol containers containing "gas only" with those that contain a propellant gas that is used to expel a liquid, powder or paste. The CS Team used established risk assessment methods based on a multidisciplinary approach, including analyzing supply chains, performing event modeling, and evaluating impacts to safety to assess the hazards associated with the containerization of aerosol products. Finally, the CS Team identified the consequences involved and the resulting risks of aerosol transportation. This section summarizes the FMEA based elements of the risk assessment, a comparative analysis based on the FMEA, and recommendations for risk mitigation.

4.1 Definitions—Risk Assessment, Risk Analysis, and Transport Scenarios

It is not uncommon for the terms "risk assessment" and "risk analysis" to be used interchangeably. For this study, the term *Risk Assessment* will be used, and will include the "failure modes and effects analysis that estimates how different containers would perform in transport scenarios."

This is consistent with the Society for Risk Analysis definition of *Risk Assessment* as a, "systematic process to comprehend the nature of risk, express and evaluate risk, with the available knowledge."[2]

Regarding "transport scenarios," the work objective as stated in the scope of work is as follows:

> "Determine if the United Nations Model Regulation's on the Transport of Dangerous Goods (UNMR) definition of aerosols maintains an equivalent level of safety to the HMR definition utilized in the United States and to assess the potential risks associated with aligning the HMR with the UNMR."

Consequently, the risk assessment will focus on comparing risks implied by the differences in definition of an aerosol in the HMR and the definition in the UNMR.

4.2 Risk Assessment FMEA

As noted above, the objective for the Risk Assessment is to determine whether or not the transportation of aerosols complying with the UNMR definition (i.e., those that may be filled solely with a gas) leads to increased risk compared to the transportation of aerosols complying with the HMR definition. Specifically, the two definitions are:

- U.S. DOT HMR Definition:

> "*Aerosol* means an article consisting of any nonrefillable receptacle containing a gas compressed, liquefied or dissolved under pressure, the sole purpose of which is to expel a nonpoisonous (other

[2] https://www.sra.org/sites/default/files/pdf/SRA%20Glossary%20-%20FINAL.pdf; "Society for Risk Analysis Glossary" Society for Risk Analysis, 2018.

than a Division 6.1 Packing Group III material) liquid, paste, or powder and fitted with a self-closing release device allowing the contents to be ejected by the gas."

- UN Model Regulation Definition:

  "*Aerosol or aerosol dispenser* means an article consisting of a nonrefillable receptacle meeting the requirements of 6.2.4, made of metal, glass or plastics and containing a gas, compressed, liquefied or dissolved under pressure, with or without a liquid, paste or powder, and fitted with a release device allowing the contents to be ejected as solid or liquid particles in suspension in a gas, as a foam, paste or powder or in a liquid state or in a gaseous state."

It should be noted that these definitions are distinct from the chemical definition of an "aerosol" as "a suspension of fine solid particles and/or liquid droplets in a gas." Specifically, an "aerosol" is the mixture of the contained liquid, paste or powder with either air or air and the propellant gas expelled from the articles as defined in the regulations.

For clarity, "aerosol" and "aerosol dispenser" will be treated as *synonyms* referring to *the nonrefillable receptacles*; when an aerosol in the *chemistry* sense is intended, the text will use "*actual* aerosol."

There are two important distinctions between the HMR and UNMR treatments of 'aerosol' and 'aerosol dispenser.'

- First, while the HMR refers exclusively to articles which dispense an *actual* aerosol, the UNMR encompasses *both* containers which dispense an *actual* aerosol and those which simply dispense a gas—in all cases, so long as any articles comply with the associated regulations.

- The second distinction lies in requirements for packaging and labeling aerosols and placarding vehicles used for ground transportation.

Importantly, there is no difference between the maximum aerosol dispenser size in the HMR and UNMR: both sets of regulations allow aerosol dispensers up to one liter in size. There are some minor differences in buckle and burst pressures, which can be seen in Table 4.1.

Table 4.1 United States, Canada, and Europe Aerosol Can Regulations

Country	Rating	Can Size Limit	Product Maximum Pressure: Temp. (ºC/F)	Product Maximum Pressure: Pressure (bar/psig)	Minimum Can Performance: Buckle (bar/psig)	Minimum Can Performance: Burst (bar/psig)	Minimum Plate Thickness (mm/in.)	Marking
U.S. and Canada	Nonspecification	1 liter	54.4/130	9.66/140	9.66/140	14.48/210	N/A	N/A
	DOT 2P			11.03/160	11.03/160	16.55/240	0.18/0.007	DOT 2P + MFG[1]
	DOT 2Q			12.41/180	12.41/180	18.62/270	0.20/0.008	DOT-2Q + MFG[1]
	Maximum Pressure			12.41/180				Exemption cans avail.
Europe[2]	Minimum can	1 liter	50/122	6.7/97	10.0/145	12.0/174	N/A	Inverted epsilon required
	"12 Bar"			8.0/116	12.0/174	14.4/209	N/A	
	"15 Bar"			10.0/145	15.0/218	18.0/261	N/A	
	"18 Bar"			12.0/174	18.0/261	21.6/313	N/A	
	Maximum Pressure			12.0/174	18.0/261	21.6/313	N/A	
Australia	Minimum can	1 liter	50/122	6.7/97	10.0/145	12.0/174	N/A	N/A
	Other (12/15/18 Bar)			P=pressure (can rating)	1.5xP	1.8xP	N/A	
	Maximum Pressure[3]			12.0/174	18.0/261	21.6/313	N/A	
Japan[4]	None	1 liter[5]	37/98	7.86/114	12.8/185	14.7/213	N/A	N/A
			50/122	P=pressure	1.5xP	1.8xP	N/A	
Argentina	Standard	Unknown			10/145	15/219	N/A	Unknown
	2P				11.4/163	17.2/245	N/A	Unknown
	2Q				12.8/185	19.4/281	N/A	Unknown
Korea[6]	None	Unknown			12.8/185	14.7/213	0.22/0.0085	N/A

Source: Blum, John J, Ph.D., 2012, "Global Aerosol Can Strength/Performance Requirements," presentation.

1 Manufacturer's symbol or number must be registered with the U.S. DOT.

2 Europe's ratings are convention, not law. The law is based on pressure at 50ºC/122ºF, and the can minimum buckle is 1.5 times this pressure and minimum burst is 1.8 times this pressure.

3 Australia also has an additional "nonflammable compressed gas" regulation, with a maximum product pressure of 15 bar at 50ºC/122ºF. Australia is adopting the European 12/15/18 bar grouping.

4 Japan's listed pressure is the maximum allowable. For can performance, use the second line, but product pressure cannot exceed 7.86 bar/114 lbs. per square in gauge (psig) at 37ºC/98ºF.

5 Cans are exempted from the Gas Safety Law in Japan if 1 liter or less.

6 There is no information on Korean product pressure or temperature.

4.2.1 What is a Failure Mode and Effects Analysis?

As noted above, the risk assessment is to include an FMEA. The specific purpose of the FMEA is to estimate "how different aerosol containers would perform in transport scenarios."

For this analysis, the "*different aerosol containers*" are interpreted to principally mean the differing performance of aerosol containers that would result from *the differing contents* allowed under the definitions. For instance, a nonrefillable receptacle containing a nonflammable gas (propellant) and a flammable liquid might involve risks that are different from a nonrefillable receptacle containing only nonflammable gas. For this reason, the FMEA focuses on representative examples of the nonrefillable receptacles with varying types of contents, which may create distinct hazard profiles.

The FMEA framework used here relies upon the approach advocated by the ASQ.[3] In summary, the steps for this approach include the following:

FMEA Steps

- Identify the principal *functions* of a device, system or process. This is the *scope* of the FMEA.
- Enumerate the potential ways in which those function can fail (*failure modes*) by a team of experts and reviewers.
- Characterize the potential effects of those failure modes, yielding a numerical, though qualitative, *severity rating* (1 to 10, with 10 being the most severe) for each failure mode.
- Enumerate potential causes of each failure mode by a team of experts and reviewers, and each potential cause is assigned an *occurrence rating* (1 to 10, with 10 being the most frequent).[4]
- Evaluate process controls and assign a *mitigation rating* (1 to 10, with 10 being the least detectable), which considers the ability of process controls to detect in advance and/or mitigate or prevent failures for each potential cause.[5]
- Using the severity, occurrence and mitigation ratings, calculate a Risk Priority Number (RPN) to provide guidance for ranking potential failures in the order they should be addressed.

It should also be noted that the preceding factors (functions, failure modes, and ratings for severity, occurrence and mitigation) are revised iteratively as the FMEA is conducted, so as to obtain an internally consistent result.

Within that framework, the key functions, failure modes, and effects (discussed in more detail below) are expected to be generally similar in each transport scenario. However, as the different scenarios may allow or imply different contents, it is expected that the severity could vary from one scenario to another.

---

3 https://asq.org/quality-resources/fmea.

4 Note that this is the frequency of the cause', not necessarily the frequency of a resulting failure. Control measures in place may result in effective management of the cause, preventing any adverse consequences or failure.

5 In standard ASQ nomenclature, this is a "detection" rating.

4.2.2 Why was a Failure Mode and Effects Analysis Chosen?

A particular advantage of an FMEA approach is that it can be employed even if there are limited historical data for reference.

First, it allows for a transparent expert evaluation of the relative risks, using expert judgment as a proxy for detailed historical data. This is one of the reasons that “internal consistency” was noted above: even if the absolute magnitude of risks is subject to uncertainty, the relative hazards estimated for one scenario or another can be identified.

Second, because comparisons can be made to whatever limited historical incident data exists, the expert judgment can be relied upon to ensure that the FMEA findings are at least roughly consistent with that data.

4.3 Products to be Considered in the FMEA

In order to conduct the FMEA, it was necessary to choose representative products for evaluation, along with failure modes, and root causes. To examine the relative risks of transporting aerosol containers conforming to the UNMR but not the HMR, and filled only with a gas, to those of transporting an aerosol container conforming to the HMR, and therefore filled with a gas propellant *and* with a liquid, powder, or paste, the CS Team chose representative products for the analysis. These products are modeled on common consumer and industrial products in aerosol containers that contain either only a gas propellant or a propellant and contents.

To be representative, the CS Team included examples where both propellant and contents are flammable or nonflammable. When flammable contents or propellants are present in the examples, examples were chosen with higher flammability to represent the more substantial risk, which are considered to pose the greatest hazard in transport.

Some aerosols may contain corrosive materials such as oven cleaners. Aerosol containers are restricted by regulation to low-level toxic materials (only Packing Group III authorized), so toxic aerosols were not considered in the analysis. However, some aerosols contain toxic liquids, including Chloroform, UN 1888 and Methylene chloride (common name Dichloromethane). Methylene chloride which is widely used as an industrial solvent and can be found in certain aerosol and pesticide products. The question regarding chloroform or any other toxic liquid is outside the scope of the risk analysis because these materials are already authorized to be transported according to the HMR. The CS Team was tasked with considering the implications of adopting the UN MR definition of the aerosols which does not mandate that the contents contain a liquid, powder or paste. The CS Team did not consider the inadvertent release of an aerosol filled with a toxic gases because the HMR and UN MR prohibit aerosols to be filled with a toxic gas. In order for a toxic gas or any other hazardous material to be authorized for transport in an aerosol receptacle the listing in the hazmat table for the product would need to indicate “306” in column 8A of the Hazardous Materials Table (HMT). There are no toxic gases listed in the HMT that have 306 indicated in column 8A. They are forbidden to be transported in an aerosol receptacle. While the HMR clearly does not authorize a toxic gas to be filled solely in an aerosol dispenser there is no provision for prohibiting a toxic propellent.

Based on the review of incident data and discussions with industry representatives with knowledge of aerosol incidents in both transportation and storage, the CS Team concluded that the risk of exposure to toxic or corrosive substances or the risk of asphyxiation is minimal because (1) there is a small quantity of gas in each aerosol container; and (2) there are air exchanges in transport vehicles, cargo vessels and aboard aircraft. For these reasons, the risk analysis focused mainly on the flammable hazards associated with the content of aerosol containers. Further analysis regarding the quantity of an aerosol dispenser's contents needed to result in an oxygen deficient environment can be found in Appendix G: Flammability and Oxygen Deficiency Conditions for Aerosols.

Note that in most cases, "gas only" type products are shipped under the HMR, via special permit.

The example products considered are summarized in Table 4.2.

Table 4.2 Products Considered in Failure Mode and Effects Analysis

Propellant	Contents	Example
Flammable	Flammable liquid	Vandal Mark Remover
Nonflammable	Flammable liquid	Brake Parts Cleaner
Flammable	Insecticide liquid/paste	Aerosol Insecticide
Nonflammable	Nonflammable liquid/paste	Auto A/C Treatment
	Flammable (gas only)	Butane Fuel
	Flammable (gas only)	Hydrofluorocarbon (HFC) -152a Air Duster
	Nonflammable (gas only)	R-134a Air Duster

Source: CS Team, industry input.

Notes for Table 4.2:

- The products considered were not intended to be exhaustive and were intended to represent products allowed under the current aerosol definition in the HMR and those that would be allowed under a definition harmonized with the UNMR. The products were chosen to represent the worst case in terms of hazard, based on an assessment that flammability represents the greatest hazard.

- Butane Fuel is not an aerosol under either the HMR or UNMR definitions, as it does not have a release device. However, the contents are considered in the analysis as an example of potential aerosol dispenser contents in the case of harmonization of the definition of aerosols in the HMR with that in the UNMR.

When discussing flammable contents, the heat of combustion of the contents is an important factor. The heat of combustion (also called the heating value, energy value, or calorific value) is the amount of heat released during the combustion of a specific amount of the substance. Substances with higher heats of combustion, such as hydrocarbons, release more energy when combusted, leading to increased hazards in the case of a fire or explosion. Conversely, similar amounts of substances with a lower heat of combustion, such as carbon dioxide, pose a smaller hazard in case of a fire, due to the smaller amount of energy released. Each product has an associated chemical heat of combustion based on its contents, as the overall fire hazard of an aerosol product in a metal container is a function of (among other things) the chemical HOC of the combined elements.

Usage of 'heat of combustion' demands some definitions, as various groups use this term in varying ways. Strictly speaking, the heat of combustion is the negative enthalpy of combustion ($\Delta \boldsymbol{H}_c$). That is, the amount of energy released by a combustion reaction where the reactants (e.g., fuel and oxygen) and products (e.g., CO_2 and H_2O) are considered at the same standard conditions. Engineers also use the terms higher heating value (HHV) and lower heating value (LHV). The HHV is essentially the negative enthalpy of combustion (-$\Delta \boldsymbol{H}_c$).[6] LHV is just the HHV less the energy required to evaporate the water formed.[7]

The NFPA uses yet another definition. NFPA defines heat of combustion in NFPA 30B Annex H as "the product of the theoretical heat of combustion and a combustion efficiency, usually less than 1.0 and typically around 0.95, or 95 percent."[8] The NFPA classifies aerosols as Level 1, 2, or 3, based on what they describe as "chemical heat of combustion," with Level 3 being the most flammable and therefore most hazardous.

In the analyses that follow, the lower heating value, or LHV is used to approximate the heat of combustion, and the two terms are used interchangeably. The LHV represents a middle value between the NFPA values and the HHV. Further, as water vapor is produced when the fuels considered are burned, this water vapor should not be counted towards the products' heat content.

The characteristics of each product are summarized in Table 4.3.

Table 4.3 Characteristics of Example Products Considered in Failure Mode and Effects Analysis

Product	Container Size[1]	Heat of Combustion (Energy per Container)[2]
Flammable/Flammable (Vandal Mark Remover)	16 oz (454 g)	**HHV:** 17 Megajoules (MJ) per dispenser **LHV: 15 MJ** **NFPA:** 14 MJ
Nonflammable/Flammable (Brake Parts Cleaner)	14 oz–29 oz (397–822 g)	**HHV:** 11-23 MJ/dispenser **LHV:** 11-22 MJ **NFPA:** 10-20 MJ
Flammable/Insecticide (Aerosol Insecticide)	16.0 oz (454 g)	**HHV:** 9 MJ/dispenser **LHV: 8 MJ** **NFPA:** 6 MJ
Nonflammable/Nonflammable (Auto A/C treatment)	3.0 oz (85 g)	**HHV:** 1.6 MJ/dispenser **LHV: 1.5 MJ** **NFPA:** 1.5 MJ
Flammable (Gas Only—Butane Fuel)	3.0–10.0 oz (85–284 g)	**HHV:** 4.2-14.1 MJ/dispenser **LHV:** 3.9-12.9 MJ **NFPA:** 3.7-12.3 MJ
Flammable (Gas Only—HFC-152a Air Duster)	12 oz (340 g)	**HHV:** 3.1 MJ/dispenser **LHV:** 2.7 MJ **NFPA:** 2.1 MJ
Nonflammable (Gas Only—R-134a Air Duster)	10 oz (284 g)	**HHV:** 0 MJ/dispenser **LHV:** 0 MJ **NFPA:** 0 MJ

Source: CS Team Analysis, 2019. https://www.engineeringtoolbox.com/standard-heat-of-combustion-energy-content-d_1987.html

[6] Very small differences may exist, due to slightly different choices of standard conditions.

[7] This is useful for practical applications where the water is lost as steam in the exhaust; it carries away some of the HHV, making that energy unavailable for work.

[8] National Fire Protection Association, *30B Annex H*, 2019.

Notes: Estimated percentages by weight of components are chosen to maximize the percentages of products with the highest heat of combustion. High Heat of Combustion Value.

[1] The container sizes listed are the container sizes of actual products on the market.

[2] The LHV is used as the heat of combustion in the analyses.

4.3.1 Discussion of Product Sizes

The products considered in the FMEA are representative of actual products, so the container size varies. However, it is important to discuss the potential heat of combustion for each product in the case of the maximum container size (one liter). Table 4.4 shows the heat of combustion of representative propellants; the physical state of each propellant at 130ºF and 140 pounds per square in gauge (psig); the maximum contents of each propellant in a one liter container at each of three pressures, 140, 160, and 180 psig (corresponding to buckle pressure regulations for non-specification, 2P and 2Q cans, respectively); and the total energy in each container at each pressure. The total energy in each container is the product of the heat of combustion and the maximum contents.

As seen in the table, a one-liter container of butane contains a total of between 25.4 and 26.7 MJ (depending on whether it is i-Butane or n-Butane). This energy value is similar to the energy value of a large container of brake parts cleaner (22 MJ), a product which is on the market and shipped as an aerosol. The large brake parts cleaner contains 22 ounces of product, equivalent to approximately 0.62 liters. This suggests that a similarly sized container of brake parts cleaner would have a similar (if not higher) total energy to a container filled only with butane and pose a similar hazard in transportation in the event of a fire. This will be further expanded in the FMEA, beginning in Section 4.9. Further information on the selection of these propellants is provided in Appendix F.

Table 4.4 Maximum Propellant Gas Contents in a One Liter Aerosol Dispenser for Representative Propellants

Propellant Components	Heat of Combustion (kJ/g)	Gas or Liquid at 130ºF, at 140 psig	Max Contents in 1 L at 140 psig (g)	Max Contents in 1 L at 160 psig (g)	Max Contents in 1 L at 180 psig (g)	Total Energy at 140 psig (MJ)	Total Energy at 160 psig (MJ)	Total Energy at 180 psig (MJ)
Methane (74-82-8)	55.5	Gas	6.3	7.1	7.9	0.3	0.4	0.4
Propane (74-98-6)	50.3	Gas	17.3	19.5	21.7	0.9	1.0	1.1
i-Butane (75-28-5)	50.0	Liquid	~508	~508	~508	25.4	25.4	25.4
n-Butane (106-97-8)	49.5	Liquid	~540	~540	~540	26.7	26.7	26.7
1,1-difluoroethane (75-37-6)	18.5	Gas	25.6	29.2	32.5	0.5	0.5	0.6
Nitrogen (7727-37-9)	0.0	Gas	11	12.5	13.8	0.0	0.0	0.0
CO2 (124-38-9)	0.0	Gas	17.2	19.5	21.7	0.0	0.0	0.0
1,1,1,2-tetrafluoroethane (811-97-2)	0.0	Gas	40	45.1	50.3	0.0	0.0	0.0

Source: CS Team analysis, 2019.

4.3.2 Discussion of Flammability Ranges

The Flammable Range is the concentration range of a gas or vapor that will burn if an ignition source is introduced. Three basic requirements must be met for explosion to take place:

- flammable substance - fuel
- oxidizer - oxygen or air
- source of ignition - spark or high heat

Below the flammable range, the mixture is too lean to burn and above the upper flammable limit the mixture is too rich to burn. The limits are commonly called the "Lower Flammable Limit" (LFL) and the "Upper Flammable Limit" (UFL).

Table 4.5 Heat of Combustion and Flammability Ranges for Representative Propellants

Propellant Components	Heat of Combustio n (kJ/g)	Gas or Liquid at 130ºF, at 140 psig	Lower Flammable Limit (LFL) % volume by air	Upper Flammable Limit (UFL) % volume by air
Methane (74-82-8)	55.5	Gas	4.4	16.4
Propane (74-98-6)	50.3	Gas	2.1	10.1
i-Butane (75-28-5)	50.0	Liquid	1.80	8.44
n-Butane (106-97-8)	49.5	Liquid	1.86	8.41
1,1-difluoroethane (75-37-6)	18.5	Gas	6	11
Nitrogen (7727-37-9)	0.0	Gas	NA	NA
CO2 (124-38-9)	0.0	Gas	NA	NA
1,1,1,2-tetrafluoroethane (811-97-2)	0.0	Gas	NA	NA

Source: CS Team analysis, 2020.

It is important that areas that store flammable gases are well ventilated. When designing ventilation systems be aware of the specific gravity of the actual gas. The gas mixture from a leakage will not be homogeneous and lighter gases concentrates along the ceiling. Heavy gases concentrates along the floor.

Ventilation, natural or mechanical, must be sufficient to limit the concentration of flammable gases or vapors to a maximum level of 25% of their "Lower Explosive or Flammable Limit" (LEL/LFL). [9]

[9] Engineering Toolbox, https://www.engineeringtoolbox.com/explosive-concentration-limits-d_423.html

4.3.3 Failure Modes

To determine the failure modes for consideration, the CS Team evaluated the functions an aerosol container is intended to serve. The CS Team determined that the purpose of aerosol containers is to contain their contents.

When an aerosol container does not contain its contents, it is considered to have failed. The failure could occur due to any number of potential causes, and the failure could also lead to any number of potential effects, which are covered in the subsequent subsections.

4.4 Root Causes and Precipitating Events

As part of the risk assessment of the transportation of aerosols, the CS Team collected and reviewed data on incidents involving the transportation of aerosols in both the United States and Canada. These transportation incidents will be referred to as "incidents" or "aerosol incidents" in the remainder of this report. Data for incidents in the U.S. were sourced from the PHMSA Hazmat Incident Report Search.[10] Data for Canada were provided by Transport Canada, the governmental agency responsible for dangerous goods transportation policy in Canada. Data from both sources were for incidents involving hazardous materials classified as UN1950, the UN hazardous materials code for aerosols. The CS Team requested incident data related to aerosol containers filled purely with gas (e.g., air dusters) from PHMSA. There were no related data available even though almost every special permit requires reporting of incidents, including the requirement that each grantee must notify the Associate Administrator for Hazardous Materials Safety, in writing, of any incident involving a package or operation conducted under the terms of this special permit.[11] This may either mean that these incidents are uncommon during transportation or that grantees are not appropriately reporting.

The CS Team processed data from both sources to better understand the failure modes, consequences and frequency of reported incidents involving aerosol containers with release of a substance (i.e., gas, liquid, powder, or paste). After data cleaning, from 1988 through 2018, there were 15 aerosol incidents reported to Transport Canada and 36 reported to PHMSA.[12] Based on a review of the incidents in both sources, the CS Team identified common root causes of failure to be included in the FMEA. These failure modes are summarized in Table 4.5, with the total consequences from each, classified as a spill only, explosion, or fire.

It is worth noting that there were no incidents in the U.S. resulting in an explosion and only one (of unknown cause) in Canada. Furthermore, there is no evidence of any incidents involving the transportation of aerosols in the U.S. or Canada resulting in injuries or fatalities due to asphyxiation, and any spills of poisonous or corrosive substances did not result in an injury requiring more than washing the affected area or minor first-aid treatment. Additionally, based on the potential failure modes identified the CS team does not believe that a sufficient quantity of gas could be released from an incident involving aerosol shipments that could pose an asphyxiation hazard or a significant enough release of Division 6.1, PG III toxic material to create a toxic

[10] https://portal.phmsa.dot.gov/analyticsSOAP/saw.dll?Dashboard.

[11] Special permits contain a clause which states, "Shipments or operations conducted under this special permit are subject to the Hazardous Materials Incident Reporting requirements specified in 49 CFR §§ 171.15 Immediate notices of certain hazardous materials incidents, and 171.16 Detailed hazardous materials incident reports. In addition, the grantee(s) of this special permit must notify the Associate Administrator for Hazardous Materials Safety, in writing, of any incident involving a package, shipment or operation conducted under terms of this special permit."

[12] Additional information on the data cleaning process can be found in the supply chain section of the report.

hazard (see Appendix G). Since there was no evidence of any incidents involving the transportation of aerosols in the U.S. or Canada resulting in injuries or fatalities due to asphyxiation, and any spills of poisonous or corrosive substances, the CS Team focused on flammability concerns for aerosol transport. This was also corroborated through outreach with industry experts and representatives from the aerosol manufacturing companies, none of whom could document any incidents in transport or storage involving asphyxiation or spills of poisonous or corrosive substances. For these reasons, and based on discussions with industry representatives, fire was determined to be the most significant risk posed by aerosols.

Based on the analysis of incidents and discussion with industry representatives, the following potential causes of a failing aerosol container were considered:

- Package Dropped.
- Load Shifts.
- External Object Crushes.
- External Object Punctures.
- Defective Container.
- Vehicle Accident.

Table 4.6 Failure Modes and Consequences in United States and Canada Aerosol Incident Data

Root Cause	Consequences: Canada Spill Only	Canada Explosion[1]	Canada Fire	United States Spill Only	United States Explosion[1]	United States Fire
Closure Damaged	0	0	0	2	0	0
Closure Not Secured Properly	0	0	0	10	0	0
Container Punctured by Other Items	1	0	0	2	0	0
Defective Container	0	0	0	1	0	0
Load shift	3	0	0	0	0	0
Outer Packaging Dropped or Otherwise Damaged	2	0	0	3	0	1
Run Over by Forklift	1	0	0	0	0	0
Static Electricity from Conveyor Belt	0	0	0	0	0	2
Vehicle Accident	1	0	0	1	0	0
Unknown	3	1	2	7	0	6
Other	0	0	1	1	0	0
Total	**11**	**1**	**3**	**27**	**0**	**9**

Sources: CS Team, United State Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Hazardous Materials Incident Database https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/Welcome.aspx. Transport Canada, "Accident Summary Report: Period 1988–2018 Inclusive," email from Tracey Boicey to Bob Richard, May 7, 2019.

[1] There were no aerosol incidents resulting in an explosion in the United States and only one in Canada between 1988 and 2018.

4.5 Failure Mode and Effects Analysis Occurrence Ratings

Based on the review of aerosol incident data in the U.S. and Canada, as well as discussions with industry experts, each failure mode was assigned an occurrence rating as part of the FMEA. The occurrence rating ranges from 1 to 10, with one indicating the failure mode never occurs and 10 indicating it always occurs. Ratings between 1 and 10 reflect frequencies of occurrence between never and always and are based on discussions with industry experts. They reflect the approximate number of occurrences per day and were chosen to give a representative range of frequencies with sufficient differentiation to meaningfully classify scenarios. The full list of occurrence ratings as used herein is shown in Table 4.6.

Table 4.7 Failure Mode and Effects Analysis Occurrence Ratings

Occurrence Rating	Definition
1	Never occurs
2	1 per 1000 days
3	1 per 500 days
4	1 per 100 days
5	1 per 50 days
6	1 per 10 days
7	1 per 5 days
8	1 per day
9	10 per day
10	Always occurs

Source: CS Team, 2019.

4.6 Failure Mode and Effects Analysis Severity Ratings

As part of the FMEA, the CS Team developed a rating scale for the severity of incidents occurring during the transportation of aerosols. This rating scale was based on aerosol incident data from PHMSA and Transport Canada and reports of incidents provided by the FEA.[13] The effects range from a small release of contents, with no hazard created, to catastrophic, involving multiple fatalities, a building collapse with occupants, etc.

Based on the analysis of incident data and discussions with industry representatives, the following effects were considered in the FMEA:

- Personnel or Equipment Exposed to Leaked Released Contents.
- Leaked or Released Contents Ignite.
- Projectile Created (e.g., can “rockets”).
- Violent Release (can bursts releasing high-velocity fragments).

[13] For example: https://www.abc.net.au/news/2019-04-06/driver-killed-in-south-eastern-freeway-truck-crash/10978140 and https://www.wdrb.com/story/39003762/truck-carrying-axe-body-spray-explodes-in-texas/.

It should be noted that there is no record of aerosol incidents that would be classified as catastrophic. Many of the cases, such as those listed above, were derived from actual effects in the incident data reviewed, but cases such as multiple fatalities were included for evaluation purposes. These severe incidents are unlikely to occur and so would have a low occurrence rating in the FMEA. Further information on the conditions necessary for flammability and oxygen deficiency for different substances is provided in Appendix G. The severity ratings as used herein are summarized in Table 4.7.

Table 4.8 Failure Mode and Effects Analysis Severity Ratings

Severity Rating	Definition	Example(s)/Description
1	Insignificant	Small release, contained within outer packaging, no hazard created
2	Inconsequential incident	Hazard created, but no consequences.
3	One minor injury	Minor = first aid only.
4	Multiple minor injuries	
5	One severe injury	Severe = hospital treatment.
6	Multiple severe injuries	
7	Incident involving a fire that causes injuries, property damage or highway closure	Any incident where an aerosol can burst, rockets or fragments or where there is a fire resulting in injury or property damage or highway closure
8	Major infrastructure operations impact	Flight operations altered; fire aboard an aircraft; public evaluated for more than one hour; roadways closed
9	Fatality	
10	Catastrophic	Multiple fatalities; building collapse with occupants; aircraft crash

Source: CS Team, 2019, PHMSA and Transport Canada Incident Data.

4.7 Failure Modes and Effects Analysis Mitigation Ratings

The final component of an FMEA is the mitigation rating, which is a rating of how likely any given failure is to be mitigated.[14] This could occur through detection of the failure prior to any effect or through the containment of the failure, preventing or reducing any adverse effect. Like the severity and occurrence ratings, the mitigation rating ranges from 1 to 10, with one being always mitigated and 10 being never mitigated. Ratings between 1 and 10 reflect mitigation rates between always and never and are based on discussions with industry experts. They reflect the approximate mitigation rate per container and were chosen to give a representative range of rates with sufficient differentiation to meaningfully classify scenarios. The full range of mitigation ratings used herein are shown in Table 4.8.

[14] In ASQ terminology this is the “detection” rating (D).

Table 4.9 Failure Mode and Effects Analysis Mitigation Ratings

Mitigation Rating	Definition
1	Always mitigated[1]
2	1 in 10,000 escape mitigation
3	1 in 1,000 escape mitigation (usually mitigated)
4	1 in 500 escape mitigation
5	1 in 100 escape mitigation (often mitigated)
6	1 in 50 escape mitigation
7	1 in 10 escape mitigation (mostly mitigated)
8	1 in 5 escape mitigation
9	1 in 2 escape mitigation
10	Never mitigated

Source: CS Team, 2019.

[1] "Always mitigated" means that even if the aerosol dispenser is damaged or compromised, mitigation measures (e.g., strong outer packaging, valve protection, pressure receptacle safety features) mitigate the hazard so that there are no adverse consequences.

The mitigation may depend on factors such as packaging or testing requirements, which are often determined by regulations.

The combination of the frequency of occurrence and the frequency of mitigation indicates the overall frequency that an incident results in the indicated outcome. For example, an occurrence rating of 5 (1 per 50 days) and a mitigation rating of 4 (1 in 500 escape mitigation), would indicate that the outcome of the incident is expected to occur once every 2,500 days, or approximately once every seven years.

4.8 RPN Explained

Once a severity rating, an occurrence rating, and a mitigation rating have been assigned to a particular candidate problem, they are multiplied together to determine the candidate problem's RPN. As each rating is based on a scale from 1 to 10, the RPN ranges from one to 1,000 (10 x 10 x 10), with the highest rating indicating that a particular candidate problem always occurs, is never mitigated, and is catastrophic in nature.

Because the three ratings are multiplied, there are multiple combinations of ratings that could result in the same RPN. For example, a candidate problem with a severity rating of 10, occurrence rating of 2, and mitigation rating of 2 has an RPN of 40, equal to that of a candidate problem with a severity rating of 2, occurrence rating of 2, and mitigation rating of 10. However, it would be logical to conclude that the former candidate problem is of greater concern than the latter given its catastrophic severity, compared to a problem with low severity that is never mitigated. The former problem, in fact, may be determined to be more severe than a problem with a higher RPN, given the catastrophic severity of its outcome. For this reason, problems may be promoted or demoted for greater or lesser consideration based on expert judgment of relative risks of each.

4.9 Failure Mode and Effects Analysis for Select Aerosol Products, Root Causes, and Effects Scenarios

For the FMEA, an analysis of all possible combinations of products, root causes, and effects would have quickly led to hundreds of scenarios to consider, many of which would be nearly indistinguishable from each other. Even considering the seven products, six causes of failure, and four effects of failure discussed above would result in 168 (7 x 6 x 4) scenarios.

To reduce the number of scenarios, the CS Team considered a subset of the scenarios that are most common or most likely to lead to undesired consequences, as shown in Table 4.10. In the table, a check mark indicates the effect (in columns) is considered possible to result from the cause (in rows), whereas other effects are not considered likely for the given cause. These are based on conversations with industry experts and analysis of aerosol incident data.

For example, a dropped package is unlikely to result in more than a leaking container, as the force is not great enough to create a projectile or violent release. Cells shaded a similar color indicate groups of events that were considered equivalent. For example, whether an external object crushes or punctures an aerosol container, whatever the effect, the resulting risk and occurrence should be the same—that is, aerosols are damaged inside the package only, and do not pose a risk to workers. Similarly, a vehicle accident resulting in only the release of a product could be grouped with an external object crushing or puncturing the container as the accident would result in a similar effect.

However, the ignition of a container's contents in the case of a vehicle accident differs from their ignition in the case of an external object crushing or puncturing the container because an ignition in a vehicle could affect many more people on a roadway.

Table 4.10 Combinations of Aerosol Container Causes and Effects and Reduction of Scenarios

	Effects			
Root Cause	**Personnel or Equipment Exposed**	**Leaked or Released Contents Ignite**	**Projectile Created**	**Violent Release (can bursts releasing high-velocity fragments)**
Package Dropped	✓	0	0	0
Load Shifts	✓	0	0	0
External Object Crushes	✓	✓	0	0
External Object Punctures	✓	✓	✓	0
Defective Container	✓	✓	0	0
Vehicle Accident	✓	✓	✓	✓

Source: CS Team, 2019, PHMSA and Transport Canada Incident Data.

Notes: A check mark indicates the effect was determined to be plausible for the given cause, whereas other effects were determined not to be plausible (e.g., a dropped package could lead to a leak, but the force is not expected to be sufficient to create a projectile. Cells shaded a similar color indicate groups of events that were considered equivalent. For example, whether an external object crushes or punctures an aerosol container, whatever the effect, the resulting risk and occurrence should be the same.

The CS team validated these scenarios against available incident data and through conference calls, meetings, and discussions with industry representatives, including shippers, carriers and warehouse workers that are familiar with the frequency, causes, and outcomes of incidents involving aerosol containers both in transport and storage. Based on discussions with the various industry representatives, the most common cause of aerosol container damage or the release of contents is based on handling incidents which generally occur in warehouses, distribution centers or parcel facilities. In some instances, these incidents can be characterized as being in transport if they occur during loading and unloading incidental to movement (see definitions in §171.8 for Loading or Unloading incidental to movement).[15]

The likelihood of an incident involving an aerosol container with a propellant that expels a liquid, powder, or paste and one that expels strictly a gas are considered to be equal. The reduction in scenarios resulted in nine combinations of causes and effects to consider. The scenarios addressed in the FMEA are summarized in Table 4.10. As a result, a total of 63 (9 x 7) combinations of products and causes and effects of container failure were considered.

Table 4.11 Combined Root Causes and Effects Considered in the Failure Mode and Effects Analysis[1]

Scenario	Root Cause	Effect
A	Package Dropped	Leaked or Released Contents: Personnel or Equipment Exposed
B	Load Shifts	Leaked or Released Contents: Personnel or Equipment Exposed
C	External Object Crushes	Leaked or Released Contents: Personnel or Equipment Exposed
D	External Object Crushes	Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source
E	External Object Crushes	Rocket/Jet Projectile
F	Defective Container	Leaked or Released Contents: Personnel or Equipment Exposed
G	Defective Container	Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source
H	Vehicle Accident (with fire)	Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source
I	Vehicle Accident (with fire)	Violent Release

Source: CS Team, 2019, PHMSA and Transport Canada Incident Data.

1 Based on analyses of 30 years of U.S. and Canadian incident data and multiple conversations with industry experts, these scenarios represent the worst-case scenarios for the failure modes and effects analysis.

For each scenario, the CS Team developed a story line, which briefly describes how scores for the occurrence rating and mitigation rating were considered and assigned. The severity rating then depends on the product being considered, and those scores, with the reasoning behind them are provided for each

15 **Loading incidental to movement** means loading by carrier personnel or in the presence of carrier personnel of packaged or containerized hazardous material onto a transport vehicle, aircraft, or vessel for the purpose of transporting it, including the loading, blocking and bracing a hazardous materials package in a freight container or transport vehicle, and segregating a hazardous materials package in a freight container or transport vehicle from incompatible cargo. (172.8).

scenario and product. Finally, the resulting RPN is calculated and summarized for comparison of the relative risk of each product and scenario.

4.9.1 Typical Transportation Conditions for Aerosols

Aerosol containers are filled at over 100 manufacturing facilities in the United States; from there they are transported to distribution centers and on to retailers and customers. Most aerosols are transported by truck in dry cargo van trailers. This includes shipments to Mexico and to Canada. There are some rail movements of aerosols in the U.S., primarily to the West Coast since most aerosol manufacturing facilities are located in the East Coast, Midwest, and Gulf Coast regions. Several industries transport aerosols by truck to ports where aerosols are shipped to Asia, the Caribbean, and South America. Aerosols also are transported by truck to airports for air shipments. Other countries also manufacture and transport aerosols within each continent. Therefore, intercontinental shipments of aerosols are the exception, not the rule. The Supply Chain Chapter describes aerosol transportation by mode in more detail. This section describes the most common transportation of aerosols from manufacturing facilities to customers in the U.S. Most aerosols are transported in strong outer packaging and are shipped palletized and shrink wrapped providing a high level of safety and reduced probability of damage during transport with the exception of e-commerce and parcel shipments shipped directly from distribution centers to consumers. Since these packages are in some cases shipped individually and are subjected to more frequent handling, they may experience a higher probability of being dropped or crushed during transportation. However, in assessing occurrence ratings a general approach was taken considering both transport scenarios collectively.

Manufacturing Facility to Warehouse

The aerosol can fill process involves injecting cans with product and a propellant through a multistep assembly line process. This highly automated process has been improved over the past 40 years and has undergone many modifications to improve efficiency and safety. Cans also are tested during the assembly process by being subjected to a hot water bath per regulations. The finished product, or filled aerosol containers, are then loaded into boxes (or cases) which are assembled into pallets, all by machine. In one industry example, 16-ounce cans are sorted into 6-pack or 12-pack cases and assembled into pallets which are then loaded into a dry cargo van and transported a short distance to a warehouse.

Warehouse to Customer

At the warehouse, the pallets are either designated for a customer (full pallet) or unloaded to and/or mixed with other aerosol products for other customers. From interviews with industry representatives, more than 80 percent of aerosol shipments are transported in LTL quantities. This is due to the fact that many different customers use aerosols in the U.S. Pallets are sorted by customer needs and wrapped for transport. Designated pallets are loaded into dry van trailers and remain intact until reaching the customer. The pallets may be moved on and off several other truck trailers and/or intermodal containers between origin and destination depending on trip distance. The other 20 percent of shipments are transported in FTLs to distribution centers or directly to a customers. Big-box retailers will send their own dry van trailers to the aerosol manufacturer’s warehouse and transport to distribution centers and to stores. Big box retailers represent approximately 40 percent of overall aerosol shipments in the U.S. In one industry example, less than one percent of aerosol containers are transported by parcel carriers such as UPS, FedEx, U.S. Postal Service and others. In these examples, aerosol container packages also are loaded in LTL shipments in mixed pallets using carrier dry van trailers. At carrier sorting and distribution centers, aerosol packages are transported along high-speed conveyer systems before being loaded in delivery vehicles mixed with other parcels being delivered to customers.[16] Based on discussions with parcel carriers, the CS team learned that there have been instances where aerosol container packages were dropped or crushed releasing content. In some instances, the presence of static electricity resulted in ignition of the releases flammable constituents, but none resulted in a high-consequence event. In one other incident a transport worker was exposed to a mildly corrosive substance (oven cleaner) and sustained a minor injury.

4.9.2 Circumstances

In order to evaluate different transport scenarios, the CS Team developed "circumstances" with "story lines" to illustrate circumstances under which the stated failures might occur. A full "scenario" includes the example aerosol dispenser with its contents. The CS Team developed a total of nine circumstances (A through I), in increasing levels of severity, from "A: Package Dropped" to "I: Vehicle Fire." The process in the development of these circumstances is described in Table 4.10.This section describes each circumstance in detail, with occurrence and mitigation ratings for each. Note that the occurrence and mitigation ratings are independent of the actual contents.

Circumstance A. Package Dropped Leading to Leaked or Released Contents: Personnel or Equipment Exposed[17]

During routine transportation, a package containing aerosol containers, shipped under special permit or as a limited quantity in strong outer packaging, is dropped. Even though the fraction of packages dropped may be small compared to the total number shipped (see text box), they are nevertheless very frequent overall. For that reason, drops, some of which *might* be severe enough to overcome the protection of packaging, are assumed to happen frequently, **yielding an occurrence rating of 9:** that is, 10 packages containing aerosol containers endure a drop causing damage of some kind each day. While this is a frequent occurrence, it is a very small percentage of the 10 million daily packages in transport. Note that the discussion here is independent of the actual contents, so this occurrence and mitigation rating will apply to all example products in Circumstance A.

Research reveals that package drops most often occur in warehouses or distribution centers when larger shipments are segregated and resorted for final delivery, or else in the "last mile" of transport (e.g., by parcel, fleet, or contract carrier). As noted, shipments can be LTL, TL or by parcel carrier (less than one percent. For LTL shipments, pallets are regularly unloaded and loaded by forklifts multiple times between distribution centers. For TL shipments, pallets are unloaded fewer times. In examples involving parcel carriers, packages may be loaded and reloaded as many as five times and sorted by a variety of means, including manual or mechanical, on high-speed belts, slides, chutes, and rollers. Longer distance shipments will likely be subjected to even more loading, unloading, and sorting. Given the automated process of handling packages and the many stages of transportation, packages delivered by parcel carriers are routinely subjected to forces that have the potential to damage packages. Consequently, drops are a major cause of damage to packages and products, and they often occur when the package is manually handled during loading and unloading. Studies show that impacts to shipments are mostly rotational drops on edges or corners, with relatively few flat or perfect edge/corner drops.

Studies have shown that the majority of shocks result from non-free fall impacts, mostly equivalent to a drop from a relatively low height. However, about five percent of all shipments receive at least one impact above an equivalent drop height of 30 inches. In one study of next-day shipments, the maximum drop height was

[16] Estimates based on interviews with multiple aerosol industry experts from HCPA and COSTHA.

[17] In this section, "packages" refer to "boxes" or "cases" designed to transport aerosols.

nearly 8.5 feet (2.6 meters), and five percent of all drops over three inches of the packages studied were over 4.8 feet (1.45 meters), which is above the distance of 3.9 feet (1.2 meters) specified in the UNMR and HMR for packaging testing of drop height. The same study found an average of over two drops per package for one-day shipments. In one industry example, an average of five cases are damaged per day in a warehouse.[18, 19]

While many outer packages containing aerosol containers may be dropped or experience forces similar to being dropped each day, they are required to meet the "strong outer packaging" requirements specified in §173.24 and §173.24a. These requirements stipulate:

(b) Each package used for the shipment of hazardous materials under this subchapter shall be designed, constructed, maintained, filled, its contents so limited, and closed, so that under conditions normally incident to transportation—

(1) Except as otherwise provided in this subchapter, there will be no identifiable (without the use of instruments) release of hazardous materials to the environment.

(2) The effectiveness of the package will not be substantially reduced; for example, impact resistance, strength, packaging compatibility, etc. must be maintained for the minimum and maximum temperatures, changes in humidity and pressure, and shocks, loadings and vibrations, normally encountered during transportation.

In the study by Saha, Singh, and Singh 90 percent of the dropped packages were dropped from a height of 2.5 feet (0.77 meters) or less, a distance limited quantity packages generally can withstand. Consequently, the CS Team assumed that "strong outer packaging" is sufficient to prevent damage to the inner contents in 90 percent of all drops. That yields a **mitigation rating 7** (1 in 10 packages fail in a drop). Thus, a drop is considered severe enough to cause sufficient damage to the package that one or more contained aerosol containers discharge their contents within the damaged packaging, soaking the package and exposing nearby personnel or equipment to the contents, with an overall frequency of 1 per day.

Circumstance B. Load Shifts Leading to Leaked or Released Contents: Personnel or Equipment Exposed

During routine transportation (see also the first text box, under Circumstance A, above), most loads will shift to some degree due to various movements occurring within a trailer, railcar, or intermodal container.[20] In one study conducted in the United Kingdom, researchers found load shifts resulting in falling loads occurred as

[18] K. Saha, J. Singh, and S. P. Singh, "Measurement, Analysis and Comparison of Drops Experienced by Packages in Interstate and Intrastate Next Day Shipments in United States," Journal of Applied Packaging Research, Vol. 4, No. 2, April 2010, https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1052&context=it_fac.

[19] Institute of Packaging Professionals, Guide to Packaging for Small Parcel Shipments, March 2002, https://www.iopp.org/files/public/IoPPSmallParcelShippingGuidelines.pdf

[20] S. P. Singh, J. Antle, J. Singh, and E. Topper, "Load Securement and Packaging Methods to Reduce Risk of Damage and Personal Injury for Cargo Freight in Truck, Container and Intermodal Shipments," *Journal of Applied Packaging Research*, 6.1 (2014), https://scholarworks.rit.edu/cgi/viewcontent.cgi?article=1008&context=japr.

often as every hour or more frequently.[21] Given this, load shifts of cargo comprising aerosol containers are considered to happen with the same frequency as drops, yielding an **occurrence rating for a load shift of 9** (10 per day).

As was the case for drops, the likelihood of any specific shift causing a failure will vary with the severity of the shift and the ability of the packaging to withstand the applied forces. In the absence of concrete data on this, **the mitigation rating for a load shift is assumed to be the same as for a drop, 7** (1 in 10 packages fail in a load shift). Thus, a load shift is considered severe enough to cause sufficient damage to the package that one or more contained aerosol containers discharge their contents within the damaged packaging, soaking the package and exposing nearby personnel or equipment to the contents, with an overall frequency of 1 per day.

Note that the discussion here is independent of the actual contents, so this occurrence and mitigation rating will apply to all example products in Circumstance B.

Circumstance C. External Object Crushes Leading to Leaked or Released Contents: Personnel or Equipment Exposed

During routine transportation it also is possible for an outer package, containing aerosol containers, to be compressed or crushed by another package in a stack or an external object such as a forklift. Compression and crushing are often the result of flimsy or ill-fitting packaging, overfilled packaging, and packages that are stacked too high or the result of a package or aerosol container falling on the ground and being run over by a forklift.

In some cases, during normal transportation, aerosols may be packaged in display packs intended for retail sale (49 CFR §173.156), which are comprised of aerosol containers packed into trays that secure individual containers from shifting inside the completed combination package during transportation. The trays are placed into a fiberboard box, and the fiberboard box is banded and secured to a pallet by metal, fabric, or plastic straps to form a single palletized unit. These display packs do not provide the same protection for the top of an aerosol container as a fiberboard box, and the containers may be more susceptible to crushing.

Interviews with industry personnel indicate that damage from forklifts is, in fact, a leading cause of issues during transport. While a crushing event by an external object is considered to happen with lesser frequency than drops or load shifts—we assign it an **occurrence rating of 8** (one per day)—it seems likely that any such event would be sufficient to overcome the protection of the packaging, leading to a **mitigation ration of 10** (never mitigated). As for drops and shifts, this results in an overall frequency of one per day for this failure.

Circumstances A to C Consolidated

The preceding analysis of failure modes resulting in the exposure of personnel or equipment due to drops, cargo shifts, or package (or container) crushing yielded similar results for each circumstance (an overall estimated frequency of unmitigated failures), estimating that one failure per day occurs. In other words, whether a package is dropped, shifted, or crushed, the contents of the damaged aerosols within the package

[21] N. C. M. Day, G. P. White, and A. McGillivray, “Load Security on Curtain Sided Lorries,” *Health and Safety Executive Report*, September 2008, https://www.hse.gov.uk/research/rrpdf/rr662.pdf.

are contained within (or mitigated by) the “strong outer packaging.” Therefore, the causes resulted in the same effects.

For that reason, in the subsequent analysis), Circumstances A, B and C were consolidated into a single circumstance, since a “drop, shift or crush” leads to ‘personnel or equipment exposed’ circumstance that is mitigated by strong outer packaging. In this view, a drop, shift or crush will lead to a ‘leaker’ (personnel or equipment exposed) one to three times each day (up to three, given three possible root causes).

Circumstance D. External Object Crushes Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source

As discussed in Circumstance C, the occurrence rating for a crushed package is assumed to be 8 (one aerosol containing package crushed each day). However, for the present circumstance, it seems clear that not all crushed packages would occur in the vicinity of an ignition source. Many crushed packages occur in transit, inside a truck trailer, rail car, shipping container, or aircraft, where there are no sources of ignition.

Based on industry discussions, one source of ignition that is becoming more prevalent is increased static charges from high-speed automatic conveyor belts made of composite materials instead of stainless steel and used in sorting facilities or warehouses. Another relatively common source of ignition that was provided by industry stakeholders was frictional heat produced by truck brakes. However, these conditions are relatively rare. As a result, it is our assumption that exposure to ignition should be approximately 1000 times less likely than simple exposures of personnel or equipment (Circumstances A, B, C), therefore, **the mitigation rating for crushed packages in the presence of an ignition source is 3** (1 per 1000 crushing events). Overall, this yields a frequency of one object crushed, resulting in a “leaker” exposed to an ignition source once every 1000 days. If one assumes here that, as above, drops or shifts would also contribute, the overall frequency will become one to three per 1000 days (2.7 years).

Circumstance E. External Object Crushes Leading to Rocket/Jet Projectile

As discussed in Circumstance C, the occurrence rating for a crushed package is assumed to be 8. However, a package would need to be crushed in the presence of not only an ignition source but also be heated to a high enough temperature to cause the container to burst and produce a rocket/jet projectile. According to research by French workers, when pallets of aerosol containers are exposed to a large fire, bursting is nearly inevitable.[22] However, the formation of a rocket or projectile is significantly less frequent. For that reason, for a circumstance in which an external object crushes a package containing aerosol containers, is considered less likely (say, 10 times) to result in a Rocket/Jet projectile than simple participating in a fire. That leads to **a mitigation rating of 2** (1 in 10,000 crushes leads to a “Rocket/Jet Projectile,” and an overall frequency of a projectile from crushing of 1 in 10,000 days (27 years). Given the absence of reports of this in the incident history, this appears to be consistent with the data.

[22] Korkeck, M. A., Study on the relevance of the system of exemption for the transport of hazardous goods packed in limited quantities, February 2002.

Circumstance F. Defective Container Leading to Leaked or Released Contents: Personnel or Equipment Exposed

According to one study, the frequency of defective aerosol containers from manufacturing is approximately 0.05 percent.[23] Conversations with industry representatives corroborated this, indicating that there are few defective containers. If a rate of 0.05 percent is assumed, with around four billion aerosol containers produced each year in the U.S., in principle there might be 5,550 defective aerosol containers produced each day. However, based on a review of data and conversation with industry representatives, most of these defective containers are rejected during production and it is very rare for a defective container to make it into the transportation system. Based on that, **the occurrence rating of a defective aerosol container in transportation is 2** (1 per 1,000 days).

Aerosol containers undergo considerable testing prior to leaving the production facility. Regulations in the HMR prescribe that every container be tested in a hot water bath to test for leakage and deformation. There must be "no indication of leakage or permanent deformation." There are alternatives to the hot water bath test for heat sensitive products, requiring two containers out of every lot of 2,000 be subjected to leakage and pressure tests. If one of the inspected containers fails, the entire lot of 2,000 containers must be discarded. The remaining containers must be visually inspected. Further tests are required for weight and leakage, and containers must be periodically inspected at random. If a randomly inspected container is found to be defective, all containers produced since the last random inspection must be discarded.[24]

However, once a defective container enters the transport system, there are few mitigation measures in place. Based on that, a **mitigation rating of 9** (one in two mitigated) is assigned to a defective container in transport leading to a "leaker" (personnel or equipment exposed). Overall, then we estimate that the frequency of a leaker due to a defective container in transport is one per 2000 days (5.5 years).

Circumstance G. Defective Container Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source

As discussed in Circumstance F, the **occurrence rating of a defective aerosol container in transportation is 2** (1 per 1,000 days). Following the logic in Circumstance E, exposure to an ignition source is expected to occur only in one of 1000 cases of a simple 'leaker'. However, this leads to an extremely low overall occurrence rate (1 in 1,000,000 days, or approximately 2,700 years). While it may be correct that a defective container essentially never results in a leaker + an ignition source, we more conservatively set **the mitigation rating here to 6.5 or 1 in 20 are not mitigated,** so as to achieve an overall frequency of one leaker every 20,000 days (approximately 55 years).

---

[23] M. A. Farooq, R. Kirchain, H. Novoa, and A. Araujo, "Cost of Quality: Evaluating Cost-Quality Tradeoffs for Inspection Strategies of Manufacturing Processes," International Journal of Production Economics, 188, 2017, https://www.researchgate.net/profile/Muhammad_Farooq132/publication/315982597_Cost_of_Quality_Evaluating_Cost-Quality_Tradeoffs_for_Inspection_Strategies_of_Manufacturing_Processes/links/59d541dcaca2725954c450ff/Cost-of-Quality-Evaluating-Cost-Quality-Tradeoffs-for-Inspection-Strategies-of-Manufacturing-Processes.pdf.

[24] 49 CFR § 173.306, https://www.ecfr.gov/cgi-bin/text-idx?SID=e38e040fabcd5db02dab613e0499a0d2&mc=true&node=se49.2.173_1306&rgn=div8

Circumstance H. Vehicle Accident (with Fire) Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source

Vehicle accidents are common events in the transportation of freight in the U.S. According to the Federal Motor Carrier Safety Administration (FMCSA), in 2017, there were over 390,000 crashes involving large trucks or buses resulting in property damage only, 116,000 crashes resulting in at least one injury, and nearly 4,500 crashes resulting in at least one fatality.[25,26] Therefore, there are over 1,000 crashes involving large trucks or buses in the U.S. each day. Put another way, the crash rate for large trucks and buses is approximately 12 per 100 million vehicle miles traveled (VMT) for property damage-only crashes, four per 100 million VMT for crashes with at least one injury, and 0.14 per 100 million VMT for crashes with at least one fatality.

Based on conversations with industry stakeholders, aerosols are primarily transported by truck, an observation which is further corroborated by data on the transportation of all gases classified as hazardous materials showing over 60 percent of all gases by weight are transported by truck.[27] To estimate the percentage of aerosols within all hazmat, the CS Team used Tier II data from the EPA for a representative State. Industries storing certain reportable quantities of hazardous materials in the U.S. are required each year to file Tier II reports to the EPA. These reports document the total pounds of hazmat stored at facilities during the previous year.[28] Using this approach, the CS Team determined that aerosols represent less than 0.1 percent of all hazardous materials by weight.

The U.S. Census Bureau conducts a commodity flow survey every five years to help policy makers and transportation planners assess the demand for transportation facilities and services, energy use, and safety risk and environmental concerns in the transportation of goods around the U.S. The latest results are for the 2012 Commodity Flow Survey (CFS). The results include the shipment of hazardous and nonhazardous materials in the U.S. by hazard class and transportation mode. According to the 2012 CFS, hazardous materials account for approximately eight percent of total ton-miles of goods transported by truck in the U.S. Assuming that 0.1 percent of all hazardous materials are aerosols, then approximately 0.008 percent of all ton-miles of goods transported in the U.S. are aerosols. Applying this share to the total VMT by large trucks and buses from the FMCSA data, aerosol VMT are approximately 250 million miles.

Applying these estimated crash rates to the estimated VMT for trucks transporting aerosols, there is approximately one crash, including aerosol dispenser cargo every 10 days resulting in property damage only, one crash every 50 days resulting in at least one injury, and one crash every 1,000 days resulting in at least one fatality for trucks transporting aerosols. Because an accident resulting in a fire is likely a more severe accident, it is assumed that the accident would be severe enough to result in at least one injury.

Not all crashes with result in a fire; trucks are designed with safety features to mitigate risks to the driver and others in the occurrence of a crash. According to one study of nearly 2,000 accidents that occurred during the transport of hazardous materials by road and rail from the start of the 20th century to July 2004, the most

---

25 A large truck is defined as a truck with a gross vehicle weight rating (GVWR) greater than 10,000 pounds.

26 Federal Motor Carrier Safety Association, *Large Truck and Bus Crash Facts 2017*, May 2019, https://www.fmcsa.dot.gov/sites/fmcsa.dot.gov/files/docs/safety/data-and-statistics/461861/ltcbf-2017-final-5-6-2019.pdf.

27 United States Census Bureau, Commodity Flow Survey: United States: 2012, Hazardous Materials, February 2015, https://www.census.gov/library/publications/2015/econ/ec12tcf-us-hm.html.

28 U.S. EPA, EPRCRA Reporting Requirements for Tier II—https://www.epa.gov/epcra/tier-ii-forms-and-instructions.

frequent result of an accident was simply a release of contents. Fires were found to occur as a result of an accident approximately 30 percent of the time.[29]

Given the preceding, our estimate is that the frequency of accidents involving aerosol cargo and a fire is intermediate between that of injuries (1 per 50 days) and fatalities (1 per 1000 days). This leads to an **occurrence rating for a truck accident, including an aerosol shipment is 3** (1 per 500 days).

Because the incident data shows relatively few incidents with actual vehicle fires, including aerosol cargo, and because it is logical to assume that some fires will be minor and/or extinguished prior to reaching the cargo, **a mitigation rating of 8** (one in five fires reach the aerosol cargo) **is assigned.** This leads to an overall frequency of fires involving aerosol cargo of 1 per 2,500 days (7 years).

Circumstance I. Vehicle Accident (with Fire) Leading to Violent Release

As discussed in Circumstance H, **the occurrence rating for a truck accident is 3** (1 per 500 days).

A French study conducted by Ineris the National Institute within France that serves as the national expert on the transportation of a wide range of dangerous goods.[30] The study was submitted to the UN Transport of Dangerous Goods Subcommittee by the expert from France during the discussions on harmonizing limited quantity provisions.[31] The study included testing of aerosol containers involved in serious fire conditions showed that this generally leads to bursting of aerosol containers, and so a Violent Release is highly likely in an extreme fire where the aerosol containers are subjected to the heat and fire. Consequently, the mitigation rating here should be identical to that in Circumstance H: **a mitigation rating of 8** (one in five fires reach the aerosol cargo) **is assigned**. This leads to an overall frequency of fires involving aerosol cargo with a violent release of 1 per 2,500 days (7 years).

Circumstance H & I Consolidated

The analysis above shows that circumstances H and I are actually a single circumstance, and so should be consolidated.

[29] A. Oggero, R. M. Darbra, M. Muñoz, E. Planas, and J. Casal, “A Survey of Accidents Occurring During the Transport of Hazardous Substances by Road and Rail,” *Journal of Hazardous Materials*, Vol. 133, Issues 1-3, May 2006, https://www.academia.edu/9615403/A_survey_of_accidents_occurring_during_the_transport_of_hazardous_substances_by_road_and_rail.

[30] see https://www.ineris.fr/en/research-support-public-policy/acciental-risks/transportation-dangerous-goods-and-pipelines

[31] see ST/SG/AC.10/C.3/2002/47

Circumstance Summary

The circumstances enumerated here can be summarized as follows:

Table 4.12 Aerosol Circumstance Summary

Scenario	Occurrence	Mitigation	Root Cause	Effect	Overall Frequency of Failure	Comment
A, B, C	9, 9, 8	7, 7, 10	Drop, Shift, Crush	Leaked or Released Contents: Personnel or Equipment Exposed	1–3 'leakers' every day.	A, B, C Drop, Shift, Crush considered same likelihood and effect
D	8 (1 aerosol package crushed each day)	3 (1 in 1000 crushes → leaker + ignition source)	External Object Crushes (also drop or shift)	Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source	8 + 3; 1–3 every 1,000 days (2.7 years)	Drop, Shift, Crush considered same likelihood as A, B, C. But the ignition is 1000 times less likely
E	8 (1 aerosol package crushed each day)	2 (1 in 10,000 crushes → Rocket)	External Object Crushes	Rocket/Jet Projectile	8 + 2; 1 every 10,000 days (27 years)	Considered a very unlikely outcome. 10 times less likely than a drop, shift, crush with ignition
F	2 (1 defective can in transport per 1000 days)	9 (1 in 2 defectives in transport) → 'leaker'	Defective Container	Leaked or Released Contents: Personnel or Equipment Exposed	2 + 9; 1 every 2,000 days	1 in 5.5 years
G	2 (1 defective can in transport per 1000 days)	"6.5" = 1 in 20 escapes	Defective Container	Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source	Set to be 10x less likely than "leaker" 1 every 20,000 days	1 in 55 years
H, I	3 (1 vehicle accident with aerosol cargo every 500 days)	8 (1 in 5 fires reach the aerosol cargo)	Vehicle Accident (with fire)	Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source	3 + 8; 1 every 2,500 days (7 years)	1 in 7 years (based on French work, consolidated with I; any fire that reaches aerosol cargo will lead to violent release)

4.9.3 Severity Ratings by Scenario (Circumstance + Product)

The severity ratings by product for each scenario are as follows, where the products are listed in the format "Propellant characteristic/Contents characteristic (example):

Flammable/Flammable (e.g., Vandal Mark Remover):

- Circumstances A to C: Package Drop/Shift/Crush Leading to Leaked or Released Contents: Personnel or Equipment Exposed—Some contents from the aerosol containers saturate the outer packaging, exposing personnel or equipment to the contents. Some of the (gas) propellant escapes into the surrounding atmosphere. Some of the flammable liquid, powder, or paste contents may also evaporate. Consequently, any personnel or equipment in the vicinity are exposed to the contents of the aerosol dispenser, which in this case are a flammable propellant and flammable contents, with an average heat of combustion of approximately 15 MJ for a container of 454 grams. Because of the high heat of combustion, a hazard is created, but since there are no consequences beyond loss of substance, **the severity rating is 2** (hazard created, but no consequences).

- Circumstance D: External Object Crushes Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source—In this scenario, because the contents of the aerosol container have a heat of combustion of approximately 15 MJ, there will be a fire in a release with ignition source present. A **severity rating of 7** (any incident where an aerosol can burst, rockets or fragments, or where there is a fire resulting in injury or property damage or highway closure).

- Circumstance E: External Object Crushes Leading to Rocket/Jet Projectile—In this scenario, it is assumed an external object crushes an aerosol container, moreover in order to achieve a rocket/jet outcome, a phenomenon called Boiling Liquid Expanding Vapor Explosion (BLEVE) had to have occurred.[32]

- Arguably, the severity rating here could in this case range from at least a 7 (fire causing images, property damage, or highway closure) to a 9 (fatality).[33] Taking the worst case, **a severity rating of 9 is assigned**.

- Circumstance F: Defective Container Leading to Leaked or Released Contents: Personnel or Equipment Exposed—As in Circumstances A to C, a release of contents with an approximate heat of combustion of 15 MJ creates some hazard, but with only a spill, there is no consequence, so **the severity rating is 2** (hazard created, but no consequences).

- Circumstance G: Defective Container Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source—As in Circumstance D, a release of contents with an approximate heat of combustion of 15 MJ near an ignition source could result in ignition. Consequently, as for Circumstance E, a **severity rating of 9** (worst case, fatality) is assigned.

---

[32] In a BLEVE, the internal pressure increases at the same time as the physical resistance of the container decreases, until the burst pressure is reached. This results in a sudden vaporization of the propellant and, eventually, the liquid, powder, or paste. A fireball develops and a rocket/jet projectile is produced, contributing to the fire's propagation S. Descourrière and E. Bernuchon, Institut National de l'Environnement Industriel et des Risques, *Modélisation d'un Incendie Affectant un Stockage de Générateurs d'Aérosols*, September 2002, https://www.cfa-aerosol.com/wp-content/uploads/2018/05/rapport_ineris.pdf.

[33] L. Greene and M. Burke, "Popular French Lifestyle Blogger Rebecca Burger Dies in Freak Accident by Exploding Whipped Cream Canister," *New York Daily News*, 22 June 2017, https://www.nydailynews.com/news/world/french-blogger-rebecca-burger-killed-exploding-canister-article-1.3267961?barcprox=true.

- Circumstance H to I: Vehicle Accident (with Fire) Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source—As in Circumstance D, a release of contents with an approximate heat of combustion of 15 MJ near an ignition source is assigned a **the severity rating of 9** (worst case, fatality).

Nonflammable/Flammable (e.g., Brake Parts Cleaner):

Here, the only practical difference between this specific example and the preceding example is the total heat of combustion (11 MJ for a 14-ounce container versus 15 MJ for a 16 ounce per 454-gram container). Consequently, the severity ratings here will follow those for the prior example. In other words, even if the propellant is nonflammable, with flammable contents the consequences can be just as severe.

Nonflammable/Flammable (e.g., Aerosol Insecticide):

- Circumstance A to C: Package Drop/Shift/Crush Leading to Leaked or Released Contents: As above.

- Circumstance D: External Object Crushes Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source—In this scenario, because the contents of the aerosol container have a lower heat of combustion compared to the other products above of approximately 8 MJ, it can be assumed that any fire would be less severe. In recognition of this the severity rating can be reduced by one, relative to the prior examples, leading to a severity rating is 6 (multiple severe injuries).

- Circumstance E: External Object Crushes Leading to Rocket/Jet Projectile—Following the logic of the preceding circumstance, the severity rating can be reduced by one, relative to this circumstance in the prior examples, yielding a severity rating of 8 (Major infrastructure impact; multiple severe injuries, etc.).

- Circumstance F: Defective Container Leading to Leaked or Released Contents: As above.

- Circumstance G: Defective Container Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source—As in Circumstances D and E, the severity rating can be reduced by one, relative to this circumstance in the prior examples, yielding severity rating of 8 (Major infrastructure impact; multiple severe injuries, etc.).

- Circumstances H to I: Vehicle Accident (with Fire) Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source—As in Circumstances D and E, the severity rating can be reduced by one, relative to this circumstance in the prior examples, yielding severity rating of 8 (Major infrastructure impact; multiple severe injuries, etc.).

Nonflammable/Nonflammable (e.g., Auto A/C Treatment):

- Circumstances A to C: Package Dropped Leading to Leaked or Released Contents: Personnel or Equipment Exposed—A product such as auto A/C treatment has a very low heat of combustion, equivalent to approximately 1.5 MJ per 3-ounce container. With nonflammable propellants and liquid, powder, or paste, there is no risk of fire. So, a spill only would have no consequences, and **the severity rating is 1** (insignificant).

- Circumstance D: External Object Crushes Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source—In this scenario, because the contents of the aerosol container are nonflammable, the exposure to an ignition source does not change the consequences compared to a simple spill. Therefore, **the severity rating is 1** (insignificant).

- Circumstance E: External Object Crushes Leading to Rocket/Jet Projectile—The mechanism for achieving Rocket/Jet outcome was assumed to involve a fire. While in this case the contents would not contribute to a fire, the bursting is still possible. Therefore, **a severity rating of 4** (multiple minor injuries) is assigned.

- Circumstance F: Defective Container Leading to Leaked or Released Contents: Personnel or Equipment Exposed. As in Circumstance A, a release of contents with an approximate heat of combustion of 1.5 MJ results in no consequence, so **the severity rating is 1** (insignificant).

- Circumstance G: Defective Container Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source. As in Circumstance D, a release of contents with an approximate heat of combustion of 1.5 MJ near an ignition source does not result in worse circumstances than a simple spill, so **the severity rating is 1** (insignificant).

- Circumstance H to I: Vehicle Accident (with Fire) Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source. As in Circumstance E, a release of contents with an approximate heat of combustion of 1.5 MJ near an ignition source does not contribute to the fire. However, bursting remains possible, so **the severity rating is 4** (multiple minor injuries).

Flammable (Gas Only—Butane Fuel):

In this case the only contents are the flammable gas, an average heat of combustion of approximately 13 MJ for a container of 10 ounces. This is a similar heat of combustion to that of the flammable/flammable aerosol container example. Consequently, the circumstances here are scored identically.

Flammable (Gas Only—HFC-152a Air Duster):

This product example has a very low heat of combustion, equivalent to approximately 2.7 MJ per 12-ounce container. This is a very low heat of combustion energy, but as the gas is flammable, it must be assumed to contribute somewhat to a fire. Here, we will treat it as similar to the Nonflammable/Flammable Aerosol Insecticide above, but with the in-fire severity reduced by another step.

- Circumstances A to C: Package Drop/Shift/Crush Leading to Leaked or Released Contents: Personnel or Equipment Exposed. A product such as compressed gas duster has a very low heat of combustion, equivalent to approximately 2.7 MJ per 12-ounce container. However, the gas is flammable, and a hazard is created, but since there are no consequences beyond loss of substance, **the severity rating is 2** (hazard created, but no consequences).

- Circumstance D: External Object Crushes Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source. In this scenario, because the contents of the aerosol container have a lower heat of combustion compared to the other products above of approximately 2.7 MJ, the severity rating is reduced by 1 relative to that for Circumstance D in the Aerosol Insecticide example, yielding a **severity rating of 5** (one severe injury).

- Circumstance E: External Object Crushes Leading to Rocket/Jet Projectile. Following the logic of the preceding circumstance, the severity rating can be reduced by one, relative to circumstance E in the

Aerosol Insecticide example, yielding a **severity rating of 7** (fire with injuries, property damage, highway closing, etc.).

- Circumstance F: Defective Container Leading to Leaked or Released Contents: Personnel or Equipment Exposed. As in Scenario A, a release of contents with an approximate heat of combustion of 2.7 MJ creates some hazard, but with only a spill, there is no consequence, so **the severity rating is 2** (hazard created, but no consequences).

- Circumstance G: Defective Container Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source. Following the logic of the Circumstances D and E, the severity rating can be reduced by one, relative to circumstance G in the Aerosol Insecticide example yielding a **severity rating of 7** (fire with injuries, property damage, highway closing…).

- Circumstance H to I: Vehicle Accident (with Fire) Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source. As in Circumstance G, we assign a **severity rating of 7** (fire with injuries, property damage, highway closing…).

Nonflammable (Gas Only—R-134a Air Duster):

- Circumstances A to C: Package Drop/Shift/Crush Leading to Leaked or Released Contents: Personnel or Equipment Exposed. A product such as R-134a Air Duster has a heat of combustion equivalent to approximately zero MJ per 10-ounce container. Therefore, a spill only would have no consequences, and **the severity rating is 1** (insignificant).

- Circumstance D: External Object Crushes Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source. In this scenario, because the contents of the aerosol container are nonflammable, the exposure to an ignition source does not change the consequences compared to a simple spill. Therefore, **the severity rating is 1** (insignificant).

- Circumstance E: External Object Crushes Leading to Rocket/Jet Projectile. Following the logic above in Circumstance E for the Nonflammable/Nonflammable example, **the severity rating is 4** (multiple minor injuries).

- Circumstance F: Defective Container Leading to Leaked or Released Contents: Personnel or Equipment Exposed. As in Circumstance A, a release of contents with an approximate heat of combustion of zero MJ results in no consequence, so **the severity rating is 1** (insignificant).

- Circumstance G: Defective Container Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source. As in Circumstance D, a release of contents with an approximate heat of combustion of zero MJ near an ignition source does not result in worse circumstances than a simple spill, so **the severity rating is 1** (insignificant).

- Scenario H-I: Vehicle Accident (with Fire) Leading to Leaked or Released Contents: Leaked or Released Contents Exposed to Ignition Source. Following the logic above in Circumstances H to I for the Nonflammable/Nonflammable example, bursting remains possible, so **the severity rating is 4** (multiple minor injuries).

4.10 Risk Assessment Summary

The severity rating, occurrence rating, and mitigation rating, with the resulting RPN for each product and scenario are presented in Table 4.13.

Table 4.13 Failure Mode and Effects Analysis Full Scoring Summary

Contents	Circumstance	Severity	Occurrence	Mitigation	RPN
Flammable/Flammable (Vandal Mark Remover)	A–C	2	8.5	8.5	144.5
	D	7	8	3	168
	E	9	8	2	144
	F	2	2	9	36
	G	9	2	6.5	117
	H–I	9	3	8	216
Nonflammable /Flammable (Brake Parts Cleaner)	A–C	2	8.5	8.5	144.5
	D	7	8	3	168
	E	9	8	2	144
	F	2	2	9	36
	G	9	2	6.5	117
	H–I	9	3	8	216
Flammable/Insecticide (Aerosol Insecticide)	A–C	2	8.5	8.5	144.5
	D	6	8	3	144
	E	8	8	2	128
	F	2	2	9	36
	G	8	2	6.5	104
	H–I	8	3	8	192
Nonflammable /Nonflammable (Auto A/C treatment)	A–C	1	8.5	8.5	72.25
	D	1	8	3	24
	E	4	8	2	64
	F	1	2	9	18
	G	1	2	6.5	13
	H–I	4	3	8	96
Flammable (Gas Only—Butane Fuel)	A–C	2	8.5	8.5	144.5
	D	7	8	3	168
	E	9	8	2	144
	F	2	2	9	36
	G	9	2	6.5	117
	H–I	9	3	8	216

Contents	Circumstance	Severity	Occurrence	Mitigation	RPN
Flammable (Gas Only—HFC-152a Air Duster)	A–C	2	8.5	8.5	144.5
	D	5	8	3	120
	E	7	8	2	112
	F	2	2	9	36
	G	7	2	6.5	91
	H–I	7	3	8	168
Nonflammable (Gas Only—R-134a Air Duster)	A–C	1	8.5	8.5	72.25
	D	1	8	3	24
	E	4	8	2	64
	F	1	2	9	18
	G	1	2	6.5	13
	H–I	4	3	8	96

Source: CS Team, 2019.

The overall RPN for each product and scenario is provided in Table 4.14.

Table 4.14 Overall Risk Priority Number by Product and Scenario

Product	A–C	D	E	F	G	H–I
Flammable/Flammable (Vandal Mark Remover)	144.5	168	144	36	117	216
Nonflammable/Flammable (Brake Parts Cleaner)	144.5	168	144	36	117	216
Flammable/Insecticide (Aerosol Insecticide)	144.5	144	128	36	104	192
Nonflammable/Nonflammable (Auto A/C treatment)	72.25	24	64	18	13	96
Flammable (Gas Only—Butane Fuel)	144.5	168	144	36	117	216
Flammable (Gas Only—HFC-152a Air Duster)	144.5	120	112	36	91	168
Nonflammable (Gas Only—R-134a Air Duster)	72.25	24	64	18	13	96

Source: CS Team, 2019.

5.0 Findings and Recommendations

5.1 Findings

- **No indication of increased risk.** From the results of the FMEA, there is no indication of increased risk when transporting aerosol containers with only a gas compared to those containing a gas propellant and liquid, powder, or paste based on comparable HOCs.

- **Risk Priority Numbers are identical.** The RPNs for aerosol containers filled with flammable gas only are identical to those filled with a flammable propellant and/or liquid, powder, or paste. These RPNs are shown in Table 5.1 below.

- **Severity is the most Important score in the FMEA.** Because the mitigation and occurrence scores were calculated independent of the contents, the most important score was the severity score because the severity was determined by the likelihood of injuries, property damage or fatalities resulting from exposure to the aerosol contents (product and propellant).

Table 5.1 Most Severe RPN by Products and Scenario

Product	A–C	D	E	F	G	H–I
Flammable/Flammable (Vandal Mark Remover)	144.5	168	144	36	117	216
Nonflammable/Flammable (Brake Parts Cleaner)	144.5	168	144	36	117	216
Flammable (Gas Only—Butane Fuel)	144.5	168	144	36	117	216

- **Brake Parts Cleaner and Vandal Mark Remover have the highest HOC.** The FMEA results showed that the highest HOC for the products considered was for (1) the nonflammable propellant and flammable contents in the brake parts cleaner; and (2) the flammable propellant and flammable contents, modeled as vandal mark remover, also had a higher heat of combustion than the butane fuel only.

- **International Civil Aviation Organization (ICAO) does not limit aerosols.** The CS team found that the ICAO Technical Instructions do not limit aerosol containers to those that expel a liquid, powder or paste, and there have not been any documented incidents demonstrating the need to restrict them from containing only gas.

- **Both Brake Parts Cleaner and Vandal Mark Remover** already are eligible to be shipped as aerosols under the limited quantity exceptions according to the HMR. Further, while the butane fuel is not technically packaged in an aerosol container, products such as the air dusters are packaged in aerosol containers. These products currently rely on special permits with PHMSA, such as Special Permits (SP) 20464, 10232, 14188, and 14286. SP-10232 has been renewed 22 times. In fact, gas hazardous materials with special permits were implicated in a total of six incidents reported to PHMSA between 1971 and 2019, four of which were for SP-10232. In all cases, the result was only a spill, with no fires, explosions, injuries or fatalities. The total material damage caused in these six incidents amounted to $125, an average of less than $3 per year. Each of the six incidents, with the cause and result, is summarized in Table 5.2.

Table 5.2 PHMSA Aerosol Incidents Involving Special Permits

Special Permit	Incident Date	Incident Cause	Incident Result
10232	6/23/1995	Crushed Can	Spill only
10232	5/20/2010	Impact with Sharp or Protruding Object	Spill only
10232	1/10/2013	Human Error	Spill only
10232	1/15/2013	Human Error	Spill only
7951	1/15/2014	Undeclared Shipment	No release
7951	11/21/2014	Undeclared Shipment	No release

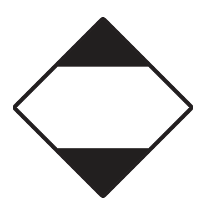
Source: United State Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Hazardous Materials Incident Database, https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/Welcome.aspx.

5.2 Recommendations

While no increased risk was found in the transportation of aerosols conforming to the UNMR definition of an aerosol compared to those conforming to the HMR definition, the CS Team compiled the following recommendations to further reduce risks during aerosol transportation.

- **Test Aerosol Contents and Propellants.** While the results of the FMEA suggest HOC was an important measure of flammability, aerosol testing should be conducted to corroborate the results of the risk assessment. This will provide actionable information and data to assist PHMSA in considering rulemaking required for proposed harmonization of the HMR and UNMR regulations pertaining to the transportation of aerosols. For the Test Phase, the CS Team proposes to conduct a literature review of existing aerosol tests, two flammability tests, a puncture test and an asphyxiation test using the representative products from the FMEA. The flammability tests required for the HMR and the UNMR include an ignition distance test and an enclosed space ignition test. For the puncture test, the CS Team proposes to conduct a test to simulate an aerosol dispenser punctured and exposed to an ignition source, which is likely to result in a higher release rate than aerosol contents released through the design actuator.

- **Improve Hazard Communication.** The hazard communication required for a shipment of aerosols according to the limited quantity exceptions affords more information than most of the special permits authorized for aerosol containers filled with only gas. Most of the special permits authorize the use of an alternative shipping name "Consumer commodity" and the ORM-D marking which is much less visible as compared to a package with the limited quantity mark.[34]

  The limited quantity mark must be at least 50 mm on each side. However, most aerosol container packages observed by members of the CS team during site visits and discussion with industry representatives have the 100 x 100 limited quantity mark. The consumer commodity/ORM designation must be placed within a rectangle that is approximately 6.3 mm (0.25 in.) larger on each side than the designation. The special permits do not allow the products to be classified as "aerosols, UN 1950" but in most cases authorize them to be transported as "Consumer Commodities." Consumer commodities also

[34] A marking for mail or shipping in the United States that identifies other regulated materials for domestic transport only.

do not require shipping papers, labels, placards or specification packaging and afford less hazard communication because the package marking only the ORM-D mark and the SP number (see Figure 5.1 and Figure 5.2).

Figure 5.1 Aerosol Containers Package Requiring Special Permit Markings

Source: CS Team.

Figure 5.2 Aerosol Containers Package Requiring Limited Quantity Markings

Source: CS Team.

If PHMSA were to authorize aerosol containers filled with gas only, the proper shipping name of the gas could be required in addition to the limited quantity mark on the package.

- **Protect Aerosol Release Mechanisms.** Consistent with the ICAO Technical Instructions, PHMSA should consider requiring all aerosol containers to have a means of protection for the release mechanism in the form of a protective cap or safety feature that prevents inadvertent release of contents under normal conditions of transport. This already is an industry standard practice so requiring it through regulations would not have significant economic impact on industry. Since manufacturers do not know in advance whether their aerosol containers will be shipped by air, they must assume that they will be shipped by air. Therefore, they all generally meet the additional air transport requirements. Gas cartridges are similar to aerosols containers and are authorized to be filled with only gas. Generally, the same container specifications apply, and the only difference is there is no release device. However, a close examination of these receptacles shows that while they do not have a “release device” they in some cases are more vulnerable to the inadvertent release of gas as compared to an aerosol container with release mechanism protection.

- **Limit Aerosol Containers Containing Gas-Only Contents.** PHMSA should consider limiting aerosol containers that contain only flammable gases to specification containers (DOT 2P, DOT 2Q, DOT 2Q1) unless approved under a special permit.

6.0 Selected Regulatory References

6.1 Aerosols in Transit: Loading and Unloading

Based on discussions with the various industry representatives, the most common cause of aerosol container damage or the release of content is based on handling incidents which generally occur in warehouses, distribution centers or parcel facilities. These incidents are considered “in transport” as they occur during loading and unloading incidental to movement as defined in in §171.8 for Loading or Unloading Incidental to Movement.

6.2 §171.8 includes definitions for loading and unloading

Loading incidental to movement means loading by carrier personnel or in the presence of carrier personnel of packaged or containerized hazardous material onto a transport vehicle, aircraft, or vessel for the purpose of transporting it, including the loading, blocking and bracing a hazardous materials package in a freight container or transport vehicle, and segregating a hazardous materials package in a freight container or transport vehicle from incompatible cargo. For a bulk packaging, *loading incidental to movement* means filling the packaging with a hazardous material for the purpose of transporting it. *Loading incidental to movement* includes transloading.

Unloading incidental to movement means removing a packaged or containerized hazardous material from a transport vehicle, aircraft, or vessel, or for a bulk packaging, emptying a hazardous material from the bulk packaging after the hazardous material has been delivered to the consignee when performed by carrier personnel or in the presence of carrier personnel or, in the case of a private motor carrier, while the driver of the motor vehicle from which the hazardous material is being unloaded immediately after movement is completed is present during the unloading operation. (Emptying a hazardous material from a bulk packaging while the packaging is on board a vessel is subject to separate regulations as delegated by Department of Homeland Security Delegation No. 0170.1 at 2(103).) *Unloading incidental to movement* includes transloading.

6.3 Display Packs

Display pack means a package intended to be placed at retail locations which provide direct customer access to consumer commodities contained within the package when all or part of the outer fiberboard packaging is removed.

> (c) *Display packs.* Display packs, as defined in §171.8 of this subchapter, of consumer commodity or limited quantity packages that exceed 30 kg gross weight limitation may be transported by container/trailer in trailer-on-flatcar (TOFC) or container-on-flat-car (COFC) service, RoadRailer and/or RailRunner trailers, motor vehicle, or cargo vessel under the following conditions:
>
> > (1) *Packaging.* Combination packages must conform to the requirements of subpart B of this part and meet the following, as appropriate:
> >
> > > (i) Primary containers must conform to the quantity limits for inner packagings prescribed in §§173.150(b), 173.152(b), 173.154(b), 173.155(b) and 173.306(a) and (b), as appropriate.

(ii) Primary containers must be packed into trays that secure individual containers from shifting inside the completed combination package during transportation.

(iii) Tray(s) must be placed into a fiberboard box, and the fiberboard box must be banded and secured to a pallet by metal, fabric, or plastic straps to form a single palletized unit; and

(iv) The maximum net quantity of hazardous material permitted in one palletized unit is 550 kg (1,210 lbs.).

(2) *Marking.* The outside of each package must be plainly and durably marked in accordance with one of the following, as appropriate:

(i) As a consumer commodity as prescribed in §172.316 of this subchapter; or

(ii) As a limited quantity as prescribed in §172.315 of this subchapter.

Appendix A. Definitions and Terms

Third-party logistics (3PL) is the use of an outside and unaffiliated business to outsource transportation services, including distribution, warehousing or storage, and delivery.

Freight forwarders act as experts in logistics and organize shipments between buyers and suppliers, often contracting with multiple carriers.

Container on flat car.
Photo Credit: Mick Hall.
([CC BY 2.0](CC BY 2.0))

Less than truckload (LTL) is the transport of goods that do not fill an entire trailer. These small shipments can also be combined with other small shipments, in order to make efficient use of the space in the trailer. Some carriers specialize in serving LTL customers and are involved in the coordination and logistics of handling pickups and deliveries that require multiple origins and destinations.

Full truckload (FTL) is the transport of goods using a truck dedicated to a single shipment from origin to destination.

A **chassis** is a load-bearing metal frame with axles and wheels that carries the truck trailer and also is connected to the truck tractor.

Roll-on/roll-off (RO/RO) are ships and railcars designed to carry wheeled cargo such that an entire truck, including the tractor unit trailers can be loaded onto the railcar or ship. RO/RO also applies to railcars that can be rolled onto ships.

Trailer on flat car

Container on flat car (COFC) is an intermodal unit that consists of an intermodal container that is placed on a flat railcar for rail transport.

Trailer on flat car (TOFC) *i*s an intermodal unit wherein the truck trailer is placed on a flat railcar for rail transport.

A.1 Definitions from the Clean Air Act, as defined in § 68.3 of the rule

“Stationary source” basically means facility. The CAA and, thus Part 68 use the term “stationary source” and “facility” interchangeably.

“Process” is given a broad meaning in this rule and document. Most people think of a process as the mixing or reacting of chemicals. Its meaning under this rule is much broader. It basically means any equipment, including storage vessels, and activities, such as loading, that involve a regulated substance and could lead to an accidental release.

“Regulated substance” means one of the 140 chemicals listed in part 68. “Threshold quantity” means the quantity, in pounds, of a regulated substance which, if exceeded, triggers coverage by this rule. Each regulated substance has its own threshold quantity. If you have more than a threshold quantity of a regulated substance in a process, you must comply with the rule.

“Vessel” means any container, from a single drum or pipe to a large storage tank or sphere.

"Public receptor" generally means any place where people live, work, or gather, with the exception of roads. Buildings, such as houses, shops, office buildings, industrial facilities, the areas surrounding buildings where people are likely to be present, such as yards and parking lots, and recreational areas, such as parks, sports arenas, rivers, lakes, beaches, are considered public receptors.

"Environmental receptor" means a limited number of natural areas that are officially designated by the State or Federal Government.

Appendix B. Aerosol Industry Outreach

B.1 Freight Forwarder, April 26, 2019

Aerosols pose a higher risk for ground transport due to the limited quantity designation. However, no incidents have occurred in transport. LTL shipments are generally made between buildings and FTL shipments between hubs. Local deliveries occur using 28', 48' or 53' trailers. Ground shipments in limited quantities are shipped in pallets in LTL trailers. Air Cargo shipments are fully regulated and include mostly medical supplies such as inhalers and high-end products such as paints, resins, military needs and marine coatings. No aerosol incidents have occurred in air transport over the past 25 years, due in part to sturdier boxes designs. The high-speed conveyor systems are becoming more widespread, creating risks of static electricity. Some damages occur when boxes fly off conveyors, particularly around corners. Four incidents occurred over the past 60 days in distribution warehouses. In one example, a 2.2 type can burst, injuring one employee with shrapnel. According to the freight forwarder, this was a rare occurrence. This example helped the CS Team to develop circumstances as part of the FMEA that corroborated with how often such incidents occurred and how industry was mitigating these occurrences.

B.2 Aerosol Manufacturer, May 8 and 14, 2019

This manufacturer maintains facilities in the U.S., Europe, Africa, Middle East, and Australia with distribution centers for handling distribution on each continent. European manufacturing sites are located in Belgium and the UK with distribution facilities in Germany, Finland, France, Spain, and Hungary. There have been no reportable incidents involving aerosols in transport. In the U.S. there is a manufacturing facility with a nearby warehouse for east coast distribution and another warehouse in Western U.S. for west coast distribution. The company ships out of the Ports of Philadelphia and New York for shipments to the far east (mostly China). However, China recently closed several ports due to chemical explosions not related to aerosols. The company uses the Port of Miami for shipments to South America and the Port of San Francisco for shipments to Asia-Pacific. Shipments to Canada and Mexico are made by truck. Most shipments are 6 or 12 cans per box, distributed to other distributors and companies such as MSC, Granger, West Cove, Amazon, Home Depot and Walmart. Containers are loaded on ships to Asia and to South America. There are issues with labeling that create headaches between U.S. and overseas destinations due to differences in regulations. For example, 2P cans cannot be shipped to Europe, 2Q is 12 bar only, 2p and 2Q are both compliant in the U.S. Every product is measured for latent HOC for storage which determines NFPA Levels 1, 2 and 3. The company can produce 200 cans per minute on one machine and 400 cans per minute on another. Batches range from 300 to 5,000 cans per batch, depending on the customer. All cans go through a water bath test with water temps between 122°F and 140°F and they check each hour for any bubbles to determine if there is a can failure. Boxes are assembled into pallets (6 layers per pallet), or 114 boxes per pallet, 20 pallets per truckload for a total of 2,280 aerosols per truck load (as an example).

On average, there are approximately five torn boxes per day damaged due to handling mishaps and an average of one skid is dropped per year from a forklift. Approximately two times per month UPS claim, with damage occurring during the last mile, generally due to poor handling or placement of cases in truck next to steel items. These types of industry examples helped inform the circumstances developed as part of the FMEA. The percentage LTL/FTL is 90/10 (most LTL) and percentage by Parcel (UPS mostly) 200 cases per day. LTL travels to Texas, stops three times, generally and skids are wrapped, delivered to customer intact.

B.3 Aerosol Fire Specialist with Health Care Manufacturer - May 17

This interview was with a fire specialist from a major health care manufacturer of aerosols who served on a committee that reviewed NFPA 30B Levels 1, 2, and 3 for fire standards over a five-year period. They conducted many fire tests and developed aerosol protocols and design standards based on those tests. The discussion for the interview centered around consideration for understanding HOC for entire can contents and the CS Team explained the FMEA process and assumptions to date regarding HOC for representative aerosol products. The NFPA standards are different than 2.1 and 2.2 classes of gases as defined in the HMR and UNMR. The different levels represent different levels of risk for aerosols stored in warehouses and distribution centers. NFPA 30B Level 3 represents the greatest risk. For example, straight propellants have the highest HOC, and Level 3 includes petroleum solvents (such as WD40 and CRC), insect controls, carburetor cleaners, and paints. Level 2 has a lower risk and includes hair sprays and Level 1 is the lowest risk, and generally includes water-based aerosols and food products.

B.4 Aerosol Manufacturer June 21, 2019

The company produces nontoxic, nonflammable, highly regulated products. “Solstice” propellant is a relatively new product (1234ZE) and they also use HFO1234ZE Petrofluoroprotein made by Honeywell. Nitrogen does not provide enough pressure to be used as a propellant and is too heavy. The product is only distributed to the U.S. and Canada through contract carriers. Customers also pick up shipments directly from the manufacturer. Forklifts occasionally damage products—as a result they have shifted to a one-piece design (valve+actuator) and they use a safety seal around the cap made of adhesive tape. They ship by truck only unless requiring expedited air cargo service. Sometimes samples are shipped via Fed Ex. There have been no incidents in ground or air transport over the past 13 years.

B.5 Aerosol Manufacturer July 18, 2019

This contract packager fills aerosol cans with flammable products, and CO2 is injected into cans through the valve. They fill many different products, including WD40 and engine starting fluid. The company can process 600 cans per minute. Some companies can do longer production runs because there are fewer modifications required. The company fills standard 2N, 2P and 2Q cans and they maintain that pressures stay within DOT required ranges. They do use can safety features, including a rim vent release to release pressure if needed. The company produces the 100 percent duster sprays, which represents approximately 10 percent of their business. They also produce the “all propane or butane” products in containers for cook stoves, torches, etc. These are no more than 4 fluid oz or less and therefore do not need to be regulated. They have not had any incidents in transport. One interesting product that is impacted by the regulations is mould release agent. This is used to release moulds for plastics, etc. Mould release contains 95 percent propellant, and five percent mould release agent (both of which are flammable). This meets the definition of “aerosol” even though less than five percent represents product. The CS Team asked if mould release, which is 100 percent flammable could be shipped as a limited quantity, why not 100 percent butane? We discussed differences between LPG (propane) and butanes, which have different pounds per square inch (PSI) characteristics. The 2Q, 2N and 2P cans are not capable of containing propane, but butane and normal butane can be put in an aerosol dispenser. The company uses Fed Ex freight and other FTL and LTL carriers, all of which contracted. They have the same warehousing and shipping profile as other industries, with products shipped in pallets to distribution centers and then to customers via other distribution centers. There are no special requirements for most drivers since the company produces almost exclusively limited quantity shipments. However, for the very small percentage of “butane-only” products, hazmat-trained drivers are needed, and costs go up for transportation of those products. NFPA 30B requirements are met for storing aerosols in warehouses. About 15 years ago, PHMSA changed the requirements for engine starting fluid only, and allowed this product to be shipped as an aerosol under limited quantities.

B.6 Aerosol Manufacturer, September 9, 2019

This company has six aerosol manufacturing facilities in the U.S., mostly in the Northeast, Midwest, and in Texas. Aerosols represent less than five percent of their business, of which 70 percent is spray paint and 30 percent "other aerosol products." The supply chain is similar to other industries, with U.S. manufacturing facilities shipping to other countries, including Canada, the Caribbean, Mexico and South America. In one example when researching a product line, they discovered that over 1500 distributors were involved in the transportation of just one product, illustrating the complexity and scope of the overall aerosol distribution nationwide and worldwide.

B.7 Aerosol Manufacturer October 8, 2019

This manufactures 900 million aerosols each year, or about 23 percent of all aerosols manufactured in the U.S. They currently have 15 facilities, two in Georgia, four in Missouri, three in Illinois, three in Toronto, two in California and one in Massachusetts. The Missouri, Illinois, and Canadian plants are all large facilities, the rest are smaller in size. The representative reported an average of 200 trucks serve these facilities each day, or approximately 20 trucks per facility per day.

Appendix C. Aerosol Incidents

C.1 Introduction

As part of the risk assessment of the transportation of aerosols, the CS Team collected and reviewed data on incidents involving the transportation of aerosols in both the United States and Canada. These transportation incidents will be referred to as "incidents" or "aerosol incidents" in the remainder of this report. Data for incidents in the U.S. were sourced from PHMSA Hazmat Incident Report Search.[35] Data for Canada were provided by Transport Canada, the governmental agency responsible for transportation policy in Canada. Data from both sources were for incidents involving hazardous materials classified as UN1950, the UN hazardous materials code for aerosols.

Data from both sources were processed and analyzed to include only reported incidents of gases in aerosol containers with release of a substance. After data cleaning, from 1988 through 2018, there were 15 aerosol incidents reported to Transport Canada and 36 reported to PHMSA. There were some differences between the U.S. and Canada in aerosol incidents by transportation mode or phase of transportation. However, there was no significant difference between the U.S. and Canada in the rate of fire or explosion in aerosol incidents, despite Canada's use of the UNMR definition of an aerosol, which allows an aerosol container to be filled only with a gas.

In addition to the detailed incident reports from Transport Canada and PHMSA, the FEA provided a description of nine incidents involving aerosols that occurred during transportation by truck from July 2014 to July 2019. Those incidents are summarized after the discussion of the U.S. and Canadian incidents.

Further details on the data processing methodology and analyses and subsequent results are provided below.

C.2 Data Processing

Data from Transport Canada and PHMSA were provided in different formats and with differing levels of detail. To compare incidents in the U.S. and Canada, data were processed to ensure the comparison of similar levels of incident reporting in both countries.

Transport Canada provided aerosol incident data with several automated charts. These data were first transcribed into an Excel workbook for analysis. There was a total of 41 incidents included in the data. However, many of these incidents did not include any release of a substance and were reported because they were undeclared shipments of aerosols. After removing any incidents with no release and any incidents not involving aerosol containers (there were several involving rail tank cars or tank trucks), a total of 15 incidents remained for further analyses. These 15 incidents will be referred to as the "Canadian Comparison Incidents" in the remainder of this report.

Data from PHMSA came from the online Hazmat Incident Report Search database and were output in an Excel workbook with columns corresponding to fields in Hazardous Materials Incident Report Form DOT F 5800.1, used for incident reporting. There was a total of 5,582 incidents in the data; however, like the Transport Canada data, the data from PHMSA included incidents of undeclared shipments with no release of

[35] https://portal.phmsa.dot.gov/analyticsSOAP/saw.dll?Dashboard.

hazardous material. Incidents that were included in the final analysis were those with a release of contents and that met the reporting requirements in the Canadian Transport of Dangerous Goods (TDG) Regulations:[36]

- Release of contents.
- At least one of the following:
  - Death.
  - Injuries.
  - Evacuation or shelter in place.
  - Closure of a facility, road, main railway line, or main waterway.

After the removal of incidents that did not meet the reporting requirements in the TDG Regulations, 36 total incidents involving aerosols remained for further analysis in the PHMSA data. These 36 incidents will be referred to as the "U.S. Comparison Incidents" in the remainder of this report.

C.3 United States Incidents

The U.S. HMR, 49 CFR Parts 171–180, require certain types of hazardous materials incidents be reported. Section 171.15 of the HMR requires a telephonic report to the National Response Center within 12 hours following an incident. Section 171.16 requires incidents to be reported to PHMSA within 30 days of the incident through the Hazardous Materials Incident Report Form DOT F 5800.1. Certain incidents require that the HMR be updated within one year of the incident. Reports are required whenever an incident occurs during the course of transportation for commerce, including during loading, unloading, and temporary storage. Table 6.1 provides a summary of which incidents require a telephone report, Hazardous Materials Incident Report, and/or updated Hazardous Materials Incident Report.

Table 6.1 United States Hazardous Materials Regulations Reporting Requirements for Hazardous Materials Incidents

Incident Type	Telephonic Report to National Response Center (within 12 hours)	Hazardous Materials Incident Report Form DOT F 5800.1 (within 30 days)	Updated Form DOT F 5800.1 (within one year)
As a direct result of a hazardous material: [1]			
• Death of any person.	●	●	●
• Injury requiring admittance to a hospital.	●	●	
• General public is evacuated for one hour or more.	●	●	
• Major transportation artery or facility is closed or shut down for one hour or more.	●	●	

[36] http://www.tc.gc.ca/eng/tdg/clear-menu-497.htm.

Incident Type	Telephonic Report to National Response Center (within 12 hours)	Hazardous Materials Incident Report Form DOT F 5800.1 (within 30 days)	Updated Form DOT F 5800.1 (within one year)
• Operational flight pattern or routine of aircraft is altered.	●	●	
Fire, breakage, spillage, or suspected radioactive contamination occurs involving a radioactive material.	●	●	
Fire, breakage, spillage, or suspected contamination occurs involving an infectious substance other than regulated medical waste.	●	●	
Release of marine pollutant in a quantity exceeding 450 liters (119 gallons) for a liquid or 400 kg (882 lbs.) for a solid.	●	●	
A situation not meeting any other criteria is deemed serious enough to the person in possession of the hazardous material (e.g., a continuing danger to life exists at the scene of the incident).	●	●	
A fire, violent rupture, explosion, or dangerous evolution of heat occurs as a direct result of a battery of battery-powered device.	● (transport by aircraft only)	●	
An unintentional release of a hazardous material or the discharge of any quantity of hazardous waste.		●	
A specification cargo tank with a capacity of 1,000 gallons or greater containing any hazardous material suffers structural damage to the lading retention system or damage that requires repair to a system intended to protect the lading retention system, even if there is no release of hazardous material.		●	
An undeclared hazardous material is discovered.		●	
Misidentification of hazardous material or package information on a prior report.			●
Damage, loss, or related cost that was not known when the initial report was filed becomes known.			●
Damage, loss, or related cost changes by $25,000 or more, or 10 percent of the prior total estimate, whichever is greater.			●

Source: 49 CFR § 171.15–171.16, www.ecfr.gov/cgi-bin/text-idx?gp=&SID=8cf7889b5f38cc703d5942c97e77a7bc&mc=true&tpl=/ecfrbrowse/Title49/49CIsubchapC.tpl.

[1] Meets the reporting requirements in the Canadian Transport of Dangerous Goods Regulations when there is the release of contents; included in the analysis.

C.3.1 Storage Incidents

Between 1988 and 2018, there were 5,582 incident reports involving hazardous materials classified as UN1950 in the PHMSA Hazardous Materials Incident Report data. Of these, 3,753 incidents, or 67 percent of all incidents, were reported during handling (loading or unloading) or in temporary storage. When only incidents involving the release of a substance are considered, there were a total of 2,486 incidents, 1,887 (76 percent) of which occurred during handling or in temporary storage. Of the 36 U.S. Comparison Incidents, 28 of them (78 percent) occurred during handling or in temporary storage. Approximately half of all incidents occur during handling alone. Figure 6.1 shows the breakdown of incidents by transportation phase for each set of incidents.

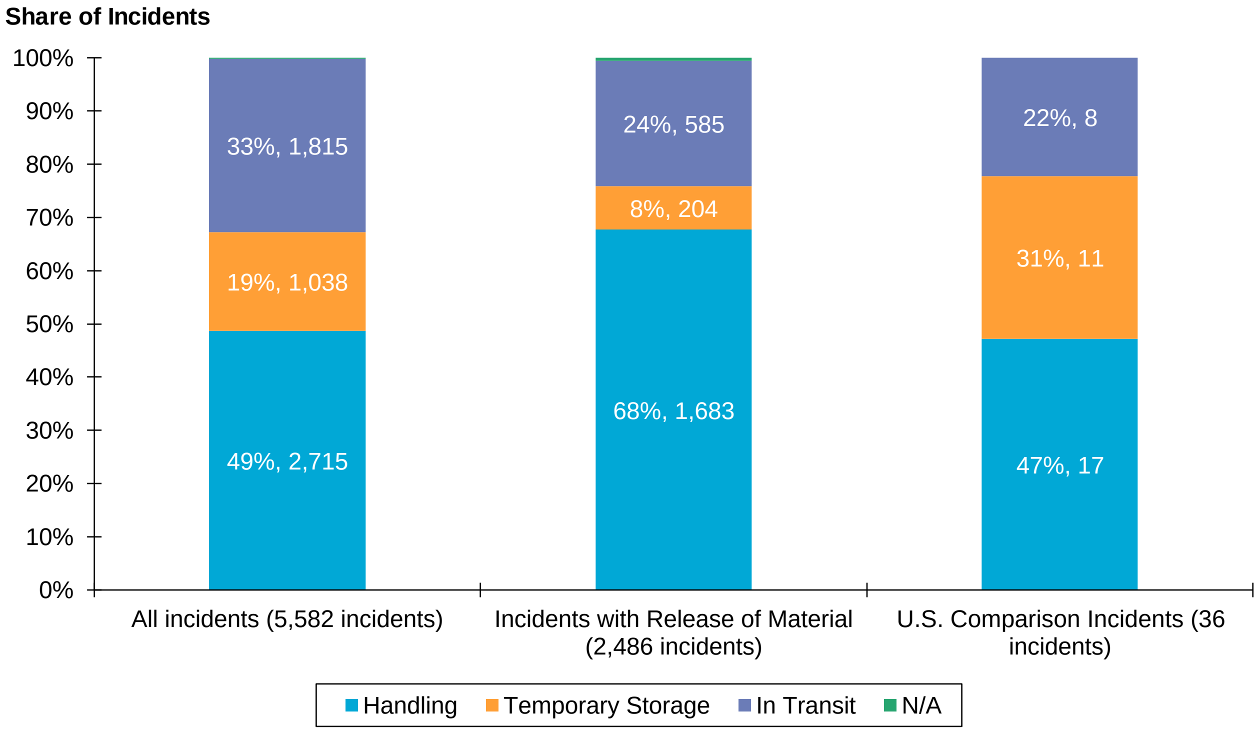


Figure 6.1 United States Aerosol Transportation Incidents
1988 to 2018

Source: PHMSA Hazardous Materials Incident Database https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/Welcome.aspx.

PHMSA defines serious incidents as those incidents where the release of a hazardous material results in one or more of the following: death, major injury resulting in a hospitalization, an evacuation of 25 or more persons, closure of a major transportation artery, alteration of an aircraft flight plan or operation, failure of a Type B radioactive packaging, release of over 11.9 gallons or 88.2 pounds of a severe marine pollutant, or release of a bulk quantity of hazardous material (over 119 gallons or 882 pounds). Of the 28 U.S. Comparison Incidents occurring during handling or in temporary storage, 12 were classified as serious incidents and 16 as not serious. All 12 of the serious incidents resulted in the evacuation of 25 or more people and one also resulted in the closure of a major transportation artery. In all 12 evacuations, solely employees were evacuated, and eight of the 12 involved a fire. The one serious incident resulting in the closure of a major transportation artery also involved a fire at a facility: the closed transportation artery is not named but appears to have been a road near the facility from the incident description. No storage incidents resulted in an explosion, fatality, or injury. Table 6.2 presents a summary of the outcomes for the U.S. Comparison Incidents.

Table 6.2 United States Comparison Incidents by Outcome

	Incident Outcomes											Serious Incidents						
Incident Mode	Spillage	Fire	Explosion	Gas Dispersion	Environmental Damage	Fire/EMS Response	Police Response	In-House Cleanup	Other Cleanup	Damage > $500	Serious Incident	Fatality	Injury	Alteration Flight Plan	25+ Evacuated	Major Artery Closed	Bulk HazMat	Marine Pollutant
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	Yes	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	Yes	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
In Transit Storage	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
Loading	No	Yes	No	No	No	Yes	No	No	No	Yes	Yes	No	No	No	Yes	No	No	No
Loading	Yes	No	No	No	No	No	No	Yes	No	No	No	No	No	No	Yes	No	No	No
Loading	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
Loading	No	Yes	No	No	No	Yes	No	No	No	Yes	Yes	No	No	No	Yes	No	No	No
Loading	Yes	No	No	No	No	No	No	No	No	No	Yes	No	No	No	Yes	No	No	No
Loading	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	No	No
Loading	No	Yes	No	No	No	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	No	No
Unloading	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Unloading	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No

	Incident Outcomes											Serious Incidents						
Incident Mode	**Spillage**	**Fire**	**Explosion**	**Gas Dispersion**	**Environmental Damage**	**Fire/EMS Response**	**Police Response**	**In-House Cleanup**	**Other Cleanup**	**Damage > $500**	**Serious Incident**	**Fatality**	**Injury**	**Alteration Flight Plan**	**25+ Evacuated**	**Major Artery Closed**	**Bulk HazMat**	**Marine Pollutant**
Unloading	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No
Unloading	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Unloading	Yes	Yes	No	No	No	No	No	Yes	No	No	Yes	No	No	No	Yes	No	No	No
Unloading	Yes	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No	Yes	No	No	No
Unloading	Yes	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No
Unloading	No	Yes	No	No	No	No	No	Yes	No	No	Yes	No	No	No	Yes	No	No	No
Unloading	No	Yes	No	No	No	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes	No	No	No
Unloading	Yes	Yes	No	No	No	No	No	Yes	No	No	Yes	No	No	No	Yes	No	No	No
Storage Incidents Subtotal	**22**	**8**	**0**	**11**	**0**	**5**	**0**	**9**	**1**	**5**	**12**	**0**	**0**	**0**	**24**	**1**	**0**	**0**
Air	No	No	No	Yes	No	Yes	No	No	No	No	Yes	No	No	No	Yes	No	No	No
Air	No	No	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	No	Yes	No	No	No	No
Truck	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Truck	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Truck	Yes	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes	No	No	No	No	Yes	No	No
Truck	Yes	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No
Truck	Yes	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No
Truck	No	Yes	No	No	No	No	No	Yes	No	Yes	Yes	No	No	No	No	Yes	No	No
Transportation Incidents Subtotal	**4**	**1**	**0**	**3**	**0**	**3**	**2**	**3**	**2**	**3**	**4**	**0**	**0**	**1**	**1**	**2**	**0**	**0**
Total Incidents	**26**	**9**	**0**	**14**	**0**	**8**	**2**	**12**	**3**	**8**	**16**	**0**	**0**	**1**	**25**	**3**	**0**	**0**

Source: PHMSA Hazmat Database, 2019.

C.3.2 Transportation Incidents

Of the 5,582 incident reports involving hazardous materials classified as UN1950 in the PHMSA Hazardous Materials Incident Report data between 1988 and 2018, 1,815 incidents, or 33 percent of all incidents, occurred in transit. Of these, 56 percent occurred during transportation by air and 41 percent occurred during transportation by truck, with the remainder occurring during maritime or rail transportation. Of the 2,486 incidents involving the release of a substance, 585 (24 percent) occurred in transit. Fifty-eight percent of these incidents occurred during transportation by truck and 42 percent during transportation by air.

Based on discussions with the various industry representatives, the most common cause of aerosol container damage or the release of content is based on handling incidents which generally occur in warehouses, distribution centers or parcel facilities. These incidents are considered "in transport" as they occur during loading and unloading incidental to movement as defined in in §171.8 for Loading or Unloading Incidental to Movement." When considering the U.S. Comparison Incidents and Canadian Comparison Incidents, the majority of incidents in both countries occur during handling or in temporary storage (e.g., in facilities). There is no significant difference in the transportation phase during which aerosol incidents occur in the U.S. and Canada.

The lower rate of incidents by air when looking at incidents involving the release of a substance compared to all reports indicates that most of the incidents occurring by air did not involve the release of any material and were instead often related to undeclared goods. The share of air incidents decreases further when considering the 36 U.S. Comparison Incidents. There was a total of eight incidents occurring in transit, 75 percent of which occurred during transportation by truck and 25 percent of which occurred during transportation by air. There were no incident reports for transportation by rail or water among those 36 incidents. Figure 6.2 shows the breakdown of incidents by transportation phase for each set of incidents.

Of the eight U.S. Comparison Incidents occurring in transit, four were serious incidents. One of the serious incidents resulted in the evacuation of at least 25 people from an aircraft when toiletries in a passenger's checked baggage leaked and caused an odor. One serious incident led to the alteration of a flight plan, and two led to the closure of a major transportation artery. In total, there was one fire due to incidents in transit, though no incidents resulted in an explosion, injury, or death. The incident outcomes are summarized in Figure 6.2.

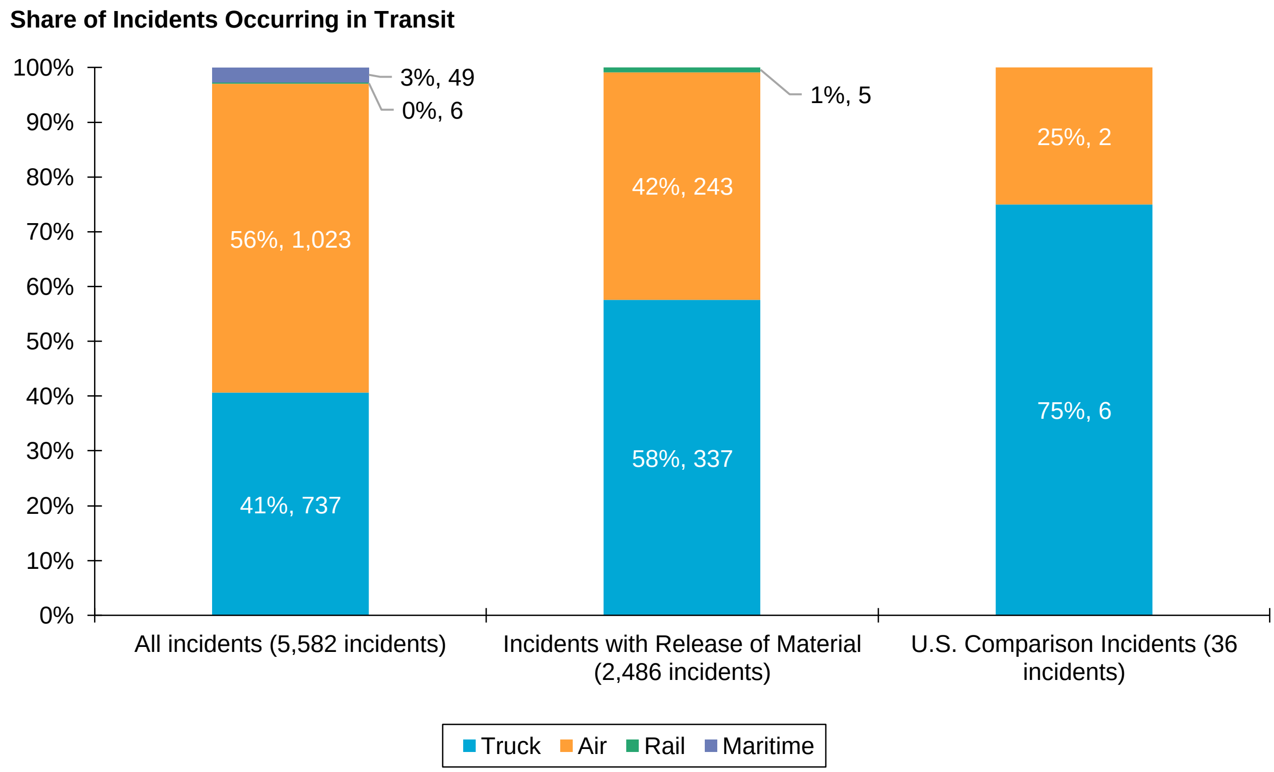


Figure 6.2 United States Aerosol Incidents in Transit, by Mode
1988 to 2018

Source: United State Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Hazardous Materials Incident Database https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/Welcome.aspx.

Truck

As shown in Figure 6.2, of the eight U.S. Comparison Incidents occurring in transit, 75 percent occurred during transportation by truck, a total of six incidents from 1988 to 2018. Two of these six incidents were serious incidents, both resulting in the closure of a major transportation artery. In one case the driver was involved in a collision, leading to a fire, and in the other the driver pulled over after being informed of smoke emitting from the front of the trailer and rear door by another driver. The cause of the incident appeared to be waste received at a collection event that was labeled incorrectly, leading to improper handling.

Rail

None of the 36 U.S. Comparison Incidents occurred during transportation by rail. From 1988 to 2018, there were a total of six incidents during transportation by rail. One of these incidents was an undeclared shipment, four resulted in spillage of hazardous material, and one resulted in a fire. None of the rail incidents resulted in an injury or fatality.

Maritime

None of the 36 U.S. Comparison Incidents occurred during maritime transportation. From 1988 to 2018, there were a total of 49 incidents during maritime transportation, all of which were undeclared shipments, and none of which resulted in the release of hazardous material. There were no injuries or fatalities due to incidents during maritime transportation.

Air

As shown in Figure 6.2 of the eight U.S. Comparison Incidents occurring in transit, 25 percent occurred during transportation by air, a total of two incidents from 1988 to 2018. Both incidents were serious incidents. One of the incidents resulted in the evacuation of an aircraft after the pilot smelled chemicals that had been released from a passenger's checked baggage. In the other incident, a passenger released pepper spray after mistaking it for perfume while the aircraft was taxiing to its arrival gate. Upon arrival, the aircraft was placed out of service for cleaning, resulting in a change in flight plan for the subsequent flight(s) scheduled to use that aircraft.

C.4 Canada Aerosol Incidents

The Transport Canada TDG Regulations have requirements for the reporting of hazardous materials incidents that differ from those in the HMR. An Emergency Report must be filed to any local authority responsible for responding to emergencies at the geographic location of the release or anticipate release of a dangerous good if the release is, or could be, in excess of quantities specified in the TDG and endangers, or could endanger, public safety. For aerosols, a release or anticipated release of any quantity necessitates an emergency report. A Release or Anticipated Release Report must be filed by telephone as soon as possible for hazardous materials transported by truck, rail, or maritime transportation when the release or anticipated release results in the death of a person, injuries to a person that require treatment by a health care professional, an evacuation or shelter in place, or the closure of a facility, road, main railway line, or main waterway. Alternatively, if the means of containment has been damaged so that its integrity is compromised or the center sill or stub sill of a tank car is broken or has a crack in the metal of at least 15 centimeters (6 in.), a report must be filed. For transportation by air, a Dangerous Goods Accident or Incident Report must be filed by phone as soon as possible after the incident when the release or anticipated release endangers or could endanger public safety and it results in the death or injury of a person, property or environmental damage, serious jeopardy to persons or aircraft, an evacuation or shelter in place, the closure of an air cargo facility, aerodrome or runway, or there are signs that the integrity of the means of containment is compromised. In addition to the telephonic report, a written report must be submitted within 30 days of the incident in the aforementioned cases. Table 6.3 provides a summary of the reporting requirements in the TDG as the apply to aerosols.

Table 6.3 Transport Canada Transport of Dangerous Goods Regulations Reporting Requirements for Aerosol Incidents

	Truck, Rail, or Maritime		Air	
Aerosol Incident Type	**Emergency Report by Telephone**	**Release or Anticipated Release Report by Telephone[1]**	**Dangerous Goods Accident or Incident Report by Telephone[1]**	**Undeclared or Misdeclared Dangerous Good Report by Telephone**
Release or Anticipated Release of Any Quantity, with outcome:				
• Endangers, or could endanger, public safety	●			
• Death		●	●	
• Any injury			●	
• Injury resulting in hospitalization		●		
• Evacuation/shelter in place		●	●	
• Closure of facility, road, main railway line, or main waterway		●		
• Means of containment damaged so its integrity is compromised		●	●	
• Property/environmental damage			●	
• Serious jeopardy to persons or aircraft			●	
• Closure of air cargo facility, aerodrome, or runway			●	
Discovery of dangerous goods without documentation or dangerous goods marks required by the TDG				●

Source: Transport Canada, *Transport of Dangerous Goods Regulations, Part 8*, http://www.tc.gc.ca/documents/SOR_2019-101.pdf.

[1] A 30-day follow-up report is required in writing within 30 days of the incident.

C.4.1 Canada Storage Incidents

Between 1988 and 2018, there were 41 incident reports involving hazardous materials classified as UN1950 in the data provided by Transport Canada. Of these, 27 incidents or 66 percent of all incidents, were reported during handling (loading or unloading) or in temporary storage.[37] Of the 15 Canadian Comparison Incidents, eight of them (53 percent) occurred during handling or in temporary storage. Approximately one-half of all incidents occurred during handling alone. Figure 6.3 shows the breakdown of incidents by transportation phase for each set of incidents.

[37] One of the 25 incidents was reported during railyard operations during the inspection of a tank car.

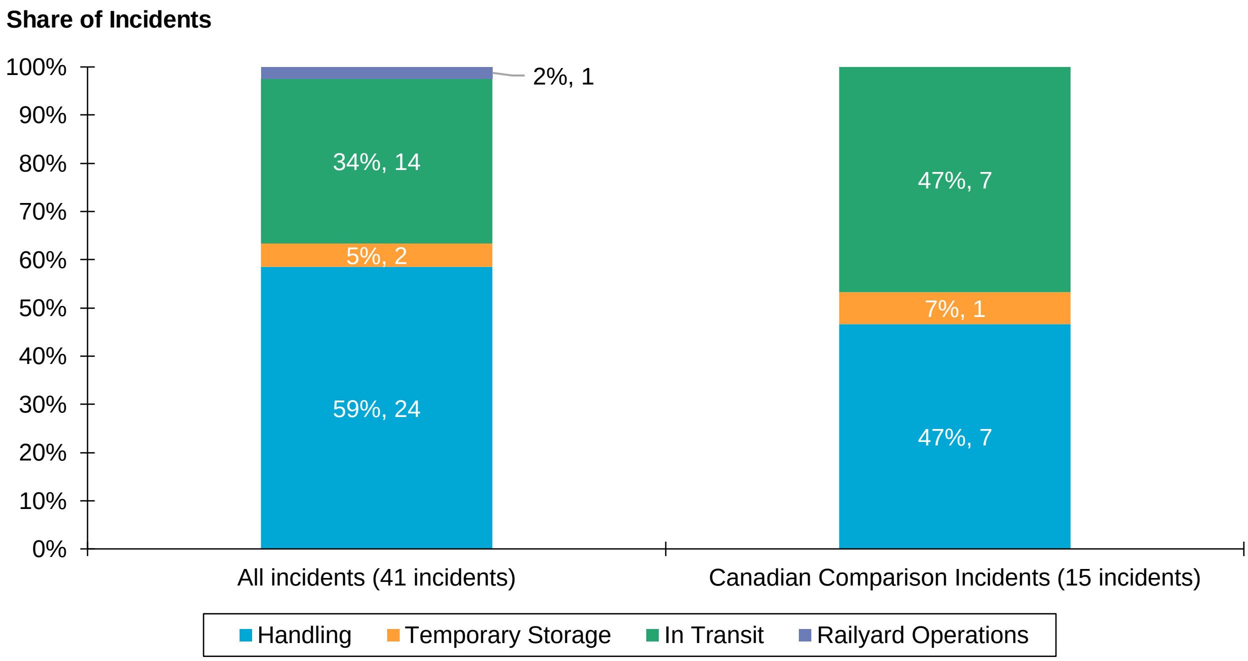


Figure 6.3 Canada Aerosol Incidents by Transportation Phase
1988 to 2018

Source: Transport Canada, "Accident Summary Report: Period 1988–2018 Inclusive," email from Tracey Boicey to Bob Richard, May 7, 2019.

Transport Canada defines incident severity based on 10 true or false questions. One point is assigned to each positive response, and the point total represents the severity level. Incidents scoring 0 to 3 are considered minor, 4 to 6 are moderate, and 7 to 10 are major. All of the Canadian Comparison Incidents were considered moderate incidents. Of the eight incidents occurring during handling or in temporary storage, six resulted in a spill only, one resulted in a fire, and one resulted in an explosion. No storage incidents resulted in an injury or fatality.

C.4.2 Canada Transportation Incidents

Of the 41 incident reports involving hazardous materials classified as UN1950 in the Transport Canada data between 1988 and 2018, 14 incidents, or 34 percent of all incidents, were reported in transit. Of these, 29 percent occurred during transportation by air, 36 percent occurred during transportation by rail, and 36 percent occurred during transportation by truck. No incidents occurred during maritime transportation.

As in the U.S. data, there was a lower rate of incidents by air in the Canadian Comparison Incidents compared to all reports, as many of the incidents occurring by air did not involve the release of any material and were instead related to undeclared goods. In the 15 Canadian Comparison Incidents, there were a total of seven incidents occurring in transit, 57 percent of which occurred during transportation by truck, 29 percent of which occurred during transportation by rail, and 14 percent of which occurred during transportation by air. There were no incident reports for maritime transportation among those 15 incidents.

Of the seven Canadian Comparison Incidents occurring in transit, all were moderate incidents. Five of them resulted only in a spill, and two resulted in a fire. The two incidents with a fire were during transportation by rail. One of the fires was caused by a defective heater and the other had no stated cause. In both cases, all the contents were lost, but there were no explosions, injuries, or deaths. Figure 6.4 shows the breakdown of incidents by transportation phase for each set of incidents.

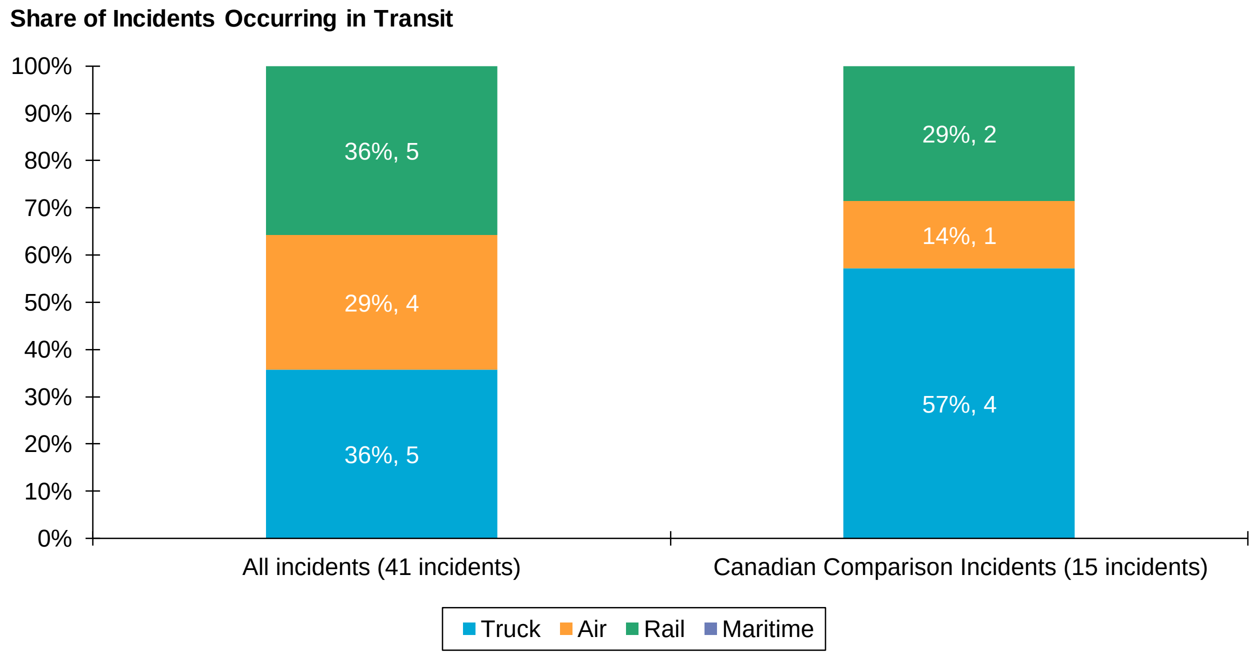


Figure 6.4 Canada Aerosol Incidents in Transit, by Mode
1988 to 2018

Source: Transport Canada, "Accident Summary Report: Period 1988–2018 Inclusive," email from Tracey Boicey to Bob Richard, May 7, 2019.

Truck

As shown in Figure 6.4, of the seven Canadian Comparison Incidents occurring in transit, 57 percent occurred during transportation by truck, a total of four incidents from 1988 to 2018, all of which were moderate incidents. All four of the incidents resulted in a spill only. In three of the incidents, a load shift during while in transit resulted in the crushing of aerosol cans or damage to the valve on aerosol cans. There were no injuries or deaths as a result of any of the incidents.

Rail

Of the seven Canadian Comparison Incidents occurring in transit, 29 percent occurred during transportation by rail, a total of two incidents from 1988 to 2018, both of which were moderate incidents. Both incidents resulted in a fire. In one, the fire was caused by a defective heater, while the cause of the other fire is unknown. Both resulted in total loss of product but did not result in any explosion, injuries, or deaths.

Maritime

None of the 41 incidents included in the Transport Canada data from 1988 to 2018 occurred during maritime transportation.

Air

Of the seven Canadian Comparison Incidents occurring in transit, 14 percent occurred during transportation by air, a total of one moderate incident from 1988 to 2018. The incident resulted in the spill of a flammable aerosol. The cause of the spill is unknown and was discovered during the unloading of a cargo aircraft. The incident did not result in any injuries or deaths.

C.5 Comparison of United States and Canada Incidents

When considering the U.S. Comparison Incidents and Canadian Comparison Incidents, the majority of incidents in both countries occur during handling or in temporary storage (e.g., in facilities). There is no significant difference in the transportation phase during which aerosol incidents occur in the U.S. and Canada. The only mode with a significant difference in the occurrence of aerosol incidents is rail: Canada had more incidents during transportation by rail than the U.S., but it only had two incidents over the 30-year period, and one was due to a collision. Figure 6.5 shows a comparison of the aerosol incidents by transportation phase in the U.S. and Canada, with error bars indicating the range of most likely values at a confidence level of 95 percent. Figure 6.6 shows a comparison of the aerosol incidents in the U.S. and Canada by transportation mode.

When comparing the results of aerosol incidents in the U.S. and Canada, there are no significant differences in the occurrence of spills, fire, or explosion in the two countries. Neither country had aerosol incidents resulting in injury or death from 1988 to 2018. Figure 6.7 shows a comparison of the incident results in each country.

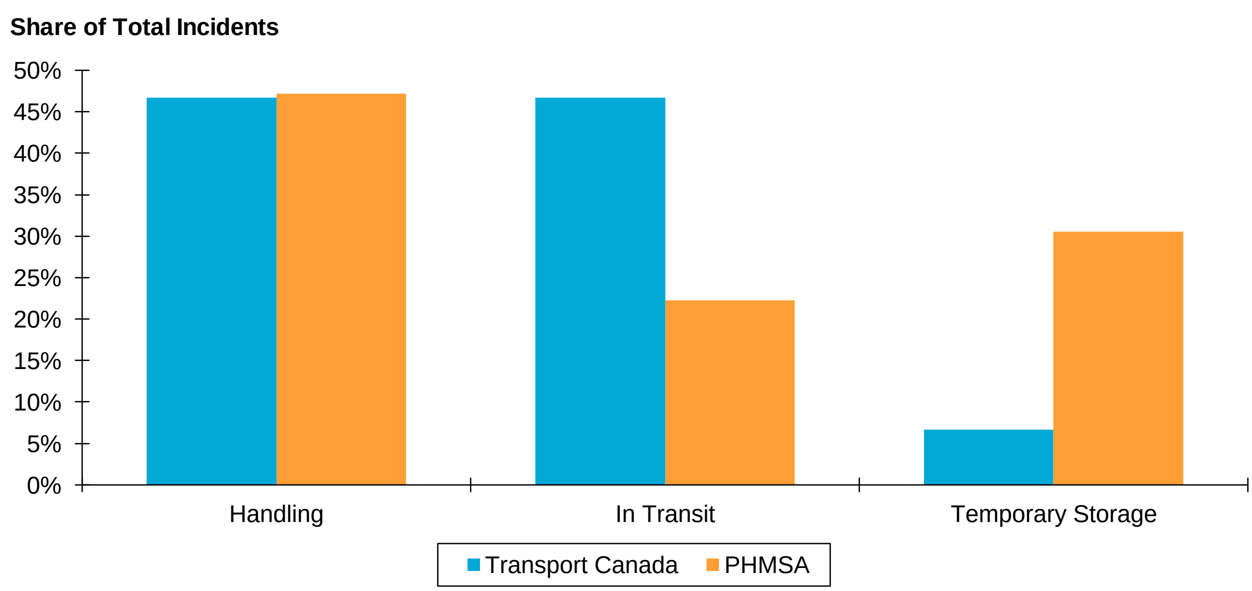


Figure 6.5 Comparison of United States and Canada Incidents by Transportation Phase

Sources: United State Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Hazardous Materials Incident Database https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/Welcome.aspx. Transport Canada, "Accident Summary Report: Period 1988–2018 Inclusive," email from Tracey Boicey to Bob Richard, May 7, 2019.

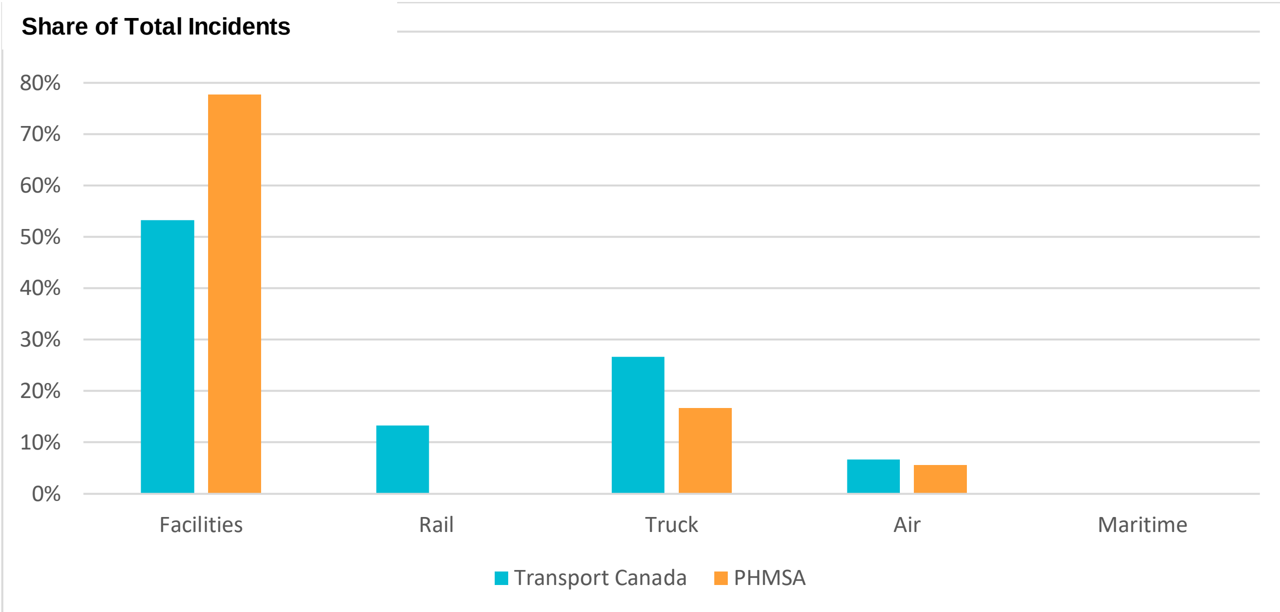


Figure 6.6 Comparison of United States and Canada Incidents by Mode

Sources: United State Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Hazardous Materials Incident Database https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/Welcome.aspx. Transport Canada, "Accident Summary Report: Period 1988–2018 Inclusive," email from Tracey Boicey to Bob Richard, May 7, 2019.

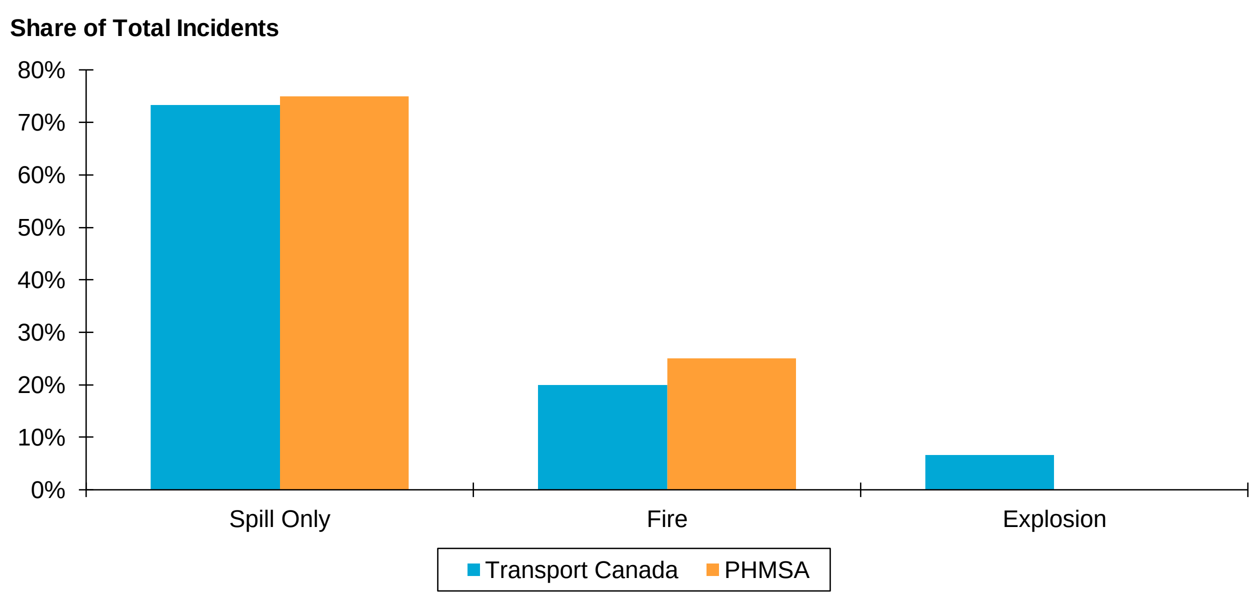


Figure 6.7 Comparison of United States and Canada Incidents by Result

Sources: United State Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Hazardous Materials Incident Database https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/Welcome.aspx. Transport Canada, "Accident Summary Report: Period 1988–2018 Inclusive," email from Tracey Boicey to Bob Richard, May 7, 2019.

C.6 Major Truck Incidents Involving Aerosols—July 2014 to July 2019 Europe, Australia, China, Mexico and the U.S.

The FEA provided a summary of nine truck incidents involving aerosols in the five years from July 2014 to July 2019. Of these nine incidents, four occurred within the European Union, two in Australia, and one each in China, Mexico, and the U.S. These nine incidents involved considerable release of material but only one resulted in a fire. One of the incidents that did not involve a fire resulted in the closure of a major road for 15 hours.[38] In the nine incidents provided by the FEA, there was one death and one minor injury.

All of the nine incidents were significant enough to have news coverage and represent extreme aerosol incidents. The aerosols transported were not cited as the cause of the fire in any of the incidents resulting in a fire, but they were cited as contributing to the fire. In the incidents in which the suspected cause was given, the ignition source was the result of sparks caused by a vehicle-to-vehicle crash, heat generated from a tire blowout igniting the aerosols, or a problem in the trailer's electrical system (news article not provided).[39,40]

38 https://www.bbc.com/news/uk-england-34060538.

39 https://www.abc.net.au/news/2019-04-06/driver-killed-in-south-eastern-freeway-truck-crash/10978140.

40 https://www.dailymail.co.uk/news/article-5039993/Moment-lorry-trailer-packed-AEROSOLS-explodes.html.

Appendix D. American Society for Quality Failure Mode and Effects Analysis Instructions

This procedure is based on an ASQ format: https://asq.org/quality-resources/fmea.

D.1 Procedure

This is a general procedure. Specific details may vary with standards of your organization or industry.

1. Assemble a cross-functional team of people with diverse knowledge about the process, product or service, and customer needs. Functions often included: design, manufacturing, quality, testing, reliability, maintenance, purchasing (and suppliers), sales, marketing (and customers), customer service.

1. Identify the scope of the FMEA. Is it for concept, system, design, process, or service? What are the boundaries? How detailed should we be? Use flowcharts to identify the scope and to make sure every team member understands it in detail. (From here on, we'll use the word "scope" to mean the system, design, process, or service that is the subject of your FMEA.)

2. Fill in the identifying information at the top of your FMEA form. The remaining steps ask for information that will go into the columns of the form.

3. Identify the functions of your scope. Ask, "What is the purpose of this system, design, process, or service? What do our customers expect it to do?" Name it with a verb followed by a noun. Usually you will break the scope into separate subsystems, items, parts, assemblies, or process steps and identify the function of each.

4. For each function, identify all the ways that it could fail to happen. These are potential failure modes. If necessary, go back and rewrite the function with more detail to be sure the failure modes show a loss of that function.

5. For each failure mode, identify all the consequences on the system, related systems, process, related processes, product, service, customer, or regulations. These are potential effects of failure. Ask, "What does the customer experience because of this failure? What happens when this failure occurs?"

6. Determine how serious each effect is. This is the severity rating, S. Severity is usually rated on a scale from 1 to 10, where 1 is insignificant and 10 is catastrophic. If a failure mode has more than one effect, write on the FMEA table only the highest severity rating for that failure mode.

7. For each failure mode, determine all the potential root causes. Use tools in books such as The Quality Toolbox that are classified as cause analysis tools, as well as the best knowledge and experience of the team. List all possible causes for each failure mode on the FMEA form.

8. For each cause, determine the occurrence rating, O. This rating estimates the probability of failure occurring because of that cause during the lifetime of your scope. Occurrence is usually rated on a scale from 1 to 10, where 1 is extremely unlikely and 10 is inevitable. On the FMEA table, list the occurrence rating for each cause.

9. For each cause, identify current process controls. These are tests, procedures, or mechanisms that you now have in place to keep failures from reaching the customer. These controls might prevent the cause from happening, reduce the likelihood that it will happen, or detect failure after the cause already has happened but before the customer is affected.

10. For each control, determine the detection rating, D. This rating estimates how well the controls can detect either the cause or its failure mode after they have happened but before the customer is affected. Detection is usually rated on a scale from 1 to 10, where 1 means the control is absolutely certain to detect the problem and 10 means the control is certain not to detect the problem, or no control exists. On the FMEA table, list the detection rating for each cause.

11. (Optional for most industries) Is this failure mode associated with a critical characteristic? Critical characteristics are measurements or indicators that reflect safety or compliance with Government regulations and need special controls. If so, a column labeled “Classification” receives a Y or to show that special controls may be needed. Usually, critical characteristics have a severity of 9 or 10 and occurrence and detection ratings above 3.

12. Calculate the risk priority number, RPN = S × O × D. Also calculate Criticality = S × O, by multiplying severity by occurrence. These numbers provide guidance for ranking potential failures in the order they should be addressed.

13. Identify recommended actions. These actions may be design or process changes to lower severity or occurrence. They may be additional controls to improve detection. Also note who is responsible for the actions and target completion dates.

As actions are completed, note results and the date on the FMEA form. Also, note new S, O, or D ratings and new RPN.

Appendix E. Detailed Characteristics of Products to Consider in Failure Mode and Effects Analysis

E.1 Vandal Mark Remover (Flammable/Flammable)

Example: United 126 Vandal Mark Remover,
SDS: https://www.unitedlabsinc.com/usa/content/pdf/msds/126sds.pdf.

Table 6.4 Vandal Mark Remover Specifications

UN Number	UN1950
Transport Hazard Class(es):	2.1
Proper Shipping Name:	Aerosols, Limited Quantity
Flammability Rating:	3
Health Rating:	3
Net Weight:	454 grams

Table 6.5 Vandal Mark Remover Product Characteristics

Component	Estimated Percent by Weight[1]	Higher Heating Value (kJ/g)[2]	Lower Heating Value (kJ/g)	NFPA (kJ/g)
Propane	6	50.3	[46]	44
Butane	24	49.5	45.3	43.3
Toluene	25	42.4	[39]	28.4
Ethanol	35	29.7	26.7	24.7
Butyl Acetate	5	[31]	[30]	27.6
Total	100	37.4	34.2	30.2
Total Energy for 16 oz (454 g)		17	15	14

Source: CS Team Analysis, 2019.

1 Estimated percentages by weight are chosen to maximize the percentages of products with the highest heat of combustion.

2 High Heat of Combustion Value, https://www.engineeringtoolbox.com/standard-heat-of-combustion-energy-content-d_1987.html.

Values in brackets are estimates.

E.2 Brake Parts Cleaner (Nonflammable/Flammable)

Example: CRC Brakleen® Brake Parts Cleaner,
SDS: http://docs.crcindustries.com/msds/5151.pdf.

Table 6.6 Brake Parts Cleaner Specifications

UN Number	UN1950
Transport Hazard Class(es):	2.1
Proper Shipping Name:	Aerosols, Limited Quantity
Flammability Rating:	4
Health Rating:	1
Net Weight:	400–800 g.

Table 6.7 Break Parts Cleaner Product Characteristics

Component	Estimated Percent by Weight[1]	Higher Heating Value (kJ/g)[2]	Lower Heating Value (kJ/g)	NFPA (kJ/g)
Carbon Dioxide	10	0.0	0.0	0.0
Acetone	88	30.8	29.6	24.4
Toluene	2	42.4	[39]	0.6
Total	100	28.0	26.7	24.9
Total Energy for 14 oz (397 g)		11	11	10
Total Energy for 29 oz (822 g)		23	22	20

Source: CS Team Analysis, 2019.

1 Estimated percentages by weight are chosen to maximize the percentages of products with the highest heat of combustion.

2 High Heat of Combustion Value, https://www.engineeringtoolbox.com/standard-heat-of-combustion-energy-content-d_1987.html.

Values in brackets are estimates.

E.3 Aerosol Insecticide (Flammable/Insecticide)

Example: Shur-Kill Aerosol Insecticide,
SDS: https://www.domyown.com/msds/Shur-Kill+AgriselSDS.pdf.

Table 6.8 Aerosol Insecticide Specifications

UN Number:	UN1950
Transport Hazard Class(es):	2.1
Proper Shipping Name:	Aerosols, Limited Quantity
Flammability Rating:	1
Health Rating:	1
Net Weight:	454 g.

Table 6.9 Aerosol Insecticide Product Characteristics

Component	Estimated Percent by Weight[1]	Higher Heating Value (kJ/g)[2]	Lower Heating Value (kJ/g)	NFPA (kJ/g)
Isopar-M	10	[48]	[45]	[41]
Propane	6	50.3	[46]	44
Butane	24	49.5	45.3	43.3
Proprietary Formula	60	N/A	N/A	N/A
Total	100	19.6	18.1	13.5
Total Energy for 16 oz (454 g)		9	8	6

Source: CS Team Analysis, 2019.

1 Estimated percentages by weight are chosen to maximize the percentages of products with the highest heat of combustion.

2 High Heat of Combustion Value, https://www.engineeringtoolbox.com/standard-heat-of-combustion-energy-content-d_1987.html.

Values in brackets are estimates.

E.4 Auto A/C Treatment (Nonflammable/Nonflammable)

Example: A/C Pro® Rejuvenator A/C System Treatment,
SDS: http://acprocold.com/wp-content/uploads/2014/03/A-C-Pro-Rejuvenator-AC-System-Treatment-2015-09.pdf.

Table 6.10 Auto A/C Treatment Specifications

UN Number:	UN3159
Transport Hazard Class(es):	2.2
Proper Shipping Name:	Limited Quantity
Flammability Rating:	0
Health Rating:	1
Net Weight:	85 g.

Table 6.11 Auto A/C Product Characteristics

Component	Estimated Percent by Weight[1]	Higher Heating Value (kJ/g)[2]	Lower Heating Value (kJ/g)	NFPA (kJ/g)
1,1,1,2-tetrafluoroethane	60	[0]	[0]	[0]
Proprietary Formula	40	[49]	[45]	[43]
Total	100	19.6	18.0	17.2
Total Energy for 3.0 oz (85 g)		1.6	1.5	1.5

Source: CS Team Analysis, 2019.

1 Estimated percentages by weight are chosen to maximize the percentages of products with the highest heat of combustion.

2 High Heat of Combustion Value, https://www.engineeringtoolbox.com/standard-heat-of-combustion-energy-content-d_1987.html.

Values in brackets are estimates.

E.5 Gas Only—Butane Fuel (Flammable)

Example: Neon Lighter Gas Refill Butane Universal Fluid; Ronson Lighter Refil, SDS: http://doryventures.scene7.com/is/content/DoryVentures/Ronson/Website/Servicing/2017%20Ronson%20Lighter%20Refill%20MSDS.pdf; https://www.alliedelec.com/m/d/13e9d24b161b4cdaeca8ffb169344975.pdf; https://www.boconline.co.uk/en/images/10021860_tcm410-55972.pdf https://www.rssd.com/sharedimages/eshopmedia/msds/max_burton_butane_fuel_cartridge_sds.pdf.

Table 6.12 Gas Only—Butane Fuel Specifications

UN Number:	UN1965
Transport Hazard Class(es):	2.1
Proper Shipping Name:	Hydrocarbon gas mixture, liquefied, n.o.s.
Flammability Rating:	2
Health Rating:	—not classified
Net Weight:	78–286 g

Table 6.13 Gas Only—Butane Fuel Product Characteristics

Component	Estimated Percent by Weight[1]	Higher Heating Value (kJ/g)[2]	Lower Heating Value (kJ/g)	NFPA (kJ/g)
Propane	22	50.3	[46]	44
Butane	24	49.5	45.3	43.3
Iso-Butane	54	[49.5]	[45.3]	[43.3]
Total	100	49.6	45.5	43.4
Total Energy for 3.0 oz (85 g)		4.2	3.9	3.7
Total Energy for 10.0 oz (284 g)		14.1	12.9	12.3

Source: CS Team Analysis, 2019.

1 Estimated percentages by weight are chosen to maximize the percentages of products with the highest heat of combustion.

2 High Heat of Combustion Value, https://www.engineeringtoolbox.com/standard-heat-of-combustion-energy-content-d_1987.html. Values in brackets are estimates.

E.6 Gas Only—HFC-152a Air Duster (Flammable)

Example: Dust-Off Compressed Gas Duster,
SDS: https://www.sisweb.com/referenc/msds/dust-off-sds.pdf.

Table 6.14 Gas Only—HFC-152a Air Duster Specifications

UN Number:	UN1030
Transport Hazard Class(es):	2.1
Proper Shipping Name:	1,1, -difluoroethane
Flammability Rating:	4
Health Rating:	1
Net Weight:	340 g.

Table 6.15 Gas Only—HFC-152a Air Duster Product Characteristics

Component	Estimated Percent by Weight[1]	Higher Heating Value (kJ/g)[2]	Lower Heating Value (kJ/g)	NFPA (kJ/g)
1,1, -difluoroethane (R-152a)	100	[9]	[8]	6.3
Total	100	9	8	6.3
Total Energy for 12 oz (340 g)		3.1	2.7	2.1

Source: CS Team Analysis, 2019.

[1] Estimated percentages by weight are chosen to maximize the percentages of products with the highest heat of combustion.

[2] High Heat of Combustion Value, https://www.engineeringtoolbox.com/standard-heat-of-combustion-energy-content-d_1987.html. Values in brackets are estimates.

E.7 Gas Only—R-134a Air Duster (Nonflammable)

Example: Business Source Nonflammable Compressed Gas Duster, SDS: https://www.sprproductinformation.com/SDS/FAL/BusinessSourceNon-Flammable134aCompressedGasDusterSDSEnglishDec2017.pdf.

Table 6.16 Gas Only—R-134a Air Duster Specifications

UN Number:	UN3159
Transport Hazard Class(es):	2.2
Proper Shipping Name:	1,1,1,2-tetrafluoroethane
Flammability Rating:	0
Health Rating:	1
Net Weight:	284 g.

Table 6.17 Gas Only—R-134a Air Duster Product Characteristics

Component	Estimated Percent by Weight[1]	Higher Heating Value (kJ/g)[2]	Lower Heating Value (kJ/g)	NFPA (kJ/g)
1,1,1,2-tetrafluoroethane (R-134a)	100	[0]	[0]	[0]
Total	100	0	0	0
Total Energy for 10 oz (284 g)		[0]	[0]	[0]

Source: CS Team Analysis, 2019.

1 Estimated percentages by weight are chosen to maximize the percentages of products with the highest heat of combustion.

2 High Heat of Combustion Value, https://www.engineeringtoolbox.com/standard-heat-of-combustion-energy-content-d_1987.html. Values in brackets are estimates.

Appendix F. Practical Limits on Propellant Gases in DOT 2P and 2Q Containers

The HMR, in 49 CFR § 173.306 (a) (3) (i) and (ii) authorizes limited quantities of compressed gases in metal aerosol containers with a capacity of up to 1 L, with a total pressure that cannot exceed 180 psig at 54.4°C (130°F). Moreover, the exact containers authorized from the list of Non-DOT specification, DOT 2P, DOT 2Q, and DOT 2Q1 containers varies according to the maximum pressure allowed, with thresholds of 140, 160 and 180 psig.

These pressure limits, by extension, limit the quantities of gas that could be potentially be included in 2P or 2Q containers, for use as aerosol propellant, as in some cases adding excess gas would result in pressures that exceed the thresholds.

Reproducing the table from the HMR, authorized containers are:

Table 6.18 Authorized Containers (Excerpt from HMR[41])

If the gauge pressure (psig) at 54.4 °C (130 °F) is	Authorized container
140 or less	Non-DOT specification, DOT 2P, DOT 2Q, DOT 2Q1
Greater than 160 but not exceeding 180	DOT 2Q, DOT 2Q1
Not to exceed 210	DOT 2Q1 (Nonflammable only)
140 or less	Non-DOT specification, DOT 2P, DOT 2Q, DOT 2Q1

Representative propellant systems taken from the example set of container contents used in this Risk Assessment FMEA exercise include:

Table 6.19 Representative Propellant Systems

Example Contents	Propellant Used/Gas Included
United 126 Vandal Mark Remover	"Propane/n-Butane"[42] (68476-86-8)
CRC Brakleen® Brake Parts Cleaner	CO2 (124-38-9)
Shur-Kill Aerosol Insecticide	"Propane/n-Butane"2 (68476-86-8)
A/C Pro® Rejuvenator A/C System Treatment	1,1,1,2-tetrafluoroethane (811-97-2)
Neon Lighter Gas Refill Butane Universal Fluid	Propel 40, 2.7 bar
Dust-Off Compressed Gas Duster	1,1-difluoro-ethane (75-37-6)
Business Source Nonflammable Compressed Gas Duster	1,1,1,2-tetrafluoroethane (811-97-2)

[41] HMR, in 49 CFR § 173.306 (a) (3) (i) and (ii)

[42] The propane/n-butane mixture in two products represents a complex combination of hydrocarbons obtained by subjecting liquefied petroleum gas mix to a sweetening process to convert mercaptans or to remove acidic impurities. It consists of hydrocarbons having carbon numbers predominantly in the range of C3 through C7 and boiling in the range of approximately 40°C to 80°C (-40°F to 176°F).

From the preceding, the following propellant components were identified:

- Propane (74-98-6).
- N-Butane (106-97-8).
- i-Butane (75-28-5).
- CO_2 (124-38-9).
- 1,1,1,2-tetrafluoroethane (811-97-2).
- 1,1-difluoro-ethane (75-37-6).

Relevant data for the propane/n-butane propellant mixture, and the Propel 40 propellant are not available, instead their component gases were included in the table above.[43]

Ideal gas calculations and data for the pressures and temperatures in the HMR table limiting pressures in metal aerosol containers are shown below:

pV = nRT, n = pV/RT

R = 0.0831446 L bar K^{-1} mol^{-1}

54.4 °C = 327.55 K

RT = 27.234

Table 6.20 Container Pressure Thresholds

Pressure threshold (psig)	Pressure threshold (bar, absolute)	Moles of gas contained in a 1 L volume
140	10.67	0.3918
180	13.42	0.4928
140	10.67	0.3918

So long as the propellant is not liquid at the specified temperature (130°F) and threshold pressure, the amount of gas contained in a one liter volume will be less than or equal to the amount of moles shown in the table above.[44] However, if the vapor pressure over the liquid phase of the propellant in question, at 130°F, is less than the threshold pressure, attempting to add propellant up to that threshold pressure will result in liquid propellant condensing inside the container, until the container is liquid full. Those that will be liquid at the threshold pressures are shown in **red**. The table below indicates whether a given propellant will be gas or

[43] For this exercise, it is necessary to know details of the pressure vs. temperature behavior of the propellants.

[44] See below for a conversion of moles to grams for a range of materials.

liquid at the threshold pressures, and the amount of propellant that can be contained in a 1 liter can. The amount of gas is based on ideal gas calculations; the amount of liquid is based on reported liquid densities.

Because specific data on the vapor pressure for Propel 40 and the propane/n-butane mixtures, their individual constituent components are included in the table instead. Nitrogen and methane have been included for comparison.

The grams of propellant contained in 1 liter, at 130°F are:

Table 6.21 Propellant Components and Pressure Limits

Propellant Components	Gas or Liquid at 130°F, at 140 psig or higher	Pressure Limit		
		140 psig	160 psig	180 psig
Nitrogen (7727-37-9)	Gas	11.0	12.5	13.8
Methane (74-82-8)	Gas	6.3	7.1	7.9
Propane (74-98-6)	Gas	17.3	19.5	21.7
n-Butane (106-97-8)	Liquid	~540	~540	~540
i-Butane (75-28-5)	Liquid	17.2	19.5	21.7
CO2 (124-38-9)	Gas	40.0	45.1	50.3
1,1,1,2-tetrafluoroethane (811-97-2)	Gas	25.6	29.2	32.5
1,1-difluoroethane (75-37-6)	Gas	11.0	12.5	13.8

As noted above, in none of our examples were pure propane, n- or i-butane used as propellant. In one case, a propane/n-butane mixture is used (LPG), in another propane/n-butane/i-butane (Propel 40) is used. It is not possible to predict their behavior here as the needed data (vapor pressure over the liquid versus temperature) is not readily available. In both cases, however, the mixture was light on propane (16.5 percent for the former, 22 percent for the latter); that makes those products very likely to condense if one attempts to add them to the indicated pressures.

Appendix G. Flammability and Oxygen Deficiency Conditions for Aerosols

Among the potential hazards related to the release of aerosols are asphyxiation (oxygen deficiency) and flammability. The release of aerosol products in sufficient quantities could cause either or both conditions in the container in which the products are being transported. The quantity of product required to be released to result in these extreme conditions depends on the size of the shipping container. Smaller containers have less air and so a smaller amount of aerosol product would need to be released to cause a flammable or asphyxiant atmosphere within the container compared to a larger container. The CS Team identified chemical properties of seven different substances under the Ideal Gas Law at 25ºC to determine the quantity of each substance that would need to be released to cause asphyxiant or flammable conditions within shipping containers of various sizes. The seven substances that were considered are:

- Carbon dioxide (CO_2), as a gas.
- Ethanol, as a liquid.
- i-Butane, as a liquid
- n-Butane, as a liquid.
- Nitrogen, as a gas.
- Propane, as a gas.
- Toluene, as a liquid.

Flammability limits are important guides to gauge the flammability of these substances. The lower flammability limit (LFL) is the lowest concentration of a gas or vapor in air that is capable of producing a flash or fire in the presence of an ignition source, while the Upper Flammability Limit (UFL) is the highest such concentration. The release of any of the substances create a flammable environment in the shipping container if the concentration of the volume of the substance released into the shipping container exceeds the LFL and is lower than the UFL. Above the UFL, there is not enough oxygen for ignition.

To create an oxygen deficient or asphyxiant environment, the concentration of the volume of the substance released into the shipping container must exceed seven percent.[45] In this event, the air inside the container becomes oxygen deficient and there is risk of asphyxiation.

In the analysis of the hazards presented by the release of the seven substances above, the amount of substance released was considered to be between one liter and 100 liters, equivalent to approximately one to 100 aerosol containers. The shipping container size was allowed to vary between 5 cubic meter ($m^{3)}$ and 85 m^3. For reference, a standard 8-foot shipping container has a volume of approximately 12 m^3, and a

[45] According to OSHA, any oxygen concentration below 19.5 percent oxygen is oxygen deficient. Normal oxygen levels are 21.0 percent, so displacing more than seven percent of the air by a gas would result in oxygen-deficient air (https://www.osha.gov/SLTC/etools/shipyard/shiprepair/confinedspace/oxygendeficient.html).

standard 40-foot shipping container has a volume of approximately 77 m^3, so the volumes considered span more than the range of likely shipping container sizes. The results are shown in Figure G-1.

In the analysis, carbon dioxide and nitrogen were combined because both are nonflammable and so they could only result in asphyxiation. In total, 30 liters of carbon dioxide or nitrogen gas would need to be released into a five cubic meter container to result in oxygen-deficient air. This increases to 59 liters in a 10-cubic meter container and 88 liters in a 15-cubic meter container. More than 100 liters would need to be released in any larger containers to create oxygen-deficient air.

The most interesting result is found when examining n-butane and toluene. Both are found in existing aerosol products, and n-butane alone could potentially be shipped as an aerosol in the event the definition of an aerosol in the HMR were harmonized with that in the UNMR to allow an aerosol dispenser to be filled solely with a gas.[46] Considering a standard 20-foot shipping container, the volume of the shipping container is approximately 38 m^3. In order to cause a flammable environment, approximately two liters of toluene would need to be released. If more than 11 liters are released, the atmosphere inside the shipping container would no longer be flammable but would be oxygen deficient. In contrast, three liters of n-butane would need to be released to create a flammable environment in a standard 20-foot shipping container. If between 12 and 14 liters were released, the atmosphere inside the shipping container would be both flammable and oxygen deficient. If 14 or more liters were released, the atmosphere would no longer be flammable but would be oxygen deficient.

The vandal mark remover considered in the FMEA analysis contains not only toluene, but also i-butane and ethanol, two other substance with similar profiles, as shown in Figure 6.8. This vandal mark remover is shipped as an aerosol under the current definition in the HMR. As discussed in the previous paragraph and shown in Figure 6.8, the release of n-butane in equivalent amounts to toluene results in similar risks, yet an aerosol dispenser filled with only n-butane is not currently allowed under the definition of an aerosol in the HMR. This finding suggests, as does the FMEA, that aerosol dispensers filled only with a gas do not pose greater risks than those filled already complying with the current definition of an aerosol in the HMR and filled with a gas propellant plus a liquid, powder, or paste.

[46] The n-butane would be liquified at the pressures in an aerosol dispenser.

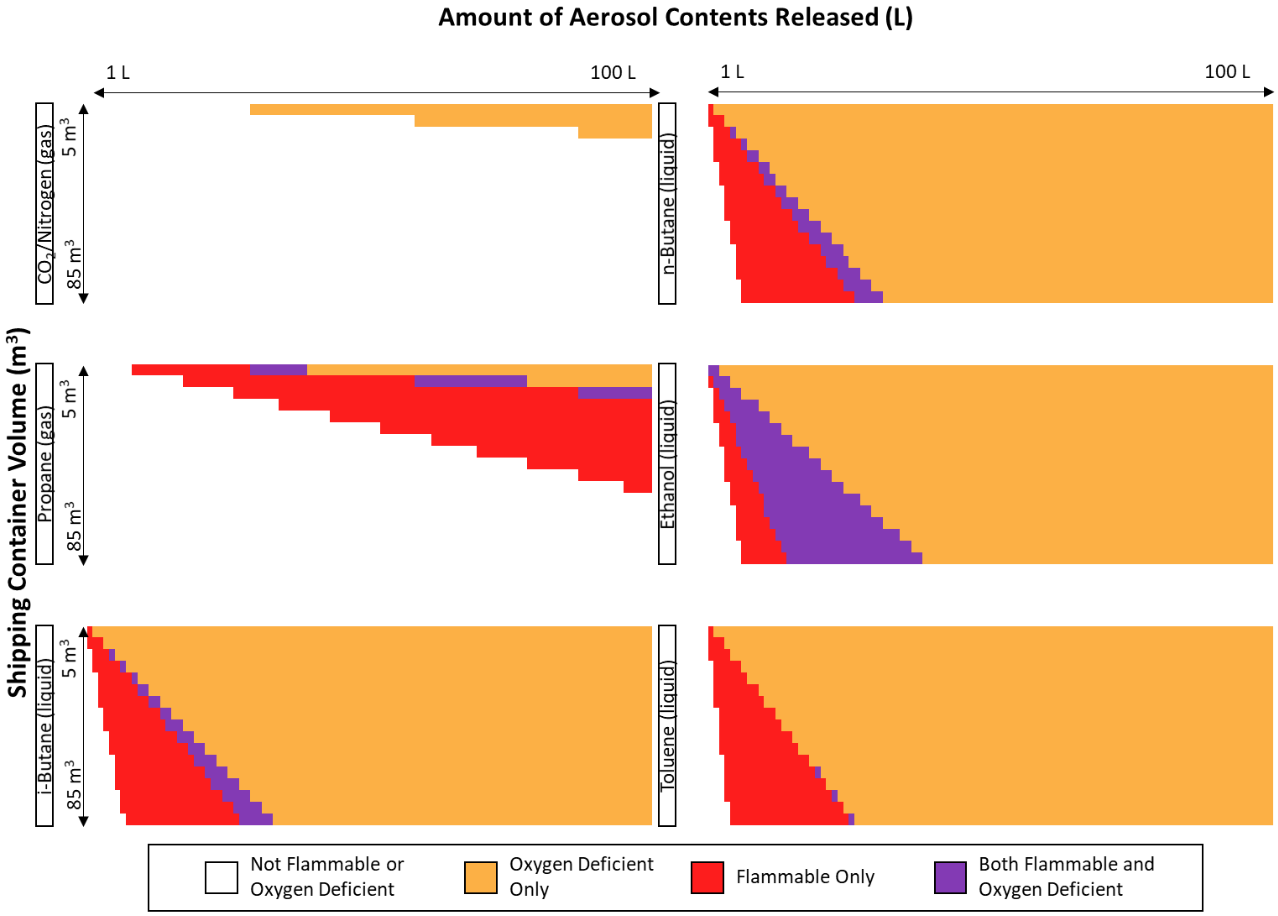


Figure 6.8 Flammable and Asphyxiant Air Conditions for Aerosol Releases, by Shipping Container Size and Amount of Aerosol Contents Released

Source: CS Team analysis, 2019.

Appendix H. Aerosol Regulations

This section identifies aerosol regulations in the U.S., Canada, and Mexico, along with the UNMR, the Federal and State regulatory framework in the U.S., global harmonization and a comparison of US and UNMR special permits for aerosol. The transportation of aerosols and other dangerous goods is regulated in different countries under various national, modal, and regional regulations that are based on the UN Model Regulations on the Transport of Dangerous Goods. These regulations generally include the definition of an aerosol, together with applicable transport requirements.

Table 4.1 provides a comparison of aerosol container pressure requirements in the U.S., Canada, and Europe, including can size limitations, pressure regulations and limitations, can performance, thickness regulations, and marking and labeling requirements. The various regulations also include any limited quantity provisions.

Table 6.22 United States, Canada, and Europe Aerosol Can Regulations

Country	Rating	Can Size Limit	Product Maximum Pressure		Minimum Can Performance		Minimum Plate Thickness (mm/in.)	Marking
			Temp. (ºC/F)	Pressure (bar/psig)	Buckle (bar/psig)	Burst (bar/psig)		
U.S. and Canada	Nonspecification	1 liter	54.4/130	9.66/140	9.66/140	14.48/210	N/A	N/A
	DOT 2P			11.03/160	11.03/160	16.55/240	0.18/0.007	DOT 2P + MFG[1]
	DOT 2Q			12.41/180	12.41/180	18.62/270	0.20/0.008	DOT-2Q + MFG[1]
	Maximum Pressure			12.41/180				Exemption cans avail.
Europe[2]	Minimum can	1 liter	50/122	6.7/97	10.0/145	12.0/174	N/A	Inverted epsilon required
	"12 Bar"			8.0/116	12.0/174	14.4/209	N/A	
	"15 Bar"			10.0/145	15.0/218	18.0/261	N/A	
	"18 Bar"			12.0/174	18.0/261	21.6/313	N/A	
	Maximum Pressure			12.0/174	18.0/261	21.6/313	N/A	
Australia	Minimum can	1 liter	50/122	6.7/97	10.0/145	12.0/174	N/A	N/A
	Other (12/15/18 Bar)			P=pressure (can rating)	1.5xP	1.8xP	N/A	
	Maximum Pressure[3]			12.0/174	18.0/261	21.6/313	N/A	
Japan[4]	None	1 liter[5]	37/98	7.86/114	12.8/185	14.7/213	N/A	N/A
			50/122	P=pressure	1.5xP	1.8xP	N/A	
Argentina	Standard	Unknown			10/145	15/219	N/A	Unknown
	2P				11.4/163	17.2/245	N/A	Unknown
	2Q				12.8/185	19.4/281	N/A	Unknown
Korea[6]	None	Unknown			12.8/185	14.7/213	0.22/0.0085	N/A

Source: Blum, John J, Ph.D., 2012, "Global Aerosol Can Strength/Performance Requirements," presentation.

[1] Manufacturer's symbol or number must be registered with the U.S. DOT.
[2] Europe's ratings are convention, not law. The law is based on pressure at 50ºC/122ºF, and the can minimum buckle is 1.5 times this pressure and minimum burst is 1.8 times this pressure.
[3] Australia also has an additional "nonflammable compressed gas" regulation, with a maximum product pressure of 15 bar at 50ºC/122ºF. Australia is adopting the European 12/15/18 bar grouping.
[4] Japan's listed pressure is the maximum allowable. For can performance, use the second line, but product pressure cannot exceed 7.86 bar/114 psig at 37ºC/98ºF.
[5] Cans are exempted from the Gas Safety Law in Japan if 1 liter or less.
[6] There is no information on Korean product pressure or temperature.

H.1 United States

The Hazardous Materials Transportation Safety Act of 1975 (HMTA) was passed to provide uniform regulations for transporting hazardous materials in the U.S. It gave the Secretary of Transportation the power to designate any "particular quantity or form" of a material that "may pose an unreasonable risk to health and safety or property" as a hazardous material. The HMTA preempts any State or local requirements on the transportation of hazardous materials, unless those requirements provide an equal or greater level of protection to the public than the HMTA requirement.

The transportation of aerosols in the U.S. is regulated under the HMR (49 CFR Parts 171 through 180), which provides general information on hazardous materials and regulation for their packaging and shipment by rail, air, vessel, and public highway in the U.S.[47] PHMSA is the Government agency responsible for developing the regulations and standards in the HMR.

In 1990, Congress enacted the Hazardous Materials Transportation Uniform Safety Act (HMTUSA) to standardize international hazardous materials regulations, as recommended by the UN, and clarify any conflicting State, local, and Federal regulations by defining the Federal preemption over local and State regulations that differ from the HMTA regulations. The HMTUSA includes provisions to encourage uniformity among different State and local highway routing regulations, to develop criteria for the issuance of Federal permits to motor carriers of hazardous materials, and to regulate the transport of radioactive materials.

There are several States with regulations regarding the transportation of hazardous materials. According to the National Conference of State Legislatures, few States regulate the transportation of all hazardous materials, while many have regulations regarding the transportation of hazardous waste and radioactive materials. In total, there are 11 States with permitting requirements related to the transportation of hazardous materials and five with registration requirements. Of these States, most adopt the definition of aerosols from the HMR. Only the District of Columbia and Ohio have a stated definition of an aerosol that differs in wording from the definition found in the HMR.

In the District of Columbia Municipal Regulations § 20-799, an aerosol product is defined as: "a pressurized spray system that dispenses product ingredients with a propellant contained in a product or a product's container, or with a mechanically induced force, excluding pump sprays."

[47] 49 CFR § 171–180, www.ecfr.gov/cgi-bin/text-idx?gp=&SID=8cf7889b5f38cc703d5942c97e77a7bc&mc=true&tpl=/ecfrbrowse/Title49/49CIsubchapC.tpl.

In Ohio, an aerosol is defined as "a product that is dispensed from an aerosol container by a propellant," and an aerosol container is defined as "a metal can, or a glass or plastic bottle designed to dispense an aerosol."

Beyond State and national regulations of aerosols, several other agencies regulate the specific contents allowed for certain uses (such as medical), storage, markings, and packaging of aerosols. These include the Federal Trade Commission, Environmental Protection Agency, NFPA, Food and Drug Administration, Consumer Product Safety Commission, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, National Institute of Standards and Technology, and OSHA. The specific regulations of each of these agencies is beyond the scope of this report.

H.2 Canada

In Canada, the transportation of aerosols is regulated under the TDG Regulations.[48] In Section 1.4, an aerosol container is defined as "an article consisting of any nonrefillable means of containment that contains a substance under pressure and that is fitted with a self-closing device that allows the contents to be ejected as:

- Solid or liquid particles in suspension in a gas.
- A foam paste or powder.
- A liquid or gas.

The definition of an aerosol container in the TDG resembles that in the UNMR; both allow the contents of an aerosol container to be ejected as a gas, allowing a container to be filled solely with a gas.

Transport Canada, the department within the Canadian Government responsible for the TDG Regulations, states that it regularly updates the Canadian regulations to harmonize with the UNMR, ICAO TI, IMDGC, and the HMR, wherever possible.

H.3 Mexico

The Mexican Secretaría de Comunicaciones y Transportes publishes and maintains the Normas Officiales Mexicanas (NOM), or Mexican Standards, which supplement the Reglamento para el Transporte Terrestre de Materiales y Residuos Peligrosos. The two documents form the basis of Mexican regulations concerning the transportation of dangerous goods. Mexico's regulations are generally consistent with older versions of the UNMR. However, they are not updated as often, leaving them about 4 to 10 years behind the latest version of the UNMR.[49] The definition for aerosols, like the UN definition, allows the container to be filled solely with a gas.[50]

[48] Government of Canada, *Transportation of Dangerous Goods Regulations*, April 8, 2019, www.tc.gc.ca/documents/tp-14877-en.pdf.

[49] "Transport of Dangerous Goods into and within Mexico," *Spray: Technology & Marketing*. February 2015, www.spraytm.com/transport-of-dangerous-goods-into-and-within-mexico.html.

[50] Secretaría de Communicaciones y Transportes, *NORMA Oficial Mexicana NOM-002-SCT/2011, Listado de las substancías y materiales peligrosos más usualmente transportadoes*, January 27, 2012, www.sct.gob.mx/fileadmin/DireccionesGrales/DGAF/Normatividad/Materiales_y_residuos_peligrosos/NOM-002-SCT-2011.pdf.

H.4 United Nations

The UN Economic and Social Council's (ECOSOC) Committee of Experts on the Transport of Dangerous Goods develops the UNMR to regulate the transportation of aerosols. The UN ECOSOC Committee of Experts on the Transport of Dangerous Goods is made up of representatives from approximately 36 Member States; 15 intergovernmental organizations (e.g., ICAO, World Health Organization, International Maritime Organization, etc.); and 40 nongovernmental organizations (e.g., European Aerosol Federation, International Air Transport Association, European Cylinder Makers Association, International Organization of Motor Vehicle Manufacturers, etc.).[51] The UNMR are not legally binding regulations on individual countries, but make up the basis for most international agreements. They are amended and updated biennially and distributed to Nations throughout the world, serving as the basis for many national, regional, and international modal regulations.

The UNMR contains the classification and definition of classes; listing of principal dangerous goods; general packing requirements; testing procedures; marking, labelling, or placarding; and transport documents. The UNMR are intended to be a recommendation, but the UN states, "It is expected that governments, intergovernmental organizations and other international organizations, when revising or developing regulations for which they are responsible, will conform to the principles laid down in these Model Regulations, thus contributing to worldwide harmonization in this field. Furthermore, the new structure, format and content should be followed to the greatest extent possible in order to create a more user-friendly approach, to facilitate the work of enforcement bodies and to reduce the administrative burden."

H.5 Aerosol Special Permits

Special permits are required by the UNMR and HMR for transporting certain aerosols not covered in the regulations. The CS Team reviewed special permits that PHMSA has issued for "gas-only" aerosol dispensers (e.g. DOT-SP 11516). There were no related data available even though almost every special permit requires reporting of incidents, including the requirement that each grantee must notify the PHMSA Associate Administrator for the Office of Hazardous Materials Safety, in writing, of any incident involving a package or operation conducted under the terms of the special permit. This may either mean that these incidents are uncommon during transportation or that grantees are not appropriately reporting.

For Special Permit 11516, aerosol cans cannot be filled to more than 79 percent and the liquid portion of the gas cannot completely fill the container at any temperature up to 130° F. The container must be capable of withstanding a pressure of one and one-half times the equilibrium pressure of the content at 130° F without bursting. Can designs vary between countries, and this is a concern for industry.

This section describes the differences between the special provisions in the UNMR and HMR (specifically SP63 in the UNMR and N82 in the HMR). These two provisions are important when examining the regulations governing aerosols. For example, both the US and UNMR assign aerosols to Division 2.1 (Flammable Gas) if the contents include 85 percent by mass or more flammable components and the chemical heat of combustion is 30kJ/g or more. Both the US and UNMR assign aerosols to Division 2.2 (nonflammable gas) if the contents contain one percent by mass or less flammable components and the heat of combustion is less than 20 kJ/g. There are also identical requirements for toxics. In the HMR, substances of Division 6.1, PG I or II, and substances of Class 8, PG I are forbidden from transportation in an aerosol

[51] Mansion, Sabrina, "Transport of Dangerous Goods: Mechanisms for the Development and Harmonization of Dangerous Goods Regulations," March 7, 2008, www.osce.org/eea/31022?download=true.

container. In the UNMR, aerosols with contents meeting the criteria for packing group I for toxicity or corrosivity shall be prohibited from transport (Table H.2).

Table 6.23 Comparison of Special Permits for 49 CFR and UN Model Regulations

49 CFR N82 (§173.115)	UN Model Regulations SP 63
N82 See §173.115 of this subchapter for classification criteria for flammable aerosols. §173.115(l) The following applies to aerosols (see §171.8 of this subchapter): (1) An aerosol must be assigned to Division 2.1 if the contents include 85 percent by mass or more flammable components and the chemical heat of combustion is 30 kJ/g or more. (2) An aerosol must be assigned to Division 2.2 if the contents contain 1 percent by mass or less flammable components and the heat of combustion is less than 20 kJ/g. (3) Aerosols not meeting the provisions of paragraphs (l)(1) or (1)(2) of this section must be classed in accordance with the appropriate tests of the UN Manual of Tests and Criteria (IBR, see §171.7 of this subchapter).[52] An aerosol which was tested in accordance with the requirements of this subchapter in effect on December 31, 2005, is not required to be retested. (4) Division 2.3 gases may not be transported in an aerosol container. (5) When the contents are classified as Division 6.1, PG III or Class 8, PG II or III, the aerosol must be assigned a subsidiary hazard of Division 6.1 or Class 8, as appropriate. (6) Substances of Division 6.1, PG I or II, and substances of Class 8, PG I are forbidden from transportation in an aerosol container. (7) Flammable components are Class 3 flammable liquids, Division 4.1 flammable solids, or Division 2.1 flammable gases. The chemical heat of combustion must be determined in accordance with the UN Manual of Tests and Criteria (IBR, see §171.7 of this subchapter).	63 The division of Class 2 and the subsidiary hazards depend on the nature of the contents of the aerosol dispenser. The following provisions shall apply: (a) Division 2.1 applies if the contents include 85 percent by mass or more flammable components and the chemical heat of combustion is 30 kJ/g or more. (b) Division 2.2 applies if the contents contain 1 percent by mass or less flammable components and the heat of combustion is less than 20 kJ/g. (c) Otherwise the product shall be classified as tested by the tests described in the *Manual of Tests and Criteria*, Part III, section 31. Extremely flammable and flammable aerosols shall be classified in Division 2.1; non-flammable in Division 2.2;[53] (d) Gases of Division 2.3 shall not be used as a propellant in an aerosol dispenser. (e) Where the contents other than the propellant of aerosol dispensers to be ejected are classified as Division 6.1 packing groups II or III or Class 8 packing groups II or III, the aerosol shall have a subsidiary hazard of Division 6.1 or Class 8. (f) Aerosols with contents meeting the criteria for packing group I for toxicity or corrosivity shall be prohibited from transport. (g) Subsidiary hazard labels may be required for air transport. Flammable components are flammable liquids, flammable solids or flammable gases and gas mixtures as defined in Notes 1 to 3 of sub-section 31.1.3 of Part III of the *Manual of Tests and Criteria.* This designation does not cover pyrophoric, self-heating or water-reactive substances. The chemical heat of combustion shall be determined by one of the following methods

[52] This refers to the flame distance, confined space tests and foam tests

[53] Same as above.

	ASTM D 240, ISO/FDIS 13943: 1999 (E/F) 86.1 to 86.3 or NFPA 30B.

Source: 49 CFR N82 (§173.115); UN Model Regulations SP 63, CS Team analysis, March 2020.

H.6 Global Harmonization

The Globally Harmonized System of Classification and Labelling of Chemicals (GHS) was adopted by the UN in 2003. It includes criteria for the classification of health, physical, and environmental hazards. It also includes specifications on information to include on labels of hazardous materials and Safety Data Sheets (SDS). GHS is not a regulation but provides a framework for regulatory agencies to use to harmonize classification and communication elements as they choose. The GHS was developed to address worker and consumer safety as well as environmental protections; prior to its development, regulations varied significantly except in the case of transport where the UN Model Regulations was in place. It aims to provide a basis for harmonization of rules and regulations on chemicals at national, regional, and worldwide level, an important factor for trade facilitation.

The GHS was adopted by OSHA in the U.S. in 2012, aligning global communications on the risks of chemicals found in the workplace in 29 CFR § 1910.1200, Hazard Communication Standard (HCS). The HCS specifies requirements for labels and standardizes SDSs that must accompany hazardous chemicals and contain more complete details regarding their handling. There are several differences between the HCS and GHS, notably regarding hazard identification, label and SDS requirements, and the classification of aerosols (e.g., The HCS has one hazard class/category for Flammable Aerosols and does not require testing. The GHS has two hazard categories). Experts anticipate that OSHA will align the aerosol classification with the GHS through a rulemaking initiative.

H.6.1 Hazard Classification in the Hazard Communication Standard

A significant difference between the HCS and GHS is the evaluation of mixtures. The HCS allows test data on mixtures to be used for all hazard classes, while the GHS criteria for mixtures vary by hazard class, allowing test data on carcinogens, mutagens, and reproductive toxins on a case-by-case basis.

In the HCS, chemical manufacturers and importers must evaluate chemicals produced in their workplaces or imported by them to determine if they are hazardous. This evaluation must be based on statistically significant evidence from at least one positive study conducted in accordance with established scientific principles. In the GHS, the criteria for many hazard classes are semiquantitative or qualitative, requiring expert judgment to interpret the data for classification purposes. When conducting hazard classification under the GHS, one must identify data regarding the hazards of the substance or mixture, review those data to determine the hazards associated with the substance or mixture, and determine the degree of hazard presented by the substance or mixture by comparing the data with the hazard classification criteria. The GHS does not require a scientific study as in the HCS.

One of the principal hazards in the transportation of aerosols is flammability. Aerosols are classified as extremely flammable (Category 1), flammable (Category 2), or nonflammable (Category 3) in the GHS. In the GHS, aerosols are classified according to the classification of the most flammable component making up more than one percent (by mass) of the components of the aerosol. In contrast, in the HCS, an aerosol is classified by the amount of flammable material it contains, the heat of combustion of the contents, or the result of a flammability test. In the GHS aerosols are defined as:

> "Aerosols means any nonrefillable receptacles made of metal, glass or plastics and containing a gas compressed, liquefied or dissolved under pressure, ***with or without*** a liquid, paste or powder, and fitted with a release device allowing the contents to be ejected as solid or liquid particles in suspension in a gas, as a foam, paste or powder or in a liquid state or in a gaseous state. Aerosol includes aerosol dispensers.

OSHA's HCS defines aerosols as:

> "Aerosol means any nonrefillable receptacle containing a gas compressed, liquefied or dissolved under pressure, and fitted with a release device allowing the contents to be ejected as particles in suspension in a gas, or as a foam, paste, powder, liquid or gas."

OSHA's definition does not restrict the aerosol from only containing a gas.

H.6.2 Labeling Requirements in the Hazard Communication Standard

Under HCS, labels for hazardous chemicals must include the product identifier; signal word; hazard statement(s); precautionary statement(s); pictogram(s); and name, address, and telephone number of the chemical manufacturer, importer, or other responsible party. Each of these elements is described in below.

- Product Identifier: This can be (but is not limited to) the chemical name, code number, or batch number as decided by the manufacturer, importer, or distributor. The product identifier must match on the label and in Section 1 of the SDS.

- Signal Word: This is used to indicate the relative level of severity of the hazard and can only be one of two words, "Danger" or "Warning." Within a specific hazard class, "Danger" designates the more severe hazards, and "Warning" the less severe hazards. The label may only contain one signal word and should be labelled with "Danger" if at least one of the hazards warrants that label.

- Hazard Statements: These statements describe the nature of the hazard(s) of a chemical, including, where appropriate, the degree of hazard. Hazard statements are specific to hazard classification categories and should always be the same for the same hazards.

- Precautionary Statements: These statements describe recommended measures that should be taken to minimize or prevent adverse effects resulting from exposure to the hazardous chemical or improper storage or handling. The four types of precautionary statements are: 1) prevention (to minimize exposure); 2) response (in case of accidental spillage or exposure); 3) storage; and 4) disposal.

- Pictograms: These are graphic symbols used to communicate specific information about the hazards of a chemical. The required pictograms consist of a red square frame set at a point with a black hazard symbol on a white background, wide enough to be clearly visible. The GHS uses a total of nine pictograms, but OSHA only enforces the use of eight. The environmental pictogram is not mandatory but may be used to provide additional information. The pictograms do not replace the diamond-shaped labels required by the U.S. DOT. The nine pictograms are shown in Figure 6.9.

Figure 6.9 Globally Harmonized System of Classification and Labelling of Chemicals Pictograms

Source: Online Electronics, Inc., “Brady 133170,” April 12, 2019, www.onlineelec.com/parts/brady/mro/133170?campaign=238033583&content=48239295983&keyword=45644&gclid=Cj0KCQjw7sDlBRC9ARIsAD-pDFoQbfJHmg2nRbEQjY9XRegRdn2b7Za1OBLCs_9NJCrKLgYVABcCFL4aApqeEALw_wcB.

For aerosols, the GHS and HCS specify the label elements for each aerosol category. The HCS does not require the second line of the hazard statement, and no hazard statement is required for nonflammable aerosols. The label elements not listed in the table (product identifier and precautionary statements) are aerosol-specific.

Table 6.24 Globally Harmonized System of Classification and Labelling of Chemicals and Hazard Communication Standard Label Requirements for Aerosols

	Category 1	Category 2	Category 3
Pictogram	Flame	Flame	None
Signal word	Danger	Warning	Warning
Hazard statement	Extremely flammable aerosol Pressurized container: May burst if heated[1]	Flammable aerosol Pressurized container: May burst if heated[1]	Pressurized container: May burst if heated[1]

Source: United Nations, 2017, *GHS of Classification and Labelling of Chemicals, Seventh Revised Edition,* Society for Chemical Hazard Communication and Occupational Safety and Health Administration Alliance (SCHC-OSHA Alliance). *Hazard Communication Information Sheet reflecting the U.S. OSHA Implementation of the GHS of Classification and Labelling of Chemicals*, March 2017.

[1] This hazard statement is not required under the HCS.

H.6.3 Safety Data Sheet Requirements in the Hazard Communication Standards

The SDSs (formerly Material Safety Data Sheets or MSDS) must be presented in a consistent, user-friendly format with 16 sections. Sections 1 through 8 contain general information about the chemical, identification, hazards, composition, safe-handling practices, and emergency control measures. Sections 9 through 11 and 16 contain other technical and scientific information, such as physical and chemical properties, stability and reactivity information, toxicological information, exposure control information, and other information, including the date of preparation or last revision. When the preparer does not find relevant information for any required element, it must be explicitly stated that no applicable information was found. Sections 12 through 15 are required, to be consistent with the GHS, but OSHA does not enforce their content because they concern matters handled by other agencies. A description of all 16 sections of the SDS is provided in Table I.3. More details on each category can be found in the OSHA brief referenced below the table.

Table 6.25 Occupational Safety and Health Administration Hazard Communication Standard: Safety Data Sheets

Section	Contents	Description
1	Identification	This section identifies the chemical on the SDS, as well as the recommended uses, and provides the essential contact information of the supplier.
2	Hazard Identification	This section identifies the hazards of the chemical presented on the SDS and the appropriate warning information associated with those hazards.
3	Composition/ Information on Ingredients	This section identifies the ingredient(s) contained in the product indicated on the SDS, including impurities and stabilizing additives. This section includes information on substances, mixtures, and all chemicals where a trade secret is claimed.
4	First-Aid Measures	This section describes the initial care that should be given by untrained responders to an individual who has been exposed to the chemical.
5	Fire-Fighting Measures	This section provides recommendations for fighting a fire caused by the chemical.
6	Accidental Release Measures	This section provides recommendations on the appropriate response to spills, leaks, or releases, including containment and cleanup practices to prevent or minimize exposure to people, properties, or the environment. It also may include recommendations distinguishing between responses for large and small spills where the spill volume has a significant impact on the hazard.
7	Handling and Storage	This section provides guidance on the safe handling practices and conditions for safe storage of chemicals.
8	Exposure Controls/ Personal Protection	This section indicates the exposure limits, engineering controls, and personal protective measures that can be used to minimize worker exposure.
9	Physical and Chemical Properties	This section identifies physical and chemical properties associated with the substance or mixture.
10	Stability and Reactivity	This section describes the reactivity hazards of the chemical and the chemical stability information. This section is broken into three parts: reactivity, chemical stability, and other.
11	Toxicological Information	This section identifies toxicological and health effects information or indicates that such data are not available.
12[1]	Ecological Information	This section provides information to evaluate the environmental impact of the chemical(s) if it were released to the environment.
13[1]	Disposal Considerations	This section provides guidance on proper disposal practices, recycling or reclamation of the chemical(s) or its container, and safe handling practices. To minimize exposure, this section also should refer the reader to Section 8 (Exposure Controls/Personal Protection) of the SDS.
14[1]	Transport Information	This section provides guidance on classification information for shipping and transporting of hazardous chemical(s) by road, air, rail, or sea.
15[1]	Regulatory Information	This section identifies the safety, health, and environmental regulations specific for the product that is not indicated anywhere else on the SDS.
16	Other Information	This section indicates when the SDS was prepared, or when the last known revision was made. The SDS also may state where the changes have been made to the previous version. You may wish to contact the supplier for an explanation of the changes.

Source: United States Department of Labor, Occupational Safety and Hazard Administration, "Hazard Communication Standard: Safety Data Sheets." February 2012, www.osha.gov/Publications/OSHA3514.html.

[1] Section is required to be consistent with UN Globally Harmonized System of Classification and Labelling of Chemicals, but it is not enforced by OSHA.