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EMISSION SCENARIO DOCUMENT ON THE USE OF AQUEOUS FILM-FORMING FOAMS IN FIREFIGHTING

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EMISSION SCENARIO DOCUMENT ON THE USE OF AQUEOUS FILM-FORMING FOAMS IN FIREFIGHTING

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INTER-ORGANIZATION PROGRAMME FOR THE SOUND MANAGEMENT OF CHEMICALS
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OECD Environment Directorate,
Environment, Health and Safety Division
2 rue André-Pascal
75775 Paris Cedex 16
France

Fax: (33-1) 44 30 61 80

E-mail: ehscont@oecd.org

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Explanatory notes

Purpose and background

This OECD Emission Scenario Document (ESD) is intended to provide information on the sources, use patterns, and potential release and exposure pathways of non-volatile chemicals used in Aqueous Film-Forming Foams (AFFFs) in firefighting applications. The document presents standard approaches for estimating the environmental releases of and occupational exposures to chemicals used in AFFF.

The series of ESDs should be seen as 'living' documents which provide the latest information available. As such, this ESD may be updated to take account of any changes and new information in relevant industries, and extended to cover the industry area in countries other than the lead country (the US). Users of the document are encouraged to submit comments, corrections, updates, and new information to the OECD Environment, Health and Safety Division (env.riskassessment@oecd.org). The comments received will be forwarded to the OECD Working Party on Exposure Assessment (WPEA), which will review the comments every two years so that the lead country can update the document. Submitted information will also be made available to users within the OECD website (http://www.oecd.org/env/riskassessment).

How to use this document

This document may be used to provide conservative, screening-level estimates of environmental releases of and occupational exposures to chemical components contained in AFFF formulations. Such estimates might result in release and exposure amounts that are likely to be higher, or at least higher than average, than amounts that might actually occur in real world practice.

The users of this ESD should consider how the information contained in the document emulates the specific scenario being assessed. Where specific information is available, it should be used in lieu of the defaults presented in this document, as appropriate. All input values (default or ESD-specific) and the estimated results should be critically reviewed to assure their validity and appropriateness.

Coverage and methodology

The US Environmental Protection Agency (EPA) developed this ESD using relevant data[1] and information on the use of AFFF, including process descriptions, operating information, types of AFFF, wastes generated, waste treatment, worker activities, and exposure information. EPA supplemented the data collected with standard models[2] to develop the environmental release and occupational exposure estimating approaches presented in this ESD. Non-occupational exposures and environmental releases during consumer use are outside the scope of this document.

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[1] Please see References for a list of the specific references used in developing this ESD.

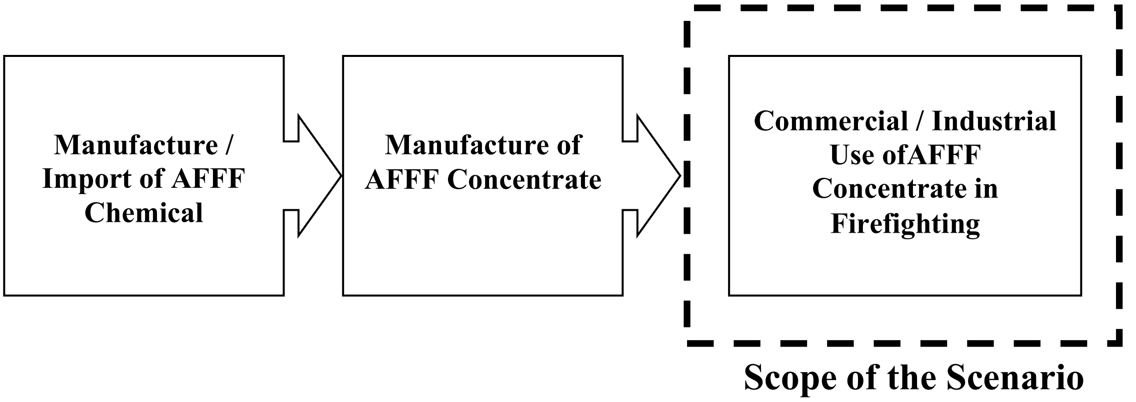
[2] EPA has developed a series of "standard" models for use in performing conservative release and exposure assessments in the absence of chemical- or industry-specific data. Several of these standard models are described in Annex B.

The primary sources of information cited in this ESD include information from the Fire Fighting Foam Coalition (FFFC), and various industry-specific sources, such as the National Fire Protection Association (NFPA) and US Fire Administration. Additional information on the sources investigated and the references cited in this document are presented in *References*.

The information in this document is based on US data. Certain aspects of the use of AFFF may differ in other countries; therefore, alternate assumptions and parameters may be necessary in some applications of this emission scenario.

This ESD includes methods for estimating the environmental releases of, and associated occupational exposures to, nonvolatile chemical components used during the use of AFFF concentrates. The scope of the proposed ESD will only cover the commercial or industrial end use of AFFF concentrates. The manufacturing of the chemical and the formulation of AFFF concentrate are outside the scope of the proposed ESD. Note that AFFF concentrate manufacture is out of the scope of this document; however, there may be releases to water from this sector due to product testing. Figure 1 provides an illustration of the scope of the proposed ESD within the lifecycle of a chemical of interest.

Figure 1. Scope of the ESD on the Use of Aqueous Film-Forming Foams in Firefighting



To estimate environmental releases for the use of AFFF concentrates, this ESD assumes that chemicals used in AFFF concentrates are nonvolatile. EPA often assumes chemicals are nonvolatile if the vapour pressure is less than 0.001 torr (0.133 Pa) (US EPA, 1995[1]). Nonvolatile chemicals result in negligible releases to air from volatilization and negligible associated inhalation exposures (US EPA, 1991[2]). However, other air releases (e.g. mists or aerosols) from process operations may occur.

The methods for estimating the following facility operating parameters and the releases and exposures to chemicals used during the use of AFFF concentrates are discussed in this ESD:

- number of sites in the US storing/using AFFF concentrate containing the chemical of interest;

- releases from transport container residue (via container cleaning or direct disposal of empty containers);
- releases from disposal of spent foam discharge;
- releases from disposal of expired AFFF inventory;
- number of workers that may come into contact with the AFFF concentrate or foam during the firefighting preparation or discharge;
- dermal exposures during container unloading;
- dermal exposures during container cleaning and disposal;
- inhalation and dermal exposures during AFFF discharge;
- dermal exposures during disposal of spent foam discharge; and
- dermal exposures during disposal of expired AFFF inventory.

The estimation methods in this ESD apply to any AFFF component, regardless of its function within the AFFF.

How this document was developed

EPA, with support from Eastern Research Group, Inc. (ERG), has developed this ESD on the use of AFFF. The scope of this ESD is designed to serve the needs of both OECD programs as well as EPA. In the US, the Risk Assessment Division (RAD) of EPA's Office of Pollution Prevention and Toxics (OPPT) is responsible for preparing occupational exposure and environmental release assessments of chemicals for a variety of programs under the Toxic Substances Control Act (TSCA), including Premanufacture Notice (PMN) reviews. While OECD ESDs traditionally focus on the potential releases of chemicals from industrial processes, this document also describes approaches for estimating potential occupational exposures to chemicals used in the use of AFFF. The occupational exposure methods are included so that the ESD may be used to fully support EPA's chemical review programs.

This document is published under the responsibility of the Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology of the OECD.

Abbreviations and Acronyms

AFCEE	Air Force Center for Engineering and the Environment
AFFF	Aqueous Film-Forming Foam
ARFF	Aircraft Rescue and Fire Fighting
BOD	Biological Oxygen Demand
CEB	Chemical Engineering Branch
ChemSTEER	Chemical Screening Tool for Exposures and Environmental Release
COD	Chemical Oxygen Demand
DOD	Department of Defense
ECF	Electrochemical Fluorination
ECHA	European Chemicals Agency
E-FAST	Exposure and Fate Assessment Screening Tool
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERG	Eastern Research Group, Inc.
ESD	Emission Scenario Document
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
FFFC	Fire Fighting Foam Coalition
IAFC	International Association of Fire Chiefs
ICG	Industrial Fire Journal
MilSpec	United States Military Standard
MLD	Million Litres per Day
NASA	National Aeronautics and Space Administration
NASWI	Naval Air Station Whidbey Island
NAVFAC	Naval Facilities Engineering Command
NFPA	National Fire Protection Association
OPPT	Office of Pollution Prevention and Toxics
PFAS	Per- and Polyfluoroalkyl Substance
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulfonate
PMN	Premanufacture Notice
POTW	Publicly Owned Treatment Works
PPE	Personal Protective Equipment
RAD	Risk Assessment Division
SCBA	Self-Contained Breathing Apparatus
TSCA	Toxic Substances Control Act
UFC	Unified Facilities Criteria
UL	foam standard of Underwriters Laboratory
US	United States

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1. Industry Summary and Background

Firefighting foam is a stable mass of small bubbles of lower density than most flammable liquids and water. Foam is a blanketing and cooling agent that is produced by mixing air into a foam solution that contains water and foam concentrate. Firefighting foams extinguish flammable or combustible liquid fires in four ways (Kidde, 2002[3]):

1. excludes air from the flammable vapours;
2. eliminates vapour release from fuel surface;
3. separates the flames from the fuel surface; and
4. cools the fuel surface and surrounding surfaces.

Aqueous film forming foam (AFFF) is the premier firefighting foam in the US and many parts of the world, and is known for its ability to rapidly extinguish flammable liquid pool fires (Darwin, 2004[4]). AFFFs are a combination of fluorochemical surfactants and synthetic foaming agents. AFFFs extinguish fires by forming an aqueous film. This film is a thin layer of foam solution that spreads rapidly across the surface of a hydrocarbon fuel causing fire knockdown. The aqueous film is produced by the action of the fluorochemical surfactant reducing the surface tension of the foam solution to a point where the solution can be supported on the surface of the hydrocarbon (Kidde, 2002[3]).

1.1. AFFF Use Industries

AFFF has wide application for use, being useful for in any situation that may involve Class B fires, which involve flammable or combustible liquids, particularly in oil and gas production (including oil platforms, oil tankers, and bulk storage), aviation, and ship engine rooms. Darwin (2004[4]) conducted a survey of AFFF inventory in the US in 2004 and identified the following major use sectors:

- Military;
- Civil Aviation - Airport Aircraft Rescue and Firefighting (ARFF);
- Civil Aviation – Aircraft Hangars;
- Municipal Fire Departments;
- Petroleum Refineries; and
- Petrochemical Manufacturing

These end use sectors represent over 97 percent of the estimated AFFF quantity in the US in 2004 and are described in the following subsections (Darwin, 2004[4]). The remaining 3% are used at other Federal Agencies (Department of Energy and National Aeronautics and Space Administration (NASA)), merchant ships/off-shore oil platforms, and other miscellaneous foam applications were not considered as major uses included in this ESD. Table 1.1 summarises the relative quantities of in each major end use sector. No AFFF concentrate production estimates were available.

Table 1.1. Estimated Quantity of AFFF Concentrate for each Major End Use Sector

End Use Sector	Estimated Quantity of AFFF Concentrate in the US (kg)	Percent of AFFF Concentrate Each End Use Sector
Military	10,736,153	29%
Civil Aviation	5,976,576	16%
Municipal Fire Departments	5,147,600	14%
Petroleum Refineries	7,191,500	20%
Petrochemical Manufacturing	7,570,000	21%
Total	36,621,829	100%

Source: (Darwin, 2004[4])

1.1.1. US Military

The US Military is one of the main users of AFFF concentrates; flammable liquids are essential to military operations, primarily as propulsion fuel for military vehicles, aircraft and ships. Military departments have been leaders in developing systems and techniques for utilising AFFF to counter various flammable liquid fire threats, and exclusively use United States Military Standard (MilSpec) AFFF because of its superior AFFF performance.

Large quantities of AFFF are deployed in fixed fire suppression installations, airfield crash trucks, most military fire department pumper apparatus, and an assortment of hose-delivered manual firefighting systems.

Ships – On a typical aircraft carrier, the entire 4 1/2 acre flight deck is protected by several hundred nozzles built into the steel flight deck that can be activated remotely to cover any portion of the deck with AFFF to protect against fires involving fuelled and armed aircraft. The entire aircraft hangar deck is protected by an overhead AFFF deluge sprinkler system, as are the fuel pump room and machinery space bilges. AFFF hose stations are also distributed around the ship in areas containing flammable liquids. Each Nimitz Class aircraft carrier carries approximately 20,000 gallons of AFFF concentrate. Nearly all Navy, Coast Guard and larger Army watercraft deploy AFFF in similar systems.

Shore Facility Installations – Fixed AFFF systems would be used to protect hazardous locations such as aircraft hangars, jet engine test facilities, hot refuelling sites, flammable storage areas and fuel farms. Large hangars may each contain in excess of 1,500 gallons of concentrate, with some larger hangars containing 5,000 gallons or more.

Firefighting Vehicles - Most military airfields are protected by ARFF vehicles. As is the practice at civilian airports, military ARFF vehicles carry AFFF. Large airfields may have five or more ARFF vehicles, each carrying about 200 gallons of AFFF concentrate. Additionally, most military fire department structural pumpers also carry AFFF for combating miscellaneous flammable liquid fires (Darwin, 2004[4]).

1.1.2. Civil Aviation

AFFF can be used in civil aviation for two different purposes: the first is for ARFF; and the second is for fixed hangar systems, which are discussed in more detail below.

1.1.2.1. Aircraft Rescue and Fire Fighting (ARFF)

Federal law requires that all airports operating regularly scheduled commercial flights, involving aircraft carrying more than 30 people, shall have firefighting capability commensurate with the size of the aircraft. While federal regulations establish the absolute legal minimum requirements, the Federal Aviation Administration (FAA) recommends agent quantities in excess of the legal minimum, more in line with the consensus standard published by the NFPA Standard 403, "Aircraft Rescue and Fire Fighting Services at Airports" (Darwin, 2004[4]). Because of the unique ability of AFFF to rapidly suppress pool fires, both the FAA and NFPA essentially mandate the use of AFFF for airport ARFF applications. AFFF has become the standard foam agent at airports in the US (Darwin, 2004[4]).

1.1.2.2. Aircraft Hangars

The national consensus standard for fire protection in this use sector is NFPA Standard 409, "Standard on Aircraft Hangars". NFPA 409 was revised in 2001 to permit high expansion foam in lieu of low expansion foam, such as AFFF. However, existing hangars would in all probability conform to pre-2001 editions, which essentially mandates overhead foam sprinkling for the entire hangar augmented by underwing foam protection. Hangars requiring foam are classified as Group I, if the floor area exceeds 40,000 square feet, or Group II, if the floor area exceeds 20,000 square feet. Most existing foam systems utilise AFFF. Typical Group I hangars would require AFFF concentrate varying between 4 – 6,000 gallons, while Group II hangars would require systems containing 2 – 3,000 gallons of AFFF concentrate (Darwin, 2004[4]).

1.1.3. Municipal Fire Departments (Non-Aviation)

Most fire departments throughout the country carry small quantities of AFFF for situations where they may encounter flammable liquids, such as an overturned tanker truck or an automobile accident with ruptured fuel tanks. Pumper trucks generally carry at least two 5-gallon containers with portable foam eductors, or some pumpers also have built-in concentrate tanks. Some larger departments also deploy foam tenders, which can bring large quantities of AFFF to the scene of major incidents involving flammable liquids. Additionally, fire departments adjacent to waterways usually have fireboats, many of which carry AFFF that can be discharged through high flow rate deck monitors (Darwin, 2004[4]).

1.1.4. Petroleum Refineries and Other Petrochemical

Both petroleum refineries and petrochemical manufacturing facilities entail the processing, movement and storage of large quantities of flammable liquids. Because of its proven performance advantages, over the years AFFF has become the dominant foam agent of choice. Fire protection for these hazardous operations consists of AFFF delivery systems of various designs, including overhead sprinklers, fixed nozzle deluge systems, remote control monitors and in some cases manually directed discharge streams (Darwin, 2004[4]).

1.2. Types of AFFF Concentrates

In the foam industry, concentrates are typically referred to as "3% concentrate" or "6% concentrate", or respectively as Type 3 or Type 6 foam, depending on the mixture rate with which the concentrate is dissolved in water.[3] A 3% (or Type 3) AFFF concentrate will be mixed into a "solution" consisting of 3 parts concentrate to 97 parts water before being applied to the fire. Similarly, a firefighting foam solution of a 6% (or Type 6) AFFF will be proportioned at 6 parts concentrate to 94 parts water (volumetric – gallons) (Darwin, 2004[4]). Therefore, the concentration of components of 3% concentrate are approximately twice the concentration of components in a 6% concentrate (Darwin, 2004[4]) (see Table 1.2 and Table 1.3 for examples). However, note that since the proportioning rate of 3% concentrate with water would be half the proportioning rate of 6% concentrate, the end concentration of the constituents in the mixed foam would be the same.

The highest usage of 6% AFFF is in the military, largely reflecting the near-exclusive use of 6% type on Navy ships. It is estimated that about 1.3 million gallons of 6% AFFF is in the military use sector. Of all the data submitted by civil aviation and aircraft hangars, less than 15% of the total was 6% AFFF, which for these two sectors would equate to less than 250,000 gallons. Use of 6% AFFF is also considered to be in the minority in fire department applications and in the miscellaneous sector (Darwin, 2004[4]).

Additionally, essentially all AFFF in the US is specified to conform to either a foam standard of Underwriters Laboratory (UL) or a more stringent military specification (MilSpec). Generally, MilSpec AFFFs contain more fluorosurfactant and more fluorine than UL agents do. According to estimates done by Darwin (2004[4]), MilSpec formulations comprised approximately 41 percent of the total AFFF inventory in the US, while UL formulations comprised 59 percent.

It is estimated that over 90% of all AFFF in the military/Federal sector is MilSpec AFFF. MilSpec AFFF predominates in the civil aviation ARFF sector as well. Based on replies from queried airports, it is estimated that 75% of the AFFF in use at airports is MilSpec qualified (Darwin, 2004[4]).

1.3. Components of AFFF Concentrates

AFFF concentrates typically contain the following ingredients (Chemguard, 2005[5]):

- synthetic foaming agents (hydrocarbon surfactants);
- solvents (i.e. viscosity leveller, freezing point depressant, foam booster);
- fluorochemical surfactants;
- salts; and
- foam stabilizers (slow drainage, increases fire resistance).

Table 1.2 presents a summary of the average compositions for MilSpec and UL 3% AFFF concentrates.

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[3] 1% percent foams are also available, but not as prevalent as 3% and 6% foams.

Table 1.2. Average Constituents of 3% AFFF Concentrate

Component	MilSpec (wt. %)	UL (wt. %)	Overall Range (wt. %)
Water	60-77	68-93	60-93
Solvents	10-20	3-25	3-25
Hydrocarbon Surfactant Actives	4-12	2-8	2-12
Fluorinated Surfactant Actives	2-5	1-4	1-5
Fluorine Content	0.7-1.8	0.3-0.9	0.3-1.8
Other (corrosion inhibitors, electrolytes, pH buffers etc.)	1-5	0.3-2	0.3-5

Source: (Darwin, 2004[4])

Table 1.3 illustrates estimated compositions of components in 6% foam concentrates.

Table 1.3. Estimated Constituents of 6% AFFF Concentrate

Component	MilSpec (wt. %)	UL (wt. %)	Overall Range (wt. %)
Water	78-91	73-7	76-97
Solvents	5-10	1.5-12.5	1.5-12.5
Hydrocarbon Surfactant Actives	2-6	1-4	1-6
Fluorinated Surfactant Actives	1-2.5	0.5-2	0.5-2.5
Fluorine Content	0.35-0.9	0.15-0.45	0.15-0.9
Other (corrosion inhibitors, electrolytes, pH buffers etc.)	0.5-2.5	0.15-1	0.15-2.5

Source: Extrapolated from 3% AFFF concentrate data in (Darwin, 2004[4])

1.4. Fluorochemicals in AFFF

AFFF has historically contained fluorosurfactants, which may be either perfluorinated or polyfluorinated materials. Until May 2000, common perfluorochemicals used in firefighting foams were PFOS (Perfluorooctane Sulphonate)-based fluorosurfactants using the Electrochemical Fluorination (ECF) process, and its derivatives. PFOA (Perfluorooctanoic Acid) was also used in early AFFF formulations (Seow, 2013[6]). AFFF formulations have also contained other fluorochemical surfactants, such as Per- and Polyfluoroalkyl Substances (PFASs).

Fluorochemicals have a potential impact upon the environment and human health due to pronounced persistence of their degradation products, and variable degrees of bioaccumulation potential and toxicity. As a result, many countries have now either banned or restricted the use of firefighting foams with perfluorochemicals. For example, many countries banned or restricted the use of PFOS following the listing of PFOS on Annex B (restrictions) of the Stockholm Convention on Persistent Organic Pollutants (POPs Convention) in 2009 (EU, 2010[7]; METI et al., 2010[8]). In addition, the European Chemicals Agency (ECHA) published a background document concerning proposed restrictions on PFOA and related substances and replacement with fluorine-free alternatives (ECHA, 2015[9]). Built upon this background document, the EU restricts the manufacture, use and placing on the market of PFOA from 2020 (EU, 2017[10]). Other countries also further restrict the use of PFOA following its listing on Annex A (elimination) of the POPs Convention in 2019 (METI, MHLW and MOE, 2020[11])

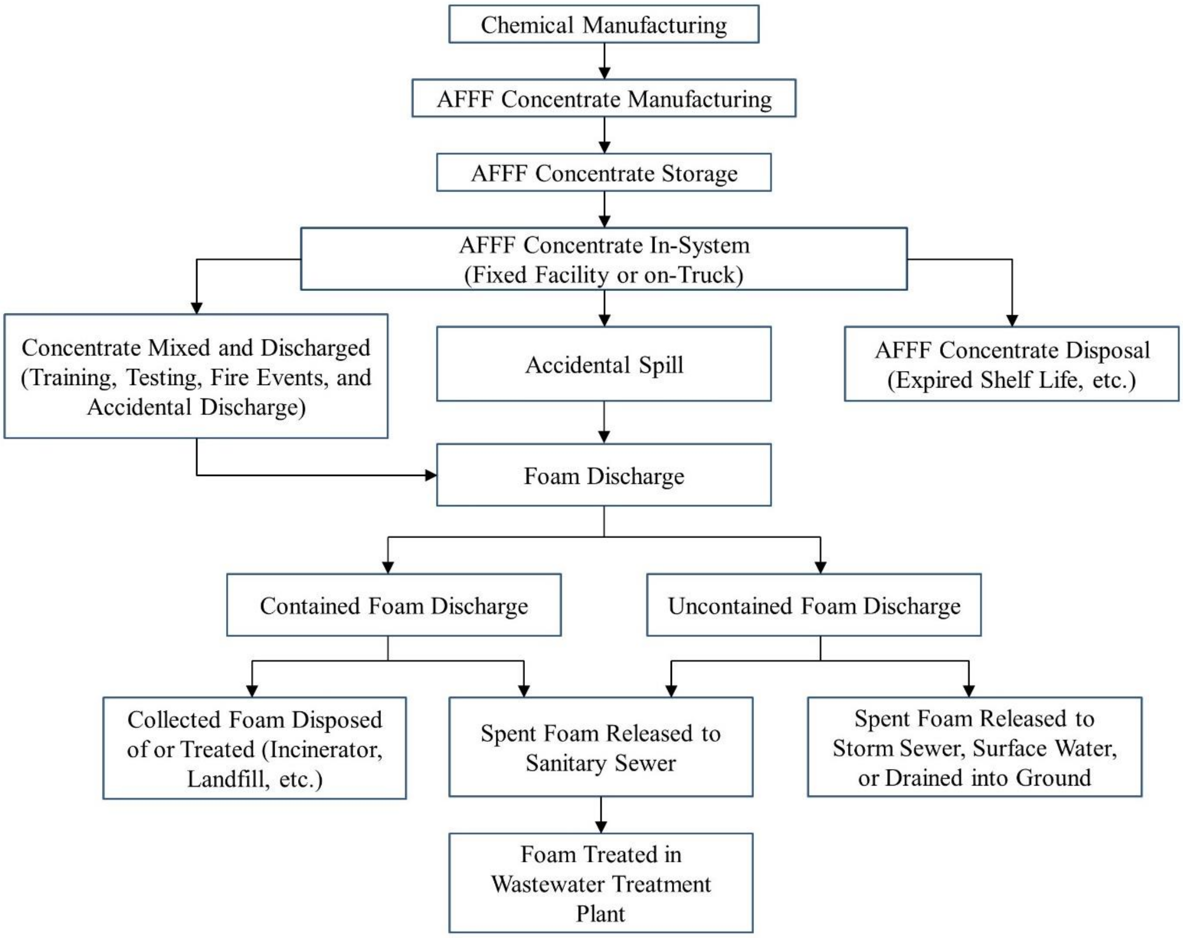
Some have explored fluorotelomer-based fluorosurfactants or non-fluorochemical alternatives. Fluorotelomer-based firefighting foams are currently still allowed to be used (Seow, 2013[6]).

The environmental impacts of firefighting foams containing perfluorochemicals are not only due to bioaccumulation, persistence or toxicity but can also be caused by Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), as is the case for all firefighting foams, due to their effect on water quality (caused by a decrease in water oxygen content) and aquatic ecology (Seow, 2013[6]).

2. Process Description

Figure 2.1 shows the life cycle of firefighting foams. After manufacture, foam ingredients are formulated into foam concentrates. These foam concentrates are used in fixed facility or mobile firefighting systems. Releases of AFFF chemicals may occur when the concentrate is discharged during testing and training exercises, during fighting fuel fires, during accidental release, and when expired or out-of-spec product must be retired and sent for disposal. These activities may result in direct discharge of AFFF to surface water, wastewater treatment, groundwater, land, and incineration (Environment Canada, 2006[12]).

Figure 2.1. Life-Cycle of Firefighting Foams



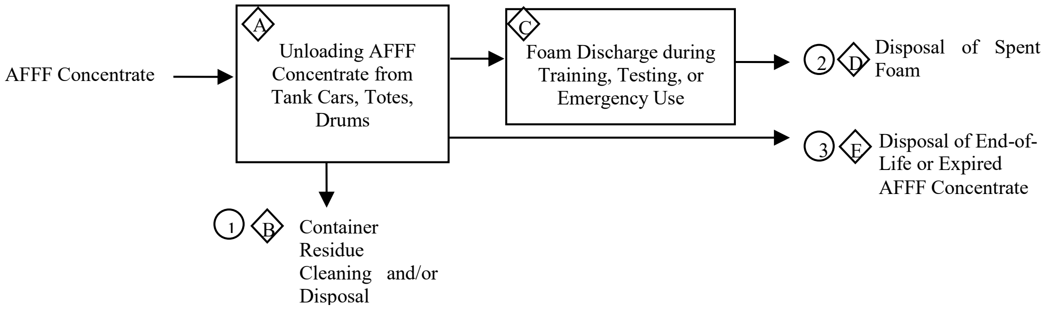
Source: Adapted from (Ruppert, Verdonik and Hanauska, 2004[13]) and (Kidde, 2002[3])

Environment Canada and Chemguard (a known AFFF manufacturer) estimate that the average lifespan of AFFF concentrate can be approximately 20-25 years or longer (Environment Canada, 2006[12]; Chemguard, 2005[5]).

Depending on the nature of the activity, it is not always possible to collect and pre-treat or contain discharged AFFF for proper disposal. Environment Canada states that collected AFFF may be treated as hazardous waste and thus sent to either a hazardous waste landfill, or to an approved thermal destruction facility for high temperature incineration (Environment Canada, 2006[12]).

Figure 2.2 outlines the specific environmental releases and occupational exposures assessed in this ESD. Note that this is relevant to all end-use sectors, but specific amounts of release/exposure and media of release may vary. In addition, note that this ESD conservatively assumes that 100 percent of the AFFF is used or disposed during a year (see Section 4.).

Figure 2.2. General Use and Disposal of AFFF Process



○ = Environmental Releases:

1. Container residues from AFFF concentrate transport container disposed to POTW, landfill, or incineration.
2. Spent foam disposed to surface water, POTW, incineration or land.
3. End of life AFFF disposed to POTW, incineration, or land.

◇ = Occupational Exposures:

A. Dermal exposure to liquid AFFF concentrate during unloading from transport containers.
B. Dermal exposure to liquid AFFF concentrate during container cleaning.

2.1. Firefighting Foam Delivery

Firefighting foam is created by combining foam concentrate, water and air, which are thoroughly mixed in specific proportions. Figure 2.3 provides an illustration of the typical equipment used in combating fires using firefighting foams. Standard firefighting foam equipment includes a foam concentrate supply container, water supply, proportioning device, delivery line, and discharge device.

Figure 2.3. General Firefighting Foam Delivery System

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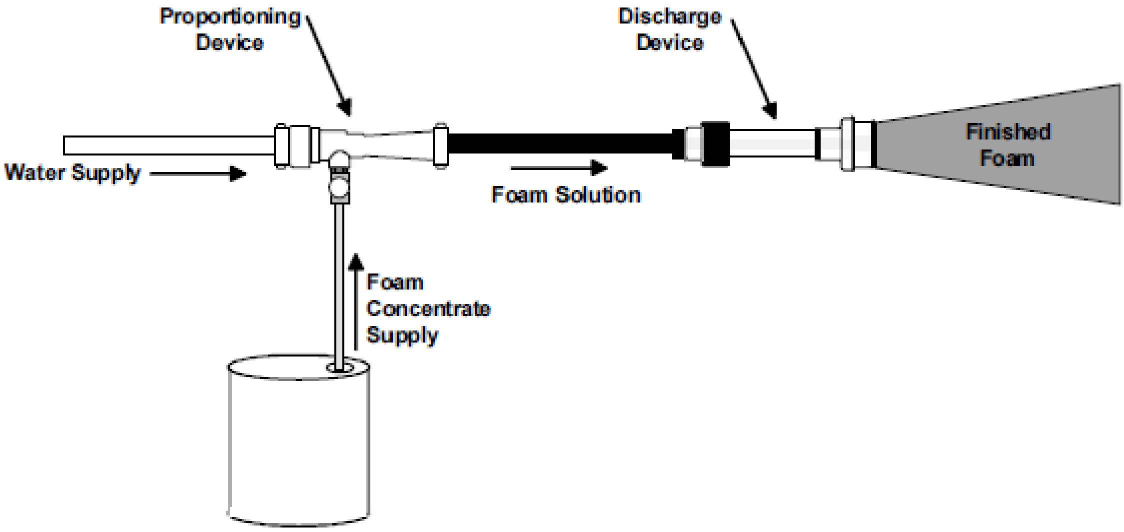

Source: (Kidde, 2002[3])

The primary difference among foam systems is the type of proportioning system used to mix the desired ratio of water and foam concentrate. The main types of proportioning systems are:

- venturi (in-line vacuum Inducing);
- pressure;
- bladder tank;
- balanced pressure;
- in-line balanced pressure;
- around the pump; and
- jet pump (Kidde, 2010[14]).

The most common types of proportioning systems are the venturi and around-the-pump systems due to their versatility and low cost. Pressure controlled systems offer a higher degree of accuracy but tend to be more expensive. A simple premix system may also be used in which the water and concentrate are premixed at a desired ratio and fed directly into the discharge line during use. Low, medium, and high expansion discharge nozzles are also available to accommodate foams of varying expansion specifications (Kidde, 2002[3]; Kidde, 2010[14]). Delivery systems used by mobile fire brigades to combat large fires are typically mounted to a deck or boom on a dedicated vehicle, as suggested by the type of equipment described in combating fires identified in a 2004 report on fuel tank fires (Persson and Lönnermark, 2004[15]). Large facilities may also have fixed AFFF systems comprised of a network of pipes and valves fed by a centralized supply of water and foam concentrate. Existing water deluge systems are readily converted to foam systems merely by adding the appropriate proportioning equipment (Kidde, 2010[14]).

2.2. AFFF Discharge Scenarios

While facilities may carry AFFF concentrate on-site year round, actual firefighting use occurs relatively infrequently. Training and testing activities comprise the majority of routine use activities, while firefighting activities comprise the smallest amount of actual AFFF use. Several discharge scenarios are listed below (FFFC, 2013[16]):

- firefighting emergencies (infrequent);
- accidental discharges (infrequent);
- system testing (NFPA standards require annual testing of fixed foam systems);
- equipment testing (ARFF and municipal fire trucks are required to regularly check vehicle proportioning systems);
- training (required on regular basis); and
- spills/leaks (infrequent).

This ESD assesses potential releases and exposures during these scenarios in Sections 4. and 5. .

2.3. Pollution Prevention Strategies

As discussed in Section 1.4, one of the main concerns with AFFF has been release of fluorosurfactants into the environment, including soil and water. Pollution during firefighting use is largely unpredictable, but there have been some efforts in the industry to mitigate pollution to surface waters during system/equipment testing and training, which are discussed in the following sections.

2.3.1. Training Pollution Prevention

AFFF may be discharged during training scenarios; however, there are specially designed training foams available from most foam manufacturers that simulate AFFF during live training but do not contain fluorosurfactants. These foams are normally biodegradable, have minimal environmental impact, and can be safely sent for treatment to the local wastewater treatment plant (FFFC, 2016[17]).

Some fire training facilities have elaborate systems designed and constructed to collect foam solution, separate it from the fuel, treat it, and in some cases re-use the treated water. At a minimum, fire-training facilities should collect the foam solution for discharge to a wastewater treatment facility (FFFC, 2016[17]). Fluorine-containing foams should be collected for incineration.

Over the past 10 years, an increasing number of foam users have eliminated or reduced use of AFFF agents for testing and training. Equipment manufacturers have responded with vehicles that have dual tanks for training foam and AFFF agents; and fire protection engineering firms have responded by offering system testing services with alternative fluids (FFFC, 2013[16]).

2.3.2. Foam System Testing Pollution Prevention

NFPA requires periodic testing of installed foam fire protection systems to assure reliable performance in an actual fire event. Typically, these tests involve full discharge of the system usually through fire hose lines connected to test outlets that are part of the system installation. Testing primarily involves engineered, fixed foam fire extinguishing systems. Two types of tests are conducted on foam systems: acceptance tests, conducted pursuant to installation of the system; and maintenance tests, usually conducted annually to ensure the operability of the system. These tests can be arranged to pose no hazard to the environment. NFPA foam related standards state that it is possible to test some systems using water or other non-foaming, environmentally acceptable liquids in the place of foam concentrates if permissible.

The major focus when evaluating foam system performance is to confirm proper function of the foam proportioning system. This is done by conducting a foam injection rate test. This testing can now be done using surrogate non-foaming environmentally acceptable test liquids in lieu of AFFF discharge. The surrogate test liquids are specifically formulated to simulate the flow behaviour (viscosity characteristics) and approximate conductivity or refractive index of the foam concentrate used in the system.

In addition to surrogate test liquids, new methods employ data acquisition instrumentation and software to enable fast “on line real time” data monitoring and recording, which enables proportioning system performance to be viewed and recorded in real time as the system operates.

When foam must be used for acceptance or maintenance tests, only a small amount of foam concentrate needs to be discharged to verify the correct concentration of foam in the foam water solution. Designated foam solution (foam and water mixture) test outlets should be designed into the piping system so that the discharge of foam solution can be directed to a controlled location. Portions of the acceptance and ongoing maintenance testing do not require the proportioning system to operate and those parts can be accomplished by discharging only water (FFFC, 2016[17]).

2.3.3. Firefighting Vehicle Tests Pollution Prevention

ARFF and municipal firefighting vehicles are required to go through periodic foam nozzle discharge tests to ensure proper function of their foam proportioning system. Traditionally, these tests have been done by discharging the AFFF foam solution. New technology is now available to enable testing these vehicles using water or a water based surrogate liquid containing an environmentally benign biodegradable dye. The dye in the surrogate test liquid can be detected in the proportioned solution stream by means of colorimeter instrumentation. When water is used as the surrogate test liquid, a flow meter system measures the water injection rate (AFFF, undated).

3. Overall Approach and General Facility Estimates for the Use of AFFF Concentrates

This ESD presents EPA's standard approach for estimating environmental releases of and occupational exposures to chemicals of interest during the commercial/industrial use of AFFF.

The estimation methods described in this document utilise available industry-specific information and data to the greatest extent possible; however, EPA acknowledges several areas in which additional industry data are needed. These data needs are summarised in Section 7. . It should be noted that the default values cited throughout this ESD are intended to be used only when appropriate site-specific or industry-specific information is not available. Because this ESD presents several alternative default assumptions or values for some estimation parameters, one must consider carefully how the selection of these defaults will affect the final assessment results.

This section presents general facility calculations for use sites, which estimate daily use or disposal rates of AFFF concentrate, the number of AFFF use sites, and the number of days that the AFFF concentrate is expected to be used or disposed.

Section 4. presents the environmental release assessments for several AFFF use and disposal sources, which use the general facility estimates to estimate the quantity of chemical released from various points in the use process and the most likely media of release for each release source.

Section 5. presents the occupational exposure assessments for AFFF use, which use both the general facility estimates and release estimates to estimate the number of workers potentially exposed while performing various activities and the corresponding potential level (quantity) and routes of those exposures.

3.1. Introduction to the General Facility Estimates

Through the remainder of this section, a method utilising available AFFF industry data is described to estimate annual inventory of AFFF concentrate ($Q_{concentrate\_site\_yr}$) per facility. This can then be used with the fraction consumed ($F_{consumed}$) and disposed ($F_{disposed}$) to estimate the number of potential AFFF use sites (N_{sites}) and annual use rate of the chemical of interest ($Q_{chem\_ site\_yr}$). By assuming a certain number of use days ($TIME_{use\_days}$), the annual use rate can also be used to estimate a daily use rate ($Q_{chem\_discharge\_site\_day}$).

Note these parameters will be determined for each end use sector; therefore, [end use sector] subscripts have been added to denote end use sectors.

The general facility estimates described in this section are summarised with their associated inputs/bases and corresponding ESD section number in Table 3.1. In addition, Table A A.2 presents a detailed summary of the default values used as inputs to each of the general facility estimates, accompanied by their references.

Table 3.1. Summary of General Facility Parameters for AFFF Use Sites

Parameter	Description	Section
X_{sector}	Fraction of AFFF concentrate used in each end-use sector	3.3
$F_{chem\_concentrate}$	Mass fraction of the chemical of interest in the AFFF concentrate (kg chemical/kg AFFF concentrate).	3.4
F_{chem_foam}	Mass fraction of the chemical of interest in the foam (kg chemical/kg foam).	3.5
$F_{consumed\_[sector]}$	Mass fraction of AFFF concentrate consumed annually per end-use sector	3.6
$F_{disposed\_[sector]}$	Mass fraction of AFFF concentrate disposed annually per end-use sector	3.7
$Q_{concentrate\_site\_yr\_[sector]}$	Annual AFFF concentrate use rate per site per end-use sector (kg AFFF concentrate/site-yr)	3.8
$Q_{chem\_site\_yr\_[sector]}$	Annual use rate for the chemical of interest per site per end-use sector (kg chemical/site-yr).	3.9
$Q_{chem\_yr\_[sector]}$	Annual use rate for the chemical of interest per end-use sector (kg chemical/yr)	3.10
$N_{sites\_[sector]}$	Number of sites using the chemical of interest per end-use sector (sites)	3.11
$TIME_{use\_days\_[sector]}$	Annual number of days the AFFF is used at each site (days/yr).	3.12
$Q_{chem\_consumed\_site\_day\_[sector]}$	Daily consumption rate for the chemical of interest at each facility per end-use sector (kg of chemical/site-day).	3.13
$N_{container\_unload\_site\_yr\_[sector]}$	Number of transport containers unloaded at each site per year per end-use sector (containers/site-yr)	3.14
$TIME_{unloading\_days\_[sector]}$	Number of Days to Unload AFFF Concentrate Containers per end-use sector (days/site-yr)	3.15

The method described in the remaining sections incorporates certain assumptions in cases where industry-specific data were not found. These key assumptions are presented throughout this section and are accompanied by a discussion of their uncertainties and potential effects on the estimates.

3.2. Facility Use Rate Estimates

As stated in Section 1.1, Darwin (2004[4]) conducted a survey of AFFF inventory in the US in 2004 and presented some estimates for the number of facilities stocking AFFF concentrate. As will be discussed further in Section 4. , this ESD assumes that 100 percent of AFFF is delivered to a site and used or disposed within the year. Therefore, the inventory and number of site numbers summarised in Table 3.2 are used to assume annual use rates that should be used in Sections 3.3 through 3.15 in the absence of industry-specific data.

Table 3.2. Facility Inventory Estimates for AFFF Use in Major End Use Sectors

Type of Use	Annual Volume of AFFF Concentrate (gallons/year)[a] ($V_{concentrate\_yr\_[sector]}$)	Fraction of AFFF per End-Use ($X_{[sector]}$)	Number of Sites ($N_{sites\_existing\_[sector]}$)	Calculated Annual Volume of AFFF Concentrate per Site (gallons/site-year) ($V_{concentrate\_site\_yr\_[sector]}$)
Military	2,836,500	0.29	301[b]	9,424
Civil Aviation	1,579,016	0.16	366[a]	4,314
Municipal Fire Departments	1,360,000	0.14	55,150[c]	25
Petroleum Refineries	1,900,000	0.20	149[d]	12,752
Petrochemical Manufacturing	2,000,000	0.21	61	32,787
Total	9,675,516	1	56,027	173

a – Estimated AFFF inventory and number of use sites in the US (Darwin, 2004[4]).

b – Darwin (2004[4]) did not estimate the number of military sites. EPA assumed the number of active Department of Defense installations as a surrogate estimate (DOD, 2014[18]).

c – Darwin (2004[4]) estimated 32,000 fire departments – to provide a more granular estimate per site, EPA references 55,150 fire stations in the US in 2013, as reported by NFPA (2014a). EPA estimates each fire station as one site.
d – (US EIA, 2014[19])

3.3. Fraction of AFFF Concentrate Used in Each End-Use Sector ($X_{[sector]}$)

Because AFFF can be used in several different end-use sectors that may have very different use profiles, EPA recommends assessing each end-use sector separately. If no information is available about specific amount of AFFF intended for each use sector, EPA recommends assuming default fractions based on the AFFF inventory outlined in Darwin (2004[4]).

$X_{[sector]}$ = Fraction of AFFF concentrate inventory for a given end use sector (kg for end-use sector/kg total) (Defaults: see Table 3.2).

Note that the sum of all $X_{[sector]}$ should equal 1:

$$\sum X_{[sector]} = 1$$

3.4. Mass Fraction of the Chemical of Interest in the AFFF Concentrate ($F_{chem\_concentrate\_[sector]}$)

As discussed in Section 1.3, various components comprise AFFF concentrates. Additionally, concentrates are typically formulated into 3% or 6% concentrate, where the components of 3% concentrate are typically twice the concentration of components in 6% concentrate.

If the type of foam (3% or 6%) and type of constituent is known, EPA recommends using the high-end of the “overall range” shown in Table 1.2 or Table 1.3, for 3% and 6% foam concentrate, respectively.

If the type of foam (3% or 6%) is known but the type of constituent is unknown, EPA recommends assuming the high-end concentration of all constituents in either the 3% or 6% foam (Table 1.2 or Table 1.3, respectively).

If the type of foam (3% or 6%) is unknown but the type of constituent is known, EPA recommends assuming the high-end concentration for that specific type of constituent in 3% foam (Table 1.2).

If the type of foam (3% or 6%) and type of constituent and is not known, EPA recommends assuming 25 percent chemical of interest in the concentrate (high-end concentration of solvent in 3% AFFF).

$F_{chem\_concentrate\_[sector]}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (Default: 0.25 kg chemical/kg AFFF concentrate; see Table 1.2)

3.5. Mass Fraction of the Chemical of Interest in the AFFF Foam ($F_{chem\_foam\_[sector]}$)

As discussed in Section 2.1, AFFF concentrates are mixed with water in discharge nozzles to produce foam. 3% concentrates are mixed at a ratio of 3 gallons AFFF concentrate with 97 gallons of water; similarly, 6% concentrates are mixed at a ratio of 6 gallons AFFF concentrate with 94 gallons of water.

AFFF concentrates primarily consist of water (63-90 wt. %); therefore, EPA recommends assuming a default density of 1 kg/L in the absence of specific concentrate information, resulting in $F_{concentrate\_foam} = 0.03$ for a 3% foam and 0.06 for a 6% foam. If a 3% foam was assumed for $F_{chem\_concentrate}$ in Section 3.4, assume $F_{concentrate\_foam} = 0.03$. Otherwise, assume $F_{concentrate\_foam} = 0.06$ as a conservative estimate. Equation 3-1 describes how to calculate the mass fraction of chemical of interest in the produced foam ($F_{chem\_foam\_[sector]}$):

$$F_{chem\_foam\_[sector]} = F_{chem\_concentrate\_[sector]} \times F_{concentrate\_foam\_[sector]} \qquad (3\text{-}1)$$

Where:

$F_{chem\_foam\_[sector]}$ = Mass fraction of the chemical of interest in the produced foam for a given use sector (kg chemical/kg foam)

$F_{chem\_concentrate\_[sector]}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (Default: 0.25 kg chemical/kg AFFF concentrate; see Section 3.4)

$F_{concentrate\_foam\_[sector]}$ = Mass fraction of the AFFF concentrate in the produced foam for a given use sector (kg AFFF concentrate/kg foam; Default: 0.03 kg AFFF concentrate/kg foam for 3% foam; 0.06 kg AFFF concentrate/kg foam for 6% foam)

3.6. Annual Consumption Fraction ($F_{consumed\_[sector]}$)

"Consumption" according to Darwin (2011[20]) means that AFFF has been discharged or emitted as a result of training evolutions, AFFF system testing, firefighting operations, inadvertent discharge or leakage, or disposal following decommissioning of a firefighting system (Darwin, 2011[20]). For the purposes of this ESD, EPA assumes that end-of-life disposal is not included in the definition of consumption and is assessed separately.

Darwin conducted a study in 2011 to estimate the amount of PFOS-type AFFF inventory remaining in the US and estimated annual consumption rates for each end-use sector. These are assumed to be generally similar to overall AFFF consumption rates; default rates are summarised in Table 3.3. Canada's overall industry estimates suggest that an average of 10% of the existing AFFF stock is expended each year (Environment Canada, 2006[12]).

$F_{consumed\_[sector]}$ = Fraction of AFFF concentrate consumed for a given use sector (kg AFFF concentrate consumed/kg AFFF concentrate stocked) (Default: see Table 3.3)

Table 3.3. Default Annual Consumption Rate by End Use Sector ($F_{consumed\_[sector]}$)

Type of Use	Average kg AFFF consumed/kg AFFF concentrate stocked	Default $F_{consumed}$ (kg AFFF consumed/kg AFFF concentrate stocked)
Military	6-7%	0.07
Civil Aviation	9-12.2%	0.122
Municipal Fire Departments	7%	0.07
Petroleum Refineries	12%	0.12
Petrochemical Manufacturing	7%	0.07

Source: (Darwin, 2011[20])

3.7. Annual Disposal Fraction per End Use Sector ($F_{disposed\_[sector]}$)

The amount of unused, expired AFFF concentrate disposed per year is unknown. However, as AFFF concentrate typically has a shelf life of 10 to 25 years, expiration is expected to be infrequent (see additional discussion in Section 4.4). This ESD recommends assuming up to 10% disposal as a conservative estimate. If other specific disposal quantities are known, those values should be used.

$F_{disposed\_[sector]}$ = Fraction of AFFF concentrate disposed annually for a given use sector (kg AFFF concentrate disposed/kg AFFF concentrate stocked; default 0.10).

3.8. Annual AFFF Concentrate Use Rate per Site in Each End Use Sector ($Q_{concentrate\_site\_yr\_[sector]}$)

Annual AFFF mass concentrate use rates can be estimated using the average annual volumetric concentrate use rates ($V_{concentrate\_site\text{-}yr\_[sector]}$) calculated in Table 3.2. As stated in Section 3.5, EPA assumes a default density of AFFF concentrate ($RHO_{concentrate}$) of 1 kg/L in the absence of specific concentrate information. Equation 3-2 describes how to calculate the annual AFFF mass concentrate use rates for each end-use sector:

$$Q_{concentrate\_site\_yr\_[sector]} = V_{concentrate\_site\text{-}yr\_[sector]} \times RHO_{concentrate} \times \frac{3.78\ L}{gal} \times \left(F_{consumed\_[sector]} + F_{disposed\_[sector]}\right) \quad (3\text{-}2)$$

Where:

$Q_{concentrate\_site\_yr\_[sector]}$ = Annual use rate of the AFFF concentrate per site for a given use sector (kg concentrate/site-yr)

$V_{concentrate\_yr\_[sector]}$ = Annual volumetric use rate of AFFF concentrate for a given use sector (gallons/site-yr) (Defaults: see Table 3.2)

$RHO_{concentrate}$ = Density of AFFF concentrate (kg/L) (Default: 1 kg/L)

$F_{consumed\_[sector]}$ = Annual consumption rate of AFFF concentrate for a given use sector (kg AFFF consumed/kg AFFF concentrate stocked) (default: see Section 3.6)

$F_{disposed\ [sector]}$ = Annual disposal rate of AFFF concentrate for a given use sector (kg AFFF disposed/kg AFFF concentrate stocked) (default: see Section 3.7)

3.9. Annual Chemical of Interest Use Rate per Site in Each End Use Sector ($Q_{chem\_site\_yr\_[sector]}$)

The annual use rate of the chemical of interest in each end use sector can be estimated using the annual AFFF concentrate use rate and the concentration of the chemical of interest in the concentrate. The annual use rate of the chemical of interest can be calculated using Equation 3-3.

$$Q_{chem\_site\_yr\_[sector]} = Q_{concentrate\_site\_yr\_[sector]} \times F_{chem\_concentrate\_[sector]} \tag{3-3}$$

Where:

$Q_{chem\_site\_yr\_[sector]}$ = Annual use of the chemical of interest per site for a given use sector (kg chemical/site-yr)

$Q_{concentrate\_site\_yr\_[sector]}$ = Annual use rate of AFFF concentrate containing the chemical of interest per site for a given use sector (kg concentrate/site-yr) (default: see Section 3.8)

$F_{chem\_concentrate\_[sector]}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (kg chemical/kg AFFF concentrate) (see Section 3.4)

3.10. Annual Chemical Use Rate for Each End Use Sector ($Q_{chem\_yr\_[sector]}$)

The annual use rate of the chemical of interest in each end use sector can be estimated using the annual AFFF concentrate use rate and the concentration of the chemical of interest in the concentrate. The annual use rate of the chemical of interest can be calculated using Equation 3-4.

$$Q_{chem\_yr\_[sector]} = Q_{chem\_yr} \times X_{[sector]} \tag{3-4}$$

Where:

$Q_{chem\_yr\_[sector]}$ = Annual use rate of the chemical of interest for a given use sector (kg chemical/yr)

Q_{chem_yr} = Annual production volume of the chemical of interest (kg chemical/yr)

$X_{[sector]}$ = Fraction of AFFF concentrate used for a given use sector (kg for end-use sector/kg total) (see Section 3.3)

3.11. Number of Sites ($N_{sites\_[sector]}$)

Typically, AFFF concentrate is sent to two types of systems, new and existing:

- *New systems* – New systems do not have any existing AFFF concentrate and the addition of AFFF concentrate is assumed to be additive.
- *Existing systems* – For existing systems, AFFF concentrate is used to replace inventory that has been consumed or disposed.

In both cases, the addition of a new AFFF concentrate is considered to be purely additive, since there is no existing AFFF containing the chemical of interest. However, it is assumed that eventually all existing stock at these sites will be AFFF concentrate that contains the chemical of interest. At this future point in time, all sites are assumed to be "existing," with consumed or disposed AFFF being replaced with the same type of AFFF.

This ESD assumes that the AFFF (containing the chemical of interest) will replace existing AFFF formulations in a certain subset of all existing sites, which are estimated according to the AFFF inventory and number of sites reported in Darwin (2004[4]) and other publicly available sources (see Table 3.2).

The number of facilities using the chemical of interest in each end-use sector ($N_{sites\_[sector]}$) depends on the total annual production of the chemical of interest ($Q_{chem\_yr\_[sector]}$) and the annual use rate of the chemical of interest ($Q_{chem\_site\_yr\_[sector]}$). Equation 3-5 demonstrates how the number of use facilities using the chemical of interest could be determined.

$$N_{sites\_[sector]} = \frac{Q_{chem\_yr\_[sector]}}{Q_{chem\_site\_yr\_[sector]}} \qquad (3\text{-}5)$$

Where:

$N_{sites\_[sector]}$[4] = Number of sites for a given use sector

$Q_{chem\_yr\_[sector]}$ = Annual use rate of the chemical of interest for a given use sector (kg chemical/yr) (Defaults: see Section 3.10)

$Q_{chem\_site\_yr\_[sector]}$ = Annual use rate of the chemical of interest used at each site for a given use sector (kg chemical/site-yr) (Defaults: see Section 3.9)

Note that the calculated value of $N_{sites\_[sector]}$ should not exceed the total number of facilities known to operate in the U.S, (or other country as appropriate) for each end use sector, as shown in Table 3.2. If this calculated value of $N_{sites\ [sector]}$ is greater than the total number of facilities listed in Table 3.2, then $N_{sites\ [sector]}$ should be set to the value from Table 3.2.

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[4] The value for N_{sites}, calculated using Equation 3-6, should be rounded up to the nearest integer value. $Q_{chem\_site\_yr}$ should then be adjusted for the N_{sites} integer value (to avoid errors due to rounding):

$$Q_{chem\_site\_yr\_[sector]} = \frac{Q_{chem\_yr\_[sector]}}{N_{sites\_[sector]}}$$

Note: If the number of sites is known, this equation may also be used to estimate the resulting average annual use rate for subsequent calculations.

Box 3.1. Summary of the Relationship of General Facility Parameters

The values for days of use ($TIME_{use\_days\_[sector]}$), daily discharge rate of the chemical of interest ($Q_{chem\_consumed\_site\_day\_[sector]}$), and number of sites ($N_{sites\_[sector]}$) are related. This box presents one method for estimating N_{sites} using estimated default values for 1) the annual production quantity of the chemical of interest and 2) the estimated annual use rate of the chemical at a single site.

If $N_{sites\_[sector]}$ and $TIME_{use\_days\_[sector]}$ are known, $Q_{chem\_consumed\_site\_day\_[sector]}$ can be calculated directly without using Equation 3-6. This alternative calculation is:

$$Q_{chem\_consumed\_site\_day\_[sector]} = \frac{Q_{chem\_yr\_[sector]} \times F_{consumed\_[sector]}}{N_{sites\_[sector]} \times TIME_{use\_days\_[sector]}}$$

If $N_{sites\_[sector]}$ is known and $TIME_{use\_days\_[sector]}$ is unknown, EPA recommends that using the default assumption that AFFF consumption occurs 3-4 days per year (see Section 3.12) and $Q_{chem\_consumed\_site\_day\_[sector]}$ be calculated using the above equation.

EPA recommends calculating the chemical of interest throughput based on the methodology presented in Section 3.13, and compare it to the throughput based on number of sites and operating days, as calculated above.

3.12. Days of Use per End Use Sector ($TIME_{use\_days\_[sector]}$)

As discussed in Section 2.2, actual use of AFFF only occurs a few days per year, on average. Firefighting comprises the smallest amount of actual AFFF use, while training and testing comprise the majority of routine use activities. For example, fixed systems in aircraft hangers are required to be tested once per year (full discharge) and portable truck systems are typically required to have periodic testing (FFFC, 2013[16]). Also stated previously in Section 2.3.2, surrogate liquids may be used in lieu of AFFF for certain testing and training exercises, but specific surrogate usage rates are unknown.

Per comments received from the American Chemistry Council (ACC), Aerospace Industries Association (AIA), American Fuel and Petroleum Manufacturers (AFPM), and American Petroleum Institute (API) (ACC et al., 2020[21]), training of firefighters is conducted at centralized training facilities and is no longer performed at individual industrial sites. However, it is unclear whether this applies to all use sectors and no specific reference was provided; therefore, EPA recommends assuming one training day per site-yr as a maximum estimate.

Because of the wide variety of situations and unpredictability involved in firefighting, EPA is unable to obtain specific estimates for number of use days. Therefore, in the absence of specific information, EPA recommends assuming the default number of use days for each end use sector as specified in Table 3.4 below. Details on the basis for each estimate are discussed in the subsections below.

$TIME_{use\_days\_[sector]}$ = Number of days AFFF concentrate discharged per year for a given use sector (Default: see Table 3.4)

Table 3.4. Default Number of Use Days for Each Major End Use Sector ($N_{use\_days\_[sector]}$)

Types of Use	Estimated Number of Days (days/site-yr)			Default Number of Days Estimate (days/site-yr)
	Training	$TIME_{use\_days\_[sector]}$	Emergencies	$TIME_{use\_days\_[sector]}$
Military	1	<1	1	3
Civil Aviation	1	1	1	3
Municipal Fire Departments	1	1	2	4
Petroleum Refineries	1	1	<1	3
Petrochemical Manufacturing	1	1	<1	3

3.12.1. Days of Use - Military

Maintenance and testing requirements for onshore fixed foam systems in the Navy (and the Air Force as well) are specified in a joint-service Department of Defense (DOD) document (Unified Facilities Criteria – UFC 3-601-02). This document mandates that a foam concentrate sample be drawn from every system tank annually and tested for quality and that every two years a full flow system discharge test be conducted to verify proper foam proportioning.

There are also strict periodic maintenance and test requirements for all shipboard firefighting systems, including AFFF systems. Every AFFF system must be flow tested with foam solution at least once every three years to confirm proportioner performance and foam distribution. Additionally, AFFF systems on aviation ships must be flow tested following a shipyard availability exceeding six months as part of the flight deck re-certification procedure prior to resuming flight operations. In addition, any repair or replacement of AFFF system components may also necessitate a full flow test (Darwin, 2011[20]).

As a conservative estimate, EPA assumes one discharge per year due to testing. The number of training days is unknown, although training may not be applicable to fixed systems. Therefore, recommends assuming annual training exercises as a conservative estimate. Information on emergencies was not found. Similar to the other end-use sectors, EPA assumes 1 emergency per year per site.

3.12.2. Days of Use – Civil Aviation

Annual vehicle foam discharges are mandated by NFPA and FAA standards. For example, NFPA 403 and 412 require annual discharge of AFFF from all vehicle turrets and nozzles to check foam quality, proportioner accuracy, stream reach and foam pattern distribution (Darwin, 2011[20]).

NFPA 403 and 405 also mandate frequent training of all ARFF fire fighters, including turret operation and “live fire training evolutions” using the ARFF vehicles (Darwin, 2011[20]). An Advisory Circular distributed by the FAA specifies that training should occur every 12 consecutive calendar months (US FAA, 2015[22]).

Therefore, EPA estimates 1 day for training and 1 day for testing. Information on emergencies was not found. Similar to the other end-use sectors, EPA assumes 1 emergency per year per site.

3.12.3. Days of Use – Municipal Fire Departments

As discussed in Section 1. , AFFF is used for extinguishing flammable liquid pool fires. NFPA tracks the number of fires that start with flammable gas or flammable or combustible liquids but does not track the use of firefighting agents. Additionally, the ignition source is recorded, but the actual fuel source is not. For example, ignition of a cooking oil could cause a structure fire, which would not be a typical application of AFFF.

Since fuel tank ruptures in vehicles may cause liquid pool fires that are extinguishable by AFFF, EPA estimates the number of vehicle fires as generally equivalent to the number of times AFFF is used per year. NFPA reported an annual average of 68,390 vehicle fires that started with ignition of flammable or combustible liquids between 2007 and 2011 (NFPA, 2014[23]). Assuming there 55,150 fire stations (per Table 3.2), results in an estimate of 1.25 fire emergencies per year per fire station. Anecdotal evidence from industry (ACC et al., 2020[21])estimates that only about 10 percent of automobile fires require the use of AFFF. However, EPA recommends assuming up to 2 fire emergencies per year per station as a maximum value.

Training and testing requirements were not found; therefore, EPA recommends assumes 1 day for training and 1 day for testing, similar to other end-use sectors.

3.12.4. Days of Use - Refineries

According to the US Chemical Safety Board and the US Energy Information Administration there have been as many as 23 refinery fires annually. Per Darwin, a smaller number of events can consume a large amount of AFFF inventory at once (Darwin, 2011[20]). Averaging across 149 refineries (per Table 3.2), EPA estimates less than 1 refinery fire per year. As a conservative estimate, EPA assumes 1 emergency per site per year.

Training and testing requirements were not found; therefore, EPA recommends assumes 1 day for training and 1 day for testing, similar to other end-use sectors.

3.12.5. Days of Use – Other Petrochemicals

Applicable NFPA standards (NFPA 11, 16 and 25) require annual flow tests with foam to verify foam proportioner performance. This is twice the flow frequency required for foam systems within DOD. The NFPA standards cited above also require that a foam concentrate sample be drawn from every foam system on an annual basis and tested for foam quality (Darwin, 2011[20]). Therefore, EPA recommends assuming 1 day for training and 1 day for testing.

A literature search described in the Industrial Fire Journal identified 480 large scale tank fires occurring in the period between 1951 and 2003 (IFJ, 2010[24]), which results in an approximate average of 10 tank fires per year. Distributing across 61 petrochemical sites (per Table 3.2), EPA estimates less than 1 petrochemical fire per site per year. As a conservative estimate, EPA assumes 1 emergency per site per year.

3.13. Daily Consumption Rate of the Chemical of Interest per End Use Sector ($Q_{chem\_consumed\_site\_day\_[sector]}$)

The daily use rate of the chemical of interest during AFFF discharge is estimated using Equation 3-6, based on the annual product inventory, the amount discharged per year, and the number of use days.

$$Q_{chem\_consumed\_site\_day\_[sector]} = \left(\frac{Q_{chem\_site\_yr\_[sector]}}{TIME_{use\ days\_[sector]}}\right) \times \left(\frac{F_{consumed\_[sector]}}{F_{consumed\_[sector]}+F_{disposed\_[sector]}}\right) \quad (3\text{-}6)$$

Where:

$Q_{chem\_consumed\_site\_day\_[sector]}$ = Daily consumption rate of the chemical of interest contained in AFFF for a given use sector (kg chemical used/site-day)

$Q_{chem\_site\_yr\_[sector]}$ = Annual use rate of the chemical of interest per site for a given use sector (kg chemical/site-yr) (see Section 3.9)

$F_{consumed\_[sector]}$ = Mass fraction of AFFF concentrate consumed for a given use sector (kg chemical used/kg chemical stocked) (Defaults: see Section 3.6)

$F_{disposed\_[sector]}$ = Fraction of AFFF concentrate disposed annually for a given use sector (kg AFFF concentrate disposed/kg AFFF concentrate stocked; default 0.10 – see Section 3.7).

$TIME_{use\_days\_[sector]}$ = Annual number of days the AFFF product is discharged for a given use sector (days/yr) (Defaults: see Section 3.12)

3.14. Number of AFFF Concentrate Containers Emptied per Facility by End Use Sector ($N_{container\_unload\_site\_yr\_[sector]}$)

The number of AFFF concentrate containers unloaded annually per site can be estimated based on the daily use rate, container size, and concentration of the chemical of interest in the formulation. AFFF concentrates are received as liquids and are typically shipped in 5-gallon pails, 55-gallon drums, and 265-gallon totes (FFFC, 2014[25]). Comments from industry (ACC et al., 2020[21]) indicate that foam concentrate is typically shipped in 265-gallon totes. Therefore, EPA suggests that a default transportation container size of a 265-gal tote should be used if no information is provided. Engineering judgment should be used to determine if another container type or size is more appropriate. EPA assumes a default density of AFFF concentrate ($RHO_{concentrate}$) of 1 kg/L in the absence of specific concentrate information, as discussed in Section 3.5.

$$N_{container\_unload\_site\_yr\_[sector]} = \frac{Q_{concentrate\_site\_yr\_[sector]}}{V_{container\_[sector]} \times RHO_{concentrate}} \quad (3\text{-}7)$$

Where:

$N_{container\_unload\_site\_yr\_[sector}$ = Number of transport containers unloaded at each site per year for a given use sector (containers/site-yr)

$Q_{concentrate\_site\_yr\_[sector]}$ = Annual use rate of the AFFF concentrate per site for a given use sector (kg chemical used/site-yr) (see Section 3.8)

$V_{container\_[sector]}$ = Volume of transport container for a given use sector (Default: 1,000 L AFFF concentrate/container (265-gallon tote); See Table A B.1 for alternative default container volumes)

$RHO_{concentrate}$ = Density of AFFF concentrate (kg/L formulation; Default: 1 kg/L for liquid)

3.15. Number of Days to Unload AFFF Concentrate Containers per End Use Sector ($TIME_{unloading\_days\_[sector]}$)

AFFF concentrate is expected to be unloaded directly from the transport containers into the firefighting equipment or connected directly to the metering system.

If no information is provided about the size of transport equipment, EPA suggests a default transportation container size of a 265-gallon tote and an unloading rate of 20 containers per hour, over an 8-hour work day (US EPA, 1991[2]). The number of days for unloading is estimated by Equation 3-9:

$$TIME_{unloading\_days\_[sector]} = \frac{N_{container\_unload\_site\_yr\_[sector]}}{RATE_{container\_unloading} \times TIME_{unloading\_hours}} \qquad (3\text{-}8)$$

Where:

$TIME_{unloading\_days\_[sector]}$ = Number of days to unload containers for a given use sector (days/site-yr)

$N_{container\_unload\_site\_yr\_[sector]}$ = Number of transport containers unloaded at each site per year for a given use sector (containers/site-yr)

$RATE_{container\_unloading}$ = Container loading/unloading rate (containers/hr; Default 20 containers/hr for totes) (US EPA, 1991[2])

$TIME_{unloading\_hours}$ = Number of hours unloading containers per day (Default: 8 hr/day) (US EPA, 1991[2])

4. Environmental Release Assessments for the Use of AFFF Concentrates

This section presents approaches for estimating the amount of the chemical of interest released during the use of AFFF. The release sources are presented in the order discussed in Section 2. (see Figure 2.2), and include the most likely receiving media (i.e. air, water, landfill, or incineration) for each end-use sector. The primary sources of release include container residue, disposal of discharged AFFF, and disposal of expired AFFF concentrate. Key default values used for the release estimates, accompanied by their respective references, are provided in Table A A.1.

Note that for the purposes of this ESD, a "what-if" scenario is presented, where 100 percent of the AFFF containing chemical of interest is assessed to be shipped to use sites and consumed or discharged during the year (100 percent loss).

It is generally assumed that during the use of AFFF foam products upstream losses are minimised. Therefore, the methodology presented in this section for estimating releases of does not include adjustments to account for pre-process or other upstream releases of the chemical (e.g. while some material may remain in the transport container, the entire volume received in the container is assumed when estimating equipment cleaning releases). Note that the total amount of chemical released from the process should not exceed the amount that enters the process.

All release equations estimate daily rates for a given site. To estimate annual releases for all sites for a given source, the release rates must be multiplied by the number of days of release and by the total number of sites using the chemical of interest (N_{sites}). Additionally, daily and annual releases to a given medium may be summed to yield total amounts.

One of the environmental release estimates presented in this document is based on standard EPA release models (Disposal of Container Residues – Section 4.2). The remaining two release estimates for estimating the amount of the chemical of interest released from the spent foam discharge (Section 4.3) and expired stock disposal (Section 4.4) are based on industry-specific information. Table 4.1 summarises the release estimation methods used in this ESD. Note that equipment cleaning releases are not assessed because firefighting equipment is typically dedicated and not cleaned (FFFC, 2014[25]).

Table 4.1. Summary of Use of AFFF Scenario Release Models

Release Source #	Description	Model Name or Description[a]	Standard EPA Model (✓)
1	Container residue losses to water, incineration or land	Specific model used is based on the type and size of the containers, and on the physical state of the formulation: *EPA/OPPT Bulk Transport Residual Model* *EPA/OPPT Drum Residual Model* *EPA/OPPT Small Container Residual Model*	✓
2	Collection and disposal of spent foam to water, incineration or land	*User-defined loss model (based on industry information)*	
3	Disposal of expired AFFF to water, incineration or land	*User-defined loss model (based on industry information)*	

Note that the standard model default values cited are current as of the date of this ESD; however, EPA may update these models as additional data become available. It is recommended that the most current version of the models be used in these calculations.

EPA has developed a software package, Chemical Screening Tool for Exposures and Environmental Release (ChemSTEER), containing these models as well as all current EPA defaults. Annex B provides additional information on ChemSTEER, including instructions for obtaining the program, as well as background information, model equations, and default values for several parameters for all standard EPA models used in this ESD.

4.1. Control Technologies

AFFF agents contain fluorosurfactants that are persistent in the environment and are not removed by passage through a wastewater treatment plant. As a result, the only way to ensure that AFFF fluorosurfactants are not released to the environment is to eliminate foam discharge altogether, which typically involves containment and controlled disposal. However, fires occur under many different circumstances, and it is not possible to collect the foam solution in some cases such as emergency firefighting or fixed system fire suppression, and may not be possible in other scenarios such as accidental release (FFFC, 2016[17]).

4.1.1. Manual Firefighting Operations

In some cases, the foam solution used during fire department operations can be collected. However, it is not always possible to control or contain the foam. Event-initiated manual containment measures are usually executed by the responding fire department to contain the flow of foam water solution when conditions and manpower permit. These operations include the following measures (FFFC, 2016[17]):

- Blocking sewer drains - This is a common practice used to prevent contaminated foam water solution from entering the sewer system unchecked. It is then diverted to an area suitable for containment.
- Portable dikes - These are generally used for land-based operations. They can be set up by the fire department personnel during or after extinguishment to collect run-off.

- Portable booms - These are used for marine-based operations, which are set up to contain foam in a defined area. These generally involve the use of floating booms within a natural body of water.

4.1.2. Fixed System Releases

This type of release is generally uncontrolled, whether the result of a fire incident or accidental release. The foam solution discharge in this type of scenario can be dealt with by event-initiated operations or by engineered containment systems (FFFC, 2016[17]):

- Event-initiated operations encompass the same temporary measures that would be taken during fire department operations: portable dikes, floating booms etc.
- Engineered containment would be based mainly on the location and type of facility, and would consist of holding tanks or areas where the contaminated foam water solution would be collected, treated, and sent to a wastewater treatment facility at a prescribed rate.

4.1.3. Facilities without Engineered Containment

Given the absence of any past requirements to provide containment, many existing facilities allow the foam water solution to flow out of the building and evaporate into the atmosphere or percolate into the ground. The choices for containment of foam water solution at such facilities fall into two categories: event-initiated manual containment measures and installation of engineered containment systems.

- Event-initiated manual containment measures are the most likely course of action for existing facilities without engineered containment systems. This can fall under the responsibility of the responding fire department and include such measures as blocking storm sewers, constructing temporary dikes, and deploying floating booms. The degree of such measures will primarily be dictated by location as well as available resources and manpower (FFFC, 2016[17]).
- Engineered containment systems are also a possible choice for existing facilities. Retrofitting an engineered containment system is costly and can adversely affect facility operations. There are special cases, however, that can warrant the design and installation of such systems. Such action is a consideration where an existing facility is immediately adjacent to a natural body of water and has a high frequency of activation (FFFC, 2016[17]).

Selection of the appropriate choice is dependent on the location of the facility, the risk to the environment, the risk of an automatic system discharge, the frequency of automatic system discharges, and any applicable rules or regulations (FFFC, 2016[17]).

4.1.4. Facilities with Engineered Containment

The military is a large user of AFFF with most of the usage pertaining to aviation. Overall, the military has equipment and procedures in place to deal with foam discharges related to training, testing, and accidental discharges. In most cases, this involves a system designed for containment and subsequent disposal of the foam solution. Any engineered containment system will usually incorporate an oil/water separator. During normal drainage conditions (i.e. no foam solution runoff), the separator functions to remove any fuel particles from drainage water. However, when foam water solution is flowing, the oil/water separator must be bypassed so that the solution is diverted directly to storage tanks. This can be accomplished automatically by the installation of motorized valves set to open the bypass line upon activation of the fixed fire-extinguishing systems at the protected property (FFFC, 2016[17]).

The size of the containment system is dependent on the duration of the foam water flow, the flow rate, and the maximum anticipated rainfall in a 24-hour period. Most new containment systems will likely only accommodate individual buildings. However, some containment systems can be designed to accommodate multiple buildings, depending upon the topography of the land and early specification in the overall site planning process. The specific type of containment system selected will also depend upon location, desired capacity, and function of facilities in question. The systems include (FFFC, 2016[17]):

- Earthen retention systems – open-top earthen berms, which usually rely upon gravity-fed drainage piping from the protected building. They can simply allow the foam water solution to percolate into the ground or can include an impermeable liner. Those containing an impermeable liner can be connected to a wastewater treatment facility or can be suction pumped out by a licensed contractor.
- Closed-top, below-ground tanks - usually consist of a gravity-fed piping arrangement and can be suction pumped out or piped to a wastewater treatment facility. A potential and frequent problem associated with this design is the leakage of groundwater or unknown liquids into the storage tank.
- Open-top in-ground tanks - usually lined concrete tanks that rely on gravity-fed drainage piping or a sump and pump arrangement. These can accommodate individual or multiple buildings. They must also accommodate the maximum anticipated rainfall in a 24-hour period. These are often piped to a wastewater treatment facility.
- Sump and pump designs (i.e. lift stations) piped to aboveground or in-ground tanks - above ground tanks incorporate a sump and pump arrangement to closed, above ground tanks. Such designs usually incorporate the use of one or more submersible or vertical shaft, large-capacity pumps. These can accommodate individual or multiple buildings.

4.2. Container Residue Losses to POTW, Incineration, or Landfill of AFFF Concentrate (Release 1)

The amount of AFFF concentrate remaining in transport containers will likely depend on the size of the transport container and the physical form of the component product. Therefore, the following standard EPA models may be used to estimate container residue releases:

- *EPA/OPPT Bulk Transport Residual Model* may be used for large containers (e.g. totes, tank trucks, rail cars) containing greater than or equal to 100 gallons of liquid;
- *EPA/OPPT Drum Residual Model* may be used for drums containing between 20 and 100 gallons of liquid;

- *EPA/OPPT Small Container Residual Model* may be used for liquid containers containing less than 20 gallons; and
- *EPA/OPPT Solid Residuals in Transport Containers Model* may be used for containers of all sizes containing solids.

Note that these models estimate between 0.2 (bulk containers) and 3 percent (drums) of the received material remain in the containers as residual amounts. The rationale, defaults, and limitations of these models are further explained in Annex B. The release estimates are based on the current version of the models. Standard EPA/OPPT models are subject to change; therefore, the current version of the standard EPA/OPPT model should be used.

AFFF concentrates are received as liquids and are typically shipped in 5 gallon pails, 55-gallon drums, and 265-gallon totes (FFFC, 2014[25]). EPA suggests that a default transportation container size of a 265-gallon tote should be used if no information is provided. Engineering judgment should be used to determine if another container type or size is more appropriate (e.g. a 50-pound bag may be more appropriate for a solid component).

The annual number of containers used per year ($N_{container\_unload\_site\_yr}$) is estimated based on the annual AFFF stock rate of the component and the container size (see Section 3.14). EPA recommends assuming 265-gallon (1,000 L) totes as default. If the fraction of the chemical in the AFFF concentrate is unknown, assume 25 percent concentration (see Section 3.4).

Foam concentrates generally have a 10 to 25-year shelf life. Therefore, the full AFFF inventory at each existing would not be typically replenished annually. Note that for a conservative estimate, EPA assumes that a full inventory is unloaded and charged into firefighting systems annually.

If the $TIME_{unloading\_days} \leq 1$, the days of release equals 1 and the daily release is calculated based on the following equation:

$$\mathrm{Elocal}_{container\_residue\_disp\_[sector]} = V_{container\_[sector]} \times RHO_{concentrate} \times F_{chem\_concentrate\_[sector]} \times F_{container\_residue} \times N_{container\_unload\_site\_yr\_[sector]} \quad (4\text{-}1a)$$

This release will occur over 1 day/year from [N_{sites}] sites.

Where:

$\mathrm{Elocal}_{container\_residue\_disp\_[sector]}$ = Daily release of chemical of interest from container residue for a given use sector (kg chemical/site-day)

$V_{container\_[sector]}$ = Volume of transport container for a given use sector (Default: 1,000 L/container (265-gallon tote; see Table A B.1 for alternative default container volumes))

$RHO_{concentrate}$ = Density of AFFF concentrate (kg/L concentrate; Default: 1 kg/L for liquid[5])

$F_{chem\_concentrate\_[sector]}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (kg chemical/kg concentrate) (See Section 3.4)

$F_{container\_residue}$ = Fraction of AFFF component remaining in the container as residue (Defaults: liquid - 0.002 kg AFFF concentrate remaining/kg shipped for totes (US EPA, 2002[26]); see Annex B for defaults used for other container types)

$N_{container\_unload\_site\_yr\_[sector]}$ = Number of transport containers unloaded at each site per year for a given use sector (containers/site-yr) (see Section 3.14)

If $TIME_{unloading\_days} > 1$, the average daily release can be estimated based on Equation 4-1b:

$$Elocal_{container\_residue\_disp\_[sector]} = [(V_{container} \times RHO_{concentrate} \times F_{chem\_concentrate} \times F_{container\_residue} \times N_{container\_unload\_site\_yr})]/TIME_{unloading\_days} \quad (4\text{-}1b)$$

This release will occur over [$TIME_{unloading\_days}$] days/year from [N_{sites}] sites.

Where:

$Elocal_{container\_residue\_disp\_[sector]}$ = Daily release of chemical of interest from container residue for a given use sector (kg chemical/site-day)

$V_{container\_[sector]}$ = Volume of transport container (Default: 1,000 L formulation/container for a given use sector (265-gallon tote; see Table A B.1 for alternative default container volumes)

$RHO_{concentrate}$ = Density of AFFF concentrate (kg/L formulation; Default: 1 kg/L for liquid[6])

$F_{chem\_concentrate\_[sector]}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (kg chemical/kg concentrate) (See Section 3.4)

$F_{container\_residue}$ = Fraction of AFFF component remaining in the container as residue (Defaults: liquid - 0.002 kg AFFF concentrate remaining/kg shipped for totes (US EPA, 2002[26]); see Annex B for defaults used for other container types)

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[5] Default values based on the density of water and atmospheric air.

[6] Default values based on the density of water and atmospheric air.

$N_{container\_unload\_site\_yr\_[sector]}$ = Number of transport containers unloaded at each site per year for a given use sector (containers/site-yr) (see Section 3.14)

$TIME_{unloading\_days\_[sector]}$ = Number of days to unload containers for a given use sector (days/site-yr) (see Section 3.15)

The FFFC indicates that empty containers are typically handled by end users or sent to container recycling facilities and cleaned according to local, state, and federal requirements (FFFC, 2014[25]). Because the ultimate end media of release is uncertain, EPA recommends assessing releases to Publicly Owned Treatment Works (POTW), incineration, or landfill, as specified in Table 4.2. EPA assumes that smaller fire departments and airports may not have large industrial POTWs available and therefore recommends assessing POTW releases to general POTW. Section 4.5 discusses potential pretreatment and metering to wastewater treatment.

Table 4.2. Default Media of Release of AFFF Concentrate Container Residue

Type of Use	Media of Release
Military	Industrial POTW, landfill, or incineration
Civil Aviation	General POTW, landfill, or incineration
Municipal Fire Departments	General POTW, landfill, or incineration
Petroleum Refineries	Industrial POTW, landfill, or incineration
Petrochemical Manufacturing	Industrial POTW, landfill, or incineration

4.3. Disposal of Consumed Foam to POTW, Incineration, or Landfill (Release 2)

Spent foam discharged in contained areas may be collected for disposal, while spent foam discharged in uncontained areas may seep into land or go directly to sewers. Daily release of chemical from spent foam is calculated using the following equation:

$$Elocal_{consumed\_AFFF\_[sector]} = Q_{chem\_consumed\_site\_day\_[sector]} \qquad (4\text{-}2)$$

This release will occur over [$TIME_{use\_days}$] days/year from [N_{sites}] sites.

Where:

$Elocal_{consumed\_AFFF\_[sector]}$ = Daily release of chemical of interest from consumption of spent foam for a given use sector (kg chemical/site-day)

$Q_{chem\_consumed\_site\_day\_[sector]}$ = Daily discharge rate of the chemical of interest for a given use sector (kg chemical/site-day) (See Section 3.13)

Because of the wide range of scenarios potentially involving spent AFFF, the breakdown of potential releases is uncertain. For the military sector, several sources indicated that some DOD sites are banned from discharging AFFF wastewater to local wastewater treatment plants (ESTCP, 2004[27]; NASWI, n.d.[28]; Ruppert, n.d.[29]); therefore, these sites must collect and ship AFFF wastewater off-site for disposal (NASWI, n.d.[28]; NAVFAC, 2016[30]). Another source indicated that land application is not recommended and some states do not approve of it as a disposal method (AFCEE, 2000[31]) Per discussion with the International Association of Fire Chiefs (IAFC), various sites over several end use sectors may also contain spent foam to an evaporation pond. Based on this information, the media of release for AFFF concentrate is inconclusive. EPA recommends assessing releases to publicly owned treatment works (POTW), incineration, or landfill, as specified in Table 4.3. EPA assumes that only large industrial sites will consistently send wastewater to industrial POTWs. Section 4.5 discusses potential pretreatment and metering to wastewater treatment.

Table 4.3. Default Media of Release of Consumed AFFF Foam

Type of Use	Media of Release
Military	General POTW, landfill, or incineration
Civil Aviation	General POTW, landfill, or incineration
Municipal Fire Departments	General POTW, landfill, or incineration
Petroleum Refineries	Industrial POTW, landfill, or incineration
Petrochemical Manufacturing	Industrial POTW, landfill, or incineration

4.4. Disposal of Unused AFFF to POTW or Incineration (Release 3)

For this conservative assessment, EPA recommends assuming that the fraction of AFFF concentrate not discharged is sent for disposal ($F_{disposed}$) once at the end of the year.

The daily release of expired AFFF concentrate is calculated using the following equation:

$$Elocal_{disposed\_[sector]} = \left(\frac{Q_{chem\_site\_yr\_[sector]}}{TIME_{disposal\_[sector]}}\right) \times \left(\frac{F_{disposed\_[sector]}}{F_{consumed\_[sector]} + F_{disposed\_[sector]}}\right) \quad (4\text{-}3)$$

This release will occur over [$TIME_{disposal}$] days from [N_{sites}] sites.

Where:

$Elocal_{disposed\_[sector]}$ = Daily release of chemical of interest from disposal of unused AFFF stock for a given use sector (kg chemical/site-day)

$Q_{chem\_site\_yr\_[sector]}$ = Annual use rate of the chemical of interest for a given use sector (kg chemical/site-yr) (See Section 3.9)

$F_{consumed\_[sector]}$ = Mass fraction of AFFF concentrate consumed for a given use sector (kg chemical used/kg chemical stocked) (Defaults: see Section 3.6)

$F_{disposed\_[sector]}$ = Fraction of AFFF concentrate stock expiring for a given use sector (kg chemical disposed/kg chemical inventoried) (Default: see Section 3.7)

$TIME_{disposal\_[sector]}$ = Number of disposal days per year for a given use sector (days/yr) (Default: 1 end of life disposal/yr)

When disposal of foam concentrate is required, the FFFC recommends that it be sent for thermal destruction (high temperature incineration) to a facility capable of handling halogenated waste or the equivalent. However, this is only a recommendation, and was controversial among manufacturers and users (FFFC, 2013[16]). The DOD also issued a Chemical & Material Emerging Risk Alert (DOD, 2011[32]) that indicated that the industry recommendation for disposal of AFFF is by thermal destruction. However, note that the risk alert was specifically for PFOS-based AFFF (DOD, 2011[32]). The 2011 AFFF inventory update did not find evidence of AFFF disposal via incineration in the US (Darwin, 2011[20]).

Contacts with petroleum and petrochemical facilities indicated that concentrate is usually shipped off-site before expiration. If the concentrate expires, they use it for on-site training exercises at the refineries. In the case that there is an excess of expired concentrate, they would donate it to firefighting facilities for training exercises (ERG, 2012[33]).

Discussions with Ansul technical support indicate that wastewater treatment is another likely media of release, since it is a more economical method of disposal than incineration (Ansul, 2002[34]). Section 4.5 discusses pretreatment and metering to wastewater treatment.

Recent comments from industry (ACC et al., 2020[21]) indicate unused foam concentrate is not accepted by (or released to) publicly owned treatment works (POTWs) or industrial waste water treatment work (WWTPs). This is due to the potential for the foam to significantly disrupt the treatment operations. Further, expired material is not used for training or donated to firefighting facilities for training. Because of uncertainty about the prevalence of these protocols and whether they apply to all use sectors, EPA recommends including potential POTW release only as a worst-case scenario.

A common theme in discussions with the various end-use sectors about end-of-life disposal of AFFF concentrate is that foam concentrates generally have a 10 to 25-year shelf life, so the need to dispose of spent or expired concentrate is very infrequent. To assessing disposal of large quantities of AFFF concentrate, as assumed by this ESD, EPA assumes that concentrate will need to be sent to Industrial POTW or for incineration, as listed in Table 4.4

Table 4.4. Default Media of Release of Unused AFFF Concentrate

Type of Use	Media of Release
Military	Industrial POTW or Incineration
Civil Aviation	
Municipal Fire Departments	
Petroleum Refineries	
Petrochemical Manufacturing	

4.5. Dilution Prior to Discharge to Wastewater Treatment

The issue that has caused the most significant problems, and has occasionally resulted in limiting the use of foam, is the upsetting of a wastewater treatment plant. This effect is caused by foaming, and as a result, efforts should be made to reduce the foaming of effluent solutions prior to release into the treatment facility. This can be achieved by de-foaming or metering the solution. The generally recommended disposal method is metering the solution into a wastewater treatment plant. If done incorrectly this can result in the plant becoming dysfunctional and releasing improperly treated sewage. The method of properly metering the solution can be found in the NFPA Standard for Low Expansion Foam (NFPA 11) (Scheffey and Hanauska, 2002[35]).

Foam manufacturers and foam users recommend dilution of foam solution before it enters a wastewater treatment plant. The required degree of dilution is dependent a number of variables, including the normal inflow of the plant and the acceptable inflow of the plant, which are variable (FFFC, 2016[17]).

There is a relationship between dilution and discharge rate. The higher the dilution rate – the higher the acceptable discharge rate will be. If, for example, the acceptable discharge rate at 500:1 dilution were 100 gallons per hour, a discharge rate of 10 gallons per hour would be acceptable at 50:1 dilution (FFFC, 2016[17]).

Ansul (2002[34]) indicated that foam wastes must be metered into the wastewater treatment system at a sufficiently slow rate so that the foam-water solution will not cause foaming in the aeration basin of the waste system. The rate will be determined by the local situation and must follow all local, state, and federal regulations, which may vary according to localities.

4.5.1. Wastewater Treatment Influent Rates

Normal inflow of wastewater treatment plants varies widely. Large wastewater treatment plants may treat up to 1 billion gallons per day, while some smaller communities operate plants that treat less than 100,000 gallons per day. Larger plants can accept less dilution and a higher diluted solution discharge rate than smaller plants (FFFC, 2016[17]).

EPA's Exposure and Fate Assessment Screening Tool (E-FAST) model uses compiled wastewater influent flow rate data to perform fate and exposure estimates. Table 4.5 summarises the default influent flow values for general and industrial POTWs. Industrial POTWs are a subset of all POTWs, and receive wastes from industrial facilities.

Table 4.5. Wastewater Influent Flow Rates

		Influent Flow (MLD – million litres per day)			
POTW Type	Percentile Facility	Harmonic Mean	30Q5[a]	7Q10[b]	1Q10[c]
General (All)	50	125.56	44.02	26.80	22.53
General (All)	10	11.11	1.94	1.06	0.96
Industrial	50	288.00	123.84	78.18	66.05
Industrial	10	39.60	13.29	7.76	7.57

a - 30 consecutive days of lowest flow over a 5-year period.
b - 7 consecutive days of lowest flow over a 10-year period.
c - Single day of lowest flow over a 10-year period.
Source: EPA's E-FAST User Guide (US EPA, 2007[36])

Depending on the end-use sector, AFFF wastes may be sent to general POTWs or specifically industrial POTWs, as specified in Sections 4.2 to 4.4.

To generate conservative metering estimates, EPA recommends using the lowest influent flow rates provided in Table 4.5. Therefore, EPA recommends assuming 0.96 million litres per day (MLD) for general (all) POTWs and 7.57 MLD for industrial POTWs.

4.5.2. Calculating Metering Time to POTW (TIME$_{metered\_release\_days}$)

Ansul recommends treatment rates of equal to or less than 100 mg/litre of sewage for 6% AFFF and 50 mg/liter for 3% AFFF. Discussions with Ansul technical support indicated that these values should be relatively similar to other AFFF concentrate formulations in the industry. The technical support also indicated that the addition of defoaming agents could roughly enable treatment rates for double the concentrations (Ansul, 2002[34]). As a worst case estimate, EPA recommends assuming the default treatment concentrations in Table 4.6.

Table 4.6. Default AFFF Concentrate Metering Concentration (CONC$_{treatment}$)

Type of Use	CONC$_{treatment}$ (mg/L)
3% AFFF	100

To estimate the number of required dilution/metering days to release foam solution to wastewater treatment, EPA recommends using Equation 4-4 below. Note that this equation should be used for every release that is assessed to POTW, for each end use sector.

$$\mathrm{TIME}_{\mathrm{metered\_release\_days}} = \frac{\mathrm{E}_{\mathrm{local}} \times \frac{\mathrm{site-day}}{1\ \mathrm{event}}}{\mathrm{CONC}_{\mathrm{treatment}} \times \frac{10^{-6}\ \mathrm{kg}}{\mathrm{mg}} \times \mathrm{F}_{\mathrm{chem\_concentrate\_[sector[}} \times \mathrm{Q}_{\mathrm{POTW\_influent}}} \qquad (4\text{-}4)$$

Where:

TIME$_{metered\_release\_days}$ = Number of days pretreated diluted) wastewater is metered to wastewater treatment (days/event)

Elocal = Release of chemical of interest to pretreatment (kg chemical/site-day; see Sections 4.2 to 4.4)

CONC$_{treatment}$ = Targeted concentration of AFFF in wastewater influent (mg AFFF conc/L wastewater; defaults = 100 mg/L for 6% AFFF; 50 mg/L for 3% AFFF)

F$_{chem\_concentrate\_sector}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (kg chemical/kg concentrate) (See Section 3.4)

Q$_{POTW\_influent}$ = Maximum POTW influent flow rate (L wastewater/day; Defaults: 960,000 L/day for all POTWs and 7,570,000 L/day for industrial POTWs)

If the TIME$_{metered\_release\_days}$ ≤ 1, then no metering is required. If TIME$_{metered\_release\_days}$ > 1, then daily metered releases can be calculated by Equation 4-5.

$$\mathrm{Elocal}_{\mathrm{metered}} = \frac{\mathrm{Elocal}}{\mathrm{TIME}_{\mathrm{metered\_release\_days}} \times \frac{1\ \mathrm{event}}{\mathrm{day}}} \qquad (4\text{-}5)$$

This release will occur over [$TIME_{metered\_release\_days}$ x $TIME_{release\_days}$ x 1 event/release day] days from [N_{sites}] sites.

Where:

$Elocal_{metered}$ = Release of chemical of interest to pretreatment (kg chemical/site-day)

Elocal = Release of chemical of interest to pretreatment (kg chemical/site-day; see Sections 4.2 to 4.4)

$TIME_{release\_days}$ = Number of days of release (days/yr; specific to each release estimate; see Sections 4.2 to 4.4)

$TIME_{metered\_release\_days}$ = Number of days pretreated diluted) wastewater is metered to wastewater treatment (days/event)

5. Occupational Exposure Assessments for the Use of AFFF Concentrates

The following section presents estimation methods for worker exposures to the chemical of interest during the use of AFFF. Table 5.1 illustrates the occupational activities performed within the use of AFFF that have the greatest potential for worker exposure to the chemical. Table 5.1 summarises the exposure estimation methods used in this ESD.

Note that the standard model default values cited are current as of the date of this ESD; however, EPA may update these models as additional data become available. It is recommended that the most current version of the models be used in these calculations.

EPA has developed a software package (ChemSTEER) containing these models as well as all current EPA defaults. Because of the complexity of the inhalation exposure to vapour models, ChemSTEER is recommended for estimating these exposures. Annex B provides additional information on ChemSTEER, including information on obtaining the program, as well as background information, model equations, and default values for several parameters for all standard EPA models.

Table 5.1. Summary of AFFF Use Scenario Exposure Models

Exposure Activity	Description	Route of Exposure / Physical Form	Model Name or Description[a]	Standard EPA Model (✓)
A	Exposure to AFFF concentrate during unloading or transferring	Dermal exposure to liquid chemical	*EPA/OPPT 2-Hand Dermal Contact with Liquids Model*	✓
B	Exposure to AFFF concentrate during container cleaning	Dermal exposure to liquid chemical	*EPA/OPPT 2-Hand Dermal Contact with Liquids Model*	✓
C	Exposure to AFFF during discharge	Dermal exposure to liquid chemical	*EPA/OPPT 2-Hand Dermal Immersion in Liquids Model*	✓
		Inhalation exposure to mists/aerosol	*EPA/OPPT Automobile Refinish Spray Coating Inhalation Exposure Model*	✓
D	Exposure to AFFF during disposal of spent foam	Dermal exposure to liquid chemical	*EPA/OPPT 2-Hand Dermal Contact with Liquids Model*	✓

a – Additional detailed descriptions for each of the models presented in this section are provided in Annex B.

5.1. Personal Protective Equipment

The FFFC states that during firefighting equipment or system charging, typical Personal Protective Equipment (PPE) is worn, including gloves, safety glasses, steel toed shoes, and coveralls or work clothes (FFFC, 2014[25]). NFPA 405 (Standard for the Recurring Proficiency of Airport Fire Fighters) specifies the following potential firefighting PPE (NFPA, 2015[37]): boots, gloves, turnout coat, turnout pants, helmet, eye protection, Self-Contained Breathing Apparatus (SCBA), protective hoods, specialized clothing, and hearing protection. These types of PPE are expected to be typical among professional firefighters.

Please note that EPA does not assess the effectiveness of PPE at mitigating occupational exposures in this ESD. The exposure mitigation by PPE is affected by many factors including availability, cost, worker compliance, impact on job performance, chemical and physical properties of the substance and protective clothing, and the use, decontamination, maintenance, storage, and disposal practices applicable to the industrial operation. Therefore, the conservative, screening-level occupational exposure estimates presented in this ESD do not account for PPE. Actual occupational exposure may be significantly less than the estimates presented in this ESD.

5.2. Number of Workers Exposed Per Site

Limited industry-specific data on the number of workers potentially exposed were found in the references reviewed for this ESD (US Census Bureau, 2013[38]). Additionally, traditional data sources available that contain information about the number of workers in certain industries (e.g. US Census Bureau) are not as applicable because they refer to the number of production workers involved in specific industry processes, and not those that might be involved in firefighting. Finally, there may be differences in the amounts of workers involved in fixed versus portable firefighting scenarios.

According to the NFPA, there were approximately 1,140,750 local firefighters and 55,150 fire departments in the US in 2013 (NFPA, 2014[39]). This results in an average of 21 firefighters per site. NFPA 403 also specifies a minimum of 2-15 ARFF personnel per airport, depending on the airport size (NFPA, 2014[40]). As an estimate, EPA recommends assuming 21 workers per site for all sites, absent site-specific information. If site-specific information is available, those estimates can be used in place of the ESD estimate.

5.3. Exposure from Unloading and Transferring AFFF Concentrate (Exposure A)

Workers may connect transfer lines or manually unload chemicals from transport containers into firefighting equipment or storage. If the concentration of the chemical in the AFFF concentrate ($F_{chem\_concentrate}$) is unknown, 25 percent concentration may be assumed as a conservative default, as previously discussed in Section 3.4.

Inhalation Exposure

Liquids

Inhalation exposure is expected to be negligible for non-volatile chemicals ($VP < 0.001$ torr) (US EPA, 1995[1]).

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

Dermal Exposure

There is potential for dermal exposure during both automated and manual unloading activities. Automated systems may limit the extent of dermal exposure more than manual unloading; however, workers may still be exposed when connecting transfer lines or manually transferring liquid chemicals from transport containers to firefighting equipment.

The *EPA/OPPT 2-Hand Dermal Contact with Liquid Model* may be used to estimate dermal exposure to the chemical of interest in a liquid formulation during these activities. The rationale, defaults, and limitations of these models are further explained in Annex B.

Liquids

To estimate the potential worker exposure to the chemical of interest in a liquid AFFF concentrate for this activity, EPA recommends using the following equation.

$$\mathrm{EXP}_{\mathrm{dermal\_[sector]}} = \mathrm{Q}_{\mathrm{liquid\_skin}} \times \mathrm{AREA}_{\mathrm{surface}} \times \mathrm{N}_{\mathrm{exp\_incident}} \times \mathrm{F}_{\mathrm{chem\_concentrate\_[sector]}} \quad (5\text{-}1)$$

This exposure will occur over $\mathrm{TIME}_{\mathrm{unloading\_days}}$ (rounded to the nearest integer; see Section 3.15), up to 250 days per year

Where:

$\mathrm{EXP}_{\mathrm{dermal\_[sector]}}$ = Potential dermal exposure to the chemical of interest per day for a given use sector (mg chemical/day)

$\mathrm{Q}_{\mathrm{liquid\_skin}}$ = Quantity of liquid component remaining on skin (Defaults: 2.1 mg component/cm^2-incident (high-end) and 0.7 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41])

$\mathrm{AREA}_{\mathrm{surface}}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$\mathrm{N}_{\mathrm{exp\_incident}}$[7] = Number of exposure incidents per day (Default: 1 incident/day)

$\mathrm{F}_{\mathrm{chem\_concentrate\_[sector[}}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (mg chemical/mg AFFF concentrate) (See Section 3.4)

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

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[7] Only one contact per day ($\mathrm{N}_{\mathrm{exp\_incident}}$ = 1 event/worker-day) is assumed because $\mathrm{Q}_{\mathrm{liquid\_skin}}$, with few exceptions, is not expected to be significantly affected either by wiping excess chemical material from skin or by repeated contacts with additional chemical material (i.e. wiping excess from the skin does not remove a significant fraction of the small layer of chemical material adhering to the skin and additional contacts with the chemical material do not add a significant fraction to the layer). Exceptions to this assumption may be considered for chemicals with high volatility and/or with very high rates of absorption into the skin.

5.4. Exposure from Container Cleaning (Exposure B)

Workers may be exposed while rinsing containers used to transport AFFF concentrate. If the concentration of the chemical in the component ($F_{chem\_concentrate}$) is unknown, 25 percent concentration may be assumed as a conservative default, as previously discussed in Section 3.4. The default number of workers exposed during this activity is provided in Section 5.2.

Inhalation Exposure

Liquids

Inhalation exposure is expected to be negligible for non-volatile chemicals (VP < 0.001 torr) (US EPA, 1995[1]).

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

Dermal Exposure

There is potential for dermal exposure during the cleaning of transport containers. The *EPA/OPPT 2-Hand Dermal Contact with Liquid Model* may be used to estimate dermal exposure to the chemical of interest in a liquid AFFF concentrate. The rationale, defaults, and limitations of the model are explained in Annex B.

Liquids

To estimate the potential worker exposure to the chemical of interest in a liquid AFFF for this activity, EPA recommends using the following equation:

$$EXP_{dermal\_[sector]} = Q_{liquid\_skin} \times AREA_{surface} \times N_{exp\_incident} \times F_{chem\_concentrate\_[sector]} \quad (5\text{-}2)$$

This exposure will occur over $TIME_{unloading\_days}$ (rounded to the nearest integer; see Section 3.15), up to 250 days per year

Where:

$EXP_{dermal\_[sector]}$ = Potential dermal exposure to the chemical of interest per day for a given use sector (mg chemical/day)

Q_{liquid_skin} = Quantity of liquid component remaining on skin (Defaults: 2.1 mg component/cm^2-incident (high-end) and 0.7 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41]))

$AREA_{surface}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$N_{exp\_incident}$[8] = Number of exposure incidents per day (Default: 1 incident/day)

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[8] Only one contact per day ($N_{exp\_incident}$ = 1 event/worker-day) is assumed because Q_{liquid_skin}, with few exceptions, is not expected to be significantly affected either by wiping excess chemical material from skin or by repeated contacts with additional chemical material (i.e. wiping excess

$F_{chem\_concentrate\_[sector]}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (mg chemical/mg concentrate; Default = 0.25 - see Section 3.4)

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

5.5. Exposure from Discharge of Foam (Exposure C)

Workers may be exposed during discharge of foam during firefighting, training, or testing exercises. If the concentration of the chemical in the AFFF (F_{chem_foam}) is unknown, 0.75 percent concentration may be assumed as a conservative default, as previously discussed in Section 3.5.

Inhalation Exposure

Liquids

Due to the lack of specific exposure data, this ESD conservatively estimates exposures during spray coating using the *EPA/OPPT Automobile Refinish Spray Coating Inhalation Exposure Model* as a surrogate scenario. This model estimates worker exposures to a non-volatile (i.e. < 0.001 torr) chemical during spray coating and can be used to estimate the amount of non-volatile chemical in mist inhaled by a worker during automobile refinish spray painting operations.

To estimate the potential worker inhalation exposure to the chemical during coating operations, EPA recommends using the following equation:

$$EXP_{inhalation\_[sector]} = C_{part\_air} \times TIME_{exposure} \times RATE_{breathing} \times F_{chem\_particulate} \quad (5\text{-}3)$$

This exposure will occur over [$TIME_{use\_days}$ (see Section 3.12)], up to 250 days per year.

Where:

$EXP_{inhalation\_[sector]}$ = Inhalation potential dose rate of chemical during spraying for a given use sector (mg chemical/day)

C_{part_air} = Mass concentration of total particulate in air (Default: 15 mg particulate/m^3 of air; conventional spray gun)

$TIME_{exposure}$ = Duration of exposure to the chemical during the coating process (Default: 8 hours/day)

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from the skin does not remove a significant fraction of the small layer of chemical material adhering to the skin and additional contacts with the chemical material do not add a significant fraction to the layer). Exceptions to this assumption may be considered for chemicals with high volatility and/or with very high rates of absorption into the skin.

$RATE_{breathing}$ = Inhalation rate (CEB default: 1.25 m^3/hr) (US EPA, 1991[2])

$F_{chem\_particulate}$ = The lesser of $F_{chem\_form}/F_{particulate\_prod}$ or 1.

$F_{chem\_foam\_[sector]}$ = Mass fraction of chemical in the foam for a given use sector (Default: 0.0075 mg chemical/mg product) (See Section 3.5)

$F_{particulate\_prod}$ = Mass fraction of solids in the foam product (CEB default: 0.25 mg particulate/mg product) (OECD, 2004[43])

The models and all current EPA defaults have been programmed into ChemSTEER; EPA recommends using this software to calculate inhalation exposure to spray coating activities. The *Generic Scenario for Automobile Spray Coating* (US EPA, 1996[44]) provides additional information about this model.

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

Dermal Exposure

The *EPA/OPPT 2-Hand Immersion with Liquid Model* may be used to estimate dermal exposure to the chemical of interest in a foam during spraying of AFFF. The rationale, defaults, and limitations of these models are further explained in Annex B.

Liquids

To estimate the potential worker exposure to the chemical of interest in a foam for this activity, EPA recommends using the following equation.

$$EXP_{dermal\_[sector]} = Q_{liquid\_skin} \times AREA_{surface} \times N_{exp\_incident} \times F_{chem\_foam\_[sector]} \quad (5\text{-}4)$$

This exposure will occur over [$TIME_{use\_days}$ (see Section 3.12)], up to 250 days per year.

Where:

$EXP_{dermal\_[sector]}$ = Potential dermal exposure to the chemical of interest per day for a given use sector (mg chemical/day)

Q_{liquid_skin} = Quantity of liquid component remaining on skin (Defaults: 10.3 mg component/cm^2-incident (high-end) and 1.3 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41]))

$AREA_{surface}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$N_{exp\_incident}$[9] = Number of exposure incidents per day (Default: 1 incident/day)

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[9] Only one contact per day ($N_{exp\_incident}$ = 1 event/worker-day) is assumed because Q_{liquid_skin}, with few exceptions, is not expected to be significantly affected either by wiping excess chemical material from skin or by repeated contacts with additional chemical material (i.e. wiping excess from the skin does not remove a significant fraction of the small layer of chemical material

$F_{chem\_foam\_[sector]}$ = Mass fraction of the chemical of interest in the foam for a given use sector (mg chemical/mg foam) (See Section 3.5)

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

5.6. Exposure from Disposal of Spent Foam (Exposure D)

Workers may be exposed while collecting and or disposing spent foam. If the concentration of the chemical in the AFFF ($F_{chem\_foam\_[sector]}$) is unknown, 0.75 percent concentration may be assumed as a conservative default, as previously discussed in Section 3.5 (assuming 25 percent chemical in AFFF concentrate, 3% concentrate). The default number of workers exposed during this activity is provided in Section 5.2.

Inhalation Exposure

Liquids

Inhalation exposure is expected to be negligible for non-volatile chemicals (VP < 0.001 torr) (US EPA, 1995[1]).

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

Dermal Exposure

There is potential for dermal exposure during the collection and/or disposal of spent foam. The *EPA/OPPT 2-Hand Dermal Contact with Liquid Model* may be used to estimate dermal exposure to the chemical of interest in a liquid AFFF. The rationale, defaults, and limitations of the model are explained in Annex B.

Liquids

To estimate the potential worker exposure to the chemical of interest in a foam for this activity, EPA recommends using the following equation:

$$EXP_{dermal\_[sector]} = Q_{liquid\_skin} \times AREA_{surface} \times N_{exp\_incident} \times F_{chem\_foam\_[sector]} \quad (5\text{-}5)$$

This exposure will occur over [$TIME_{use\_days}$ (see Section 3.12)], up to 250 days per year.

Where:

$EXP_{dermal\_[sector]}$ = Potential dermal exposure to the chemical of interest per day for a given use sector (mg chemical/day)

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adhering to the skin and additional contacts with the chemical material do not add a significant fraction to the layer). Exceptions to this assumption may be considered for chemicals with high volatility and/or with very high rates of absorption into the skin.

Q_{liquid_skin} = Quantity of liquid component remaining on skin (Defaults: 2.1 mg component/cm^2-incident (high-end) and 0.7 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41]))

$AREA_{surface}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$N_{exp\_incident}$[10] = Number of exposure incidents per day (Default: 1 incident/day)

$F_{chem\_foam\_[sector]}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (mg chemical/mg component) (See Section 3.5)

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

5.7. Exposure from Disposal of Expired AFFF Concentrate (Exposure E)

Workers may be exposed while collecting and disposing of expired AFFF concentrate stock. If the concentration of the chemical in the component ($F_{chem\_concentrate\_[sector]}$) is unknown, 25 percent concentration may be assumed as a conservative default, as previously discussed in Section 3.4. The default number of workers exposed during this activity is provided in Section 5.2.

Inhalation Exposure

Liquids

Inhalation exposure is expected to be negligible for non-volatile chemicals (VP < 0.001 torr) (US EPA, 1995[1]).

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

Dermal Exposure

There is potential for dermal exposure during the collection and disposal of expired AFFF concentrate stock. The *EPA/OPPT 2-Hand Dermal Contact with Liquid Model* may be used to estimate dermal exposure to the chemical of interest in a liquid AFFF concentrate. The rationale, defaults, and limitations of the model are explained in Annex B.

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[10] Only one contact per day ($N_{exp\_incident}$ = 1 event/worker-day) is assumed because Q_{liquid_skin}, with few exceptions, is not expected to be significantly affected either by wiping excess chemical material from skin or by repeated contacts with additional chemical material (i.e. wiping excess from the skin does not remove a significant fraction of the small layer of chemical material adhering to the skin and additional contacts with the chemical material do not add a significant fraction to the layer). Exceptions to this assumption may be considered for chemicals with high volatility and/or with very high rates of absorption into the skin.

Liquids

To estimate the potential worker exposure to the chemical of interest in an AFFF concentrate for this activity, EPA recommends using the following equation:

$$\mathrm{EXP}_{\mathrm{dermal\_[sector]}} = \mathrm{Q}_{\mathrm{liquid\_skin}} \times \mathrm{AREA}_{\mathrm{surface}} \times \mathrm{N}_{\mathrm{exp\_incident}} \times \mathrm{F}_{\mathrm{chem\_concentrate\_[sector]}} \quad (5\text{-}6)$$

This exposure will occur over [$\mathrm{TIME}_{\mathrm{disposal}}$], up to 250 days per year.

Where:

$\mathrm{EXP}_{\mathrm{dermal\_[sector]}}$ = Potential dermal exposure to the chemical of interest per day for a given use sector (mg chemical/day)

$\mathrm{Q}_{\mathrm{liquid\_skin}}$ = Quantity of liquid component remaining on skin (Defaults: 2.1 mg component/cm^2-incident (high-end) and 0.7 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41]))

$\mathrm{AREA}_{\mathrm{surface}}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$\mathrm{N}_{\mathrm{exp\_incident}}$[11] = Number of exposure incidents per day (Default: 1 incident/day)

$\mathrm{F}_{\mathrm{chem\_concentrate\_[sector]}}$ = Mass fraction of the chemical of interest in the AFFF concentrate for a given use sector (mg chemical/mg component) (See Section 3.4)

Solids

Not expected – AFFF concentrates are stored and used in liquid form.

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[11] Only one contact per day ($\mathrm{N}_{\mathrm{exp\_incident}}$ = 1 event/worker-day) is assumed because $\mathrm{Q}_{\mathrm{liquid\_skin}}$, with few exceptions, is not expected to be significantly affected either by wiping excess chemical material from skin or by repeated contacts with additional chemical material (i.e. wiping excess from the skin does not remove a significant fraction of the small layer of chemical material adhering to the skin and additional contacts with the chemical material do not add a significant fraction to the layer). Exceptions to this assumption may be considered for chemicals with high volatility and/or with very high rates of absorption into the skin.

6. Sample Calculations

This section presents an example of how the equations introduced in Sections 3. , 4. , and 5. might be used to estimate releases of and exposures to a non-volatile chemical present in a AFFF concentrate. The default values used in these calculations are presented in Sections 3. through 5. and should be used only in the absence of site-specific information. The following data are used in the example calculations:

1. Chemical of interest production volume ($Q_{chem\_yr)}$ is 52,000 kg chemical/yr.
2. Chemical of interest is present at 1.2% in a 3% AFFF concentrate
3. AFFF is used exclusively in petrochemical manufacturing facilities

6.1. General Facility Information for the Use of AFFF

6.1.1. Fraction of AFFF Concentrate Used in Each End-Use Sector ($X_{[sector]}$)

AFFF concentrate is used exclusively in petrochemical manufacturing. Therefore, $X_{petrochem} = 1$.

6.1.2. Mass Fraction of the Chemical of Interest in the AFFF Concentrate ($F_{chem\_concentrate\_petrochem}$)

Per given information, the chemical of interest is 1.2% in the AFFF concentrate. Therefore, $F_{chem\_concentrate\_petrochem} = 0.012$.

6.1.3. Mass Fraction of the Chemical of Interest in the AFFF Foam ($F_{chem\_foam\_ petrochem}$)

Per equation 3-1:

$$F_{chem\_foam\_petrochem} = F_{chem\_concentrate\_petrochem} \times F_{concentrate\_foam\_petrochem}$$

$$F_{chem\_foam\_petrochem} = \frac{0.012 \text{ kg chemical}}{\text{kg AFFF concentrate}} \times \frac{0.03 \text{ kg AFFF concentrate}}{\text{kg foam}}$$

$$F_{chem\_foam\_petrochem} = \frac{0.00036 \text{ kg chemical}}{\text{kg foam}}$$

Where:

$F_{chem\_foam\_petrochem}$ = Mass fraction of the chemical of interest in the produced foam (kg chemical/kg foam)

$F_{chem\_concentrate\_petrochem}$ = Mass fraction of the chemical of interest in the AFFF concentrate (0.012 kg chemical/kg AFFF concentrate; per Section 6.1.2)

$F_{concentrate\_foam\_petrochem}$ = Mass fraction of the AFFF concentrate in the produced foam (kg AFFF concentrate/kg foam; Default: 0.03 kg AFFF concentrate/kg foam for 3% foam)

6.1.4. Annual Consumption Fraction ($F_{consumed\_petrochem}$)

$F_{consumed\_petrochem}$ = 0.07 kg AFFF concentrate consumed/kg AFFF concentrate stocked) (Default: per Table 3.3)

6.1.5. Annual Disposal Fraction ($F_{disposed\_petrochem}$)

$F_{consumed\_petrochem}$ = 0.10 kg AFFF concentrate disposed/kg AFFF concentrate stocked) (Default: per Section 3.7)

6.1.6. Annual AFFF Concentrate Use Rate per Site ($Q_{concentrate\_site\_yr\_petrochem}$)

Per Equation 3-2:

$$Q_{\text{concentrate\_site\_yr\_petrochem}} = V_{\text{concentrate\_site-yr\_petrochem}} \times RHO_{\text{concentrate}} \times \frac{3.78\text{ L}}{\text{gal}} \times \left(F_{\text{consumed\_[sector]}} + F_{\text{disposed\_[sector]}}\right)$$

$$Q_{\text{concentrate\_site\_yr\_petrochem}} = \frac{32{,}258\text{ gallons}}{\text{site} - \text{yr}} \times \frac{1\text{ kg}}{\text{L}} \times \frac{3.78\text{ L}}{\text{gal}} \times \left(\frac{0.07\text{ kg AFFF concentrate consumed}}{\text{kg AFFF concentrate stocked}} + \frac{0.10\text{ kg AFFF concentrate disposed}}{\text{kg AFFF concentrate stocked}}\right)$$

$$Q_{\text{concentrate\_site\_yr\_petrochem}} = \frac{20{,}729\text{ kg}}{\text{site} - \text{yr}}$$

Where:

$Q_{concentrate\_site\_yr\_petrochem}$ = Annual use rate of the AFFF concentrate per site (kg concentrate/site-yr)

$V_{concentrate\_site-yr\_petrochem}$ = Annual inventory of AFFF concentrate (gallons/site-yr) (Default: 32,258 gallons AFFF concentrate/site-yr, per Table 3.2)

$RHO_{concentrate}$ = Density of AFFF concentrate (kg/L) (Default: 1 kg/L)

$F_{consumed\_petrochem}$ = 0.07 kg AFFF concentrate consumed/kg AFFF concentrate stocked) (per Section 6.1.5)

$F_{disposed\_petrochem}$ = 0.10 kg AFFF concentrate disposed/kg AFFF concentrate stocked) (per Section 6.1.6)

6.1.7. Annual Chemical of Interest Use Rate per Site ($Q_{chem\_site\_yr\_petrochem}$)

Per Equation 3-3:

$$Q_{chem\_site\_yr\_petrochem} = Q_{concentrate\_site\_yr\_[sector]} \times F_{chem\_concentrate\_[sector]}$$

$$Q_{chem\_site\_yr\_petrochem} = \frac{20{,}729\ \text{kg conc}}{\text{site} - \text{yr}} \times \frac{0.012\ \text{kg chem}}{\text{kg conc}}$$

$$Q_{chem\_site\_yr\_petrochem} = \frac{248.7\ \text{kg chemical}}{\text{site} - \text{yr}}$$

Where:

$Q_{chem\_site\_yr\_petrochem}$ = Annual use of the chemical of interest per site (kg chemical/site-yr)

$Q_{concentrate\_site\_yr\_petrochem}$ = Annual use rate of AFFF concentrate containing the chemical of interest per site (20,729 kg concentrate/site-yr; see Section 6.1.6)

$RHO_{concentrate}$ = Density of AFFF concentrate (kg/L) (Default: 1 kg/L)

$F_{chem\_concentrate\_petrochem}$ = Mass fraction of the chemical of interest in the AFFF concentrate (0.012 kg chem/kg AFFF concentrate; per Section 6.1.2)

6.1.8. Annual Chemical Use Rate ($Q_{chem\_yr\_petrochem}$)

Per Equation 3-4:

$$Q_{chem\_yr\_petrochem} = Q_{chem\_yr} \times X_{petrochem}$$

$$Q_{chem\_yr\_petrochem} = \frac{52{,}000\ \text{kg chem}}{\text{yr}} \times 1$$

$$Q_{chem\_yr\_petrochem} = \frac{52{,}000\ \text{kg chem}}{\text{yr}}$$

Where:

$Q_{chem\_yr\_petrochem}$ = Annual use rate of the chemical of interest in a specific end-use sector (kg chemical/yr)

Q_{chem_yr} = Annual production volume of the chemical of interest (52,000 kg chemical/yr; given)

$X_{petrochem}$ = Fraction of AFFF concentrate used in each end use sector (1 kg for end-use sector/kg total; per Section 6.1.1)

6.1.9. Number of Sites ($N_{sites\_petrochem}$)

Per Equation 3-6:

$$N_{sites\_petrochem} = \frac{Q_{chem\_yr\_petrochem}}{Q_{chem\_site\_yr\_petrochem}}$$

$$N_{sites\_petrochem} = \frac{\frac{52{,}000 \text{ kg chem}}{\text{yr}}}{\frac{248.7 \text{ kg chemical}}{\text{site} - \text{yr}}}$$

$$N_{sites\_petrochem} = 209.1 \text{ sites} = 210 \text{ sites}$$

Where:

$N_{sites\_petrochem}$ = Number of sites

$Q_{chem\_yr\_petrochem}$ = Annual use rate of the chemical of interest (52,000 kg chemical/yr; per Section 6.1.8)

$Q_{chem\_site\_yr\_petrochem}$ = Annual use rate of the chemical of interest used at each site (5,538 kg chemical/site-yr; per Section 6.1.7)

Since $N_{sites\_petrochem}$ is rounded, $Q_{chem\_site\_yr\_petrochem}$ and $Q_{concentrate\_site\_yr\_petrochem}$ should be recalculated.

$$Q_{chem\_site\_yr\_petrochem} = \frac{Q_{chem\_yr\_petrochem}}{N_{sites\_petrochem}}$$

$$Q_{chem\_site\_yr\_petrochem} = \frac{\frac{52{,}000 \text{ kg chem}}{\text{yr}}}{210 \text{ sites}}$$

$$Q_{chem\_site\_yr\_petrochem} = \frac{247.6 \text{ kg chem}}{\text{site} - \text{yr}}$$

$$Q_{concentrate\_site\_yr\_petrochem} = \frac{Q_{chem\_site\_yr\_petrochem}}{F_{chem\_concentrate\_petrochem}}$$

$$Q_{concentrate\_site\_yr\_petrochem} = \frac{\frac{247.6 \text{ kg chem}}{\text{site} - \text{yr}}}{\frac{0.012 \text{ kg chem}}{\text{kg concentrate}}}$$

$$Q_{\text{concentrate\_site\_yr\_petrochem}} = \frac{20{,}633 \text{ kg concentrate}}{\text{site} - \text{yr}}$$

6.1.10. Days of Use (TIME$_{use\_days\_petrochem}$)

$\text{TIME}_{\text{use\_days\_petrochem}}$ = 3 days/yr (Default, per Table 3.4)

6.1.11. Daily Consumption Rate of the Chemical of Interest (Q$_{chem\_consumed\_site\_day\_petrochem}$

Per Equation 3-6:

$$Q_{\text{chem\_consumed\_site\_day\_petrochem}} = \left(\frac{Q_{\text{chem\_site\_yr\_[sector]}}}{\text{TIME}_{\text{use days\_[sector]}}}\right) \times \left(\frac{F_{\text{consumed\_[sector]}}}{F_{\text{consumed\_[sector]}} + F_{\text{disposed\_[sector]}}}\right) \quad (3\text{-}6)$$

$$= \left(\frac{\frac{247.6 \text{ kg chemical}}{\text{site} - \text{yr}}}{\frac{3 \text{ days}}{\text{yr}}}\right) \times \left(\frac{\frac{0.07 \text{ kg AFFF consumed}}{\text{kg AFFF stocked}}}{\frac{0.07 \text{ kg AFFF consumed}}{\text{kg AFFF stocked}} + \frac{0.10 \text{ kg AFFF disposed}}{\text{kg AFFF stocked}}}\right)$$

$$Q_{\text{chem\_consumed\_site\_day\_petrochem}} = \frac{34 \text{ kg chemical consumed}}{\text{site} - \text{day}}$$

Where:

$Q_{\text{chem\_consumed\_site\_day\_petrochem}}$ = Daily consumption rate of the chemical of interest contained in AFFF (kg chemical used/site-day)

$Q_{\text{chem\_site\_yr\_ petrochem}}$ = Annual use rate of the chemical of interest per site (5,538 kg chemical/site-yr; per Section 6.1.7)

$F_{\text{consumed\_ petrochem}}$ = Mass fraction of AFFF concentrate consumed (0.07 kg AFFF concentrate consumed/kg AFFF concentrate stocked; per Section 6.1.5)

$F_{\text{disposed\_ petrochem}}$ = Mass fraction of AFFF concentrate disposed (0.10 kg AFFF concentrate disposed/kg AFFF concentrate stocked; per Section 6.1.6)

$\text{TIME}_{\text{use\_days\_ petrochem}}$ = Annual number of days the AFFF product is discharged (3 days/yr; per Section 6.1.10)

6.1.12. Number of AFFF Concentrate Containers Emptied per Facility (N$_{container\_unload\_site\_yr\_petrochem}$

Per Equation 3-7:

$$N_{\text{container\_unload\_site\_yr\_petrochem}} = \frac{Q_{\text{concentrate\_site\_yr\_petrochem}}}{V_{\text{container\_petrochem}} \times \text{RHO}_{\text{concentrate}}}$$

$$\mathrm{N_{container\_unload\_site\_yr\_petrochem}} = \frac{\frac{20{,}633\ \mathrm{kg}}{\mathrm{site-yr}}}{\frac{1{,}000\ \mathrm{L}}{\mathrm{container}} \times \frac{1\ \mathrm{kg}}{\mathrm{L}}}$$

$$\mathrm{N_{container\_unload\_site\_yr\_petrochem}} = \frac{21\ \mathrm{containers\ unloaded}}{\mathrm{site-yr}}$$

Where:

$\mathrm{N_{container\_unload\_site\_yr\_petrochem}}$ = Number of transport containers unloaded at each site per year (containers/site-yr)

$\mathrm{Q_{concentrate\_site\_yr\_petrochem}}$ = (20,633 kg chemical of interest/site-yr; see Section 6.1.6)

$\mathrm{V_{container\_\ petrochem}}$ = Volume of transport container (Default: 1,000 L AFFF concentrate/container (265-gallon tote))

$\mathrm{RHO_{concentrate}}$ = Density of AFFF concentrate (kg/L formulation; Default: 1 kg/L)

6.1.13. Number of Days to Unload AFFF Concentrate Containers (TIME$_{unloading\_days\_petrochem}$)

Per Equation 3-8:

$$\mathrm{TIME_{unloading\_days\_petrochem}} = \frac{\mathrm{N_{container\_unload\_site\_yr\_petrochem}}}{\mathrm{RATE_{container\_unloading}} \times \mathrm{TIME_{unloading\_hours}}}$$

$$\mathrm{TIME_{unloading\_days\_petrochem}} = \frac{\frac{21\ \mathrm{containers\ unloaded}}{\mathrm{site-yr}}}{\frac{20\ \mathrm{containers}}{\mathrm{hr}} \times \frac{8\ \mathrm{hr}}{\mathrm{day}}}$$

$$\mathrm{TIME_{unloading\_days\_petrochem}} =< 1\ \mathrm{day/yr}$$

Where:

$\mathrm{TIME_{unloading\_days\_petrochem}}$ = Number of days to unload containers (days/site-yr)

$\mathrm{N_{container\_unload\_site\_yr\_petrochem}}$ = Number of transport containers unloaded at each site per year (21 containers/site-yr; per Section 6.1.12)

$\mathrm{RATE_{container\_unloading}}$ = Container loading rate (containers/hr; Default 20 containers/hr for totes) (US EPA, 1991[2])

$\mathrm{TIME_{unloading\_hours}}$ = Number of hours unloading containers per day (Default: 8 hr/day) (US EPA, 1991[2])

6.2. Environmental or Waste Treatment Releases

6.2.1. Release to Water, Incineration, or Landfill from Container Residue (Release 1)

Per Section 6.1.13, $\text{TIME}_{\text{unloading\_days}} < 1$; therefore the average daily release can be estimated based on Equation 4-1a.

$$\text{Elocal}_{\text{container\_residue\_disp\_petrochem}} = \text{V}_{\text{container\_petrochem}} \times \text{RHO}_{\text{concentrate}} \times \text{F}_{\text{chem\_concentrate\_petrochem}} \times \text{F}_{\text{container\_residue}} \times \text{N}_{\text{container\_unload\_site\_yr\_petrochem}}$$

$$\text{Elocal}_{\text{container\_residue\_disp\_petrochem}} = \frac{1{,}000\text{ L AFFF}}{\text{container}} \times \frac{1\text{ kg AFFF}}{\text{L AFFF}} \times \frac{0.012\text{ kg chem}}{\text{kg AFFF}} \times 0.002 \times \frac{21\text{ containers}}{\text{yr}}$$

$$\text{Elocal}_{\text{container\_residue\_disp\_petrochem}} = \frac{0.5\text{ kg chemical}}{\text{site} - \text{day}}$$

This release will occur over 1 day/year from 210 sites.

Media of release: water (wastewater treatment or POTW), incineration, or landfill.

Where:

$\text{Elocal}_{\text{container\_residue\_disp\_petrochem}}$ = Daily release of chemical of interest from container residue (kg chemical/site-day)

$\text{V}_{\text{container\_petrochem}}$ = Volume of transport container (Default: 1,000 L formulation/container (265-gallon tote; see Table A B.1 for alternative default container volumes)

$\text{RHO}_{\text{concentrate}}$ = Density of AFFF concentrate (kg/L concentrate; Default: 1 kg/L for liquid)

$\text{F}_{\text{chem\_concentrate\_petrochem}}$ = Mass fraction of the chemical of interest in the AFFF concentrate (0.012 kg chem/kg AFFF concentrate; per Section 6.1.2)

$\text{F}_{\text{container\_residue}}$ = Fraction of AFFF component remaining in the container as residue (Defaults: liquid - 0.002 kg AFFF concentrate remaining/kg shipped for totes (US EPA, 2000[41]); see Annex B for defaults used for other container types)

$\text{N}_{\text{container\_unload\_site\_yr\_petrochem}}$ = Number of transport containers unloaded at each site per year (21 containers/site-yr, per Section 6.1.12)

$\text{TIME}_{\text{unloading\_days\_petrochem}}$ = Number of days to unload containers (1 days/site-yr; per Section 6.1.13)

6.2.2. Release to Water, Incineration, or Landfill from Disposal of Spent Foam (Release 2)

Using Equation 4-2.

$$\text{Elocal}_{\text{consumed\_AFFF\_petrochem}} = \text{Q}_{\text{chem\_consumed\_site\_day\_petrochem}}$$

$$= \frac{34 \text{ kg chemical consumed}}{\text{site} - \text{day}}$$

This release will occur over 3 days/year from 210 sites.

Media of release: water (wastewater treatment or POTW), incineration, or landfill.

Where:

$\text{Elocal}_{\text{consumed\_AFFF\_ petrochem}}$ = Daily release of chemical of interest from consumption of spent foam (kg chemical/site-day)

$\text{Q}_{\text{chem\_consumed\_site\_day\_ petrochem}}$ = Daily discharge rate of the chemical of interest (34 kg chemical/site-day; per Section 6.1.11)

6.2.3. Release to Water or Incineration from Disposal of Expired AFFF (Release 3)

Using equation 4-3.

$$\text{Elocal}_{\text{disposed\_petrochem}} = \left(\frac{\text{Q}_{\text{chem\_site\_yr\_petrochem}}}{\text{TIME}_{\text{disposal\_petrochem}}}\right) \times \left(\frac{\text{F}_{\text{disposed\_petrochem}}}{\text{F}_{\text{consumed\_petrochem}} + \text{F}_{\text{disposed\_petrochem]}}}\right)$$

$$\text{Elocal}_{\text{disposed\_petrochem}} = \left(\frac{\frac{247.6 \text{ kg chemical}}{\text{site} - \text{yr}}}{\frac{1 \text{ day}}{\text{yr}}}\right) \times \left(\frac{0.10}{0.07 + 0.10}\right)$$

$$\text{Elocal}_{\text{disposed\_petrochem}} = \frac{146 \text{ kg chemical}}{\text{site} - \text{day}}$$

This release will occur over 1 day/year from 210 sites.

Where:

$Elocal_{disposed\_petrochem}$ = Daily release of chemical of interest from disposal of AFFF stock (kg chemical/site-day)

$Q_{chem\_site\_yr\_ petrochem}$ = Annual inventory of the chemical of (247.6 kg chemical/site-yr; per Section 6.1.7)

$F_{consumed\_ petrochem}$ = Fraction of AFFF concentrate stock consumed (0.07 kg chemical consumed/kg chemical inventoried; per Section 6.1.4)

$F_{disposed\_ petrochem}$ = Fraction of AFFF concentrate stock expiring (0.10 kg chemical disposed/kg chemical inventoried; per Section 6.1.5)

$TIME_{disposal\_petrochem}$ = Number of disposal days per year (days/yr) (Default: 1 end of life disposal/yr)

6.2.4. Pretreatment and Wastewater Metering

For this example, EPA assesses metering from disposal of expired foam (Section 6.2.3). Per Section 4.4, consumed foam from petrochemical manufacturing facilities are assumed to be sent to industrial POTW or incineration.

This calculation should be repeated for every release assessed to POTW.

Using Equation 4-4:

$$\mathrm{TIME}_{\mathrm{metered\_release\_days}} = \frac{\mathrm{E}_{\mathrm{local}} \times \frac{\mathrm{site-day}}{\mathrm{1\ event}}}{\mathrm{CONC}_{\mathrm{treatment}} \times \frac{10^{-6}\ \mathrm{kg}}{\mathrm{mg}} \times \mathrm{F}_{\mathrm{chem\_concentrate}} \times \mathrm{Q}_{\mathrm{POTW\_influent}}}$$

$$\mathrm{TIME}_{\mathrm{metered\_release\_days}} = \frac{\frac{146\ \mathrm{kg\ chemical}}{\mathrm{site-day}} \times \frac{\mathrm{site-day}}{\mathrm{1\ event}}}{\frac{50\ \mathrm{mg\ AFFF\ conc}}{\mathrm{L\ wastewater}} \times \frac{10^{-6}\ \mathrm{kg}}{\mathrm{mg}} \times \frac{0.012\ \mathrm{kg\ chemical}}{\mathrm{kg\ concentrate}} \times \frac{7{,}570{,}000\ \mathrm{L\ wastewater}}{\mathrm{day}}}$$

$$\mathrm{TIME}_{\mathrm{metered\_release\_days}} = 32.1 = {\sim}33\ \mathrm{days}$$

Where:

$TIME_{metered\_release\_days}$ = Number of days pretreated diluted) wastewater is metered to wastewater treatment (days/event)

Elocal = Release of chemical of interest to pretreatment (kg chemical/site-day; see Sections 4.2 to 4.4)

$CONC_{treatment}$ = Targeted concentration of AFFF in wastewater influent (mg AFFF conc/L; defaults = 100 mg/L wastewater for 6% AFFF; 50 mg/L for 3% AFFF)

$F_{chem\_concentrate\_petrochem}$ = Mass fraction of the chemical of interest in the AFFF concentrate (0.012 kg chem/kg AFFF concentrate; per Section 6.1.2)

$Q_{POTW\_influent}$ = Maximum POTW influent flow rate (L/day; 7,570,000 L/day for industrial POTWs; see Section 4.5.2)

Since $TIME_{metered\_release\_days} > 1$, then daily-metered releases are calculated by Equation 4-5:

$$\text{Elocal}_{\text{metered}} = \frac{\text{Elocal}}{\text{TIME}_{\text{metered\_release\_days}} \times \frac{\text{1 event}}{\text{day}}}$$

$$\text{Elocal}_{\text{metered}} = \frac{\frac{\text{146 kg chemical}}{\text{site} - \text{day}}}{\frac{\text{33 days}}{\text{event}} \times \frac{\text{1 event}}{\text{day}}}$$

$$\text{Elocal}_{\text{metered}} = \frac{\text{4.4 kg chemical}}{\text{site} - \text{day}}$$

This release will occur over 33 days/yr from 210 sites.

Where:

$Elocal_{metered}$ = Release of chemical of interest to pretreatment (kg chemical/site-day)

Elocal = Release of chemical of interest to pretreatment (kg chemical/site-day; see Sections 4.2 to 4.4)

$TIME_{release\_days}$ = Number of days of release (days/yr; specific to each release estimate; see Sections 4.2 to 4.4)

$TIME_{metered\_release\_days}$ = Number of days pretreated diluted) wastewater is metered to wastewater treatment (days/event)

6.3. Occupational Exposures

6.3.1. Exposure from Unloading and Transferring AFFF Concentrate (Exposure A)

Dermal exposures are assessed using the 2-hand dermal contact to liquids model (Equation 5-1):

$$\text{EXP}_{\text{dermal\_petrochem}} = \text{Q}_{\text{liquid\_skin}} \times \text{AREA}_{\text{surface}} \times \text{N}_{\text{exp\_incident}} \times \text{F}_{\text{chem\_concentrate\_petrochem}}$$

$$\mathrm{EXP_{dermal\_petrochem}} = \frac{0.7-2.1\ \text{mg concentrate}}{\text{cm}^2\text{-incident}} \times 1{,}070\ \text{cm}^2 \times \frac{1\ \text{incident}}{\text{day}} \times \frac{0.012\ \text{mg chemical}}{\text{mg concentrate}}$$

$$\mathrm{EXP_{dermal\_petrochem}} = \frac{9\text{-}27\ \text{mg}}{\text{day}}$$

This exposure occurs over 3 days/yr from 210 sites.

Where:

$\mathrm{EXP_{dermal\_petrochem}}$ = Potential dermal exposure to the chemical of interest per day (mg chemical/day)

$\mathrm{Q_{liquid\_skin}}$ = Quantity of liquid component remaining on skin (Defaults: 2.1 mg component/cm^2-incident (high-end) and 0.7 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41]))

$\mathrm{AREA_{surface}}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$\mathrm{N_{exp\_incident}}$ = Number of exposure incidents per day (Default: 1 incident/day)

$\mathrm{F_{chem\_concentrate\_petrochem}}$ = Mass fraction of the chemical of interest in the AFFF concentrate (mg chemical/mg AFFF concentrate) (See Section 3.4)

6.3.2. Exposure from Container Cleaning (Exposure B)

Dermal exposures are assessed using the 2-hand dermal contact to liquids model (Equation 5-2):

$$\mathrm{EXP_{dermal\_petrochem}} = \mathrm{Q_{liquid\_skin}} \times \mathrm{AREA_{surface}} \times \mathrm{N_{exp\_incident}} \times \mathrm{F_{chem\_concentrate\_petrochem}}$$

$$\mathrm{EXP_{dermal\_petrochem}} = \frac{0.7-2.1\ \text{mg concentrate}}{\text{cm}^2\text{-incident}} \times 1{,}070\ \text{cm}^2 \times \frac{1\ \text{incident}}{\text{day}} \times \frac{0.012\ \text{mg chemical}}{\text{mg concentrate}}$$

$$\mathrm{EXP_{dermal}} = \frac{9\text{-}27\ \text{mg}}{\text{day}}$$

This exposure occurs over 3 days/yr from 210 sites.

Where:

$EXP_{dermal\_petrochem}$ = Potential dermal exposure to the chemical of interest per day (mg chemical/day)

Q_{liquid_skin} = Quantity of liquid component remaining on skin (Defaults: 2.1 mg component/cm^2-incident (high-end) and 0.7 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41]))

$AREA_{surface}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$N_{exp\_incident}$ = Number of exposure incidents per day (Default: 1 incident/day)

$F_{chem\_concentrate\_petrochem}$ = Mass fraction of the chemical of interest in the AFFF concentrate (mg chemical/mg AFFF concentrate) (See Section 3.4)

6.3.3. Exposure from Discharge of Foam (Exposure C)

Inhalation Exposures

To estimate the potential worker inhalation exposure to the chemical during spray operations, EPA recommends using Equation 5-3:

$$\mathrm{EXP_{inhalation\_petrochem}} = \mathrm{C_{part\_air}} \times \mathrm{TIME_{exposure}} \times \mathrm{RATE_{breathing}} \times \mathrm{F_{chem\_particulate}}$$

$$\mathrm{EXP_{inhalation\_petrochem}} = \frac{15\ \mathrm{mg\ particulate}}{\mathrm{mg\ air}} \times \frac{8\ \mathrm{hr}}{\mathrm{day}} \times \frac{1.25\ \mathrm{m^3}}{\mathrm{hr}} \times \frac{0.00036\ \mathrm{mg\ chemical}}{\mathrm{mg\ product}}\ \mathrm{x}\ \frac{\mathrm{mg\ product}}{0.25\ \mathrm{mg\ particulate}}$$

$$\mathrm{EXP_{inhalation}} = 0.2\ \mathrm{mg/day}$$

This exposure will occur over 3 days/yr over 210 sites.

Where:

$EXP_{inhalation}$ = Inhalation potential dose rate of chemical during spraying (mg chemical/day)

C_{part_air} = Mass concentration of total particulate in air (Default: 15 mg particulate/m^3 of air; conventional spray gun)

$TIME_{exposure}$ = Duration of exposure to the chemical during the coating process (Default: 8 hours/day)

$RATE_{breathing}$ = Inhalation rate (CEB default: 1.25 m^3/hr) (US EPA, 1991[2])

$F_{chem\_particulate}$ = The lesser of $F_{chem\_form}/F_{particulate\_prod}$ or 1.

$F_{chem\_form\_petrochem}$ = Mass fraction of chemical in the foam (mg chemical/mg product) (0.00036 kg chemical/kg foam - See Section 6.1.3)

$F_{particulate\_prod}$ = Mass fraction of solids in the foam product (Default: 0.25 mg particulate/mg product) (OECD, 2004[43])

Dermal Exposures

To estimate the potential worker exposure to the chemical of interest in a foam for spraying, EPA recommends using Equation 5-4:

$$\mathrm{EXP}_{\mathrm{dermal\_petrochem}} = \mathrm{Q}_{\mathrm{liquid\_skin}} \times \mathrm{AREA}_{\mathrm{surface}} \times \mathrm{N}_{\mathrm{exp\_incident}} \times \mathrm{F}_{\mathrm{chem\_foam\_petrochem}}$$

$$\mathrm{EXP}_{\mathrm{dermal\_petrochem}} = \frac{1.3 - 10.3\ \mathrm{mg\ foam}}{\mathrm{cm}^2\text{-incident}} \times 1{,}070\ \mathrm{cm}^2 \times \frac{1\ \mathrm{incident}}{\mathrm{day}} \times \frac{0.00036\ \mathrm{mg\ chemical}}{\mathrm{mg\ foam}}$$

$$\mathrm{EXP}_{\mathrm{dermal\_petrochem}} = \frac{0.5\text{-}4\ \mathrm{mg}}{\mathrm{day}}$$

This exposure will occur over 3 days/yr up to 250 days per year.

Where:

$EXP_{dermal\_petrochem}$ = Potential dermal exposure to the chemical of interest per day (mg chemical/day)

Q_{liquid_skin} = Quantity of liquid component remaining on skin (Defaults: 10.3 mg component/cm^2-incident (high-end) and 1.3 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41]))

$AREA_{surface}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$N_{exp\_incident}$ = Number of exposure incidents per day (Default: 1 incident/day)

$F_{chem\_foam\_petrochem}$ = Mass fraction of the chemical of interest in the foam (mg chemical/mg foam) (See Section 3.5)

6.3.4. Exposure from Disposal of Spent Foam (Exposure D)

Dermal exposures are assessed using the 2-hand dermal contact to liquids model (Equation 5-5):

$$\mathrm{EXP}_{\mathrm{dermal\_petrochem}} = \mathrm{Q}_{\mathrm{liquid\_skin}} \times \mathrm{AREA}_{\mathrm{surface}} \times \mathrm{N}_{\mathrm{exp\_incident}} \times \mathrm{F}_{\mathrm{chem\_concentrate\_petrochem}}$$

$$\mathrm{EXP}_{\mathrm{dermal\_petrochem}} = \frac{0.7 - 2.1\ \mathrm{mg\ foam}}{\mathrm{cm}^2\text{-incident}} \times 1{,}070\ \mathrm{cm}^2 \times \frac{1\ \mathrm{incident}}{\mathrm{day}} \times \frac{0.00036\ \mathrm{mg\ chemical}}{\mathrm{mg\ foam}}$$

$$\mathrm{EXP}_{\mathrm{dermal\_petrochem}} = \frac{0.3\text{-}0.8\ \mathrm{mg}}{\mathrm{day}}$$

This exposure occurs over 3 days/yr from 210 sites.

Where:

$\mathrm{EXP}_{\mathrm{dermal\_petrochem}}$ = Potential dermal exposure to the chemical of interest per day (mg chemical/day)

$\mathrm{Q}_{\mathrm{liquid\_skin}}$ = Quantity of liquid component remaining on skin (Defaults: 2.1 mg component/cm^2-incident (high-end) and 0.7 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41]))

$\mathrm{AREA}_{\mathrm{surface}}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$\mathrm{N}_{\mathrm{exp\_incident}}$ = Number of exposure incidents per day (Default: 1 incident/day)

$\mathrm{F}_{\mathrm{chem\_foam\_petrochem}}$ = Mass fraction of the chemical of interest in the AFFF concentrate (mg chemical/mg component) (See Section 3.5)

6.3.5. Exposure from Disposal of Expired AFFF Concentrate (Exposure E)

Dermal exposures are assessed using the 2-hand dermal contact to liquids model (Equation 5-6):

$$\mathrm{EXP}_{\mathrm{dermal\_petrochem}} = \mathrm{Q}_{\mathrm{liquid\_skin}} \times \mathrm{AREA}_{\mathrm{surface}} \times \mathrm{N}_{\mathrm{exp\_incident}} \times \mathrm{F}_{\mathrm{chem\_concentrate\_petrochem}}$$

$$\mathrm{EXP}_{\mathrm{dermal\_petrochem}} = \frac{0.7 - 2.1\ \mathrm{mg\ concentrate}}{\mathrm{cm}^2\text{-incident}} \times 1{,}070\ \mathrm{cm}^2 \times \frac{1\ \mathrm{incident}}{\mathrm{day}} \times \frac{0.012\ \mathrm{mg\ chemical}}{\mathrm{mg\ concentrate}}$$

$$\mathrm{EXP}_{\mathrm{dermal\_petrochem}} = \frac{\text{9-27 mg}}{\text{day}}$$

This exposure occurs over 1 day/yr from 210 sites.

Where:

$\mathrm{EXP}_{\mathrm{dermal\_petrochem}}$ = Potential dermal exposure to the chemical of interest per day (mg chemical/day)

$Q_{\mathrm{liquid\_skin}}$ = Quantity of liquid component remaining on skin (Defaults: 2.1 mg component/cm^2-incident (high-end) and 0.7 mg component/cm^2-incident (low-end) for routine or incidental contact (US EPA, 2000[41]))

$\mathrm{AREA}_{\mathrm{surface}}$ = Surface area of contact (Default: 1,070 cm^2 for 2 hands (US EPA, 2013[42]))

$N_{\mathrm{exp\_incident}}$ = Number of exposure incidents per day (Default: 1 incident/day)

$F_{\mathrm{chem\_concentrate\_petrochem}}$ = Mass fraction of the chemical of interest in the AFFF concentrate (mg chemical/mg AFFF concentrate) (See Section 3.4)

7. Data Gaps/Uncertainties and Future Work

This ESD relies on industry data and information gathered from various sources to generate general facility estimates, release estimates, and exposure estimates. EPA wishes to make this ESD as detailed and up-to-date as possible, such that the risk-screening assessments reflect current industrial practices. This ESD could be improved by collecting measured data and associated information to verify or supersede the anecdotal data and information.

EPA is most interested in obtaining information about AFFF use that is characterised as "typical" or "conservative" (i.e. worse case). While EPA welcomes site-specific information as valuable to this ESD, additional qualifiers of how reflective it is to the industry are needed to ensure its transparency if used in the ESD. Reviewers should also feel free to recommend additional resources that may be useful to the development of this ESD.

The key data gaps are summarised below. Note that the data gaps are listed in order of importance (the first being most important):

1. Because of the wide variety of use scenarios, there is difficulty in specifying media of release between water, incineration, and landfill. Information to provide estimates on the relatively quantities of water, incineration, and landfill releases would greatly improve release estimates.
2. Specific amounts of disposal are unknown; the ESD assumes 10% disposal but more information is needed on actual disposal rates to improve accuracy of the ESD.
3. EPA assumed one day each for training and testing exercises per year. Additional information on the number of actual training and testing days per year, including the information on the prevalence of control technologies and pollution prevention techniques (alternative testing and training fluids etc.) would further improve this ESD.
4. Industry-specific inhalation and dermal monitoring data for all operations involving workers manually handling the AFFF concentrate and foam would enhance the estimates. This includes potential exposures for fixed foam vs portable foam systems.
5. Specific data on the numbers of workers performing the various exposure activities in each of the end use sectors were not found. Therefore, the ESD assumed that the number of workers per facility to be the same as US firefighting departments. Additional information on the numbers workers performing each exposure activity in each end use sector would further enhance the calculations.
6. Amount of current AFFF stock was based on a 2004 report; updated AFFF stock values would improve the accuracy of this ESD.
7. Additional information on the typical influent flow rates for wastewater treatment plants would improve the dilution/metering estimates.

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Annex A. Summary of Release and Exposure Estimation Equations and Default Parameter Values for AFFF End use Sites

Table A A.1 summarises the equations introduced in Sections 3. to 5. . These equations may be used in evaluating releases of and exposures to chemicals used in the AFFF industry. A description of each input variable and associated default is provided in Table A A.2.

Table A A.1. AFFF Release and Exposure Calculation Summary

General Facility Estimates
Mass Fraction of the Chemical of Interest in the AFFF Foam (F_{chem_foam}): $F_{chem\_foam\_[sector]} = F_{chem\_concentrate\_[sector]} \times F_{concentrate\_foam\_[sector]}$ (Eqn. 3-1)
Annual AFFF Concentrate Use Rate per Site in Each End Use Sector ($Q_{concentrate\_site\_yr\_[sector]}$) $Q_{concentrate\_site\_yr\_[sector]} = V_{concentrate\_site\text{-}yr\_[sector]} \times RHO_{concentrate} \times \frac{3.78\ L}{gal} \times \left(F_{consumed\_[sector]} + F_{disposed\_[sector]}\right)$ (Eqn. 3-2)
Annual Chemical of Interest Use Rate per Site in Each End Use Sector ($Q_{chem\_site\_yr\_[sector]}$) $Q_{chem\_site\_yr\_[sector]} = Q_{concentrate\_site\_yr\_[sector]} \times F_{chem\_concentrate\_[sector]}$ (Eqn. 3-3)
Annual Chemical Use Rate for Each End Use Sector ($Q_{chem\_yr\_[sector]}$) $Q_{chem\_yr\_[sector]} = Q_{chem\_yr} \times X_{[sector]}$ (Eqn. 3-4)
Number of Sites per End Use Sector ($N_{sites\_[sector]}$) $N_{sites\_[sector]} = \frac{Q_{chem\_yr\_[sector]}}{Q_{chem\_site\_yr\_[sector]}}$ (Eqn. 3-5) The value for $N_{sites\_[sector]}$, calculated using Equation 3-5, should be rounded up to the nearest integer value. $Q_{chem\_site\_yr\_[sector]}$ should then be adjusted for the N_{sites} integer value (to avoid errors due to rounding): $Q_{chem\_site\_yr\_[sector]} = \frac{Q_{chem\_yr\_[sector]}}{N_{sites\_[sector]}}$ *Note: If the number of sites is known, the previous equation may also be used to estimate the resulting average annual use rate for use in subsequent calculations.
Daily Consumption Rate of the Chemical of Interest per End Use Sector ($Q_{chem\_consumed\_site\_day\_[sector]}$) $Q_{chem\_consumed\_site\_day\_[sector]} = \left(\frac{Q_{chem\_site\_yr\_[sector]}}{TIME_{use\ days\_[sector]}}\right) \times \left(\frac{F_{consumed\_[sector]}}{F_{consumed\_[sector]} + F_{disposed\_[sector]}}\right)$ (Eqn. 3-6)
Number of AFFF Concentrate Containers Emptied per Facility by End Use Sector ($N_{container\_unload\_site\_yr\_[sector]}$) $N_{container\_unload\_site\_yr\_[sector]} = \frac{Q_{concentrate\_site\_yr\_[sector]}}{V_{container\_[sector]} \times RHO_{concentrate}}$ (Eqn. 3-7)

Number of Days to Unload AFFF Concentrate Containers per End Use Sector ($\mathbf{TIME_{unloading\_days\_[sector]}}$)

$$\mathrm{TIME_{unloading\_days\_[sector]}} = \frac{\mathrm{N_{container\_unload\_site\_yr\_[sector]}}}{\mathrm{RATE_{container\_unloading}} \times \mathrm{TIME_{unloading\_hours}}} \quad \text{(Eqn. 3-8)}$$

Table A A.2. Environmental Release Calculation Summary

Source	**Possible Medium**	**Daily Release Rates (kg/site-day), Elocal (for Given Sources)**
Container Residue (liquid only) (Release 1)	POTW Land Incineration	If $\mathrm{TIME_{unloading\ days\_[sector]}}$ is less than or equal to 1: $\mathrm{Elocal_{container\_residue\_disp\_[sector]}} = \mathrm{V_{container\_[sector]}} \times \mathrm{RHO_{concentrate}} \times \mathrm{F_{chem\_concentrate\_[sector]}} \times \mathrm{F_{container\_residue}} \times \mathrm{N_{container\_unload\_site\_yr\_[sector]}}$ (Eqn. 4-1a) This release will occur over 1 day/year from [$\mathrm{N_{sites}}$] sites. If $\mathrm{TIME_{unloading\ days\_[sector]}}$ is greater than 1: $\mathrm{Elocal_{container\_residue\_disp\_[sector]}} = \left[\left(\mathrm{V_{container\_[sector]}} \times \mathrm{RHO_{concentrate}} \times \mathrm{F_{chem\_concentrate\_[sector]}} \times \mathrm{F_{container\_residue}} \times \mathrm{N_{container\_unload\_site\_yr\_[sector]}}\right)\right] / \mathrm{TIME_{unloading\_days\_[sector]}}$ (Eqn. 4-1b) This release will occur over [$\mathrm{TIME_{unloading\ days\_[sector]}}$] days/year from [$\mathrm{N_{sites}}$] sites.
Disposal of Consumed Foam (Release 2)	POTW Land Incineration	$\mathrm{Elocal_{consumed\_AFFF\_[sector]}} = \mathrm{Q_{chem\_consumed\_site\_day\_[sector]}}$ (Eqn. 4-2) This release will occur over [$\mathrm{TIME_{use\_days\_[sector]}}$] days/year from [$\mathrm{N_{sites}}$] sites.
Disposal of Unused AFFF (Release 3)	POTW Incineration	$\mathrm{Elocal_{disposed\_[sector]}} = \left(\frac{\mathrm{Q_{chem\_site\_yr\_[sector]}}}{\mathrm{TIME_{use\ days\_[sector]}}}\right) \times \left(\frac{\mathrm{F_{disposed\_[sector]}}}{\mathrm{F_{consumed\_[sector]}} + \mathrm{F_{disposed\_[sector]}}}\right)$ (Eqn. 4-3) This release will occur over [$\mathrm{TIME_{disposal\_[sector]}}$] days from [$\mathrm{N_{sites}}$] sites.

Source	Possible Medium	Daily Release Rates (kg/site-day), Elocal (for Given Sources)
POTW releases	POTW	To estimate the number of required dilution/metering days to release foam solution to wastewater treatment, EPA recommends using Equation 4-4 below. Note that this equation should be used for every release that is assessed to POTW, for each end use sector. $\mathrm{TIME}_{\mathrm{metered\_release\_days}} = \frac{\mathrm{E}_{\mathrm{local}} \times \frac{\mathrm{site-day}}{\mathrm{1\ event}}}{\mathrm{CONC}_{\mathrm{treatment}} \times \frac{10^{-6}\ \mathrm{kg}}{\mathrm{mg}} \times \mathrm{F}_{\mathrm{chem\_concentrate}} \times \mathrm{Q}_{\mathrm{POTW\_influent}}}$ (Eqn. 4-4) If the $\mathrm{TIME}_{\mathrm{metered\_release\_days}} \leq 1$, then no metering is required. If $\mathrm{TIME}_{\mathrm{metered\_release\_days}} > 1$, then daily metered releases can be calculated by Equation 4-5: $\mathrm{Elocal}_{\mathrm{metered}} = \frac{\mathrm{Elocal}}{\mathrm{TIME}_{\mathrm{metered\_release\_days}} \times \frac{\mathrm{1\ event}}{\mathrm{day}}}$ (Eqn. 4-5)

Table A A.3. Occupational Exposure Calculation Summary

Occupational Exposure Calculations
Number of Workers Exposed Per Site: As an estimate, EPA recommends assuming 21 workers per site for all sites, absent site-specific information.
Exposure from Unloading and Transferring AFFF Concentrate (Exposure A): *Inhalation (liquid):* not expected *Dermal (liquid):* *EPA/OPPT 2-Hand Dermal Contact with Liquid Model:* $\mathrm{EXP}_{\mathrm{dermal\_[sector]}} = \mathrm{Q}_{\mathrm{liquid\_skin}} \times \mathrm{AREA}_{\mathrm{surface}} \times \mathrm{N}_{\mathrm{exp\_incident}} \times \mathrm{F}_{\mathrm{chem\_concentrate\_[sector]}}$ (Eqn. 5-1) This exposure will occur over $\mathrm{TIME}_{\mathrm{unloading\_days\_[sector]}}$, up to 250 days per year.

Occupational Exposure Calculations

Exposure from Container Cleaning (Exposure B):

Inhalation (liquid): not expected

Dermal (liquid):

EPA/OPPT 2-Hand Dermal Contact with Liquid Model:

$$\mathrm{EXP}_{\text{dermal\_[sector]}} = \mathrm{Q}_{\text{liquid\_skin}} \times \mathrm{AREA}_{\text{surface}} \times \mathrm{N}_{\text{exp\_incident}} \times \mathrm{F}_{\text{chem\_concentrate\_[sector]}} \qquad \text{(Eqn. 5-2)}$$

This exposure will occur over $\mathrm{TIME}_{\text{unloading\_days\_[sector]}}$, up to 250 days per year.

Exposure from Discharge of Foam (Exposure C):

Inhalation (mist):

EPA/OPPT Automobile Refinish Spray Coating Inhalation Exposure Model:

$$\mathrm{EXP}_{\text{inhalation\_[sector]}} = \mathrm{C}_{\text{part\_air}} \times \mathrm{TIME}_{\text{exposure}} \times \mathrm{RATE}_{\text{breathing}} \times \mathrm{F}_{\text{chem\_particulate}} \qquad \text{(Eqn. 5-3)}$$

This exposure will occur over $\mathrm{TIME}_{\text{use\_days\_[sector]}}$, up to 250 days per year.

Dermal (liquid):

EPA/OPPT 2-Hand Immersion with Liquid Model

$$\mathrm{EXP}_{\text{dermal\_[sector]}} = \mathrm{Q}_{\text{liquid\_skin}} \times \mathrm{AREA}_{\text{surface}} \times \mathrm{N}_{\text{exp\_incident}} \times \mathrm{F}_{\text{chem\_foam\_[sector]}} \qquad \text{(Eqn. 5-4)}$$

This exposure will occur over $\mathrm{TIME}_{\text{use\_days\_[sector]}}$, up to 250 days per year.

Exposure from Disposal of Spent Foam (Exposure D):

Inhalation (liquid): not expected

Dermal (liquid):

EPA/OPPT 2-Hand Dermal Contact with Liquid Model:

$$\mathrm{EXP}_{\text{dermal\_[sector]}} = \mathrm{Q}_{\text{liquid\_skin}} \times \mathrm{AREA}_{\text{surface}} \times \mathrm{N}_{\text{exp\_incident}} \times \mathrm{F}_{\text{chem\_foam\_[sector]}} \qquad \text{(Eq. 5-5)}$$

This exposure will occur over $\mathrm{TIME}_{\text{use\_days\_[sector]}}$, up to 250 days per year.

Occupational Exposure Calculations

Exposure from Disposal of Expired AFFF Concentrate (Exposure E):

Inhalation (liquid): not expected

Dermal (liquid):

EPA/OPPT 2-Hand Dermal Contact with Liquid Model:

$$\mathrm{EXP}_{\mathrm{dermal\_[sector]}} = \mathrm{Q}_{\mathrm{liquid\_skin}} \times \mathrm{AREA}_{\mathrm{surface}} \times \mathrm{N}_{\mathrm{exp\_incident}} \times \mathrm{F}_{\mathrm{chem\_concentrate\_[sector]}} \quad \text{(Eq. 5-6)}$$

This exposure will occur over $\mathrm{TIME}_{\mathrm{disposal\_[sector]}}$, up to 250 days per year.

Table A A.4. Parameter Declaration and Documentation Summary

Variable	Variable Description	Default Value	Data Source
$\mathrm{AREA}_{\mathrm{surface}}$	Surface area of contact (cm^2)	1,070 (2 hands)	(US EPA, 2013[42])
$\mathrm{C}_{\mathrm{part\_air}}$	Mass concentration of total particulate in air (mg particulate/m^3 of air)	15	Section 5.5
$\mathrm{CONC}_{\mathrm{treatment}}$	AFFF concentrate metering concentration to POTW	100 (3% AFFF) 200 (6% AFFF)	Section 4.5.2
$\mathrm{Elocal}_{\mathrm{container\_residue\_disp\_[sector]}}$	Daily release of chemical from container residue per end use sector (kg chemical/site-day)	Calculated	Section 4.2
$\mathrm{Elocal}_{\mathrm{consumed\_AFFF\_[sector]}}$	Daily release of consumed foam from discharge per end use sector (kg/site-day)	Calculated	Section 4.3
$\mathrm{Elocal}_{\mathrm{disposed\_\ [sector]}}$	Daily release of unused AFFF concentrate per end use sector (kg/site-day)	Calculated	Section 4.4
$\mathrm{EXP}_{\mathrm{inhalation\_[sector]}}$	Inhalation exposure to the chemical of interest per day per end use sector (mg chemical of interest/day)	Calculated	Sections 5.3-5.7
$\mathrm{EXP}_{\mathrm{dermal\_[sector]}}$	Potential dermal exposure to the chemical of interest per day per end use sector (mg chemical/day)	Calculated	Sections 5.3-5.7
$\mathrm{F}_{\mathrm{chem\_concentrate\_[sector]}}$	Mass fraction of the chemical of interest in the AFFF concentrate per end use sector (kg chemical/kg AFFF concentrate).	0.25	Section 3.4
$\mathrm{F}_{\mathrm{chem\_foam\_[sector]}}$	Mass fraction of the chemical of interest in the AFFF foam per end use sector (kg chemical/kg foam)	Calculated	Section 3.5
$\mathrm{F}_{\mathrm{chem\_particulate}}$	Fraction of chemical in the particulate (kg chemical/kg particulate)	Calculated	Section 5.5

Variable	Variable Description	Default Value	Data Source
$F_{concentrate\_foam\_[sector]}$	Mass AFFF concentrate in the produced foam per end use sector (kg AFFF concentrate/kg foam)	0.03 (3% foam) 0.06 (6% foam - conservative)	Section 3.5
$F_{consumed\_[sector]}$	Annual consumption of total AFFF stock per end use sector	7% (Military); 12.2% (Civil Aviation); 7% (Municipal Fire Departments); 12% (Petroleum Refineries); 7% (Petrochemical Manufacturing)	Section 3.6
$F_{container\_residue}$	Fraction of AFFF concentrate remaining in the container as residue	0.03	Section 4.2 (US EPA, 2002[26])
$F_{disposed\_[sector]}$	Annual fraction of total AFFF stock disposed per end use sector	Calculated	Section 3.7
$F_{particulate\_prod}$	Mass fraction of solids in the foam product (mg particulate/mg product)	0.25	(OECD, 2004[43])
$N_{container\_unload\_site\_yr\_[sector]}$	Number of AFFF concentrate containers unloaded at each site per year for each end use sector (containers/site-yr)	Calculated	Section 3.14
$N_{exp\_incident}$	Number of exposure incidents per day (incident/day)	1	(US EPA, 2000[41])
$N_{sites\_[sector]}$	Number of sites using the chemical of interest for each end use sector (sites).	Calculated	Section 3.11
$N_{sites\_existing\_[sector]}$	Number of existing sites per sector (sites)	301 (Military); 366 (Civil Aviation); 55,150 (Municipal Fire Departments); 149 (Petroleum Refineries); 61 (Petrochemical Manufacturing)	Section 3.2
$Q_{chem\_site\_yr\_[sector]}$	Annual use rate for the chemical of interest in each end use sector (kg chemical/site-yr)	Calculated	Section 3.9
$Q_{chem\_yr\_[sector]}$	Annual chemical use rate for each end-use sector (kg chemical/yr)	Calculated	Section 3.10

Variable	Variable Description	Default Value	Data Source
$Q_{chem\_consumed\_site\_day\_[sector]}$	Daily consumption rate of the chemical of interest per use sector (kg chemical used/site-day)	Calculated	Section 3.13
$Q_{concentrate\_site\_yr\_[sector]}$	Annual AFFF concentrate use rate per site in each end use sector (kg concentrate/site-yr)	Calculated	Section 3.8
Q_{liquid_skin}	Quantity of liquid component remaining on skin (mg/cm^2-incident)	0.7 (low end) 2.1 (high-end)	(US EPA, 2000[41])
$RATE_{container\_unloading}$	Container unloading rate (containers/hr)	20 containers/hr (totes)	(US EPA, 1991[2])
$RATE_{breathing}$	Typical worker breathing rate (m^3/hr)	1.25	(US EPA, 1991[2])
$RHO_{concentrate}$	Density of the AFFF concentrate (kg/L)	1	EPA assumption
$TIME_{exposure}$	Duration of exposure (hr/day)	8	Annex B
$TIME_{metered\_release\_days}$	Number of days discharged foam is released to POTW (days/event)	Calculated	Section 4.5.2
$TIME_{use\_days\_[sector]}$	Annual number of days the AFFF concentrate is used at each facility in each sector (days/site-yr).	3 (Military); 3 (Civil Aviation); 4 (Municipal Fire Departments); 3 (Petroleum Refineries); 3 (Petrochemical Manufacturing)	Section 3.12
$TIME_{unloading\_days\_[sector]}$	Annual number of days the AFFF concentrate is unloaded at each facility in each sector (days/site-yr).	Calculated	Section 3.15
$TIME_{unloading\_hours}$	Number of hours unloading containers per day (hr/day)	8	(US EPA, 1991[2])
$V_{container\_[sector]}$	Volume of transport container per end use sector (L/container)	1,000	Annex B
$V_{concentrate\_site\_yr\_[sector]}$	Annual volume of AFFF concentrate stored on-site per sector (gallons/yr)	Calculated	Section 3.2

Variable	Variable Description	Default Value	Data Source
$V_{concentrate\_yr\_[sector]}$	Annual volume of AFFF concentrate used per year per sector (gallons/yr)	10,736,153 (Military); 5,976,576 (Civil Aviation); 5,147,600 (Municipal Fire Departments); 7,191,500 (Petroleum Refineries); 7,570,000 (Petrochemical Manufacturing)	Section 3.2
$X_{[sector]}$	Fraction of AFFF concentrate used in each end-use sector	0.29 (Military); 0.16 (Civil Aviation); 0.14 (Municipal Fire Departments); 0.20 (Petroleum Refineries); 0.21 (Petrochemical Manufacturing)	Sections 3.2, 3.3

Annex B. Background Information and Equations/Defaults for the Standard EPA Environmental Release and Worker Exposure Models

B.1. Introduction

This annex provides background information and a discussion of the equations, variables, and default assumptions for each of the standard release and exposure models used by EPA in estimating environmental releases and worker exposures. The models described in this annex are organised into the following three sections:

- Section B.2: Container Residue Release Models (non-air); and
- Section B.3: Dermal Exposure Models.

Please refer to the guidance provided in the ESD for estimating environmental releases and worker exposures using these standard models, as it may suggest the use of certain overriding default assumptions to be used in place of those described for each model within this annex.

This annex includes a list of the key reference documents that provide the background and rationale for each of the models discussed. These references may be viewed in their entirety through the ChemSTEER Help System. To download and install the latest version of the ChemSTEER software and Help System, please visit the following EPA web site:

https://www.epa.gov/tsca-screening-tools/chemsteer-chemical-screening-tool-exposures-and-environmental-releases.

B.2. Container Residue Release Models (non-air)

Model Description and Rationale

EPA has developed a series of standard models for estimating the quantity of residual chemical remaining in emptied shipping containers that is released to non-air media (e.g. water, incineration, or landfill) when the container is either rinsed or disposed. All of the residue models assume a certain portion or fraction of the chemical remains in the emptied container to be later rinsed or discarded with the empty container.

The default parameters of model are defined based upon the particular size/type of container (e.g. small containers, drums, or large bulk), as well as the physical form of the chemical residue (e.g. liquid or solid). These defaults are based upon data collected during a 1988 EPA-sponsored study of residuals in containers from which materials have been poured or pumped.

Model Equation

All of the models discussed in this section utilise the following common equation for calculating the amount of chemical residue:

$$\text{Elocal}_{\text{container\_residue\_disp}} = \text{F}_{\text{container\_residue}} \times \text{Q}_{\text{total\_daily\_container}} \quad \text{[B-1]}$$

Where:

$Elocal_{container\_residue\_disp}$ = Daily release of the chemical residue to water, incineration, or landfill from the cleaning or disposal of empty shipping containers (kg/site-day)

$F_{container\_residue}$ = Fraction of the amount of the total chemical in the shipping container remaining in the emptied container (dimensionless; see Table A B.1 for appropriate EPA default values)

$Q_{total\_daily\_container}$ = Total (daily) quantity of the chemical contained in the shipping containers prior to emptying (kg of chemical/site-day; see Table A B.2 for appropriate EPA default values)

Each model, however, utilises unique default values within that equation based upon the relative size of the container and the physical form of the chemical residue. These default values are summarised in Table A B.1 and Table A B.2. The following models are the standard EPA models for estimating container residues:

- EPA/OPPT Small Container Residual Model;
- EPA/OPPT Drum Residual Model;
- EPA/OPPT Bulk Transport Residual Model; and
- EPA/OPPT Solid Residuals in Transport Containers Model.

The default frequency with which the container residues are released ($TIME_{days\_container\_residue}$, days/site-year) must be appropriately “paired” with the total daily quantity of chemical contained in the containers ($Q_{total\_daily\_container}$) used in calculating the daily release. Thus, Table A B.2 also contains the appropriate EPA default values for $TIME_{days\_container\_residue}$.

References

US EPA. Chemical Engineering Branch. Memorandum: *Standard Assumptions for PMN Assessments*. From the CEB Quality Panel to CEB Staff and Management. October 1992.

US EPA. Office of Pesticides and Toxic Substances. *Releases During Cleaning of Equipment.* July 1988.

Table A B.1. Standard EPA Default Values for Use in the Container Residual Release Models

Chemical Form	Container Type	V_{cont_empty} (gallons)	Model Title	$F_{container\_residue}$[a]
Liquid	Bottle	1 Range: <5	*EPA/OPPT Small Container Residual Model*	Central Tendency: 0.003 High-End: 0.006
	Small Container	5 Range: 5 to <20		
	Drum	55 Range: 20 to <100	*EPA/OPPT Drum Residual Model*	Central Tendency: 0.025 High-End[b]: 0.03 (for pumping liquid out of the drum) Alternative defaults: Central Tendency: 0.003 High-End: 0.006 (for pouring liquid out of the drum)
	Tote	550 Range: 100 to <1,000	*EPA/OPPT Bulk Transport Residual Model*	Central Tendency: 0.0007 High-End: 0.002
	Tank Truck	5,000 Range: 1,000 to <10,000		
	Rail Car	20,000 Range: 10,000 and up		
Solid	Any	Any	*EPA/OPPT Solid Residuals in Transport Containers Model*	0.01

a - These defaults are based on the 1988 EPA study investigating container residue and summarised in the 1992 internal EPA memorandum (see *References* in this section for the citations of these sources).

b - The 1992 EPA memorandum reference document contains the previous default of 0.04 for the high-end loss fraction ($F_{container\_residue}$) for the *Drum Residual Model*; however, this value was superseded by an internal policy decision in 2002. Per 40 CFR 261.7(b)(1) of the Resource Conservation and Recovery Act (RCRA), "a container or an inner liner removed from a container that has held any hazardous wastes, except waste that is a compressed gas or that is identified as an acute hazardous waste…is empty if…(ii) no more than 2.5 centimetres (1 inch) remain on the bottom of the container or liner or (iii)(A) no more than 3 percent by weight of the total capacity of the container remains in the container or inner liner if the container is equal to or less than 110 gallons in size…". The 3 percent high-end default is consistent with the range of experimental results documented in the 1988 EPA study (see *References* in this section for a citation of this study).

Table A B.2. Standard EPA Methodology for Calculating Default $Q_{total\_daily\_container}$ and $TIME_{days\_container\_residue}$ Values for Use in the Container Residual Models

Number of Containers Emptied per Day	$Q_{total\_daily\_container}$ (kg/site-day)	$TIME_{days\_container\_residue}$ (days/year)
1 or more	(Mass quantity of chemical in each container (kg/container)) × (Number of containers emptied per day)	Total number of operating days for the facility/operation
Less than 1	Mass quantity of chemical in each container (kg/container)	Total number of containers emptied per site-year

B.3. Dermal Exposure Models

Model Description and Rationale

EPA has developed a series of standard models for estimating worker dermal exposures to liquid and solid chemicals during various types of activities. All of these dermal exposure models assume a specific surface area of the skin that is contacted by a material containing the chemical of interest, as well as a specific surface density of that material in estimating the dermal exposure. The models also assume *no use of controls or gloves* to reduce the exposure. These assumptions and default parameters are defined based on the nature of the exposure (e.g. one hand or two hand, immersion in material, contact with surfaces) and are documented in the references listed in this section.

In the absence of data, the EPA/OPPT standard models for estimating dermal exposures from industrial activities described in this section can be used. The models for exposures to liquid materials are based on experimental data with liquids of varying viscosity and the amount of exposure to hands was measured for various types of contact. Similar assessments were made based on experimental data from exposure to solids.

Model Equation

All of the standard EPA models utilise the following common equation for calculating worker dermal exposures:

$$EXP_{dermal} = AREA_{surface} \times Q_{remain\_skin} \times F_{chem} \times N_{event} \qquad [B\text{-}2]$$

Where:

EXP_{dermal} = Dermal exposure to the liquid or solid chemical per day (mg chemical/worker-day)

$AREA_{surface}$ = Surface area of the skin that is in contact with liquid or solid material containing the chemical (cm^2; see Table A B.2 for appropriate EPA default values)

Q_{remain_skin} = Quantity of the liquid or solid material containing the chemical that remains on the skin after contact (mg/cm^2-event; see Table A B.2 for appropriate EPA default values)

F_{chem} = Weight fraction of the chemical of interest in the material being handled in the activity (dimensionless)

N_{event}[12] = Frequency of events for the activity (EPA default = 1 event/worker-day)

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[12] Only one contact per day (N_{event} = 1 event/worker-day) is assumed because Q_{remain_skin}, with few exceptions, is not expected to be significantly affected either by wiping excess chemical material from skin or by repeated contacts with additional chemical material (i.e. wiping excess from the skin does not remove a significant fraction of the small layer of chemical material adhering to the skin and additional contacts with the chemical material do not add a significant fraction to the layer). Exceptions to this assumption may be considered for chemicals with high volatility and/or with very high rates of absorption into the skin.

Each model, however, utilises unique default values within that equation based upon the nature of the contact and the physical form of the chemical material. These default values are summarised in Table A B.3. The following models are the standard EPA models for estimating worker dermal exposures:

- EPA/OPPT 1-Hand Dermal Contact with Liquid Model;
- EPA/OPPT 2-Hand Dermal Contact with Liquid Model;
- EPA/OPPT 2-Hand Dermal Immersion in Liquid Model;
- EPA/OPPT 2-Hand Dermal Contact with Container Surfaces Model; and
- EPA/OPPT 2-Hand Dermal Contact with Solids Model.

For several categories of exposure, EPA uses qualitative assessments to estimate dermal exposure. Table A B.4 summarises these categories and the resulting qualitative dermal exposure assessments.

References

US EPA. Chemical Engineering Branch. *Options for Revising CEB's Method for Screening-Level Estimates of Dermal Exposure – Final Report*. US Environmental Protection Agency, Office of Pollution Prevention and Toxics, Washington DC. June 2000.

US EPA. Chemical Engineering Branch. *CEB Manual for the Preparation of Engineering Assessment*, Volume 1. US Environmental Protection Agency, Office of Pollution Prevention and Toxics, Washington DC. Contract No. 68-D8-0112. February 1991.

Table A B.3. Standard EPA Default Values for Use in the Worker Dermal Exposure Models

Default Model	**Example Activities**	**$AREA_{surface}$[a] (cm^2)**	**Q_{remain_skin}[b] (mg/cm^2-event)**	**Resulting Contact $AREA_{surface} \times Q_{remain\_skin}$ (mg/event)**
Physical Form: Liquids				
EPA/OPPT 1-Hand Dermal Contact with Liquid Model	• Liquid sampling activities • Ladling liquid/bench-scale liquid transfer	535 (1 hand mean)	Low: 0.7 High: 2.1	Low: 380 High: 1,100
EPA/OPPT 2-Hand Dermal Contact with Liquid Model	• Maintenance • Manual cleaning of equipment and containers • Filling drum with liquid • Connecting transfer line	1,070 (2 hand mean)	Low: 0.7 High: 2.1	Low: 750 High: 2,200
EPA/OPPT 2-Hand Dermal Immersion in Liquid Model	• Handling wet surfaces • Spray painting	1,070 (2 hand mean)	Low: 1.3 High: 10.3	Low: 1,100 High: 11,000
Physical Form: Solids				
EPA/OPPT 2-Hand Dermal Contact with Container Surfaces Model	• Handling bags of solid materials (closed or empty)	No defaults	No defaults	< 1,100[c]
EPA/OPPT 2-Hand Dermal Contact with Solids Model	• Solid sampling activities • Filling/dumping containers of powders, flakes, granules • Weighing powder/scooping/mixing (i.e. dye weighing) • Cleaning solid residues from process equipment • Handling wet or dried material in a filtration and drying process	No defaults	No defaults	< 3,100[23]

a - These default values were adopted in the 2013 EPA updates on screening-level dermal exposure estimates (US EPA, 2013[42]) and are the mean values for men taken from the EPA Exposure Factors Handbook, 2011.

b - These default values were adopted in the 2000 EPA report on screening-level dermal exposure estimates (see *References* in this section for the citation of this source). The report derived the selected ranges of values for liquid handling activities from: US EPA. *A Laboratory Method to Determine the Retention of Liquids on the Surface of Hands*. US Environmental Protection Agency, Office of Pollution Prevention and Toxics, Exposure Evaluation Division. EPA 747-R-92-003. September 1992.

c - These default values were adopted in the 2000 EPA report on screening-level dermal exposure estimates (see *References* in this section for the citation of this source). The report derived values for dermal contact for solids handling activities from: Lansink, C.J.M., M.S.C. Breelen, J. Marquart, and J.J. van Hemmen: Skin Exposure to Calcium Carbonate in the Paint Industry. Preliminary Modeling of Skin Exposure Levels to Powders Based on Field Data (TNO Report V 96.064). Rijswijk, The Netherlands: TNO Nutrition and Food Research Institute, 1996.

Table A B.4. EPA Default Qualitative Assessments for Screening-Level Estimates of Dermal Exposure

Category	Dermal Assessment
Corrosive substances (pH>12, pH<2)	Negligible
Materials at temperatures >140°F (60°C)	Negligible
Cast Solids (e.g. molded plastic parts, extruded pellets	Non-Quantifiable (Some surface contact may occur if manually transferred)
"Dry" surface coatings (e.g. fiber spin finishes, dried paint)	Non-Quantifiable (If manual handling is necessary and there is an indication that the material may abrade from the surface, quantify contact with fingers/palms as appropriate)
Gases/Vapours	Non-Quantifiable (Some contact may occur in the absence of protective clothing)

Source: US EPA. Chemical Engineering Branch. *CEB Manual for the Preparation of Engineering Assessment*, Volume 1. US Environmental Protection Agency, Office of Pollution Prevention and Toxics, Washington DC. Contract No. 68-D8-0112. February 1991.