



WHITE PAPER

From Foam to Drainage

Retiring AFFF, Seeing Through Its Fluorine-Free Replacement, and the Engineering Case for Ignitable Liquid Drainage Floor Assemblies in Aircraft Hangars

A technical and regulatory white paper on why per- and polyfluoroalkyl firefighting foams are ending, why their fluorine-free successors do not resolve the underlying liability, and why drainage-floor and sprinkler systems are now the standard backed by the U.S. Department of Defense, NFPA 409 and FM Global.

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June 2026

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Executive Summary

For more than half a century, aqueous film-forming foam (AFFF) was the default way to fight liquid fuel fires in aircraft hangars, on flight decks and at fuel depots. It worked because of per- and polyfluoroalkyl substances (PFAS) — and the same chemistry that made the foam effective made it a permanent contaminant of soil, groundwater and human blood. That trade-off is now the defining problem of hangar fire protection, and it has moved out of the laboratory and into the courtroom, the regulator's docket and the defense procurement system.

The financial reckoning is settled fact. In 2018 the State of Minnesota recovered **\$850 million** from 3M for PFAS damage to drinking water and natural resources.¹ In 2023, in the consolidated federal AFFF litigation in South Carolina, 3M agreed to pay public water systems a present value of **\$10.3 billion, capped at \$12.5 billion, over thirteen years**, with a further \$1.185 billion from DuPont, Chemours and Corteva.^{2,3} These are two different settlements, and the distinction matters: the \$850 million was Minnesota; the multi-billion figure is the national water-systems case. Liability is now spreading toward fire-protection manufacturers such as Tyco.⁴

Regulators have moved in lockstep. The European Union restricted the long-chain C8 compounds (PFOS, PFOA), then the short-chain C6 compound PFHxA, and in 2025 adopted a comprehensive restriction on PFAS in firefighting foams.^{5,6,7} In the United States, the EPA set enforceable 4 ppt drinking-water limits for PFOA and PFOS, and the Department of Defense — under a Congressional deadline of 1 October 2024 — has been removing AFFF from its hangars.^{8,9,10}

The chemical industry's answer is to sell a different foam: synthetic fluorine-free foam (SFFF, or F3). This paper argues that this is the wrong bet. Fluorine-free foam removes the persistence problem but not the hazard: a SERDP-funded study found at least one fluorine-free foam as toxic as, or more toxic than, PFAS-AFFF for every one of 14 aquatic species tested,¹¹ and a NIOSH-led study of human kidney cells found the most toxic fluorine-free foam cytotoxic at **3.3 ppm** against **109–262 ppm** for AFFF.¹² These foams still carry serious-eye-damage and organ-damage hazard classifications, and they still must be captured and destroyed after every discharge.¹³ Just as importantly, the companies now marketing these “safe” successors are the same ones whose AFFF assurances were overturned in court — a record that argues against taking their next set of assurances on trust.

The durable answer changes the fire scenario rather than the chemical. An **Ignitable Liquid Drainage Floor Assembly (ILDFA)** drains a fuel spill away before a pool fire can form, leaving conventional water sprinklers to handle the residual risk. This is not a fringe idea: NFPA 409 (2022) recognizes ILDFA as an equivalent to foam, FM Global has published both a hangar data sheet and an approval standard for it, and the U.S. Air Force's Foam Sundown Policy now designates hangars for conversion away from foam — to water sprinklers, with ILDFA as the end-state — on a Tier 1 / Tier 2 schedule.^{14,15,16} The engineering logic is reinforced by the data: a University of Maryland review found that roughly **98.8% of hangar foam discharges happen with no fire present**, so the dominant real-world risk of a foam system is the foam system itself.¹⁷

For maintenance, repair and overhaul (MRO) operators and airlines, the strategic conclusion is straightforward. Foam, of any chemistry, is a sunset technology carrying recurring cost and open-ended liability. Regulatory grace periods are finite. The facilities that plan their transition to drainage-and-sprinkler protection now — on a risk-tiered schedule — will avoid the compounding costs of doing it under deadline pressure later.

1. The Invention of AFFF: Who Built It, and Why

Aqueous film-forming foam was co-developed in the early 1960s by the U.S. Naval Research Laboratory (NRL) and the Minnesota Mining and Manufacturing Company (3M). The driving problem was specific and lethal: fuel fires aboard ships and on carrier decks, where spilled jet fuel and aviation gasoline could flash across a deck in seconds. Conventional protein foams and water were too slow and could spread, rather than smother, a burning fuel pool.

The Navy sought a patent in 1963 and was granted U.S. Patent 3,258,423 (Tuve and Jablonski) in 1966 for a method of extinguishing liquid hydrocarbon fires; the underlying chemistry had been described in NRL Report 6057 in 1964.^{18,19} The agent relied on synthetic fluorinated surfactants — the compounds now grouped under the umbrella term PFAS — to do something protein foams could not: form a thin aqueous film on the fuel surface that sealed vapor and resisted re-ignition.

Two catastrophic carrier fires gave the technology its mandate. The 1967 USS Forrestal fire killed 134 sailors; the Navy responded with a top-to-bottom overhaul of shipboard firefighting that mandated AFFF (MIL-F-24385, 1969).²⁰ From there, adoption spread quickly and globally through the 1970s: the rest of the Department of Defense, civilian airports operating under FAA rules, oil and chemical terminals, and municipal fire departments. By the time anyone asked hard questions about the chemistry, AFFF was embedded in fire-protection codes worldwide.

2. What AFFF Solved — and How It Worked

AFFF was engineered against one hazard in particular: the Class B hydrocarbon **pool fire** — a body of burning liquid fuel. A pool fire is dangerous precisely because the fuel keeps feeding the flame: heat drives off flammable vapor, the vapor burns, and the burning fuel re-ignites readily even after a knock-down. AFFF attacked this loop on three fronts at once:

Rapid spreading. Its fluorosurfactants drop the surface tension of the solution to extremely low values, so the foam and its underlying film race across the fuel surface and reach the seat of the fire fast.

Oxygen exclusion. The foam blanket physically smothers the fuel, cutting the oxygen supply the flame depends on.

Vapor suppression. The thin aqueous film left on the fuel seals the surface against the flammable, re-ignitable vapors that the fuel's own vapor pressure would otherwise release.²¹

The combined effect was near-instant knockdown with strong resistance to re-ignition — exactly what crash-rescue and shipboard crews needed. That performance is real and is not in dispute; it is why AFFF

earned its place. The problem is not that AFFF failed at firefighting. The problem is what the firefighting chemistry does afterward.

PFAS owe their stability to the carbon–fluorine bond, one of the strongest in organic chemistry. That bond is why the surfactants survive a fire — and why they do not break down in the environment or in the body. The properties that made AFFF effective are the same properties that make PFAS persistent, mobile in water, and bio-accumulative. PFAS exposure is associated with kidney and testicular cancer, thyroid disruption, and immune and developmental effects, and the compounds are now routinely detected in firefighter serum and in public drinking water.²² Every gallon of AFFF discharged — in a fire, a training exercise, or an accidental release — is a long-term contamination event.

3. Why AFFF Is Being Retired: The C8–C6 Saga

3.1 What the courts established

The case against AFFF was not made by activists; it was made in court, with the manufacturers' own records. In December 2010 the Minnesota Attorney General sued 3M for PFAS contamination of drinking water and natural resources in the Twin Cities East Metro. On 20 February 2018 the State recovered **\$850 million** — roughly \$720 million net for drinking-water and natural-resource projects in communities including Woodbury, Oakdale, Lake Elmo and Cottage Grove — in one of the largest natural-resource recoveries in U.S. history.²³ 3M admitted no liability, but the litigation surfaced internal records, and reporting on those records indicated that both 3M and the Navy had become aware of concerns about AFFF and PFAS as early as the 1970s, decades before they were disclosed to the public.²⁴

The larger reckoning came in the consolidated federal AFFF litigation (MDL 2873) in South Carolina, where public water systems across the country brought claims. In June 2023, 3M agreed to a settlement with a present value of **\$10.3 billion and a nominal cap of \$12.5 billion**, payable from 2024 through 2036, to fund PFAS testing and treatment; DuPont, Chemours and Corteva settled related claims for \$1.185 billion.^{25,26} These figures are routinely confused with the Minnesota settlement; they should not be. Minnesota was \$850 million. The multi-billion-dollar figure is the national water-systems case — a separate, later, and far larger matter. And the litigation is still widening: states such as Wisconsin have now sued fire-protection manufacturers including Tyco, signaling that exposure is moving downstream from the chemical producers toward the companies that built and sold the foam systems.²⁷

3.2 From C8 to C6 — and why C6 is not a safe harbor

The first regulatory wave targeted the long-chain C8 compounds: perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). Both are listed under the Stockholm Convention and restricted by the EU POPs Regulation; PFOS-based foam manufacture ceased around 2015, and the EU's time-limited exemption for PFOA in firefighting foam expires in December 2025.²⁸

Industry shifted to C6 chemistry — short-chain fluorotelomer foams — marketed as a safer alternative because shorter chains are less bio-accumulative. But “less bio-accumulative” is not “safe.” Short-chain PFAS such as PFHxA are in some respects **more** mobile in water and harder to remove in treatment, and

they are themselves PFAS. Regulators have drawn exactly that conclusion. The EU restricted PFHxA and its precursors under REACH in 2024, reaching foam training and testing uses from 2026 and civil aviation from 2029,²⁹ and in 2025 adopted a comprehensive restriction on PFAS in firefighting foams above 1 mg/L, with transition periods of roughly 18 months to 10 years.³⁰ C6 was never a destination; it was a layover. Writing it into a 30-year hangar asset as a “permanent” solution is planning to be non-compliant.

3.3 Where the rules now stand

In the United States, the EPA finalized enforceable drinking-water limits in April 2024 — 4.0 parts per trillion for PFOA and PFOS individually. As of mid-2026 those two limits remain in force: the EPA has proposed to retain them while extending the compliance deadline to 2031, even as it proposes to rescind the limits for four other PFAS.³¹ Whatever the fate of the secondary compounds, the headline limits for the two signature AFFF chemicals are holding. In parallel, the FY2020 National Defense Authorization Act required the Department of Defense to stop using AFFF by 1 October 2024 and to move to fluorine-free or non-foam alternatives.^{32,33} On both sides of the Atlantic, the procurement signal is the same: PFAS-based foam is being legislated and regulated out of existence.

4. The Industry’s Answer: Fluorine-Free Foam (SFFF)

Faced with this, the foam industry’s response has been to keep selling foam — only without fluorine. Synthetic fluorine-free foams (SFFF, also called F3) replace the fluorosurfactants with hydrocarbon surfactants, siloxanes and glycol-ether solvents. They are marketed, plausibly, as the answer to the PFAS problem: no PFAS, no forever-chemical persistence, drop-in compatibility with familiar foam hardware.

There is a real environmental gain here, and it should be acknowledged: fluorine-free foams do not leave behind a persistent, bio-accumulative PFAS legacy. The U.S. Department of Defense has qualified fluorine-free agents under a new specification (MIL-PRF-32725) and the FAA has published a transition plan for airports.³⁴ For some applications, fluorine-free foam is a reasonable interim step away from PFAS.

But the way the transition is being sold — as a like-for-like swap that solves the problem — obscures three things: fluorine-free foam can be acutely more toxic than the foam it replaces; it still triggers serious hazard classifications and the same capture-and-destroy disposal burden; and the assurance that it is “safe” is coming from an industry with a demonstrated record of getting that assurance wrong. The next section takes these in turn.

5. Why Fluorine-Free Foam Is the Wrong Bet

5.1 “Fluorine-free” is not “toxin-free”

Two independent bodies of evidence show that removing fluorine does not remove toxicity. In a study run under the Department of Defense’s own SERDP program, researchers measured the lethal effects of seven fluorine-free foams and one PFAS-containing AFFF across 14 aquatic species. The finding was

unambiguous: **for every species tested, at least one fluorine-free foam was as toxic as, or more toxic than, the PFAS foam.**³⁵ Fluorine-free foams break down faster, but on release they can be more acutely lethal to aquatic life — a different risk profile, not the absence of risk.

A NIOSH-led team (with the University of Rhode Island, Harvard and the University of Arizona) then screened five AFFF and five fluorine-free foams against human kidney cells, a model chosen for its relevance to firefighter renal disease. The AFFF were cytotoxic at **109–262 ppm**; the most toxic fluorine-free foam was cytotoxic at just **3.3 ppm** — between roughly 33 and 80 times more potent — while others ranged from 33 to 278 ppm.³⁶ This was a cell-based assay rather than an animal test, and the toxicity varied widely between products; but it flags an acute occupational hazard that the “green foam” framing entirely omits, and the authors expressly called for further hazard characterization before these foams are assumed safe.

It is worth being precise here, because over-claiming undermines the argument: it is **not** scientifically defensible to say that fluorine-free foam is uniformly “100 times deadlier” than AFFF. Toxicity depends on the specific product, the test organism, the exposure endpoint and the duration. What the evidence does support — and it is enough — is that **specific fluorine-free formulations are acutely more toxic than the AFFF they replace**, and that the class cannot be assumed harmless.

5.2 The hazards are on the label, and the disposal burden does not go away

The product safety data sheets make the point themselves. Many fluorine-free concentrates carry **H318** — ‘**Causes serious eye damage**’ (an irreversible-injury classification with the signal word *Danger* and the corrosion pictogram) and **H373** — ‘**May cause damage to organs through prolonged or repeated exposure**’, typically driven by their glycol-ether solvents.³⁷ These are not trivial label warnings; H318 mandates eye and face protection and specific emergency first aid, and H373 flags cumulative organ effects.

Critically, fluorine-free foam does not earn a free pass to drain. Like AFFF, it must be captured and sent for proper destruction; its aquatic toxicity and solvent load mean discharge water cannot simply be released. So a fluorine-free foam system carries the same recurring burden as the system it replaces: the concentrate must be periodically replaced, every test or accidental discharge must be collected and treated, and the changeover itself means stripping out a contaminated legacy system and cleaning and destroying its accumulated waters. Swapping AFFF for F3 re-incurs these costs rather than ending them.

5.3 Who is making the “safe” claim

There is a final reason for caution that has nothing to do with chemistry and everything to do with credibility. The companies now positioning fluorine-free foam as the responsible successor are, in large part, the same manufacturers whose AFFF safety position was tested in court and found wanting. The record — a \$850 million state recovery, a multi-billion-dollar national water-systems settlement, internal awareness of PFAS concerns reaching back to the 1970s, and litigation now reaching the fire-protection companies themselves — is not a reason to extend automatic trust to the next product line they wish to sell.^{38,39,40,41} When the party assuring you that a product is safe is the party that previously

got that judgment catastrophically and expensively wrong, the prudent response is to stop relying on chemical assurances altogether and to change the design instead.

6. ILDFA + Sprinklers: The Standard the Regulators Now Back

6.1 The hangar hazard, honestly assessed

Foam was written into hangar codes on the premise that a fuel-spill pool fire is the governing hazard. Decades of data complicate that premise. The University of Maryland's Department of Fire Protection Engineering reviewed 245 documented hangar foam discharges over roughly a 17-year window and found that **242 — about 98.8% — occurred with no fire present**; U.S. Coast Guard data suggest only about one hangar fuel spill per year nationally.⁴² These accidental discharges are growing more frequent — now on the order of once a month — and are individually expensive: they fill hangars with foam, contaminate soil and water, and damage aircraft, including sensitive avionics that foam residue and surfactants can corrode and foul; at least one inadvertent discharge has been fatal.⁴³ In other words, the dominant real-world risk associated with a hangar foam system is not the fire it might one day fight — it is the foam it routinely discharges by accident.

6.2 How an ILDFA changes the problem

An Ignitable Liquid Drainage Floor Assembly attacks the hazard at its root: instead of blanketing a burning fuel pool, it prevents the pool from forming. The floor is a hollow, extruded assembly with a perforated top surface over channels. Liquid detectors sense a fuel spill; the spill drains through the perforations into a trench system that carries it to an oil/water separator, which stores fuel and water separately. With no standing pool, there is no sustained pool fire to suppress — and therefore no need for a foam blanket at all.⁴⁴ Overhead protection reverts to conventional water sprinklers. This is an engineering control on the fuel leg of the fire triangle, not a chemical applied after the fact.

6.3 The standards and the Department of Defense now back this approach

This is no longer experimental, and it is no longer a single vendor's argument. The governing standards and the largest operator of hangars in the world have all moved the same way:

- **NFPA 409 (2022).** The Technical Committee added ILDFA as an equivalent alternative to foam systems, alongside performance-based and risk-based design pathways and a foam exemption for certain Group II hangars.⁴⁵
- **FM Global.** Property Loss Prevention Data Sheet 7-93 ("Aircraft Hangars") addresses ILDFA design directly — including aircraft alignment so that drained fuel does not expose adjacent aircraft — and FM Approvals Standard 6090 provides a dedicated approval standard for drainage-floor assemblies, under which such systems have been FM-Approved.⁴⁶
- **U.S. Air Force Foam Sundown Policy.** Issued in 2021 (updated 2022) in response to the Congressional AFFF deadline, the policy designates **all** Department of the Air Force hangars as Tier 2 facilities by default — AFFF removed and replaced with extra-hazard water sprinkler systems, with ILDFA as the end-state for foam-dependent facilities — and reserves Tier 1

(mission-critical) status for narrow exceptions requiring approval at the Assistant Secretary level (SAF/IE).⁴⁷ The Air Force has already shut down AFFF systems at 1,038 of 1,095 equipped facilities, retaining AFFF at only four mission-critical hangars, and its Civil Engineer Center has fire-tested ILDFA for chemical-free fire control.⁴⁸

- **DoD transition policy.** Defense guidance now requires AFFF systems to be completely drained from tank to sprinkler head and PFOS/PFOA releases to be calculated and reported under CERCLA — a measure of how seriously the residual-liability problem is taken even during changeover.⁴⁹

6.4 The Tier logic, applied

The Air Force framework is also the right model for civil operators. It distinguishes two classes of hangar:

- **Tier 2 — the default.** Hangars housing aircraft that exist in numbers across multiple locations, whose individual loss does not by itself reduce operational capacity. These convert away from foam now: AFFF is removed and replaced with water sprinklers, with ILDFA as the planned end-state.
- **Tier 1 — the exception.** Hangars housing few, uniquely capable, effectively irreplaceable aircraft. Even here the destination is the same — ILDFA — with an interim bridge permitted while the asset risk is managed, subject to senior approval.

In every case the trajectory is identical: away from foam, toward drainage and water. The only variable is the timetable.

7. The Grace Period — and What MROs and Airlines Should Do Now

The transition is governed by grace periods, and grace periods expire. The U.S. military deadline to stop using AFFF was 1 October 2024.⁵⁰ The EU's comprehensive foam restriction runs on sector transition windows of roughly 18 months to 10 years, with civil aviation specifically captured from 2029.^{51,52} U.S. drinking-water compliance for PFOA and PFOS is set for the end of the decade.⁵³ For a hangar operator, these dates are not distant abstractions — they are the schedule on which today's installed foam systems become tomorrow's stranded, non-compliant, liability-bearing assets.

The temptation — “we have already spent the money on foam, so we will keep it” — is precisely the trap. A legacy AFFF system is an accruing contamination liability; a fluorine-free retrofit re-incurs the recharge, testing, disposal and accidental-discharge costs while still carrying acute-toxicity and disposal obligations of its own. Neither is a settled position. Both defer a transition that the regulations have already made mandatory.

7.1 A defensible economic case

The economic argument for drainage-and-sprinkler protection should be made honestly, on a lifecycle basis rather than as a headline discount. Compared like-for-like, a foam system carries recurring costs that a drainage system does not: periodic concentrate replacement, foam-quality testing and test-discharge handling, specialised flooring, and the clean-up and disposal burden after both real and accidental discharges — plus the open-ended cost of contamination liability. ILDFA shifts spending

toward durable infrastructure (the floor, separators, sensors and sprinklers) and removes most of the recurring chemical costs. Industry project data report that drainage systems often need to cover only around two-thirds of the hangar floor rather than wall-to-wall, and that lifetime savings on the order of 30–70% are achievable once foam recharge, disposal, flooring and accidental-discharge losses are counted.⁵⁴ Those figures should be confirmed by a project-specific lifecycle cost analysis — but even a conservative analysis tends to favor drainage once the recurring and contingent costs of foam are included.

7.2 Recommended actions

- **Inventory and classify.** Identify every foam system, its chemistry (C8, C6 or fluorine-free), its concentrate age and its discharge containment, and assign each hangar a Tier 1 / Tier 2 status using the mission-criticality logic above.
- **Stop investing in foam as an end-state.** Treat any remaining foam — including fluorine-free — as an interim measure, not a 30-year solution. Do not specify foam into new hangar construction.
- **Plan drainage-and-sprinkler conversion against the deadlines.** Sequence Tier 2 conversions now and schedule Tier 1 conversions as budget allows, designing to NFPA 409 (2022), FM DS 7-93 / FM Approvals 6090 and the applicable defense or aviation criteria from the current editions.^{55,56}
- **Build the lifecycle and compliance case in parallel.** Commission a project lifecycle cost analysis and a discharge-water management plan so the environmental, regulatory and financial cases are documented before, not after, the regulator or insurer asks.

The conclusion is not that foam was a mistake — it solved a real and deadly problem for fifty years. The conclusion is that its era is ending by law, by science and by liability, and that its fluorine-free successor preserves the problems that matter most while solving only one of them. The sustainable position for aircraft hangars is to stop fighting the fuel pool with chemicals and to remove the fuel pool by design. That is what ILDFA and sprinklers do, and it is the direction the regulators, the standards bodies and the world's largest hangar operator have already chosen.

References

Detailed citations appear in the footnotes throughout. The principal primary and credible sources are listed below by category.

Court records and settlements

- Office of the Minnesota Attorney General, *State of Minnesota v. 3M Company* (filed Dec. 2010; settled 20 Feb. 2018, \$850 million). ag.state.mn.us/Office/Cases/3M/; Minnesota 3M PFAS Settlement portal, 3msettlement.state.mn.us.
- *In re: Aqueous Film-Forming Foams Products Liability Litigation*, MDL No. 2873, U.S. District Court for the District of South Carolina — 3M Public Water System Settlement (\$10.3–12.5 billion, 2024 final approval). 3M Form 8-K (22 June 2023), U.S. SEC; pfaswatersettlement.com.
- *State of Wisconsin v. Johnson Controls / Tyco Fire Products*.

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- U.S. EPA, PFAS National Primary Drinking Water Regulation (final 10 April 2024; proposed amendments 18 May 2026). [epa.gov/sdwa](https://www.epa.gov/sdwa).
- U.S. ATSDR / CDC, Toxicological Profile for Perfluoroalkyls. [atsdr.cdc.gov](https://www.atsdr.cdc.gov).
- U.S. Department of the Air Force, Foam Sundown Policy for foam fire suppression systems (2021, updated 2022); FY2020 National Defense Authorization Act (AFFF deadline 1 Oct. 2024); Office of the Assistant Secretary of Defense (EI&E), AFFF-to-fluorine-free transition memorandum (2024). [acq.osd.mil](https://www.acq.osd.mil).
- Air Force Civil Engineer Center, “Fuel Spill Fire Testing of an Ignitable Liquid Drainage Floor Assembly (ILDFA)” (2022); FAA, “Aircraft Firefighting Foam Transition Plan” (2023).
- Commission Regulation (EU) 2024/2462 (PFHxA); Commission Regulation (EU) 2025/1988 (PFAS in firefighting foams); EU POPs Regulation (EU) 2019/1021; EU CLP Regulation (EC) No 1272/2008; ECHA, echa.europa.eu.

Standards

- NFPA 409, *Standard on Aircraft Hangars* (2022 ed.). [nfpa.org](https://www.nfpa.org).
- FM Global Property Loss Prevention Data Sheet 7-93, “Aircraft Hangars”; FM Approvals Standard 6090, “Approval Standard for Ignitable Liquid Drainage Floor Assemblies.” [fm.com](https://www.fm.com).
- U.S. Air Force ETL 02-15 and UFC 3-600-01 (hangar fire-protection criteria); WBDG Unified Facilities Criteria. [wbdg.org](https://www.wbdg.org).

Peer-reviewed and university research

- D. K. Jones et al., “Acute Toxicity of Eight Aqueous Film-Forming Foams to 14 Aquatic Species,” *Environmental Science & Technology* 56(10): 6078–6090 (2022), DOI 10.1021/acs.est.1c03776 (SERDP).
- T. Stueckle et al., “Toxicity of Fluorinated and Fluorine-Free Foams: Potential Implications on Firefighter Renal Health,” *The Toxicologist* 186(S1), Society of Toxicology 61st Annual Meeting (2022); NIOSH et al., via CDC Stacks.
- J. Milke et al., “Review of Foam Fire Suppression System Discharges in Aircraft Hangars,” University of Maryland Department of Fire Protection Engineering (2020/2021).

Historical / technical

- U.S. Patent 3,258,423 (Tuve & Jablonski, 1966); Naval Research Laboratory Report 6057 (1964).

Notes

1. Minnesota Pollution Control Agency and the Minnesota 3M PFAS Settlement portal (3msettlement.state.mn.us): on 20 February 2018 the State and 3M entered an Agreement and Order; 3M provided an \$850 million restricted grant, of which roughly \$720 million (net of costs)

- funds drinking-water and natural-resource projects in the East Metropolitan Area, including Woodbury, Oakdale, Lake Elmo and Cottage Grove. 3M admitted no liability.
2. In re: Aqueous Film-Forming Foams Products Liability Litigation, MDL No. 2873, U.S. District Court for the District of South Carolina (Charleston). 3M Public Water System Settlement announced 22 June 2023; present value \$10.3 billion, nominal cap \$12.5 billion, payable 2024–2036; final court approval 2024. See 3M Form 8-K (22 June 2023), U.S. SEC; settlement administrator at pfaswatersettlement.com.
 3. DuPont, Chemours and Corteva agreed in June 2023 to a \$1.185 billion fund for public water systems within the same litigation.
 4. State of Wisconsin v. Johnson Controls / Tyco Fire Products – among the first state actions against firefighting-foam manufacturers, indicating that liability is broadening beyond chemical producers toward fire-protection companies.
 5. PFOS and PFOA are listed under the Stockholm Convention on Persistent Organic Pollutants and restricted by the EU POPs Regulation (EU) 2019/1021. PFOS-based foam manufacture ceased c. 2015; the EU derogation for PFOA in firefighting foam expires December 2025.
 6. Commission Regulation (EU) 2024/2462 (Official Journal, 19 September 2024) restricting undecafluorohexanoic acid (PFHxA, a C6 PFAS) and related substances under REACH Annex XVII; firefighting-foam training/testing uses restricted from October 2026 and civil aviation/airports from 10 October 2029.
 7. Commission Regulation (EU) 2025/1988 (in force 23 October 2025), REACH Annex XVII entry 82: prohibits placing on the market, use and export of PFAS-containing firefighting foams above 1 mg/L, with sector transition periods of roughly 18 months to 10 years. ECHA’s Committee for Socio-Economic Analysis estimated the measure could avoid ~13,200 tonnes of PFAS emissions over 30 years. See echa.europa.eu (PFAS).
 8. U.S. EPA, PFAS National Primary Drinking Water Regulation, finalized 10 April 2024: enforceable Maximum Contaminant Levels of 4.0 ppt for PFOA and PFOS individually, with limits for PFHxS, PFNA and HFPO-DA and a Hazard Index for mixtures. On 18 May 2026 EPA proposed to retain the PFOA/PFOS limits while extending compliance to 2031, and to rescind the limits for the four other PFAS (comment period to 20 July 2026). epa.gov/sdwa.
 9. U.S. Department of Defense transition from the AFFF specification MIL-PRF-24385 to the fluorine-free land-based specification MIL-PRF-32725 (QPL-32725 established 12 September 2023), driven by the FY2020 National Defense Authorization Act; FAA, “Aircraft Firefighting Foam Transition Plan” (2023).
 10. U.S. Department of the Air Force, Foam Sundown Policy for foam fire suppression systems (November 2021; updated December 2022). The policy designates all DAF hangars and similar facilities as Tier 2 facilities (AFFF removed and replaced with extra-hazard water sprinkler systems, with Ignitable Liquid Drainage Floor Assemblies (ILDFA) as the end-state for foam-dependent facilities); Tier 1 (mission-critical) exceptions require approval by the Assistant Secretary of the Air Force for Energy, Installations and Environment (SAF/IE). AFFF to be replaced no later than 1 October 2024.
 11. D. K. Jones et al., “Acute Toxicity of Eight Aqueous Film-Forming Foams to 14 Aquatic Species,” *Environmental Science & Technology* 56(10): 6078–6090 (2022), DOI 10.1021/acs.est.1c03776; conducted under the U.S. DoD Strategic Environmental Research and Development Program (SERDP). Across all 14 species, at least one PFAS-free foam was as toxic as, or more toxic than, the PFAS-containing AFFF.
 12. T. Stueckle, M. Calkins, J. Coyle, A. Slitt, B. Ruyle, E. Sunderland, S. Beitel, J. Burgess and L. Rojanasakul, “Toxicity of Fluorinated and Fluorine-Free Foams: Potential Implications on Firefighter Renal Health,” *The Toxicologist* (Supplement to Toxicological Sciences) 186(S1), March 2022;

- presented at the Society of Toxicology 61st Annual Meeting & ToxExpo, San Diego, 27–31 March 2022 (NIOSH, University of Rhode Island, Harvard University, University of Arizona). In human renal proximal-tubule cells (RPTEC-OAT1), the five AFFF were cytotoxic (IC50) at 109–262 ppm, while the most toxic fluorine-free foam was cytotoxic at 3.3 ppm; others ranged 33–278 ppm. Via CDC Stacks (stacks.cdc.gov/view/cdc/249274).
13. Hazard statements under the EU CLP Regulation (EC) No 1272/2008 (aligned to the UN GHS): H318 “Causes serious eye damage” (Eye Dam. Cat. 1; signal word Danger; corrosion pictogram GHS05); H373 “May cause damage to organs through prolonged or repeated exposure” (STOT RE Cat. 2; signal word Warning; health-hazard pictogram GHS08). Many fluorine-free concentrates carry these statements owing to glycol-ether solvent content.
 14. U.S. Department of the Air Force, Foam Sundown Policy for foam fire suppression systems (2021, updated 2022).
 15. FM Global Property Loss Prevention Data Sheet 7-93, “Aircraft Hangars,” which addresses ILDFA design (including aircraft alignment so drained liquid does not expose additional aircraft) and references NFPA 409 hangar groups; and FM Approvals Standard 6090, “Approval Standard for Ignitable Liquid Drainage Floor Assemblies.” [fm.com](https://www.fm.com).
 16. NFPA 409, Standard on Aircraft Hangars, 2022 edition: the Technical Committee voted (July 2021) to add ILDFA as an equivalent alternative to foam systems, alongside performance-based and risk-based design pathways and a foam exemption for certain Group II hangars.
 17. J. Milke et al., “Review of Foam Fire Suppression System Discharges in Aircraft Hangars,” University of Maryland Department of Fire Protection Engineering (2020/2021). Of 245 documented foam discharges over roughly a 17-year window, 242 (≈98.8%) occurred with no fire present; U.S. Coast Guard data indicate roughly one hangar fuel spill per year nationally.
 18. R. L. Tuve and E. J. Jablonski, “Method of Extinguishing Liquid Hydrocarbon Fires,” U.S. Patent 3,258,423 (granted 28 June 1966; assigned to the Secretary of the U.S. Navy); see also R. L. Tuve et al., “A New Vapor-Securing Agent for Flammable-Liquid Fire Extinguishment,” Naval Research Laboratory Report 6057 (1964).
 19. GZA GeoEnvironmental, “Per- and Polyfluoroalkyl Substances – Part I: A Focus on the History of Aqueous Film-Forming Foams”; U.S. Environmental Working Group, “The Pentagon’s 50-Year History with PFAS” (2019). The U.S. Navy first sought the patent in 1963; it issued in 1966.
 20. U.S. military specification MIL-F-24385 required AFFF from 1969 following the 1967 USS Forrestal fire; use spread through the 1970s to the wider Department of Defense, civilian airports (FAA Part 139) and municipal fire services.
 21. Mechanism per U.S. Patent 3,258,423 and NRL Report 6057: fluorocarbon surfactants reduce surface tension to below ~17 dynes/cm, allowing an aqueous film to spread beneath the foam and seal fuel vapors.
 22. PFOA, PFOS and PFHxS are documented in firefighter serum and in drinking water; PFAS exposure is associated with kidney and testicular cancer, thyroid disruption, immune and developmental effects. See U.S. ATSDR, Toxicological Profile for Perfluoroalkyls (CDC); U.S. EPA PFAS resources (epa.gov/pfas).
 23. Minnesota 3M PFAS Settlement portal (3msettlement.state.mn.us): \$850 million settlement, 20 February 2018.
 24. S. Lerner, reporting in The Intercept, and U.S. Environmental Working Group (2019), citing records indicating that 3M and the Navy became aware of concerns regarding AFFF/PFAS by the 1970s; internal documents were surfaced through the Minnesota litigation.
 25. 3M Public Water System Settlement, MDL 2873 (D.S.C.): \$10.3–12.5 billion, payable 2024–2036; final approval 2024.
 26. DuPont, Chemours and Corteva public water systems settlement (\$1.185 billion, 2023).

27. State of Wisconsin v. Johnson Controls / Tyco Fire Products.
28. Stockholm Convention; EU POPs Regulation (EU) 2019/1021 (PFOS, PFOA).
29. Commission Regulation (EU) 2024/2462 (PFHxA / C6) under REACH.
30. Commission Regulation (EU) 2025/1988 (PFAS in firefighting foams; 1 mg/L limit).
31. U.S. EPA PFAS National Primary Drinking Water Regulation (final 2024; proposed amendments 2026).
32. FY2020 NDAA AFFF deadline (1 Oct. 2024); MIL-PRF-32725; FAA F3 Transition Plan (2023).
33. U.S. Department of the Air Force, Foam Sundown Policy for foam fire suppression systems (2021, updated 2022).
34. FY2020 NDAA AFFF deadline (1 Oct. 2024); MIL-PRF-32725; FAA F3 Transition Plan (2023).
35. Jones et al., Environmental Science & Technology 56(10): 6078–6090 (2022) (SERDP).
36. Stueckle et al., The Toxicologist 186(S1), Society of Toxicology 61st Annual Meeting (2022) (NIOSH et al.; CDC Stacks).
37. EU CLP Regulation (EC) No 1272/2008: hazard statements H318 and H373.
38. Minnesota 3M PFAS Settlement portal (3msettlement.state.mn.us): \$850 million settlement, 20 February 2018.
39. Reporting and litigation records indicating 3M/Navy awareness of AFFF/PFAS concerns by the 1970s (The Intercept; EWG, 2019).
40. 3M Public Water System Settlement, MDL 2873 (D.S.C.): \$10.3–12.5 billion, payable 2024–2036; final approval 2024.
41. State of Wisconsin v. Johnson Controls / Tyco Fire Products.
42. Milke et al., University of Maryland Department of Fire Protection Engineering (2020/2021).
43. AXA XL, “Hangar Fire Foam Suppression Systems: Is it time for an alternative?” (2021); NPR/KGOU (2024) reporting that accidental hangar foam releases now occur on average about once a month and are increasing in frequency and cost.
44. Operating principle per NFPA 409 (2022), FM DS 7-93 and AFCEC testing: a perforated, channelled floor drains spilled fuel into trenches feeding an oil/water separator, removing the ignitable-liquid pool before a sustained pool fire can form.
45. NFPA 409, Standard on Aircraft Hangars (2022 edition).
46. FM Global Property Loss Prevention Data Sheet 7-93 (Aircraft Hangars); FM Approvals Standard 6090 (ILDFA).
47. U.S. Department of the Air Force, Foam Sundown Policy for foam fire suppression systems (2021, updated 2022).
48. Air Force Materiel Command / Air Force Civil Engineer Center statements (reported by Stars and Stripes, 2024): AFFF systems shut down at 1,038 of 1,095 equipped facilities, with AFFF retained at only four mission-critical hangars; affected hangars converted to water-only sprinkler systems. AFCEC, “Fuel Spill Fire Testing of an Ignitable Liquid Drainage Floor Assembly (ILDFA) for Chemical-Free Fire Control/Suppression” (2022).
49. Office of the Assistant Secretary of Defense (Energy, Installations & Environment), memorandum on transition from AFFF to fluorine-free alternatives (2024), requiring systems to be completely drained of AFFF from tank to sprinkler head and PFOS/PFOA mass releases to be calculated and reported under CERCLA. acq.osd.mil.
50. FY2020 NDAA AFFF deadline (1 Oct. 2024); MIL-PRF-32725; FAA F3 Transition Plan (2023).
51. Commission Regulation (EU) 2024/2462 (PFHxA / C6) under REACH.
52. Commission Regulation (EU) 2025/1988 (PFAS in firefighting foams; 1 mg/L limit).
53. U.S. EPA PFAS National Primary Drinking Water Regulation (final 2024; proposed amendments 2026).

54. Lifecycle-cost and floor-coverage figures are drawn from ILDFA system manufacturers and project data (e.g., reported average floor coverage of ~65% versus wall-to-wall foam coverage, and lifetime savings on the order of 30–70% when foam recharge, disposal, flooring and accidental-discharge losses are included). These are industry figures and should be confirmed by a project-specific lifecycle cost analysis.
55. FM Global Property Loss Prevention Data Sheet 7-93 (Aircraft Hangars); FM Approvals Standard 6090 (ILDFA).
56. NFPA 409, Standard on Aircraft Hangars (2022 edition).