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Water Mist Fire Suppression System Feasibility Study

DOT/FRA/ORD-23/08

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14. ABSTRACT
The Federal Railroad Administration tasked a team from the John A. Volpe National Transportation Systems Center to research the technical background and use of water mist fire suppression systems in handling on-board fires in locomotives and passenger cars. The team researched the feasibility and safety benefits of installing new and retrofitted water mist suppression systems in locomotives and passenger railcars to gain an understanding of the feasibility and applicability of water mist systems to the U.S. rail environment and how they can be best used in a variety of passenger railcars and their associated locomotives.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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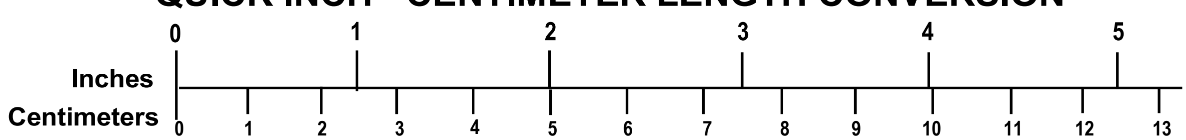
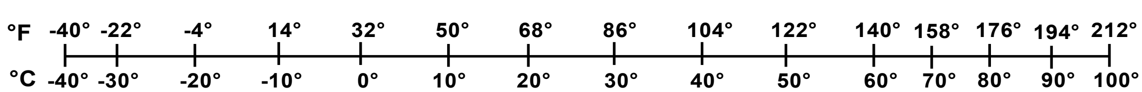
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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Cover Photo: New Jersey Transit Bombardier ALP45-DP No. 4508 at Sunnyside Yard in Queens. Photo credit: Bernard J. Kennedy IV (May 2017)

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Executive Summary

The Federal Railroad Administration (FRA) tasked a team from the John A. Volpe National Transportation Systems Center (Volpe Center) to research the technical background and use of water mist fire suppression systems in handling on-board fires in locomotives and passenger cars. The team researched the feasibility and safety benefits of installing new and retrofitted water mist suppression systems in locomotives and passenger railcars to gain an understanding of the feasibility and applicability of water mist systems to the U.S. rail environment and how they can be best used in a variety of passenger railcars and their associated locomotives.

Water mist fire suppression systems are a type of fire protection system that use fine water mist to help control, suppress, and extinguish fires. Water mist systems control the fire by reducing the heat release rate, displacing the oxygen around the fire with vaporized water, and wetting and cooling the surrounding surfaces to prevent re-ignition. These systems are customizable for their specific applications and have been installed in buildings, tunnels, ships, and transit and railroad equipment. Researchers identified one railroad operator in the U.S. and one railroad operator in Canada that use water mist fire suppression systems in locomotives and international operators that use the systems in passenger railcars.

The Volpe Center reviewed FRA Office of Safety Analysis data on accident/incidents involving Fire/Violent Rupture cause codes, as well as reviewed previous studies on rail accidents. For the years 2015-2020, there were 27 reportable events under the Fire/Violent Rupture cause code. Several of the fire events involving locomotive fires had reported equipment damages exceeding $500,000 and rendered the locomotives out of service until they had been fully repaired. Nine of the 27 reported incidents (one-third) were due to engine fires, and the total damage likely could have been reduced had a water mist fire suppression system been installed.

The decision to install fire suppression systems onboard locomotives and passenger railcars is usually driven by regulatory requirements and the results of a fire safety analysis that identifies, analyzes, and determines countermeasures for onboard fire safety. In the United States, the Code of Federal Regulations requires that railroads complete and submit a fire safety hazard analysis for FRA approval for both new and existing passenger railcars and locomotives. As part of the fire safety analysis, the railroad must consider the use of fire suppression devices and systems as possible mechanisms for reducing fire risk, but the U.S. regulatory requirements for railroad applications of water mist systems are non-prescriptive and subjective to the railroad's determination of the need for such systems as countermeasures.

1. Introduction

The Federal Railroad Administration (FRA) Office of Research, Development, and Technology tasked a team from the John A. Volpe National Transportation Systems Center (Volpe Center) to research the technical background and use of water mist fire suppression systems in handling on-board fires in locomotives and passenger cars. The research was conducted between 2020 and 2021. Fires onboard passenger trains are quite rare, but when they do occur they can have deadly consequences. Water mist fire suppression systems have become a useful countermeasure against fires in buildings, tunnels, ships, and transit vehicles.

1.1 Background

Since the early 1980s there have been very few major fire events (i.e., involving major interior damage/destruction/death) onboard passenger trains. Examples of major railcar fires that occurred include Gibson, CA (1983), Bourbonnais, IL (1999), Miriam, NV (2011), and Valhalla, NY (2015) (Federal Railroad Administration, 2021). The aftermath of the Valhalla, NY, fire is shown in Figure 1.

In 2017, FRA tasked a team to research the use of fire detection and suppression systems onboard passenger trains. As a follow on to that research effort, FRA tasked the Volpe Center to research the feasibility and safety benefits of water mist fire suppression systems in passenger railcars and locomotives.

Figure 1. Interior of Valhalla, NY, passenger car after fire event (National Transportation Safety Board, 2017)

1.2 Objective

The team researched the feasibility and safety benefits of installing water mist suppression systems in new locomotives and passenger railcars as well as retrofitting the systems into existing rail equipment. The research team's overall objective was to gain an understanding of the feasibility and applicability of water mist systems to the rail environment and how they can be best utilized in a variety of passenger railcars and locomotives.

1.3 Overall Approach

The Volpe Center conducted research on railroads using water mist fire suppression systems in the United States and internationally through publications, manufacturer literature, and communication with users and experts. Specifically, the Volpe Center team spoke with representatives from New Jersey Transit, Exo (Montreal's Commuter Rail System), the Los Angeles County Metropolitan Transportation Authority, and representatives from FOGTEC Fire Protection to gain an understanding of how these rail systems use water mist fire suppression systems.

The Volpe Center team also looked at FRA Office of Safety Analysis data on accidents/incidents involving Fire/Violent Rupture cause codes and reviewed previous studies on rail accidents. The Volpe Center team reviewed and analyzed the data to gain a greater understanding of reportable accidents/incidents involving fires onboard passenger trains.

1.4 Scope

The scope of this study included researching the feasibility and safety benefits of water mist fire suppression systems, studying current uses in rail and other applications, determining possible future applications of water mist fire suppression systems in rail equipment, and reviewing fire safety regulations governing fire suppression systems in the passenger rail environment.

1.5 Organization of the Report

The report is divided into seven sections. Section 2 provides an overview of the current use of water mist fire suppression systems in the rail and other industries. Section 3 reviews accident/incident data from fire events. Section 4 discusses potential applications for water mist systems onboard rail equipment. Section 5 provides more detailed information on water mist systems, including principles of operation, benefits, challenges, and costs. Section 6 reviews regulations governing fire suppression systems onboard rail equipment. Section 7 provides overall findings, conclusions, and recommendations for further work.

2. Uses of Water Mist Fire Suppression

Water mist fire suppression systems are a type of fire protection system that use fine water mist to help control, suppress, and extinguish fires. These systems are customizable for their specific applications and have been installed in buildings, tunnels, ships, and transit and railroad equipment.

Water mist systems work in enclosed spaces by reducing the rate at which the fire releases energy (i.e., the heat release rate), displacing the oxygen around the fire with vaporized water, and wetting and cooling the surrounding surfaces to control the fire. The high cooling capacity from water mist ensures that only a limited amount of water is needed to put out a fire, which is important for rail applications that require storage tanks for the water supply. Additionally, these systems are safer for people and the environment than chemical agent systems as they achieve rapid cooling of the hot surfaces with reduced potential for re-ignition. These systems also have minimal interaction with electrical systems, which makes them safer to use in many applications, and the water mist itself has low conductivity. Studies have shown that fine water mist from fire suppression systems does not cause serious electrical leakage or damage to electrical and electronic equipment (Liu & Kim, 2001) and no measurable current is present in the water mist (Dirkmeier & Redding, 2020).

This section discusses current uses of water mist fire suppression systems. A more detailed discussion of system principles and benefits is included in Chapter 5.

2.1 Current Use of Water Mist Fire Suppression in Railroad Applications

Passenger railroad operators in the United States, Canada, and other countries currently use water mist fire suppression onboard passenger trains.

2.1.1 Uses in the United States

Research for this study revealed that one passenger railroad in the U.S. uses water mist fire suppression systems onboard its trains. New Jersey Transit operates 35 Bombardier ALP-45DP locomotives with water mist fire suppression and ordered 25 additional units in 2019 (Figure 2). The Bombardier ALP-45DP is a dual-mode diesel/electric locomotive that can run under diesel power or electric power. The ALP-45DP was designed with a FOGTEC water mist fire suppression system in the two diesel engine compartments (D'Andrea, 2020).

Figure 2. New Jersey Transit ALP-45DP Locomotive (Kennedy IV, 2017)

2.1.2 Uses in Canada

Exo also operates Bombardier ALP-45DP locomotives. These units were acquired in a joint procurement with New Jersey Transit. Similar to the New Jersey Transit locomotives, the Exo units are equipped with a FOGTEC Water Mist Fire Suppression System in the two diesel engine compartments (Bigras, 2021).

2.1.3 Uses in Other Countries

Water mist fire suppression is used in the rail environment on a much larger scale internationally, particularly across Europe on several high speed rail trainsets, as well as on regional and inter-city trains. Many of these trainsets are equipped with water mist fire suppression systems in the passenger compartments, while in the U.S. and Canada the systems are found in the locomotive engine compartment. Examples of international use are below.

- Italian high-speed train operator Nuovo Trasporto Viggiatori (NTV) operates Alstom AGV high-speed rail trainsets across four lines in the country. These trainsets are equipped with water mist fire suppression systems in the passenger coaches through the trainset.
- Switzerland's national railway SBB (Swiss Federal Railways) operates Stadler's EC250 low-floor high-speed rail trainset between Basel and Zurich to Milan through the Gothard Base Tunnel. These trainsets are equipped with water mist suppression systems in the passenger coaches.
- Italian operator Trenitalia and Switzerland's SBB both operate Alstom ETR 610 trainsets These trainsets are protected in the passenger coaches with a water mist fire suppression system.
- German operator NVR operates Siemens Miero electric multiple unit (EMU) trains on the Rhine-Ruhr Express (RRX). These trainsets are equipped with water mist fire suppression systems in the bathrooms in each passenger coach.
- United Kingdom's Intercity Express Programme uses the Hitachi AT 300 running between major cities in Northern England and Scotland. The Hitachi AT 300 units are dual mode units that can operate under diesel power or electric power. These units are equipped with water mist systems in the diesel engine compartments.

2.2 Other Relevant Applications

Water mist fire suppression systems are widely used for fire protection in other industries, including the light-rail transit industry (i.e., underground transit systems and elevated monorails), maritime industry, buildings, and tunnels. System designs and lessons learned can be adapted from other industries to passenger rail applications.

2.2.1 Transit

The Los Angeles County Metropolitan Transportation Authority (LA Metro) Subway System has finalized procurement of 64 new heavy rail subway cars from CRRC Corporation Limited for LA Metro's Red and Purple Lines. These subway cars will feature an "open gangway," which means that passengers can travel from car to car without having to exit the train (Figure 3). In open gangway subway cars, there are no end doors between married pairs of cars. The open, non-compartmentalized nature of the open gangway subway cars means that a fire could easily spread throughout the married pair. The National Fire Protection Association (NFPA) 130 Standard for Fixed Guideway Transit and Passenger Rail Systems requires that vehicles with open gangways have features to deter both smoke and fire spread from car to car (National Fire Protection Association, 2020). A computational fluid dynamics model showed that a fast growing fire in the railcars would require fire suppression and tunnel-based sprinkler systems would not be sufficient. Instead, a water mist fire suppression system will be installed to allow for adequate fire protection (Los Angeles County Metropolitan Transit Authority, 2016).

Water mist fire suppression systems are also found in several monorail systems and underground subway (i.e., metro) systems. Sao Paulo's Line 15 Monorail in Brazil operates Bombardier Innovia Monorail 300 units that use a water mist system in the passenger areas. The Sao Paulo Metro also operates rolling stock built by Construcciones y Auxiliar de Ferrocarriles (CAF) and Hyundai Rotem, which both use water mist systems in the passenger areas.

Figure 3. Mock-Up of new LA Metro subway cars with open gangways (The Source, 2019)

2.2.2 Maritime

Water mist fire suppression systems are also used in the maritime industry on passenger cruise ships, luxury yachts, and cargo ships. Maritime codes require fire suppression systems to be installed in hazardous spaces and water mist fire suppression systems have been successfully used in machinery spaces, service areas, public spaces, cargo spaces, accommodation rooms, kitchen deep fryers, inside air duct systems, and along balconies. Several of the systems have been "type-approved" by the U.S. Coast Guard and other marine classification societies, meaning these standard designs have been tested and proven successful in accordance with independent technical rules developed based on experience, research, and calculations.

One difference between maritime and rail applications is that the water supply is never depleted in maritime applications. If the onboard water tanks are emptied, the system can switch to use seawater for continuous fire protection.

2.2.3 Buildings

Water mist fire suppression systems are used in different building applications including offices, hotels, hospitals, museums, and data centers. Water mist systems can be especially useful in historic and sensitive locations where damage from sprinkler water would be unacceptable. Standard sprinkler fire suppression systems use a much larger amount of water and can cause extreme water damage, whereas water mist systems use limited amounts of water. Additionally, standard sprinkler systems can become costly when buildings are retrofitted, whereas water mist systems can be installed independently throughout the building. Some examples of fixed water mist suppression systems installed in buildings include the Mecca Clock Tower in Saudi Arabia, Palacio de Cibeles, an historic town hall in Madrid, Spain, and the Baden-Mödling hospital in Austria (FOGTEC Fire Protection, 2020).

2.2.4 Tunnels

Water mist fire suppression systems have been installed in tunnels where fire can cause a major disruption to transport. Examples of systems currently installed in tunnels include the Dartford tunnel passing under the River Thames in England and the Channel Tunnel connecting the United Kingdom and France. The systems are also used by Eurostar passenger trains and freight trains. In the United States, the Brooklyn Battery Tunnel connecting Brooklyn and Manhattan is in the process of installing a water mist fire suppression system.

3. Accident/Incident Data Analysis

The Volpe Center research team reviewed FRA Office of Safety Analysis data on accidents/incidents involving Fire/Violent Rupture cause codes and previous studies on rail accidents. The team analyzed these data to gain a greater understanding of reportable accidents/incidents involving fires onboard passenger trains.

3.1 FRA Office of Safety Analysis Accident/Incident Data

FRA Office of Safety Analysis accident/incident reporting regulations require railroads to report all rail equipment accidents/incidents above the reporting threshold for that calendar year to the agency. In 2015 and 2016, the reporting threshold was $10,500. Between 2017 and 2020, the reporting threshold was $10,700 (Federal Railroad Administration, 2021).

For the years 2015-2020, there were 27 reportable events under the Fire/Violent Rupture cause code (Federal Railroad Administration, 2020). The data show that the fires were primarily caused by the following equipment: traction motors, diesel engines, diesel engine turbos, and passenger coach batteries. There were no reported injuries or deaths due to these fire events. Several of the fire events involving locomotive fires had reported equipment damages exceeding $500,000 and rendered the locomotives out of service until they were fully repaired. A summary of the accident/incident data is shown in Table 1.

Water mist fire suppression systems have been shown to be effective on diesel engine fires that occur in enclosed spaces. Nine of the 27 reported incidents (i.e., one-third) were due to engine fires and the total damage likely could have been reduced had a water mist fire suppression system been installed.

Table 1. Accident/Incident Fire/Violent Rupture Cause Code 2015-2020

Date	State	Nearest City/Town	Railroad	Cause
7-Oct-2020	MA	WHITMAN	MBTA	Traction Motor Fire
5-Oct-2020	NJ	PENNSAUKEN	NJ TRANSIT	Engine Fire
19-Aug-2020	FL	DEERFIELD BEACH	SFRTA	Traction Motor Fire
19-Jul-2019	VA	CLIFTON FORGE	AMTRAK	Engine Fire - Turbo
21-Apr-2019	MI	DOWAGIAC	AMTRAK	Passenger Coach Battery Fire
4-Apr-2019	IL	MENDOTA	AMTRAK	Traction Motor Fire
2-Mar-2019	PA	CROYDON	SEPTA	Traction Motor Fire
31-Jan-2019	NJ	PENNSAUKEN	NJ TRANSIT	Engine Fire
30-Jan-2019	CO	DENVER	AMTRAK	Electrical Fire - Locomotive
3-Dec-2018	IL	MORTON GROVE	METRA	Engine Fire
29-Aug-2018	PA	GLENSIDE	SEPTA	Electrical Fire
21-May-2018	NC	FAYETTEVILLE	AMTRAK	Passenger Coach Battery Fire
20-Apr-2018	CA	SAN JOSE	CALTRAIN	Passenger Coach Battery Fire
8-Apr-2018	CA	NEDLES	AMTRAK	Engine Fire
4-Mar-2018	NJ	BORDENTOWN	NJ TRANSIT	Engine Fire - Turbo
26-Feb-2018	FL	MIAMI-DADE	SFRTA	Engine Fire
20-Feb-2018	NY	CANASTOTA	AMTRAK	Traction Motor Fire

Date	State	Nearest City/Town	Railroad	Cause
12-Feb-2018	PA	PHILADELPHIA	SEPTA	Electrical Fire
14-Jan-2018	IN	CHESTERTON	NICD	Electrical Fire - Locomotive
22-Dec-2017	CA	GOLETA	AMTRAK	Electrical Fire-Locomotive
30-Nov-2017	WA	SEATTLE	AMTRAK	Engine Fire
14-Dec-2015	MA	WEYMOUTH	MBTA	Electrical Fire - Locomotive
14-May-2015	WI	MILWAUKEE	AMTRAK	Engine Fire
14-Mar-2015	NJ	NEWARK	PATH	Electrical Fire - Locomotive
7-Feb-2015	PA	VILLANOVA	SEPTA	Electrical Fire
26-Jan-2015	AZ	HOLBROOK	AMTRAK	Passenger Coach Battery Fire

3.2 Review of Accident Data for Fires Under Railcars

The Volpe Center research team also reviewed a previous study on accident data for fires under railcars (McKinnon, Caton, Lattimer, & Simeoni, 2017). This report surveyed passenger railway incidents, with an emphasis on incidents that involved exposure of the locomotive or passenger cars to external fires. The incidents identified in Table 2 include fires started exterior to the train due to collisions, mechanical issues, fuel spills, electrical fires, or track fires. Of the 51 incidents listed, 21 involved exterior fires that impinged or penetrated the interior of the locomotive or train cars. Nine of the fires also occurred after a derailment. Note that the data do not always identify whether fire or smoke entered the train or whether the train derailed in each incident.

Table 2: Review of Accident Data for Fires Under Railcars

Date	Incident Location	Fire/Smoke Enter Train?	Did Train Derail?
14-Sep-2016	Bulgaria	No	-
8-Jul-2016	Bulgaria	No	-
16-Jun-2016	Bulgaria	No	-
13-Apr-2016	Bulgaria	No	-
13-Oct-2015	Bulgaria	No	-
3-Feb-2015	Valhalla, NY	Yes	No
30-Jan-2015	UK	Yes	-
7-Nov-2013	Ireland	No	-
8-Jan-2013	UK	No	-
19-Dec-2012	Bulgaria	No	-
2-Aug-2012	Romania	No	-
20-Jul-2011	Bulgaria	Yes	-
24-Jun-2011	Miriam, NV	Yes	No
11-May-2011	Romania	No	-
2-Nov-2010	Romania	No	-
23-Aug-2010	Romania	No	-
7-Feb-2010	Romania	-	-
26-Dec-2009	France	Yes	-
30-Nov-2009	Bulgaria	-	-
16-Aug-2009	Richmond, ON	No	No

Date	Incident Location	Fire/Smoke Enter Train?	Did Train Derail?
12-Sep-2008	Chatsworth, CA	Yes	Yes
30-Jul-2008	Czech Republic	Yes	-
24-Jun-2008	France	Yes	-
6-Aug-2005	France	Yes	-
10-Mar-2004	Queens, NY	No	No
5-Jan-2004	Hong Kong	Yes	-
18-Feb-2003	South Korea	Yes	-
24-Jan-2002	Japan	-	-
5-Oct-1999	UK	Yes	-
15-Mar-1999	Bourbonnais, IL	Yes	Yes
13-Nov-1997	Japan	-	-
14-May-1997	Branson, MO	No	Yes
16-Feb-1996	Silver Spring, MD	Yes	Yes
8-Sep-1995	UK	Yes	-
14-Apr-1995	Japan	-	-
20-Nov-1994	Brighton, ON	Yes	Yes
22-Mar-1994	Japan	-	-
22-Sep-1993	Mobile, AL	Yes	Yes
27-Aug-1993	Japan	-	-
17-Mar-1993	Ft. Lauderdale, FL	No	No
29-Aug-1992	Japan	-	-
12-Dec-1990	Boston, MA	No	Yes
18-Dec-1989	Stockton, CA	Yes	Yes
4-Jan-1987	Chase, MD	Yes	Yes
22-Oct-1985	Japan	-	-
26-Sep-1985	Japan	-	-
6-Feb-1983	Japan	-	-
14-Mar-1982	Mineola, NY	No	No
25-Feb-1982	Japan	-	-
2-Jan-1982	Southampton, PA	Yes	No
28-Dec-1966	Everett, MA	Yes	No

Because these incidents involved exterior fires, it is unlikely a water mist system would have suppressed the initial fire. Water mist fire suppression systems work best in enclosed locations where oxygen can be displaced with water vapor, not in exterior locations. It is also not known whether a water mist fire suppression system would survive major accidents and derailments where there is potential for physical damage to the system. However, for fires that propagated to the interior of the locomotive or passenger car, it is possible that a water mist system could have reduced the impact of fire and smoke on passengers (e.g., smoke inhalation and egress time) or could have reduced damage caused by the fire incident.

4. Potential Applications for Water Mist Fire Suppression

Water mist fire suppression systems can be useful to control onboard fires in a variety of situations, such as providing additional protection to allow passengers and crew members to safely evacuate from the train or affected area and potentially reducing physical damage due to the fire. This section describes potential railroad applications.

4.1 Locomotive Water Mist Systems

As discussed in Section 3.1, out of the 27 reported incidents, 9 of those events were classified as engine fires. Installing onboard water mist fire suppression systems would allow for automatic protection to mitigate the risk of a damaging fire. If a fire is detected, the system is designed to activate immediately and control or extinguish the fire which would reduce the probability of major damage.

4.2 Commuter and Amtrak Passenger Coaches

Fires onboard passenger trains in sleeping cars, café, and diner cars, as well as any fire in a storage locker or baggage car can become deadly for passengers and crew onboard. Currently, fire or smoke detection is only required in unoccupied compartments when the hazard analysis determines that it is necessary (Passenger Equipment Safety Standards, 49 CFR § 238.103(c)(5), 2019).

Water mist systems can be designed to fit in storage lockers, on the roof, or be undercar mounted, and can be customized for the different types of rail equipment and operating territory. Sleeping cars located on long distance trains could benefit from the implementation of these systems as fires that start in sleeper cars can potentially go undetected for a length of time, especially during hours when most passengers are sleeping in their rooms overnight. For example, in 1983, Amtrak experienced a major fire onboard a passenger train in Gibson, CA, which originated in a sleeping car but was left undiscovered for an unknown amount of time. By installing a water mist fire suppression system, the sleeper car could be protected by a system which would automatically activate when a fire is detected.

In Amtrak and commuter train coach cars, detection normally occurs when the passengers riding in a car notice there is a fire and then notify a crewmember. The crewmember or passengers would then use a fire extinguisher to put out the fire. One extinguisher is required per passenger car (Passenger Train Emergency Preparedness, 49 CFR § 239.101(a)(6)(A), 2019). However, a water mist system could be used to automatically detect and suppress a fire in a coach car if no passengers or crewmembers are nearby.

These systems could also be useful in the kitchen areas of café and diner cars where there is a higher risk of fire due to the heat and potential ignition sources necessary for cooking and preparing meals.

4.3 Tunnels and Underground Stations

Fires that occur in locomotives and passenger cars in tunnels and underground stations can create a serious safety risk for passengers and crew members. When there is a fire onboard a train in a tunnel, evacuation of passengers and crew is affected because of the limitation of free movement, either onto the right of way or along tunnel bench walls. In tunnels and underground stations, if the ventilation system is not adequate, toxic smoke and gases can build up and harm people evacuating from the train. Onboard water mist fire suppression systems could activate immediately when a fire is detected and could help control and extinguish fires.

5. Water Mist Fire Suppression Technical Information

Water mist fire suppression systems are beneficial to protect both locomotives and passenger cars from onboard fires. These systems are designed to help minimize the possibility of a fire spreading, as they can detect a fire quickly and activate the nozzles closest to the fire. This section describes detailed technical information, benefits, design challenges, and costs for water mist fire suppression systems in rail applications.

5.1 Principles of the System

Water mist systems work to control fires by reducing the heat release rate, displacing the oxygen in the area of the fire with vaporized water, and wetting and cooling the surrounding surfaces to prevent re-ignition (FOGTEC Fire Protection, 2020). Water mist systems have a high cooling capacity due to the size of the water droplet dispensed. Once discharged, water mist is suspended in the air to ensure rapid cooling of the fire and surrounding areas to prevent re-ignition. The water vapor that is created helps reduce the oxygen supply to the fire source and extinguish the fire. Water mist systems work best in a confined environment where the water mist can remain in place without dissipation.

Water mist fire suppression systems are available in a variety of designs depending on their application. The systems can be designed for different pressures (low, intermediate, and high). They can be single-fluid systems with water only, or twin-fluid systems with gaseous additives (e.g., compressed air or nitrogen) to help atomize the water into very fine particles or droplets (water mist systems have droplets smaller than 1,000 microns). Heating systems can be used in low-temperature applications, or chemicals such as antifreeze can be added to reduce the freezing temperature of the water.

A typical water mist fire suppression system in a locomotive or passenger car consists of several components including water and nitrogen cylinders, section valves and nozzles, and a central processing unit (CPU) main controller. The water mist system works in conjunction with fire detection systems (e.g., smoke detectors, temperature sensors, and heat detectors) that detect a fire and send a signal to the system CPU main controller which then activates the water mist system.

Water mist systems can be designed for total flooding or local application. A total flooding system is designed to discharge water mist throughout an entire enclosed compartment. In local applications, the water mist system targets the specific area where fire is detected.

5.2 Benefits of the System

A water mist fire suppression system offers many benefits over a typical sprinkler system or chemical suppression system.

5.2.1 Efficiency

Regular sprinkler systems have water droplet sizes around 5,000 microns and are designed to flood the area with water to extinguish the fire. Water mist systems use water droplets smaller than 1,000 microns. Smaller water droplets are more efficient at extinguishing a hot fire as the water mist can spray a larger number of droplets over the fire for fast cooling and suppression.

The high cooling capacity of the water mist means limited water is needed to put out the fire, so only a small capacity tank is required onboard.

5.2.2 Less Physical Damage

As typical water sprinkler systems are designed to flood an entire space with water, they can cause significant water damage to structures and equipment. Chemicals in fire suppression systems can cause corrosion and equipment damage. Conversely, in a water mist system, the mist settles slowly once it is discharged into the area with high humidity. A typical water mist system outputs less than 20 gallons over the entire discharge period, causing less water damage. Further, equipment in locomotives and passenger cars are often designed to be resistant to humidity and sprays.

Water mist systems also have insignificant interaction with electrical components and do not cause significant damage to electrical systems, which makes them safer to use in many applications. In testing at high voltages (up to 5 kilovolts) there was no measurable current present in the water mist (Dirkmeier & Redding, 2020). Additionally, the small total volume of water from water mist does not cause serious electrical leakage or damage to electrical and electronic equipment (Liu & Kim, 2001).

5.2.3 Safer for People and the Environment

Although effective, gaseous and foam fire suppression systems can be harmful to people and the environment. Some gaseous and foam agents have been shown to be carcinogens, harmful to drinking water, and harmful to the environment and aquatic life. Carbon dioxide systems are designed to displace oxygen in the space and can cause suffocation and death. Conversely, water mist is inherently safe for people and the environment.

5.2.4 Flexibility of Installation

Water mist systems can be installed in a variety of locations in railcars and in locomotives, including in equipment lockers, roof assemblies, and suspended (i.e., undercar) assemblies. The flexibility of installation allows for easier retrofit in existing equipment.

5.3 Design Challenges

Some design challenges may have to be addressed when integrating water mist fire suppression systems into commuter and intercity passenger rail environments. When installed on new locomotives and railcars, placement of the water mist equipment is not usually an issue as the locomotive or railcar manufacturer will include the water mist systems early in the design. When retrofitting existing locomotives or railcars, additional considerations are required to properly design and install the equipment.

Water mist fire suppression system can be installed in a variety of locations and configurations (e.g., within the locomotive and cars, on railcar roofs, or undercar). When choosing water mist equipment placement, the railroad should consider the operating environment, weather conditions, and maintenance capabilities.

- If the systems are to be installed on the railcar roofs, an analysis should be performed to ensure the extra height will not cause any clearance issues under bridges, in tunnels, or going into maintenance facilities. The railcar weight and any center of gravity changes after the systems are installed should also be analyzed.

- If the locomotives or railcars operate in an environment that is subject to freezing conditions, precautions should be taken to ensure the water in the system does not freeze and damage the water mist equipment. When powered, the water mist systems can use heating elements to ensure the equipment does not freeze. However, if the locomotives or railcars are stored in a yard without access to electricity or heating, the water mist system may freeze and become damaged. The use of appropriate non-toxic antifreeze chemicals may be required.
- As with all assets, the railroad would want to consider its maintenance capabilities before installation. Water mist systems, like all fire suppression systems, require annual inspections, testing, and certifications from fire protection specialists to ensure proper operation. The railroads would want to ensure they have access to appropriate maintenance personnel. If the water mist equipment is installed on railcar roofs or undercar, the railroad would need to ensure they have tools and equipment which can support maintenance in these locations.

5.4 Costs

Water mist fire suppression systems can be cost effective compared to the cost of fire damage. The estimated cost for installation on a diesel locomotive water mist fire suppression system is about $7,000 per module and $15,000 per module for a passenger car system (Dirkmeier & Redding, 2020). Yearly maintenance costs are minimal and typically only involve inspections and testing of the systems. Conversely, some locomotive fires have resulted in damages ranging from $100,000 to $500,000, not including the cost of locomotive downtime. Although total lifecycle costs (including annual testing) must be considered, the overall cost of installation and maintenance over the life of a water mist fire suppression system can be less expensive than the cost of repairing a passenger locomotive or passenger car after a fire.

6. Fire Safety Regulatory Approach

The decision to install a fire suppression system onboard locomotives and passenger railcars is usually driven by regulatory requirements. This section describes requirements in the United States, Canada, and the European Union.

6.1 Federal Regulations

FRA regulations on Fire Safety are contained in the Code of Federal Regulations (CFR) Title 49. Part 238.103 describes the fire safety requirements that must be followed prior to placing a passenger railcar or locomotive into service. The regulation outlines that materials used in constructing a new passenger car must meet fire test performance criteria for flammability and smoke emission characteristics as specified in Part 238.103, Appendix B. In addition, on or after November 8, 1999, materials introduced in a passenger railcar or a locomotive cab, as part of any rebuild, refurbishment, or overhaul of the car or cab, shall also meet the test performance criteria for flammability and smoke emission characteristics. References to standards issued or recognized by an expert consensus organization such as NFPA are also included.

The regulation requires that railroads complete and submit a fire safety hazard analysis for FRA approval for both new and existing passenger railcars and locomotives. The fire safety hazard analysis ensures that railroads evaluate all fire safety hazards and that appropriate fire safety features are designed into their railcars. The analysis is done based on a formal hazard analysis process such as the Department of Defense Standard Practice for System Safety (MIL-STD-882E, 2012). By identifying and prioritizing any fire hazards that are present in the design of the equipment, the railroad will be able to identify and select materials that provide sufficient fire resistance, provide an acceptable level of risk, and allow adequate time to detect a fire and safely evacuate passengers and crew in the event of a fire. As part of the fire safety analysis, the railroad shall also consider the use of fire suppression devices and systems. The analysis shall determine whether any occupied or unoccupied space requires any additional portable fire extinguisher in addition to those already required and, if so, the proper type and size of the fire extinguisher for each location and hazard. Each passenger car is required to have a minimum of one portable fire extinguisher (Passenger Train Emergency Preparedness, 49 CFR § 239.101(a)(6)(A), 2019). If the analysis performed indicates that one or more additional portable fire extinguishers are needed, they must be installed.

The regulation also states that the benefit of including a fixed, automatic fire-suppression system shall also be analyzed on a case-by-case basis. A fixed, automatic fire-suppression system shall be installed in any unoccupied compartment when the fire hazard analysis determines that such equipment is practical and necessary to ensure sufficient time for the safe evacuation of passengers and crewmembers from the train. Consideration should be given to any unoccupied train compartment that contains equipment or material that poses a fire hazard, and the railroad will determine the proper type and size of the automatic fire-suppression system for each such location (Passenger Equipment Safety Standards, 49 CFR § 238.103(c)(7), 2019). One such example is the installation of a dry chemical fire suppression system for an onboard diesel generator in a passenger dome car.

6.2 NFPA 130

The NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems states that on-board fire suppression systems for commuter/intercity railroad use in the United States has been relatively low. Additionally, Annex E provides informational guidance on the Fire Hazard Analysis Process. Annex E makes mention of fire detection and suppression systems as possible mechanisms for reducing fire risk, but the requirements are non-prescriptive and subjective (National Fire Protection Association, 2020).

The 2017 edition of NFPA 130 included an Annex G which provided background information regarding on-board fire suppression systems, including benefits and challenges of the systems, but notes that the annex is not a part of the requirements of the NFPA document (National Fire Protection Association, 2017). Annex G was not part of the 2020 edition of NFPA 130 but is expected to be reinstated in the upcoming 2023 edition.

6.3 American Public Transportation Association

The American Public Transportation Association (APTA) *Recommended Practice for Fire Safety Analysis for Existing Passenger Rail Equipment* provides additional information for completing a fire safety analysis (American Public Transportation Association, 2001). The document breaks the analysis into a twelve step process, but generally follows the requirements identified in 49 CFR 238.103 and NFPA 130.

6.4 Transport Canada

Transport Canada Railway Passenger Car Inspection & Safety Rules outline the minimum safety standards for passenger cars operating in Canada (Transport Canada, 2001). Transport Canada does not specifically address water mist or fire suppression systems. However, the NFPA 130 standard is used by both the United States and Canada. Transport Canada requires that all passenger trains include emergency tools and equipment such as working fire extinguishers, one of which shall be in the galley area onboard the train.

6.5 European Norm 45545

European Norm (EN) 45545 is the European standard for fire protection on railway vehicles. EN 45545 Part 6 describes areas requiring fixed firefighting equipment, however the standard does not specify what type of fixed fire suppression system should be used (European Norm 45545-6, 2015). These requirements only apply to trains with a single locomotive. EN 45545 Part 1 describes how railway vehicles are classified according to categories based on the type of service they provide and the infrastructure over which they are operated (European Norm 45545-1, 2013). These operation categories as defined in EN 45545 are repeated verbatim below:

- Operation Category 1
  - Vehicles for operation on infrastructure where railway vehicles may be stopped with minimum delay and where a safe area can be reached immediately
- Operation Category 2
  - Vehicles that operate in underground tunnels and/or elevated structures that have side evacuation points available or rescue stations that have a place of safety for passengers reachable within a short running time

- Operation Category 3
    - Vehicles that operate in underground tunnels and/or elevated structures that have side evacuation points available or rescue stations that have a place of safety for passengers reachable within a long running time
- Operation Category 4
    - Vehicles that operate in underground tunnels and/or elevated without side evacuation available and where stations or rescue stations that have a place of safety to passengers is reachable within a short running time

EN 45545 Part 1 also describes how railway vehicles are classified into design categories for the different types of rail equipment.

- Design Category A – vehicles forming part of an automatic train having no emergency trained staff on board
- Design Category D – double decked vehicles
- Design Category S – sleeping vehicles
- Design Category N – all other vehicles (standard vehicles)

Table 3 describes areas requiring fixed firefighting equipment as it relates to the operation and design categories described above.

Table 3. EN 45545 Part 6 – Areas Requiring Fixed Firefighting Equipment (European Norm 45545-6, 2015)

	Operation category	Combustion engines	Technical cabinets containing traction equipment
Design Categories N and D	1	nr	nr
	2	nr	nr
	3	X	X
	4	X	X
Design Categories S and DS	1	nr	nr
	2	nr	nr
	3	X	X
	4	X	X
Design Category A	1	nr	nr
	2	nr	nr
	3	X	X
	4	X	X
X indicates requirement nr indicates no requirement			

7. Conclusion and Recommendations

Water mist fire suppression systems control the spread of fire by reducing the heat release rate, displacing the oxygen around the fire with vaporized water, and wetting and cooling the surrounding surfaces. Water mist systems are currently in limited use in rail applications in the United States and Canada but are used more widely in other applications.

Based on publications, manufacturer literature, and communication with users and experts, the research team found that historically there have been limited onboard fire events on passenger trains in the United States, and none of these fire events occurred in equipment with water mist fire suppression. However, when on-board fires do occur and are not controlled in a timely manner, they can become quite costly and potentially catastrophic for passengers and crew. The team found that recent data indicate most fires on passenger trains not caused by major accidents are caused by diesel engine fires, traction motor fires, and other electrical fires. Water mist systems have been shown to work well in enclosed locations such as engine rooms and passenger spaces. However, researchers found that it is not known how a water mist fire suppression system would survive in major accidents or derailments where there is potential for physical damage to the systems, or how the system would perform when fires start exterior to the locomotive or passenger railcars.

The team found that water mist fire suppression systems can be used in additional applications in the United States, including locomotives, commuter rail and passenger coaches, and in tunnels and underground stations. These systems are efficient, cause less damage than other fire suppression systems, are safer for people and the environment, and have flexible installation options. These systems appear to be cost effective as damage from a fire can greatly exceed the cost of installation and maintenance of such systems over the lifetime of the equipment. However, researchers determined that some design challenges that will have to be addressed during design and installation, such as freezing weather conditions and maintenance capabilities.

Regulations in the United States do not mandate the use of fire suppression systems but the use of fixed fire suppression systems is taken into consideration when performing the fire safety hazard analysis required by FRA.

7.1 Recommendations

The research team recommends the following future work to gain further understanding into the usefulness of water mist fire suppression systems onboard locomotives and passenger railcars.

1. Continue to work with the NFPA 130 Technical Committee on further developing technical guidance on water mist fire suppression and other onboard fire suppression systems that can be used in railcars and locomotives.
2. Understand how fire incident/accident data are being reported and analyzed by FRA. Look into smaller scale fire events that do not meet the accident/incident reporting threshold to better quantify the number of fire events in which water mist systems could have been used to suppress onboard fires. A multi-pronged approach can be used to gather incident data below the reporting threshold, including contacting safety and maintenance departments of railroads to request incident reports, working with the FRA System Safety Program and the APTA Safety Management Audit Program to determine

if aggregate incident data or incident reports are available, and querying railroads through APTA for an additional level of anonymity.

3. Model how water mist fire suppression systems can benefit fire safety and emergency egress by providing longer tenability for onboard passengers and crew.

8. References

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Abbreviations and Acronyms

ACRONYM	DEFINITION
APTA	American Public Transportation Association
CPU	Central Processing Unit
CFR	Code of Federal Regulations
CAF	Construcciones y Auxiliar de Ferrocarriles
EMU	Electric Multiple Unit
EN	European Norm
FRA	Federal Railroad Administration
FOGTEC	FOGTEC Fire Protection
FRA RD&T	FRA Office of Research, Development and Technology
NFPA	National Fire Protection Association
NTV	Nuovo Trasporto Viggiatori
RRX	Rhine-Ruhr Express
SBB	Swiss Federal Railways
U.S. DOT	U.S. Department of Transportation
Volpe Center	John A. Volpe National Transportation Systems Center