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RESEARCH ON THE EFFICIENCY AND IMPROVEMENT OF ENVIRONMENTALLY FRIENDLY FLUORINE-FREE FIREFIGHTING FOAMS UNDER THE CONDITIONS OF UZBEKISTAN

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Abstract: The increasing environmental and public health concerns associated with per- and polyfluoroalkyl substances (PFAS) have accelerated the global transition from conventional aqueous film-forming foams (AFFF) to fluorine-free firefighting foams (F3). Although fluorinated foams remain highly effective in suppressing liquid fuel fires, their persistence in the environment and potential adverse effects on ecosystems and human health have led to stricter regulations worldwide. This study evaluates the applicability, effectiveness, and improvement potential of fluorine-free firefighting foams under the climatic and industrial conditions of Uzbekistan. Particular attention is paid to the country's oil and gas facilities, fuel storage terminals, airports, and industrial enterprises. Based on comparative analysis of international research findings, environmental assessments, and operational requirements, recommendations are proposed for the development of climate-adapted fluorine-free foam technologies suitable for Central Asian conditions. The study concludes that fluorine-free foams can provide an environmentally sustainable alternative to conventional AFFF systems, provided that their formulations are adapted to high-temperature and low-humidity environments.

Keywords: Fluorine-free foam, PFAS, firefighting foam, environmental safety, fire suppression, sustainable firefighting technologies, Uzbekistan, industrial fire protection.

1. Introduction

Fire suppression foams have been among the most effective agents for combating Class B fires involving flammable liquids such as gasoline, aviation fuel, crude oil, and petroleum products. For more than five decades, aqueous film-forming foams (AFFF) containing fluorinated surfactants have been widely used because of their rapid extinguishing capability and superior burn-back resistance.

However, recent scientific evidence has identified PFAS compounds contained in many AFFF formulations as persistent environmental pollutants. These substances exhibit exceptional chemical stability and resistance to natural degradation processes, leading to their classification as “forever chemicals.” Studies conducted by environmental and health agencies have demonstrated that PFAS compounds can accumulate in groundwater, surface waters, soils, wildlife, and human tissues, posing long-term environmental and health risks.

The U.S. Environmental Protection Agency (EPA) has emphasized that PFAS contamination is associated with serious ecological concerns and potential adverse health effects. Likewise, the Federal Aviation Administration (FAA) and the U.S. Department of Defense have initiated extensive programs aimed at replacing PFAS-containing firefighting foams with fluorine-free alternatives. As a result, fluorine-free firefighting foams (F3) have become a major focus of international research and industrial innovation.

For Uzbekistan, the issue is of particular importance. The country possesses significant oil and gas infrastructure, fuel storage facilities, chemical enterprises, and transportation hubs where liquid fuel fires remain among the most critical industrial hazards. Simultaneously, the arid climate, limited water resources, and growing environmental protection requirements create a need for firefighting technologies that combine operational effectiveness with ecological sustainability.

Despite substantial international progress, there remains a lack of scientific studies evaluating fluorine-free foam performance under Central Asian climatic conditions. This gap forms the basis of the present research.

2. Literature Review and Scientific Background

Global concern regarding PFAS contamination has significantly influenced firefighting foam development over the past decade. According to the Federal Aviation Administration (FAA), PFAS-containing foams have historically been regarded as the most effective firefighting agents for aviation fuel fires. Nevertheless, increasing evidence regarding their environmental persistence has accelerated the development of fluorine-free alternatives.

Modern fluorine-free foams utilize hydrocarbon surfactants, biodegradable stabilizers, polymers, and advanced foam-enhancing additives instead of fluorinated compounds. Their extinguishing mechanism remains similar to that of AFFF systems: the formation of a foam blanket that isolates fuel vapors from atmospheric oxygen and suppresses heat transfer.

Research conducted by the U.S. Fire Administration indicates that fluorinated foams generally exhibit superior extinguishment performance and vapor suppression characteristics. However, fluorine-free formulations have achieved substantial improvements in recent years and can now satisfy many operational requirements previously met only by AFFF systems.

One of the most important scientific findings is that environmental sustainability should not be evaluated solely based on the absence of PFAS. According to EPA investigations, fluorine-free foams contain high concentrations of hydrocarbon surfactants that may also affect aquatic ecosystems and microbial communities. Although these effects are generally less persistent than PFAS contamination, they demonstrate the necessity of comprehensive environmental evaluation of all firefighting foam technologies.

Recent biodegradation studies have shown that fluorine-free foams degrade significantly faster under aerobic environmental conditions than PFAS-containing formulations. Nevertheless, incomplete degradation and formation of intermediate compounds may occur in anaerobic environments, indicating the need for continued environmental monitoring.

Consequently, the scientific community increasingly recognizes that the future of firefighting foam technology should focus not merely on PFAS elimination but on the development of environmentally optimized formulations capable of balancing fire suppression performance, ecological safety, and economic feasibility.

3. Problem Statement for Uzbekistan

The climatic and industrial conditions of Uzbekistan create unique challenges for firefighting foam application.

Summer temperatures frequently exceed 40°C, while relative humidity remains comparatively low in many regions. Such environmental conditions accelerate foam drainage, water evaporation, and blanket degradation. As a result, foam systems developed primarily for temperate European climates may demonstrate reduced effectiveness under local operating conditions.

In addition, strategic sectors of the Uzbek economy—including petroleum storage facilities, natural gas processing plants, airports, railway fuel depots, and chemical industries—require firefighting systems capable of suppressing large-scale hydrocarbon fires rapidly and reliably.

Therefore, the direct adoption of imported fluorine-free foams without local adaptation and testing may not provide optimal fire protection performance.

The present study proposes that Uzbekistan should develop a national scientific framework for evaluating fluorine-free firefighting foams based on local climatic, environmental, and operational requirements. Such an approach would facilitate the transition toward environmentally sustainable fire suppression technologies while maintaining high levels of industrial fire safety.

4. Results and Discussion

4.1 Environmental Assessment of PFAS-Containing and Fluorine-Free Foams

Recent international studies indicate that the primary environmental concern associated with conventional AFFF firefighting foams is the presence of PFAS compounds. These substances demonstrate exceptional resistance to biodegradation and may persist in soil and groundwater for decades. Environmental monitoring programs conducted in North America and Europe have identified PFAS contamination around airports, military installations, and industrial facilities where firefighting foams have been extensively used.

The transition toward fluorine-free foams (F3) has therefore become a strategic objective in many countries. Nevertheless, recent EPA research suggests that fluorine-free formulations should not automatically be considered environmentally harmless. Some F3 products contain high concentrations of hydrocarbon surfactants that may exhibit acute toxicity toward aquatic organisms and microbial communities under certain exposure conditions. Aerobic biodegradation rates are generally high, while degradation in anaerobic environments remains incomplete and may generate intermediate by-products. (US EPA)

These findings suggest that environmental sustainability should be evaluated through a complete life-cycle assessment rather than solely on the basis of PFAS absence.

4.2 Performance Evaluation Under Uzbekistan Conditions

Uzbekistan's climatic conditions differ significantly from those of many regions where fluorine-free foams have been tested and certified.

The country's industrial facilities frequently operate under ambient temperatures exceeding 40°C during summer months. Elevated temperatures accelerate foam drainage, increase water evaporation, and reduce foam blanket persistence. Consequently, foam formulations developed for temperate climates may experience decreased effectiveness under Central Asian environmental conditions.

Theoretical analysis conducted within this study identifies four critical performance parameters:

Parameter	Operational Importance
Foam expansion ratio	Determines blanket coverage area
Drainage time	Influences foam stability
Burn-back resistance	Prevents reignition
Thermal stability	Maintains effectiveness at high temperatures

Among these parameters, thermal stability appears to be the most important factor for Uzbekistan due to prolonged exposure to extreme summer temperatures.

4.3 Strategic Advantages of Fluorine-Free Technologies

Although conventional AFFF formulations may still demonstrate superior extinguishing performance in certain scenarios, fluorine-free technologies offer significant long-term advantages:

Evaluation Criterion	Conventional AFFF	Fluorine-Free Foam
Fire suppression efficiency	Very high	High
PFAS contamination risk	High	None
Groundwater protection	Limited	Improved
Regulatory sustainability	Declining	Increasing
Future environmental liability	High	Low

International regulatory trends indicate that fluorine-free technologies are becoming the preferred solution for airports, industrial facilities, and emergency response organizations. The FAA has already established qualification pathways for fluorine-free foams through military specifications and approved product lists, facilitating broader implementation within aviation firefighting systems.

4.4 Proposed Scientific Innovation for Uzbekistan

A significant contribution of this research is the proposal to establish a **National Fluorine-Free Foam Evaluation Program** specifically designed for Uzbekistan.

The proposed program would include:

- High-temperature performance testing (+45°C to +50°C);
- Low-temperature storage testing (-20°C);
- Hydrocarbon pool-fire suppression trials;
- Burn-back resistance assessment;
- Water-consumption efficiency analysis;
- Environmental toxicity screening;
- Long-term storage stability evaluation.

Such a system would allow firefighting agencies to select foam products based on local operational requirements rather than relying exclusively on foreign certification standards.

4.5 Future Development Directions

The next generation of fluorine-free firefighting foams is expected to incorporate:

- Bio-based surfactants derived from renewable resources;
- Silicone–hydrocarbon hybrid surfactant systems;
- Advanced foam stabilizers;
- AI-assisted formulation optimization technologies.

Recent scientific investigations suggest that combinations of silicone and hydrocarbon surfactants may significantly improve foam stability and fire suppression efficiency while maintaining environmental compatibility.

Scientific Conclusion

The results of this study indicate that the future of firefighting foam technology in Uzbekistan should not focus solely on replacing fluorinated products with fluorine-free alternatives. Instead, the priority should be the development of climate-adapted, environmentally assessed, and operationally optimized fluorine-free foams specifically engineered for Central Asian conditions.

Such an approach would simultaneously improve industrial fire safety, reduce long-term environmental risks, and support Uzbekistan's transition toward sustainable emergency management systems. (US EPA)

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