SERDP

FINAL REPORT

Advancing Alternatives Assessment and Informed Substitution for Chemicals of Concern - The Case Example of AFFF

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SERDP Project WP19-1424

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14. ABSTRACT

Specific research objectives included:
1.Understanding gaps in comprehensive alternatives assessments for AFFF by reviewingexisting assessments;
2.Developing generalizable approaches and guidance to strengthen future alternativesassessments by:
a.defining criteria for a “safer” non-fluorinated AFFF alternatives; and
b.determining “fit for purpose” performance assessment considerations;
3.Understanding lessons learned from existing efforts to accelerate the adoption of saferalternatives to AFFF, including barriers and enabling factors.
This report summarizes work associated with our 3 primary research objectives above, drawing from 4 reports that were developed. The work was guided by a Project Support Committee (Annex A), which met on four occasions over the project period, and also engaged in between meetings, including providing reviews of draft reports. Reports developed for this project are included as annexes (Annexes B-E). Lessons learned from these activities are reviewed and suggested next steps are identified.

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Overview and Objectives of Project # WP19-1424

The Fiscal Year (FY) 2020 National Defense Authorization Act (NDAA) requires the US Department of Defense (US DoD) to phase out use per and polyfluoroalkyl substances (PFAS) based aqueous film forming foams (AFFF) at military installations by October 1, 2024 (NDAA 2019).[1] Due to growing concerns about PFAS in firefighting foams, over the last few years there has been tremendous investment in the PFAS-free alternatives to AFFF. The purpose of our University of Massachusetts research project, supported by the US DoD's Strategic Environmental Research and Development Program (SERDP) (Project # WP19-1424), was to improve the ability of the US DoD to make informed, efficient choices regarding the use of PFAS-free alternatives to AFFF by strengthening and building consistency in the approaches used to identify, compare, and adopt alternatives. The ultimate goal of this research project was to strengthen and expand use of alternatives assessment methods to better support government and industry in making informed choices to accelerate the adoption of high performing, safer, and more sustainable chemicals, products, and processes. Improved methodologies for assessing alternatives and addressing barriers to commercialization and adoption can improve the long-term results of assessments that identify safer and effective options and reduce current and future liabilities.

Specific research objectives included:

1. Understanding gaps in comprehensive alternatives assessments for AFFF by reviewing existing assessments;
2. Developing generalizable approaches and guidance to strengthen future alternatives assessments by:
    a. defining criteria for a "safer" non-fluorinated AFFF alternatives; and
    b. determining "fit for purpose" performance assessment considerations;
3. Understanding lessons learned from existing efforts to accelerate the adoption of safer alternatives to AFFF, including barriers and enabling factors.

This report summarizes work associated with our 3 primary research objectives above, drawing from 4 reports that were developed. The work was guided by a Project Support Committee (Annex A), which met on four occasions over the project period, and also engaged in between meetings, including providing reviews of draft reports. Reports developed for this project are included as annexes (Annexes B-E). Lessons learned from these activities are reviewed and suggested next steps are identified.

[1] NDAA [National Defense Authorization Act]. 2019. National Defense Authorization Act for Fiscal Year 2020. S. 1790 – 11^{6th} Congress (2019-2020). December 20. Accessed May 20, 2021 at: https://www.govinfo.gov/content/pkg/PLAW-116publ92/html/PLAW-116publ92.htm

1. Understanding gaps in comprehensive alternatives assessments for AFFF by reviewing existing assessments

Alternatives assessment supports the evaluation and adoption of safer alternatives and helps to minimize regrettable substitutes by ensuring that hazards and potential trade-offs – including human health, ecological health and sustainability attributes – are considered alongside issues of performance and cost. The goal of alternatives assessment is informed substitution – the considered transition from higher concern to lower concern chemicals using the best available information. The objective of this study was to support the informed substitution of PFAS in AFFF with safer and feasible alternatives by understanding the strengths and weaknesses of alternatives assessments conducted to date. The full report is included as Annex B.

Evaluations of alternatives were required to meet four criteria to be considered a comprehensive alternatives assessment and included in this review:

a. evaluates commercially available alternatives;
b. evaluates hazard, cost and performance attributes (exposure and life cycle attributes optional);
c. uses standardized assessment criteria to systematically evaluate and compare alternatives to the incumbent; and
d. includes fluorine-free alternatives and the incumbent product (AFFF)/chemical of concern.

Existing alternatives assessments were reviewed against two seminal alternatives assessment frameworks: the US National Research Council's (NRC), *A Framework to Guide Selection of Chemical Alternatives*[2] and the Interstate Chemicals Clearinghouse's (IC2) *Alternatives Assessment Guide Version 1.1.*[3]

Only one alternatives assessment met all four inclusion criteria and was included in this critical review – an alternatives assessment undertaken to support regulatory risk management options by the European Chemicals Agency (ECHA).[4] Although data in the alternatives assessment (referred to as the ECHA study) in the report (Annex B) was limited to information that 3rd party researchers were able to collect – which was highly dependent on the voluntary compliance by industry parties – the assessment was generally aligned with approaches for alternatives assessment outlined by the NRC and IC2 frameworks. Future AFFF alternatives assessment can learn from and improve upon the ECHA study in the following ways:

- **Consider incorporating case studies into alternatives assessment practice.** One of the contributions of the ECHA study to the field of alternatives assessment was the use of case studies to exemplify attributes of the technical and economic feasibility assessments. The case studies added greater understanding of specific assessment criteria.

[2]United States National Research Council. 2014. A framework to guide selection of chemical alternatives. Washington (DC): National Academies Press.
[3]Interstate Chemicals Clearinghouse. 2017. Alternatives Assessment Guide Version 1.1.
[4]Wood, Ramboll and Cowi. June 2018. *The Use of PFAS and Fluorine-Free Alternatives in Fire-Fighting Foams.* Report for European Commission and the European Chemicals Agency.

- **Consider broadening the assessment scope (during the problem formulation step) and not limit the functional use for AFFF alternatives to just film forming foams.** Only film forming foams were considered in the ECHA study. This may preclude different alternative processes or technologies that have the capacity to extinguish fires in a number of different scenarios but do so by mechanisms other than the use of chemical surfactants/wetting agents to smother the flames.

- **Examine a broader set of hazard endpoints using measured and modeled data sources rather than depending solely on Safety Data Sheets (SDS).** Using reviews of primary research studies will go further in terms of understanding specific hazard traits beyond those noted on an SDS.

- **Consider reasonable and foreseeable exposure scenarios and relevant physicochemical properties that would inform the exposure potential of alternatives.** This is especially important if alternatives have different forms, use patterns or physicochemical properties than the AFFF.

- **Support deeper engagement by stakeholders**. Stakeholder engagement is important to address issues including use parameters, the inclusion of additional hazard traits of primary concern, and which specific life cycle considerations should be addressed in assessments.

- **Augment the alternatives assessment in the near future and on an ongoing basis as needed to stay current.** The ECHA study is already considered outdated by some given the quickly evolving innovation landscape. Additional alternatives assessments that are more comprehensive in nature and that consider the emergence of newer commercially available alternatives will be needed the near future. Future alternatives assessments could leverage current and emerging assessments of PFAS-free alternatives regarding their hazards, performance, cost as well as broader life cycle impacts. It is important to note that the alternatives assessment method can also be used at earlier stages of product development.[5] The comparative assessment approach across hazard, performance and cost attributes can support not only substitution decisions, but also product design decisions where the focus is on the evaluation and selection of product chemistries that are meet criteria for being safer, high performing and cost effective.

2a. Developing generalizable approaches and guidance to strengthen future alternatives assessments by defining criteria for a "safer" AFFF alternatives

To support assessments of PFAS-free firefighting foam products in identifying safer alternatives, for this component of SERDP Project # WP19-1424 we developed specific criteria to evaluate and determine whether alternatives are safer as compared to current PFAS-containing AFFF

[5] Tickner J, et al. 2021. The nexus between alternatives assessment and green chemistry: supporting the development and adoption of safer chemicals, Green Chemistry Letters and Reviews, 14:1, 23-44, DOI: 10.1080/17518253.2020.1856427

products (Annex C). The criteria should be considered the *minimum requirements* for a safer AFFF alternative determination. Criteria are drawn from existing approaches, in particular the Organization for Economic Cooperation and Development's (OECD) "Guidance on Key Considerations for the Identification and Selection of Safer Alternatives"[6] and supplemented by others such as the Green Screen Certified for Fire Fighting Foam.[7]

The minimum requirements for a safer AFFF alternative determination include Part A and Part B as displayed below in Table 1. Conformance with Part A ensures that problematic groups of substances are not used as ingredients (intentionally added or impurities/residuals) in an alternative formulation for such formulation to be considered "safer". Conformance with Part B includes hazard endpoints and/or associated hazard classifications that cannot be of "high" concern for an alternative AFFF formulation to be considered safer.

Table 1. Minimum Requirements for a Safer AFFF Alternative

Part A	**Part B**
A **safer** AFFF alternative cannot include the following classes of substances and/or substances: 1. Fluorinated substances (no PFAS) 2. Alkylphenols and alkylphenol ethoxylates unless test data for endpoints in Part B demonstrate safety 3. Cyclic volatile methyl siloxanes: – octamethylcyclotetrasiloxane (D4) – decamethylcyclopentasiloxane (D5) – dodecamethylcyclohexasiloxane (D6)	A **safer** AFFF alternative cannot contain any chemical ingredient* classified as "high" concern associated with the following hazard endpoints: 1. Carcinogenicity* 2. Germ cell mutagenicity* 3. Reproductive/developmental toxicity* 4. Acute mammalian toxicity 5. Systemic toxicity, repeated dose 6. Endocrine disruption 7. Chronic aquatic toxicity Or either of the following classifications: 8. Persistent, Bioaccumulative, and Toxic (PBT)* 9. very Persistent, very Bioaccumulative (vPvB)* A **safer** AFFF alternative tested at the product-level cannot be classified as "high" concern associated with the following hazard endpoint: • Acute aquatic toxicity

The guidance details methods and criteria for evaluating the minimum requirements above, including use of authoritative lists for an initial rapid screen of problematic ingredients, applying criteria/thresholds using the Globally Harmonized System (GHS) of Classification and Labelling of Chemicals, and using GreenScreen® criteria for persistence and bioaccumulation to support a PBT or very persistent very bioaccumulative (vPvB) classification based on US EPA criteria

[6]Organization for Economic Cooperation and Development. 2021. Guidance on Key Considerations for the Identification and Selection of Safer Chemical Alternatives. Series on Risk Management No. 60.
[7]CPA [Clean Production Action]. 2021. GreenScreen Certified™ Standard for Fire Fighting Foam V 2.1.

and/or the Registration, Evaluation and Authorization of Chemicals (REACH) regulation in the EU. For acute aquatic toxicity, the guidance recommends evaluating the full product rather than the hazard traits of individual ingredients. The guidance also outlines specific physicochemical properties for evaluating the exposure potential of formulation ingredients, which is especially important for understanding the need for exposure mitigation strategies if ingredients are deemed of "moderate" concern for specific hazard endpoints of interest. Going beyond the minimum is recommended *wherever and whenever possible* to further reduce the likelihood that an alternative to AFFF will result in unintended consequences to the environment, workers, and the public. As such, the guidance outlines additional hazard endpoints to consider beyond the minimum requirements and calls attention to the inclusion of mobility, respiratory and skin sensitization and endocrine disruption data (for the latter going beyond the use of authoritative lists) where available data and criteria permit such assessments.

2b. Guidance for Evaluating the Performance of Alternatives: Fit-for-Purpose Performance (Version 1.0)

Traditional approaches to evaluating technical performance in an alternatives assessment are often based around a single performance metric, require performance through specific mechanisms, or require feasibility of adoption considerations as part of the performance evaluation. For this component of SERDP Project #WP19-1424 we developed guidance to guide decision-making associated with the performance of potentially safer alternatives, emphasizing a focus on a *fit-for-purpose* performance, a strategy for assessing performance based on application-specific contexts (Annex D). A fit-for-purpose performance approach underlines the importance of evaluating whether the chemical, material, product, or process of concern achieves sufficient performance in a specific application; this guidance further expands the thinking around performance as a range and acknowledges important considerations around trade-offs with environmental health and safety performance. The guidance builds on and broadens the thinking around performance when evaluating and choosing safer alternatives and draws primarily from two well-established alternatives assessment frameworks also used in project component 1, above, the IC2 guide and the US NRC framework. Ultimately, the performance evaluation will form part of a broader alternatives assessment process that considers hazard, comparative exposure, economic feasibility, and other factors to compare alternative solutions to replace the chemical, material, product, or process of concern.

Six guiding considerations form this performance evaluation process. Depending on the context, some considerations may be revisited more than once, as this is an iterative process. The amount of information and testing required to address each consideration is likely case specific. These guiding considerations balance the need for detailed key performance criteria but include flexibility for a broad range of alternatives that achieve sufficient function for the intended application, and suggest to:

1. **Determine the *function* of the chemical/material/product/process of concern for the specific application and understand this function within the production chain.**
    - Key questions to consider:
        - *What is the function of the chemical, and is it necessary?*

- *If upstream processes are changed, is the function of the chemical/material/product/process of concern needed?*
- *If the function is still needed, is it changed in any way?*

2. **Define the *application*-specific scenario(s) in which the substance of concern is used and identify alternatives that are suitable for that particular purpose.**
   - Key questions to consider:
     - *For what application(s) is the chemical/material/product/process of concern being used?*
     - *Do alternatives under consideration meet the functional performance need for the application(s) (even if they are used in different ways for other applications), perhaps with minor adjustments?*

3. **Establish and/or use performance standards that have been developed *independent* of the existing chemicals/materials/products/processes of concern (as much as possible) and adjust them based on available alternatives or alternatives on the horizon.**
   - Key questions to consider:
     - *What are the technical/standard performance requirements that the potential alternatives need to meet? Are there regulatory, industrial sector, customer and/or other specification requirements?*
     - *Were performance standards built around specific existing technologies or mechanisms of action? If so, can new iterations of the standard be adopted that are more function-oriented?*

4. **Develop and use a *range* of performance standard benchmarks, from "inadequate" to "sufficient" to "best in class" to evaluate the alternative for the specific application(s).**
   - Key questions to consider:
     - *Have potential alternatives been eliminated based on binary performance criteria (meets or does not meet a gold standard) that should be reconsidered?*
     - Define a range of fit-for-purpose performance criteria that encompass "inadequate", "sufficient", and "best in class" benchmarks for the application. *How do different alternatives compare within this range?*

5. **Consider technical performance *separately* from technical feasibility (feasibility of adoption) of potential alternatives.**
   - Key questions to consider:
     - *When only performance is considered (and not the feasibility of their adoption), what are the alternative solutions that can be assessed and compared?*
     - *What additional process/product modifications may be needed to increase the feasibility of adoption?*

6. **Consult *stakeholders* to determine acceptable tradeoffs between performance results and other elements such as environmental health and safety.**
   - Key question to consider:

- Hold discussions with an appropriately diverse group of stakeholders on the tradeoffs that would occur for each alternative under consideration. *Which tradeoffs are acceptable under various application-specific scenarios?*
- *What alternatives under consideration best minimize potential trade-offs between performance and environmental and health and safety concerns?*

These considerations are elaborated in the guidance itself, which uses the case study of AFFF in military land-based applications. The case study is built from interviews conducted with firefighting experts as part of project component 3 described below.

3. Understanding lessons learned from existing efforts to accelerate the adoption of safer alternatives to AFFF, including barriers and enabling factors

The objective of this component of SERDP Project #WP19-1424 was to explore lessons learned from existing efforts to accelerate the adoption of PFAS-free alternatives to AFFF (Annex E). Reviews of the literature, including peer-reviewed publications and reports in the grey literature, were used to delve deeper into topics and themes that emerged in the interviews.

Five primary factors were repeatedly identified as barriers to an effective transition to safer and feasible AFFF alternatives including:

1. **Transition costs**: Although the purchase price of PFAS-free alternatives is cost competitive, replacement costs related to equipment/components, decontamination and disposal costs of contaminated components and legacy fluorinated foams may be significant.

2. **Lack of knowledge of performance for specific real-world scenarios:** Proof of concept or demonstration-level performance tests of the PFAS-free alternatives are simply not enough to give assurances to some users that alternatives will work as needed for their firefighting circumstances.

3. **Substitution regret:** Some users are unwilling or unable to transition to PFAS-free alternatives because of the lack of certifications/approvals needed in some sectors. There are also lingering questions about the health and safety of alternatives for both workers and the environment given the limited test data on formulations, that need to be addressed.

4. **Standards:** Performance standards/specifications, especially the US DoD performance specification (MIL-PRF-2435F(SH)) in the US, are hindering adoption of alternatives. In addition, there are an array of standards related to the use of firefighting foams, which has created confusion related to procurement among some entities and has limited continued innovation in fire extinguishment technologies for Class B fires due to costs involved in achieving certifications.

5. **Lack of a coherent national transition strategy:** The lack of a clearly communicated strategy to support the transition to PFAS-free alternatives has left users, especially in the US with more questions than answers about addressing needs related to financial support, technical assistance and training related to both the use of PFAS-free alternatives and decontamination and disposal challenges associated with the legacy fluorinated foams and related equipment.

Four primary enabling factors that are working to accelerate a transition to PFAS-free alternatives were also identified, including:

1. **"Just do it" – using direct experience and mock exercises to understand performance of alternatives and adoption needs:** The counterpoint to only having proof of concept/demonstration performance testing is the utility of users conducting their own large-scale tests. Collaborative testing programs have proven to be effective in demonstrating the capacities of PFAS-free alternatives as well as equipment and firefighting tactics to tune performance.

2. **Financial liabilities with continued use of AFFF:** Insurance liabilities and the potential for future litigation and financial responsibilities associated with use and contamination from PFAS containing firefighting products is a significant driver for change to the alternatives.

3. **Fit-for-purpose performance standards:** Standards designed to reveal varying performance levels that are suitable for a range of firefighting uses have been able to support a quicker transition to PFAS-free alternatives than those designed only for the worst-case/maximum credible event firefighting scenario.

4. **Policy mandates:** Policy requirements to stop using AFFF have been instrumental in the transition to PFAS-free alternatives. Investment in the development of alternatives and broad implementation of substitutes will often be held back unless there are policy (government or private sector) mandates that motivate and accelerate the pace of change.

Going forward, priority needs to accelerate an effective and broad-based transition to safer PFAS-free firefighting foam alternatives include:

- **Issuing a comprehensive and collaborative implementation strategy.** Such a strategy should be a multi-agency/institutional effort given the expertise and engagement needed to address the array of substitution challenges including ensuring a sufficiency of market supply of the alternatives, addressing firefighting performance/technical feasibility needs, providing firefighting education and training, addressing occupational health and safety concerns and ensuring environmental compliance and public health protections related to AFFF decontamination and disposal.

- **Enhancing education and training**. Continued education and training activities need to address "resistance to change" that is still being experienced among some facets of fire and rescue personnel, including a lack of understanding of the problem and a lack of confidence about the solution. Training programs will need to be co-developed along with

the PFAS-free alternatives as changes in firefighting techniques are expected. Programs should also use PFAS-free products that will be deployed in real incidents using the same fuels which will be encountered will increase confidence in the foams ability to extinguish fires.

- **Establishing collaborative performance testing/demonstration sites**. Enhanced collaborative large-scale performance tests are needed where the burden of costs is shared among interested parties/organizational partners who also contribute to designing parameters of the testing protocol. Results of such tests need to be broadly disseminated. Collaboration is also needed to fill gaps in testing to obtain accreditation for specific uses of PFAS-free products (such as in sprinkler systems) where insurers are still not willing to underwrite risk for facilities using these AFFF alternatives.

- **Establishing systems for ongoing monitoring.** Monitoring and evaluation are essential for the early identification of potential unintended consequences of the adoption process. Systems need to include, but are not limited to, environmental surveillance programs to monitor for impacts on a broader array of ecological endpoints, testing to ensure adequate decontamination of PFAS in reused equipment, agree-upon validation testing to ensure that new foams are indeed fluorine-free, industrial hygiene evaluations and discussions with firefighting personnel about the impacts of the transition and to adjust training, equipment and standards of practice as needed. Many of these issues need to be inserted into an substitution implementation strategy outlined above.

Project lessons learned and suggested next steps

As stated above, the ultimate goal of this research project was to strengthen and expand use of alternatives assessment methods to better support government and industry in making informed choices to accelerate the adoption of high performing, safer, and more sustainable chemicals, products, and processes. Applying the tools of alternatives assessment to AFFF helped us to advance methods for the hazard assessment, performance assessment, and implementation steps. It also helped us to explore how alternatives assessment approaches can inform and support policy decisions regarding chemicals of concern.

Key lessons learned from this work that inform needs and next steps include:

1. **There is a need for an updated comprehensive alternatives assessment on AFFF.** As mentioned in (1) above, only one alternatives assessment on AFFF has been conducted and is already considered outdated by many given the rapidly developing innovation landscape. Future alternatives assessments can leverage current and emerging assessments on hazard, performance and cost. These include for example, hazard assessments conducted under the auspices of the GreenScreen Certified™ Standard for Fire Fighting Foam and coordinated performance, ecotoxicity testing and life cycle costing evaluations that are currently ongoing by various SERDP-supported research groups. Such an alternatives assessment can fill gaps in the alternatives assessment conducted to support regulatory actions in the European Union and utilize criteria and guidance documents developed under this project, including criteria for defining a safer AFFF

alternatives and fit-for-performance criteria. Such an assessment could be a test case for the National Research Council Framework (which has never been fully applied) and an important foundational assessment for the establishment of a public-private Center of Excellence (CoE) on Alternatives Assessment. Exploratory conversations during this project revealed the need for a trusted institution to conduct high-quality, model alternatives assessments for critical substances and applications of national significance that supports substitution and product design decisions for industry, governments, and other stakeholders.

2. **Conformance with criteria developed under this project to determine a safer AFFF alternative requires additional product-level testing for specific hazard endpoints**. Based on feedback from our Project Support Committee, criteria for aquatic toxicity require testing at the product-level, rather than assessing the hazard profile at the ingredient-level, which is more typical of hazard assessment methods. Members of our Project Support Committee recommended such a practice because these basic tests need to account for issues such as the concentration used and the mixture of ingredients represented in the product, which may have different effects than single ingredients alone. It is also commonly understood that for hydrocarbon-based surfactants, most demonstrate high aquatic toxicity if the concentration used is not considered in the assessment. Ecotoxicity tests on 7 AFFF alternatives at the product-level are being conducted in ongoing studies by researchers at Purdue University (Hoverman and colleagues), although considering full-concentration of the product, not concentration used. However, based on recent conversations with researchers at the National Institute for Environmental Health Sciences, tests may be possible at the product-level using various New Approach Methodologies (NAMs).

3. **There was resonance in the use of a "fit-for-purpose" performance assessment process for AFFF among stakeholders engaged throughout this project – including representatives of performance standard organizations.** Stakeholders noted the importance of considering comparable performance versus equivalent performance when it comes to identifying feasible substitutes for AFFF. The "fit-for-purpose" guidance was developed for alternatives assessments in general, not specific to the AFFF context. It recommends considering a range of acceptable tolerances, rather than using criteria that are written for the worst-case scenario – as in the case of the MIL-PRF-24385F. Although use of multiple standards could be used to implement a fit-for-purpose performance assessment approach, such as is used for International Civil Aviation Organization's Level A-C for firefighting foam, stakeholders gathered from standard setting organizations also expressed limitations. Narrower, more specific standards improve interoperability across users, which protects against misinterpreting using a lower performing product on a higher hazard scenario. Tighter standardization also supports regulatory/inspectional services enforcement actions.

4. **In the U.S., the Milspec (MIL-PRF-24385F) is still holding back adoption of alternatives to AFFF, but Congressional deadlines in place for US DoD's efforts to assess alternatives and support research and development of green chemistry alternatives has accelerated the pace of substitution in comparison to other lingering substitution challenges, such as halogenated solvents or halogenated flame retardants.** Although rapid innovation is being driven in part because of the Congressional AFFF substitution

deadline, a narrow range of options are being considered given the short timelines, which require alternatives that can be dropped into existing equipment with minimal modification. However, the SERDP/ESTCP funding program has demonstrated how pre-competitive and collaborative research programs can accelerate the innovation and substitution process by allowing researchers, including those conducting performance evaluations, scientists, innovators, and established companies to share and receive knowledge that advance solutions. This will create opportunities for even safer and effective AFFF replacements to succeed in the future.

5. **Additional collaborative and comparative performance testing programs such as those completed at China Lake are needed for the array of users that have lingering questions about the performance of alternatives in specific scenarios.** Filling gaps in the understanding of performance for specific use scenarios can advance through the expansion of collaborative performance testing programs where costs are shared and distributed among interested users who also are involved in designing the test parameters. This will support broader trust and understanding of the performance capabilities of alternatives under conditions of use that better align with users' needs. Collaboration is also needed to fill gaps in (and reduce costs of) testing to obtain accreditation for specific uses of PFAS-free products (such as in sprinkler systems) where insurers are still not willing to underwrite risk for facilities using these alternatives.

During December 2021 Project Support Committee call, we discussed the topic of a dissemination strategy for our project results in order to enhance the impact of this work. Some dissemination has already happened, such as a poster presented during the International Symposium on Alternatives Assessment (October 29, 2021) on our work related to Objective 1 noted above. We intend to better design all four reports and post on our university's website for easier access and distribute through social media channels. We hope that these will also be posted on the SERDP/ESTCP website. We are envisioning a journal article that synthesizes worked across all 3 objectives to be written in early 2022 and submitted by spring. We will also share project findings through appropriate professional lists, webinars to audiences, such as the European Defense Industry, the Aircraft Fire and Rescue Working Group, the Interstate Chemicals Clearinghouse, at conferences as well as short articles written for trade journals, such as Industrial Fire World.

We are committed to disseminating work from this project and working with US DoD and the SERDP research community to strengthen and expand use of alternatives assessment methods to better support government and industry to accelerate the evaluation and adoption of safer and effective PFAS-free alternatives to AFFF. We believe these approaches can be helpful in addressing other chemical challenges that DoD faces.

List of Annexes

[note: the original pagination of reports used]

- **Annex A.** Project Support Committee
- **Annex B.** Report - *A Critical Review of Alternatives Assessments of Fluorine-Free Alternatives to Poly- and Perfluoroalkyl Substances in Aqueous Film-Forming Foams*
- **Annex C.** Report – *Criteria for Safer: Alternatives to Aqueous Film Forming Foam Products*
- **Annex D:** Report – *Guidance for Evaluating the Performance of Alternatives: Fit-for-Purpose Performance (Version 1.0)*
- **Annex E:** Report – *Scaling Adoption of Alternatives to Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous Film-Forming Foams (AFFF): Lessons Learned on Needs and Opportunities*

Annex A. Project Support Committee

Committee Person	Organization
Jerry Back	Jensen Hughes
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Holly Davies	Washington Department of Health
John Farley	Naval Research Laboratory
Shari Franjevic	Clean Production Action/ GreenScreen
Liz Harriman	Massachusetts Toxics Use Reduction Institute
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Randy Krause	SEATAC Airport
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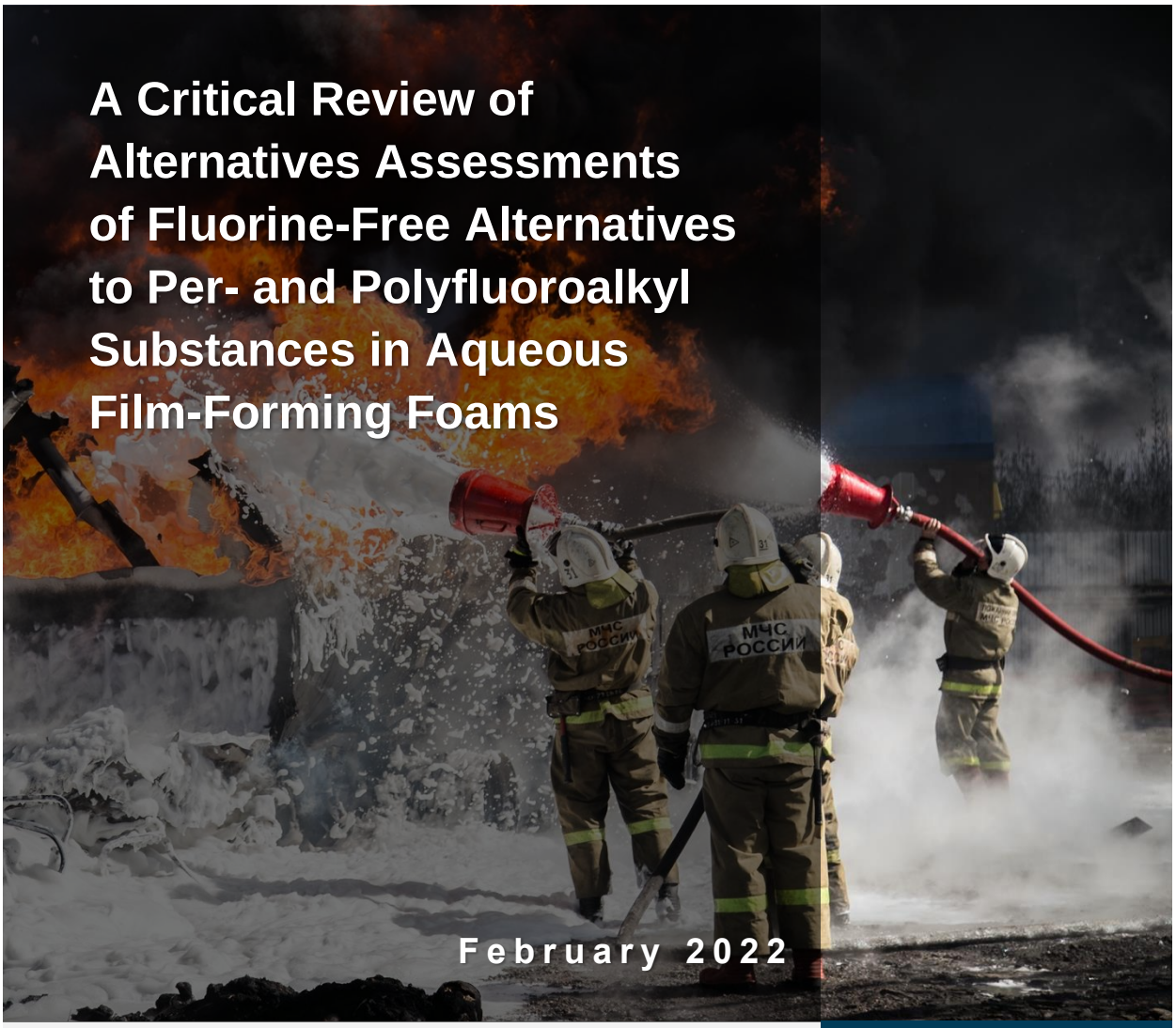
John Payne	National Foam
Niall Ramsden	LastFIRE
Ian Ross	Arcadis

Annex B. Report - *A Critical Review of Alternatives Assessments of Fluorine-Free Alternatives to Poly- and Perfluoroalkyl Substances in Aqueous Film-Forming Foams*

University of Massachusetts Lowell

A Critical Review of Alternatives Assessments of Fluorine-Free Alternatives to Per- and Polyfluoroalkyl Substances in Aqueous Film-Forming Foams



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ABOUT

The Sustainable Chemistry Catalyst is an independent research and strategy initiative, based at the Lowell Center for Sustainable Production (University of Massachusetts Lowell), that is focused on accelerating the transition to safer, more sustainable chemistry through research and analysis, and stakeholder engagement with scientists, policymakers, and commercial actors.

The Catalyst works to understand barriers and opportunities to commercialization of safe and sustainable chemistry, identifies model solutions and strategies, develops methods to evaluate safer alternatives, and builds a community of expertise to support the transition to safer, more sustainable chemistries and technologies.

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ACRONYMS USED

AFFF	Aqueous Film Forming Form
CMR	Carcinogen, Mutagen, Reproductive Toxicant
DoD	US Department of Defense
ECHA	European Chemicals Agency
ESTCP	Environmental Security Technology Certification Program
EPA	US Environmental Protection Agency
EU	European Union
F3	Fluorine-Free Foam
FY	Fiscal Year
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
IC2	Interstate Chemicals Clearinghouse
ICAO	International Civil Aviation Organization
NGOs	Non-governmental Organizations
NRC	US National Research Council
REACH	Registration, Evaluation and Authorization of Chemicals
PBT	Persistent, Bioaccumulative and Toxic
PFAS	Per- and Polyfluoroalkyl Substances
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulfonate
SDS	Safety Data Sheet
SERDP	Strategic Environmental Research and Development Program
SVHC	Substance of Very High Concern
UL	Underwriters Laboratory
US	United States
vPvB	very Persistent and very Bioaccumulative

SUMMARY

The objective of this study was to support the informed substitution of per- and polyfluoroalkyl substances (PFAS) in aqueous film forming forms (AFFF) by understanding the strengths and weaknesses of alternatives assessments conducted to date. Evaluations of alternatives were required to meet four criteria to be considered an alternatives assessment and included in this review: (1) evaluates commercially available alternatives; (2) evaluates hazard, cost and performance attributes (exposure and life cycle attributes optional); (3) uses standardized assessment criteria to systematically evaluate and compare alternatives to the incumbent and (4) includes fluorine-free alternatives and the incumbent product (AFFF)/chemical of concern. Existing alternatives assessments were reviewed against two seminal alternatives assessment frameworks: (1) the US National Research Council's (NRC)*, A Framework to Guide Selection of Chemical Alternatives* (2014) and (2) the Interstate Chemicals Clearinghouse's (IC2) *Alternatives Assessment Guide Version 1.1* (2017)**.**

Only one alternatives assessment met all four inclusion criteria and was included in this critical review: Wood, Ramboll and Cowi. *The Use of PFAS and Fluorine-Free Alternatives in Fire-Fighting Foams* (2018). This alternatives assessment was undertaken to support regulatory risk management options by the European Chemicals Agency (ECHA). The ECHA study (as referred to in this report) identified a priority list of seven fluorine-free foam (F3) alternatives from an initial screening of 168 identified. Although data in the ECHA study was limited to information that 3rd party researchers were able to collect – which was highly dependent on the voluntary compliance by industry parties – the assessment was aligned with the general approaches for alternatives assessment outlined by the NRC and IC2 frameworks. Future alternatives assessment can learn from and improve upon the ECHA study in the following ways:

- **Consider incorporating case studies into alternatives assessment practice.** One of the contributions of the ECHA study to the field of alternatives assessment was the use of case studies to exemplify attributes of the technical and economic feasibility assessments. The case studies added greater understanding of specific assessment criteria.

- **Consider broadening the assessment scope (during the problem formulation step) and not limit the functional use for AFFF alternatives to just film forming foams.** Only film forming foams were considered in the ECHA study. This may preclude different alternative processes or technologies that have the capacity to extinguish fires in a number of different scenarios but do so by mechanisms other than the use of chemical surfactants/wetting agents to smother the flames.

- **Examine a broader set of hazard endpoints using measured and modeled data sources rather than depending solely on Safety Data Sheets (SDS).** Using reviews of primary research studies will go further in terms of understanding specific hazard traits beyond those noted on an SDS.

- **Consider reasonable and foreseeable exposure scenarios and relevant physicochemical properties that would inform the exposure potential of alternatives.** This is especially important if alternatives have different forms, use patterns or physicochemical properties than the AFFF.

- **Support deeper engagement by stakeholders**. Stakeholder engagement is important to address issues including use parameters, the inclusion of additional hazard traits of primary concern, and which specific life cycle considerations should be addressed in assessments.

- **Augment the alternatives assessment in the near future and on an ongoing basis as needed to stay current.** The ECHA study is already considered outdated by some given this quickly evolving innovation landscape. Additional alternatives assessment that are more comprehensive in nature and that consider the emergence of newer commercially available alternatives will be needed the near future. Future alternatives assessments can leverage current and emerging assessments on hazard, performance, cost as well as broader life cycle impacts.

OVERVIEW

Background on AFFF

Aqueous film forming foam (AFFF) is a highly efficient fire suppressant agent used for Class B fires – flammable and combustible liquids and gases; petroleum greases, tars, oils and gasoline; and solvents and alcohols. Beginning in the 1970s, the US Department of Defense (DoD) began using AFFF that was based on perfluorooctane sulfonate (PFOS) and in some formulations, perfluorooctanoic acid (PFOA) (US DoD 2018). The US Federal Aviation Administration also adopted use of AFFF in airports nationally (US DoD 2018).

By the early 2000s, toxicological evidence from both industry and academic studies demonstrated impacts posed by PFOA, including immunotoxicity, liver effects and cancer (Grandjean and Clapp 2015; Grandjean 2018). Two decades later, a significant body of scientific evidence now links both PFOS and PFOA to increased cholesterol levels, changes in liver enzymes, decreased birth weight, decreased vaccine response in children, and increased risk of kidney and testicular cancer among other health impacts (Lopez-Espinosa et al. 2012; Vieira et al. 2013; Stein et al. 2009; Frisbee et al. 2010; ATSDR 2021). In addition, PFOS and PFOA are also extremely persistent, mobile and bioaccumulative (ATSDR 2021; Lindstrom et al 2011).

Through the early 2000s, PFOS was used in the manufacturing of AFFF (ASTSWMO 2015). Based on industry agreements with the US Environmental Protection Agency (EPA) under its PFOA Stewardship Program, all manufacturers of PFOA and PFOS in the US agreed to a complete phase out by 2015 (US EPA 2017). However, stockpiles of AFFF containing these compounds still remain (US DoD 2018; ASTSWMO 2015). The DoD began issuing guidelines and policies to control the release of AFFF into the environment in 2011 (US DoD 2018; US DoD 2011). By 2016, evidence of widespread drinking water contamination surrounding industrial facilities, military bases, airports, and firefighting training areas emerged (Hu et al. 2016). AFFF was reformulated in the early 2000s with other shorter-chain per and polyfluoroalkyl substances (PFAS), such as 6:2 fluoro-telomer alcohols and sulfonate derivatives (US DoD 2018; ASTSWMO 2015; Peshoria et al. 2020). Although a full understanding of the toxicity of shorter chain per- and polyfluoroalkyl substances (PFAS) is still emerging, there are suggestions for concern especially for breakdown products, such as perfluorohexanoic acid (PFHxS) and perfluorohexanesulfonate (PFHxA) (Rice et al. 2020; Danish EPA 2015). Moreover, persistence and mobility are still of critical concern for these shorter chain PFAS (ATSDR 2021).

The Fiscal Year (FY) 2020 National Defense Authorization Act (NDAA) requires DoD to phase out use of PFAS-containing AFFF at military installations by October 1, 2024 (NDAA 2019). Due to growing concerns about PFAS in firefighting foam, over the last few years there has been tremendous investment in the development of fluorine-free foam (F3) alternatives to AFFF. This research is being supported by requirements in the FY 2021 (NDAA) for DoD to prioritize research on AFFF alternatives that utilize "green and sustainable chemicals that do not pose a threat to public health or the environment" (NDAA 2021). Dozens of F3 alternatives are now commercially available and even more are under development (Back 2020). Yet are these alternatives safer and feasible? Is there the potential for regrettable substitutions? Alternatives assessment seeks to answer these exact questions.

Background on Alternatives Assessment

Alternatives assessment supports the evaluation and adoption of safer alternatives and minimizes regrettable substitutes by ensuring that hazards and potential trade-offs – including human health, ecological health, and sustainability attributes – are considered alongside issues of performance and cost. The goal of alternatives assessment is informed substitution – the considered transition from higher concern to lower concern chemicals using the best available information. As defined by the US National Research Council (US NRC), alternatives assessment is a process for identifying, comparing, and selecting safer alternatives to chemicals of concern based on their hazards, comparative exposure, performance, and economic viability (NRC 2014). Alternatives assessment focuses on identifying a range of potential alternatives that can provide the function needed for a given application (e.g., fire extinguishment) that is

currently being served by the chemical of concern (e.g., PFAS). A safer and feasible alternative that can achieve the desired function may be a chemical substitute, a change in materials and processes, or a design change that eliminates the need for a chemical altogether. The alternatives assessment approach emerged in the US in the late 1990s as a comparative process to evaluate substitutes to toxic chemicals used in specific industry sectors (US EPA 1996). Since then, alternatives assessment has evolved as a critical approach to support informed substitution and is embedded in business practice among leading firms and in laws in Europe and in several US states to drive a transition away from toxic chemicals of concern and towards safer alternatives (Jacobs et al. 2015; Tickner et al. 2019b). The six general steps involved in an alternatives assessment are shown in **Table 1**.

TABLE 1: Alternatives Assessment – A Snapshot of its components as outlined in the National Research Council (2014) and Interstate Chemicals Clearinghouse (2017) Frameworks (Tickner et al. 2019a; Tickner et al. 2019b)

Component	What it involves
1. Scoping, problem formulation, identifying alternatives for consideration	Establishes the scope of and plan for the assessment. Identifies stakeholders to engage and decision rules that will guide the assessment. Gathers data on the chemical of concern, its function and application. Identifies performance and cost needs for alternatives. Determines the assessment methodology and identifies alternatives to be considered.
2. Hazard/comparative exposure assessment	Evaluates human health and ecological hazards and assesses comparative exposures.
3. Technical feasibility assessment	Assesses the performance of alternatives against the needs established during the problem formulation step above.
4. Economic feasibility assessment	Assesses the economic feasibility of alternatives.
5. Other life cycle considerations	Addresses additional potential up-stream or downstream ecological and human health hazards as well as other potential trade-offs such as energy, climate change impacts, and natural resources.
6. Decision making	Combines information from previous steps to evaluate trade-offs and preferences to identify acceptable alternatives. Addresses situations where no alternatives are currently viable by initiating R&D to develop new alternatives or improve existing ones and establishes an implementation and adoption plan to identify potential trade-offs during adoption.

STUDY OBJECTIVES AND METHODS

The objective of this study was to support the informed substitution of PFAS in AFFF by understanding the strengths and weaknesses of alternatives assessments conducted to date. A key question investigated was whether any assessment conducted to date approximates a complete alternatives assessment as defined below**.** Only fluorine-free alternatives were addressed given the need for DoD to phase out all PFAS-containing firefighting foam by 2024.

The research team used literature reviews and outreach with experts in the field to identify and evaluate governmental and non-governmental assessments that have been conducted on AFFF alternatives. Although studies and evaluations that focus on individual components of an alternatives assessment were collected (i.e., those conducting just for a performance assessment or just a hazard assessment), only those that met criteria for being considered an alternatives assessment were included in this evaluation.

Evaluations of alternatives were required to meet the following criteria to be considered an alternatives assessment and included in this review:

1. Evaluates commercially available alternatives
2. Evaluates hazard, cost, and performance attributes (exposure and life cycle attributes optional)
3. Uses standardized assessment criteria for attributes noted in #2 to systematically evaluate and compare alternatives to the incumbent
4. Includes fluorine-free alternatives and the incumbent product (AFFF)/chemical of concern

It is important to note that later-stage innovations (i.e., those currently at the pilot phase) that are not yet commercially available can be included in alternatives assessments. This is often important, especially if newer innovations are demonstrating preferable characteristics on critical assessment attributes, including performance and hazard criteria. Alternatives assessment methods can also be adapted for use during the design phase of new chemical products and technologies such that hazard, performance and cost metrics are used as design criteria, not just informed substitution criteria (Tickner et al. 2021). However, this project limited the scope of its review to commercially available alternatives to assist with current decision-making needs regarding the viability of existing fluorine-free alternatives.

Existing assessments were compared to two widely accepted alternative assessment frameworks that were developed to support informed substitution activities: the National Research Council's (NRC) framework and the Interstate Chemicals Clearinghouse's (IC2) framework, the latter of which was developed in collaboration with several US state agencies (NRC 2014; IC2 2017). This critical review focused on the methods used in the alternatives assessment, endpoints addressed, and how issues of uncertainty and data gaps were addressed.

PRIMARY FINDINGS

Alternatives Assessments Included for Review

There was only one alternatives assessment that met all four inclusion criteria:

- Wood, Ramboll and Cowi. 2018. *The Use of PFAS and Fluorine-Free Alternatives in Fire-Fighting Foams*. Report for European Commission and the European Chemicals Agency. June.

This report outlines the findings from a European Chemicals Agency (ECHA) commissioned study (referred to as the ECHA study in this report) on the assessment of alternatives to PFAS-containing firefighting foams and the potential socio-economic impacts of substitution. The aim of the ECHA study was to collect information to support risk management options that address the human and environmental risks associated with using PFAS in firefighting foams, including information necessary for the consideration of alternatives in a restriction proposal/dossier under the European Commission's Registration, Evaluation, and Authorization of Chemicals (REACH) regulation – the main chemicals management legislation in Europe.

Alternatives Assessments Not Included in the Review

Other comprehensive assessments of alternatives to AFFF were identified. However, these reports did not meet the review inclusion criteria, including:

- IPEN 2018/POPRC-14. 2018. White paper, Fluorine-free firefighting foams (3F) – Viable alternatives to fluorinated aqueous film-forming foams (AFFF). September.
- New York State Pollution Prevention Institute, Rochester Institute of Technology. 2019. Per-and Polyfluorinated Substances in Firefighting Foam. Developed for the Interstate Chemicals Clearinghouse. April.

The IPEN report did not meet inclusion criteria 3. The report compares commercially available F3 alternatives (criteria 1 and 4) to AFFF, addresses attributes of hazard, performance, and cost (criteria 2), but is structured as a position paper, not a systematic assessment (criteria 3). The report does not include the use of explicit criteria for systematically assessing and comparing the list of alternatives to AFFF. Rather than tabulating evaluation criteria for hazard, performance, and cost attributes across all the F3 alternatives examined, the report uses specific criteria related to hazard, cost, and performance for the named alternative products to support a given argument.

The New York State Pollution Prevention Institute describes their report as precursory work to assist with scoping an alternatives assessment of PFAS-containing AFFF. The report does not address inclusion criteria 2 or 3. It identifies critical information to assist with defining the parameters of a future alternatives assessment but does not use standardized criteria to directly evaluate the hazard, cost, and performance of alternatives in comparison to AFFF.

Several additional assessments of alternatives identified to date focus on single components of an alternatives assessment. Because an alternatives assessment is based on a comparison of multiple attributes, namely hazard, cost and performance, these assessments were also excluded, but can be utilized going forward in future comprehensive alternatives assessments. Notable examples include:

- **Hazard Assessments**
  - Though its GreenScreen Certified™ Standard for Fire Fighting Foam, Clean Production Action has examined the hazard profiles for over a dozen F3 alternatives. All alternatives are commercially available, and the products evaluated are identified on the GreenScreen® Website (Clean Production Acton 2021).
  - The Petroleum Environmental Research Foundation has sponsored research into the hazards of 2 short-chain PFAS and 4 F3 alternatives for oil and gas operations. (Hutching 2021).

- **Performance Assessments**
  - The Naval Research Lab shared approval-scale performance testing (e.g., 28 ft^2 fire pan) documentation under ESTCP Project # WP20-5373 (Farley 2021). Twenty-two commercially available products were tested. Four alternatives were considered "top performers".
  - Jensen Hughes tested 20 commercially available F3 alternatives (Back 2021). Testing included similar approval-scale tests as those conducted by Farley (2021), as well as real-scale tests (400 ft^2 pan). The five top performers, "demonstrated good capabilities".
  - The Fire Protection Research Foundation sponsored performance testing research on five F3 alternatives to inform the general performance capabilities of the "class" of F3 foams to guide standard setting activities (Back and Farley 2020).

Strengths and Limitations in the ECHA Commissioned Alternatives Assessment

Components of the ECHA study are reviewed below against the NRC and IC2 framework based on key assessment components outlined in **Table 1**.

1. Scoping, Problem Formulation, Identifying Alternatives for Consideration

The NRC and IC2 Approach

The NRC framework identifies several key elements in establishing the scope of the alternatives assessment. These elements include:

- Information and parameters needed for the assessment, including goals, principles, and decisions rules for the assessment
- Stakeholder engagement plan
- Information on the chemical of concern, including the function or "service" that the chemical of concern provides in products and processes

- Methods and tools for each assessment step
- Procedures on how data gaps and uncertainty will be handled

The IC2 framework is not as detailed regarding the scoping step of an alternatives assessment but does include an explicit focus on stakeholder engagement. Stakeholder engagement can refine the assessment plan, support data collection efforts, and optimize outcomes including greater buy-in regarding the results of the assessment and less opposition to change.

Strengths and Limitations of the ECHA Alternatives Assessment

ECHA itself outlined the goals and primary scope of the study in the terms of reference used to contract with consultants. The focus was to identify alternative products that could fulfill the required function delivered by PFAS in AFFF. This is a traditional, but narrow, scope regarding functional use. It focuses on substitution options that would provide the function of the chemical – surfactant/vapor suppression/film formation of PFAS in the foams. Yet a broader focus on function could have focused on the product function of flame extinguishment, supporting the consideration of other non-chemical/process alternatives. The characterization of function is a key element in the scoping/problem formulation step of the NRC framework is considered critical for the successful identification, prioritization, and adoption of feasible alternatives (NRC 2014). Both the IC2 and NRC frameworks also start the scoping/problem formulation step of an alternatives assessment by first asking whether the chemical of concern serves a necessary function; if the function is not necessary, then elimination rather than substitution may be an option.

Other than narrow definition of functional use, The ECHA study is a strong example of the scoping/problem formulation stage of an alternatives assessment under the NRC and IC2 frameworks. The scope was specific to an analysis of technical feasibility, economic feasibility, availability of alternatives and the environmental and human health risks of alternatives. Priority evaluation criteria to address in each component were outlined in the terms of reference and were used to guide information gathering by stakeholders. Hazard criteria and associated decision rules were mentioned in the summary results of the assessment and correspond with criteria as defined by law under REACH (Article 57) which outline hazard endpoints that establish the REACH list of Substance of Very High Concern (SVHC). Substitutes cannot be carcinogenic, mutagenic, toxic for reproduction; persistent, bioaccumulative and toxic (PBT) substances; very persistent and very bioaccumulative substances (vPvB) or demonstrate probable serious effects to human health or the environment of an equivalent level of concern, such as endocrine disruption.

ECHA consultants first identified F3 alternatives available on the market using literature reviews and market analyses. A total of 168 alternatives were identified. ECHA consultants used a questionnaire to both engage stakeholders in helping to define the scope of the assessment as well as to collect information on alternatives for consideration that supplemented what could be found on Safety Data Sheets (SDSs) and product specification documentation. Stakeholders included industry representatives (firefighting foam users and manufacturers), industry associations, government authorities, non-governmental organizations (NGOs) and researchers in academia and consultancies. A stakeholder workshop was also convened to discuss information collected. Through this stakeholder engagement, alternatives that were available and in use in the EU were identified. Potential alternatives (namely siloxane-based alternatives) were excluded from consideration because of health and safety concerns. Experience with alternative product use and information on technical and economic feasibility of the alternatives was also collected.

2. Hazard/Comparative Exposure Assessment

The NRC and IC2 Approach

Hazard Assessment

Both the NRC and IC2 frameworks recommend the use of authoritative lists, which rely on government bodies and expert groups that have performed comprehensive hazard assessments of chemicals and have published lists of chemicals of concern for various hazard traits, as a starting point. Authoritative lists are

useful tools to screen out alternatives because they are likely to be regrettable substitutes. More rigorous and comprehensive assessments within both frameworks utilize the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) criteria. GHS provides internationally standardized criteria for classifying chemicals, according to their health, physical, and environmental hazards. Reviewing measured and modeled data and applying GHS criteria for a given endpoint allows assessors to review available hazard data and categorize an alternative as Low, Moderate, or High concern for a specific hazard (or some similar ranking scheme). Such criteria and categorization schemes are used by GreenScreen®, which is a chemical hazard assessment method outlined specifically in the IC2 framework. GreenScreen® includes methods for characterizing data gaps, an issue which is specifically addressed in both the NRC and IC2 frameworks. Both note the need to be explicit about data gaps for specific hazard endpoints and where expertise and resources allow, to use other sources of data, such as *in vitro* and *in silico* models to address gaps.

Comparative Exposure Assessment

In both the NRC and IC2 frameworks, the purpose of a comparative exposure assessment is to determine differences in the intrinsic potential for exposure between the potential alternatives and incumbent chemical or product that is being replaced. Characterizing exposure in alternatives assessment is not used to calculate risk, but rather to understand whether differences in physicochemical properties or use characteristics across the life cycle can increase or decrease specific hazards prior to the use of external exposure controls (such as personal protective equipment) (NRC 2014). The primary method used in both frameworks are considerations of exposure scenarios, assessment of physicochemical properties, and, where needed, use of exposure models. Specific physicochemical properties that can inform intrinsic exposure potential are outlined in **Table 2**. For example, vapor pressure can inform the potential for exposure during the manufacturing or during the use phase and solubility can inform the potential for exposure in the aquatic environment.

TABLE 2: Examples of comparative exposure criteria/physicochemical properties in the NRC (2014) and IC2 (2017) frameworks

Type	Property	Rationale for inclusion
Physical Properties	Flammability	Associated with flammability hazard
	Corrosivity	Associated with the ability to gradually destroy materials by chemical reactions
	Oxidizing ability	Associated with ability to give off oxidizing substances or oxidize combustible materials, increasing fire or explosion hazards
	Melting and boiling point	Impacts environmental fate and transport, as well as potential bioavailability
	Vapor pressure	Impacts environmental fate and transport, as well as potential bioavailability
Solvation Properties	Acidity (pKa)	Determines ionization state; ionization state in turn impacts other properties, such as water solubility and partition coefficients, which directly impact toxicokinetics
	Aqueous solubility	Reflects ability to partition into aquatic environment and mobility within water
	Octanol-water coefficient (log*P or Kow*)	Important determinant of human/mammalian oral and skin bioavailability; relevance to acute & chronic aquatic toxicity and directly related to bioconcentration
	Henry's law constant (log $P_{w/g}$)	Relevance to environmental partitioning and transport as well as human/mammalian alveolar absorption
Environmental Fate	Biodegradation	Indicator of persistence
	Bioconcentration factor (BCF)	Bioconcentration enhances the hazard potential of lipophilic chemicals; BCFs provide a comparative basis for assessing the potential for a chemical to have effects that resonate through the food chain

Table 3 outlines recommended hazard criteria for consideration in an alternatives assessment in the NRC and IC2 frameworks. Both frameworks are informed by the early hazard assessment methodology established by the US EPA's Design for Environment Program (now the Safer Choice Program) and refined by other approaches, such as the GreenScreen®. IC2 differs from the NRC in that it establishes increasing

levels of assessment comprehensiveness depending on the nature and purpose of the alternatives assessment; it was developed such that small and medium-sized enterprises could undertake an assessment with limited technical expertise. The NRC framework separates out the assessment of ecological and human health endpoints. For this review, we have consolidated both into the component of hazard assessment in general.

Strengths and Limitations of the ECHA Alternatives Assessment

As described above, the ECHA study addressed hazard endpoints that constitute the definition of an SVHC. Examples of endpoints not addressed directly in the assessment as compared to those recommended by the NRC/IC2 frameworks (**Table 3**) include endocrine activity/endocrine disruption, neurotoxicity, specific organ toxicity, respiratory sensitization, dermal sensitization as well as safety hazard endpoints, such as corrosivity (which may be addressed in a performance assessment – if a product is corrosive to metals, it likely will be corrosive to human tissues/organs as well).

TABLE 3: Hazard assessment endpoints in the NRC (2014) and IC2 (2017) frameworks

Hazard Endpoint	NRC Framework	IC2 Framework Level of Assessment	ECHA Study
HUMAN HEALTH			
Carcinogenicity	X	All Levels	X
Mutagenicity and Genotoxicity	X	All levels	X
Reproductive Toxicity	X	All levels	X
Developmental Toxicity	X	All levels	X
Endocrine Activity	X	All levels	
Acute Mammalian Toxicity	X	All levels	
Repeated Dose/Specific Organ Toxicity	X	Levels 2 and 3 (more comprehensive)	
Neurotoxicity	X	Levels 2 and 3 (more comprehensive)	
Skin sensitization	X	Levels 2 and 3 (more comprehensive)	
Respiratory sensitization	X	Levels 2 and 3 (more comprehensive)	
ECOLOGICAL HEALTH			
Acute Aquatic Toxicity	X	All levels	X
Chronic Aquatic Toxicity	X	Levels 2 and 3 (more comprehensive)	X
Other Ecotoxicity	X	Levels 3 (most comprehensive)	
Eutrophication		Levels 3 (most comprehensive)	
PHYSICAL HAZARDS			
Corrosivity	X	Addressed as corrosivity related to human health impacts (e.g., skin/eye damage)	
Flammability	X	All levels	
Reactivity	X	All levels	
Explosivity	X	Not addressed	
Oxidizing Properties	X	Not addressed	
Pyrophoric Properties	X	Not addressed	
ENVIRONMENTAL FATE			
Persistence	X*	All levels	X
Bioaccumulation	X*	All levels	X

**Note the NRC framework considers these endpoints in the comparative exposure assessment step.*

From the initial 168 products that were identified, the ECHA study narrowed the initial stakeholder input on 30 alternatives and then narrowed again on a prioritized short-list of 7 alternatives based on those that have been most widely used in the European market. These short-listed alternatives and a comparison of their hazard attributes identified are displayed in **Table 4**.

The main hazard assessment method used in the ECHA study was an examination of specific GHS hazard codes/statements noted on the product SDS. However, neither the NRC nor the IC2 framework recommends

the use of SDSs as the primary approach from which to derive information about hazards in an alternatives assessment. SDSs, despite being an important hazard communication tool, have several weaknesses, particularly if being used as the only source of hazard assessment data and information. SDSs do not always include the most recent evidence regarding hazard information, such as newer studies as published in the scientific peer-reviewed literature. Except for harmonized GHS hazard statements, the information provided in SDSs is at the discretion of the chemical/product supplier and may result in conflicting hazard classifications. In addition, the hazard data associated with proprietary ingredients and active/inactive ingredients that do not meet threshold quantity requirements do not have to be disclosed, which limits the completeness of the assessment. Limitations regarding the use of SDSs were acknowledged in the ECHA study.

TABLE 4: ECHA study – Hazard/comparative exposure results

	Angus Fire Respondol ATF 3-6%	**Solberg** Re-Healing Foam RF3x6 ATC	**Solberg** Re-Healing RF1 1%	**Dr. Sthamer** Mousool FF 3x6 F-15	**Dr. Sthamer** FOAMOUSSE 3% F-15	**BIOex SAS** Ecopol Premium	**Orchidex** BlueFoam 3x3
HAZARDS							
CMR Properties	No	No	No	No	No	No	No
Other Human Health Concerns	Skin and serious eye irritation (H315, H319)	Serious eye irritation H319	Skin irritation and eye damage (H315, H318)	Serious eye irritation H319; damage to kidneys if swallowed (H373)	Skin and serious eye irritation (H315, H319)	Serious eye damage (H318)	Serious eye irritation H319
Other Environmental Concerns	Very toxic to aquatic life (H400)/Very toxic to aquatic life with long lasting effects (H410)*	None	Very toxic to aquatic life (H400)	Very toxic to aquatic life (H400)	None	None	Harmful to aquatic life with long-lasting effects (H412)
EXPOSURE POTENTIAL							
PBT/vPvB	No	Insufficient data in SDS	Insufficient data in SDS	No	No	No	Not tested

**ECHA study authors note this product has undergone additional aquatic toxicity testing at the product level (rather than ingredient level) demonstrating no significant aquatic toxicity concerns (LC50 and/or EC50 values >10mg/l for fish, aquatic invertebrates, and algae).*

None of the alternatives had GHS classifications for CMR properties. The main hazards noted among all the alternatives included skin/eye irritation or damage and some alternatives include ingredients that demonstrate acute or chronic aquatic toxicity impacts. In the case of Angus Fire's Respondol ATF 3-6%, ingredient-level assessment through the SDS revealed aquatic toxicity hazards. However, the product received a bronze-level certification under the GreenScreen Certified™ Standard for Firefighting Foam, which requires additional product-level aquatic toxicity testing. The product-level testing demonstrated no significant aquatic toxicity concerns. Several of the products also had incomplete or insufficient data in the SDS related to persistence and/or bioaccumulation.

3. Technical Feasibility Assessment

The NRC and IC2 Approach

The NRC's primary approach to performance assessment in an alternatives assessment is outlined in the scoping section of the framework. There is only a short section on performance considerations in a section

on lifecycle, performance, and cost considerations. Primary performance assessment elements in the NRC, IC2 and ECHA study approaches are outlined in **Table 5**.

TABLE 5: Performance assessment elements in the NRC and IC2 frameworks and comparison with the ECHA study

	NRC Elements	IC2 Elements	ECHA Study
Performance Requirements	Define the specific functional requirements at the chemical, material, product level: the more completely the function can be defined, the easier it will be to set criteria to determine whether a potential alternative is viable.	Identify performance requirements at the chemical, material, product, and process levels, specific to the application of use. This is done by reviewing readily available qualitative and quantitative information, querying technical experts.	Compare performance function provided by PFAS foams and their alternatives.
	Identify relevant structures and physicochemical properties that determine the chemical of concern's function.		
	Define performance acceptability criteria and testing criteria using consensus standards where available.	Use test data indicating the likelihood of the alternative satisfying performance criteria for application as reviewed by technical experts. *[more comprehensive assessment]* Conduct performance tests based on specific standards to indicate likelihood of satisfying the performance criteria within accepted tolerances. *[more comprehensive assessment]*	Understand performance efficacy to fight various types of fires, including liquid fuel fires (Class B) – compliance with specific international performance standards.
	Identify regulatory, customer, specification, and certification needs and requirements, including use conditions and constraints.	Understand the reliability of the product/process, quality and useful life of the product, acceptance by consumers, efficiency of production process, maintenance requirements including workforce training.	Understand the need for changes in equipment.
		If the alternative under performs, understand whether the process or product be modified to accommodate the alternative and improve its performance. Is the difference in performance critical to the product?	Understand critical uses where alternatives do not meet (fully or partially) the required performance standard and how.
Market Availability		Identify whether the alternative has already been identified as favorable with respect to performance.	Identify examples of use experience.
		Identify whether the alternative is already being used for the same or similar function.	Identify specified use applications/scenarios.
		Identify whether the alternatives are already being used for similar products available on the commercial market.	Identify whether F3 alternatives are commercially available on the EU market. *[considered under "Availability" in the study]*
		Identify whether the alternative is being marketed for providing the desired function for the application of interest.	
Authoritative Review		Identify whether an authoritative body demonstrated that the alternative functions adequately for both the process and product.	

As shown in **Table 5**, the IC2 approach to a technical feasibility assessment goes beyond performance requirements and pursues issues such as market availability and whether authoritative bodies have demonstrated and substantiated the performance of a given alternative. IC2's guidance is framed as a hierarchy of questions, with the basic level of assessment using only existing, publicly available data while

the more comprehensive evaluations undertake specific testing using standardized protocols. Guidance in both frameworks is very generic as every performance assessment in an alternatives assessment is considered to be case-specific to the particular application.

Strengths and Limitations of the ECHA Alternatives Assessment

The ECHA study reviewed most elements outlined in the NRC and IC2 frameworks to support a comparative understanding of performance, including broader technical feasibility attributes, such as equipment needs or changes in comparison to AFFF. Information to support the assessment was derived from product specifications documentation as well as information collected through the stakeholder consultation processes.

As previously noted, ECHA limited the scope of the question regarding functional use/functional performance to only consider alternatives that could achieve the surfactant/film-forming function of PFAS in AFFF. A broader functional use scope that instead focused on the ultimate function needed – fire extinguishment – would have opened the door to the consideration of other technological alternatives, rather than chemical-only alternatives.

The ECHA study screened out alternatives that were not commercially available, a performance attribute elevated in the IC2 framework. Compliance with broadly accepted international fire protection performance standards, as described in the available product specifications, were used to demonstrate performance efficacy. Those most commonly noted for the 7 "short-listed" alternatives, included European Standard EN 1568 Parts 1-4, International Civil Aviation Organization (ICAO), Underwriters Laboratory (UL) 162, and LASTFIRE. Some stakeholders questioned the use of some of these standards as they were considered "outdated" (i.e., developed for PFAS-based foams) and do not cover the multiple applications needed within the aviation sector (e.g., ICAO). The study also revealed specific examples of current scenarios as well as critical uses or applications where the product does not meet the required performance. If data were unavailable for any of the desired performance elements, it was noted in summary tables. Results from the technical feasibility assessment for the shortlisted alternatives are shown in **Table 6**.

A unique feature of the ECHA study is the inclusion of case studies for two of the alternatives. The case studies describe in more detailed, narrative form, the specific technical feasibility attributes, including merits and challenges. One case study examined the experience at the Copenhagen Airport in Denmark which substituted AFFF with Solberg Re-healing foam RF3x ATC for both training and emergency response. In this case, additional performance tests were conducted beyond those described in product specification documentation. Some additional technical feasibility measures were linked to implementation, including performance as linked to training and new equipment use. A second case study examined the use of Solberg Re-Healing RF1% and RF3% in offshore oil rigs in Norway. Implementation of the substitutes identified some potential technical challenges, for example the higher viscosity and density of the products compared to AFFF could be problematic for some foam pumps. However only minor equipment adjustments were required. These case studies provide critical data to understand performance during the implementation phase.

In addition to the case studies, stakeholder input also provided knowledge on additional technical feasibility attributes, such as the role of temperature during application.

TABLE 6: ECHA study – Technical feasibility assessment results (as described in product specifications and through stakeholder consultation)

	Angus Fire Respondol ATF 3-6%	**Solberg** Re-Healing Foam RF3x6 ATC	**Solberg** Re-Healing RF1 1%	**Dr. Sthamer** Mousool FF 3x6 F-15	**Dr. Sthamer** FOAMOUSSE 3% F-15	**BIOex SAS** Ecopol Premium	**Orchidex** BlueFoam 3x3
Application/ Examples of used Experience	Class B hydrocarbon fuels at 3% and polar solvent fuels at 6%/ Class A fuels (as wetting agent) No "real world" use identified	Class B hydrocarbon fuels at 3% and polar solvent fuels at 6%/ Class A fuels Used for airport fire service, rescue, and training Copenhagen Airport; Melbourne Metropolitan Fire Brigade	Class B hydrocarbon fuels (see limitations below) Class A fuels Used at offshore facilities in Norway	Polar and non-polar hydrocarbons and their mixtures (Class A and B) Used at Swedish airports, UK Heathrow airport, and Norwegian offshore oil sector	Non-polar hydrocarbon fires Mainly used in the petroleum industry and on oil tankers (no case example identified, but "real world" use confirmed	Industrial fires; hydrocarbon fires; polar solvent fires; urban fires Actual use experience unclear, but product specification states use in oil, chemical, pharmaceutical, aviation, marine and fire/rescue industries	Aviation, petrochemical sector Use at one airport in Germany
Conformance with Relevant Performance Standards	EN1568 Part 3 and 4; Highest approval rating on all fuels using all waters	EN1568 Part 3 and 4; ICAO Levels B and C	EN1568 Part 3	EN 1568 Part 3; ICAO Levels B (Low expansion foam); DIN EN 3 21 A	EN1568 Part 3	EN 1568 Part 1 & 2); Part 3; 1A and Part 4 (1A); LAST FIRE; CEREN; UL162	EN 1568 Part 3 (Grade 1B); Part 4 (Grade 1A/2B); LAST FIRE; ICAO Level B
Use Limitations	Not intended for use in the aviation sector	None	Not intended for use on Class B polar solvent fuels	Must be aspirated, which reduces throw length; Not appropriate for tank pit and large puddle fire scenarios	Only applicable for smaller fires and not applicable for the aviation sector and other sectors with higher requirements	Not technically feasible for large-scale industrial tank fires	Difficult for isopentane fires, but possible to overcome with equipment changes and higher application rates
Need for Equipment Changes	Adjustment and component changes in some cases	None – Used with new trucks	Equipment adjustment necessary	No data	No data	No data	Changes of trucks may be needed

4. Economic Feasibility Assessment

The NRC and IC2 Approach

The NRC framework's approach to assessing economic feasibility is limited. It mentions comparing direct costs, such as cost of materials, or retooling manufacturing equipment to accommodate the alternative, labor, energy, and other direct costs. Using approaches such as the calculation of net present value, were also mentioned to accommodate economies of scale when considering the market price of newer alternatives.

The IC2 framework is more comprehensive regarding an economic assessment and addresses both broader questions regarding economic feasibility as well as narrower cost parameters, such as direct costs. It is important to note that the issue of availability is addressed in both IC2's performance and economic assessment components. Being available on the market provides preliminary support that the alternative works and that it is commercially/economically available. However, an evaluation beyond simply being "available" is needed to demonstrate performance related to specific functional needs. Economic assessment elements in the NRC and IC2 framework are outlined in **Table 7** and compared to economic attributes evaluated in the ECHA study. It is important to note that additional metrics in the ECHA study were mentioned as part of the scope, yet not summarized for each of the 7 short-listed alternatives. However, additional cost elements were included in the ECHA socio-economic assessment study, which was a separate evaluation beyond the alternatives assessment.

TABLE 7: Cost assessment elements in the NRC and IC2 frameworks and the ECHA study

	NRC Elements	IC2 Elements	ECHA Study
Availability		Currently used for the application of interest.	Note: included and addressed separately from economic feasibility.
		For sale for the application of interest.	
		Being produced in sufficient quantity to meet demand.	
Cost	Direct costs, e.g., materials, retooling, manufacturing equipment to accommodate the alternative, labor, training, energy, and other direct costs	Cost competitive or prohibitive. *[more comprehensive assessment]*	Unit price with explicit comparison to PFAS containing foam.
			Relative volume required to achieve comparable/best performance.
		Changes can be made to the material to affect the overall cost of the product. *[more comprehensive assessment]*	
		Steps that can be taken to make the alternative cost-effective or that make the re-designed product desirable from a market perspective? *[more comprehensive assessment]*	
		Substantive increases or decreases in the cost of the alternative (inputs and outputs and associated indirect health/environmental impacts from a life cycle perspective of the product)? *[more comprehensive assessment]*	
			Storage (including temperature limits); shelf life.
		Can any negative cost and availability impacts be mitigated to eliminate or minimize the impact? *[more comprehensive assessment]*	

Strengths and Limitations of the ECHA Alternatives Assessment

ECHA's economic feasibility assessment was semi-quantitative as shown in **Table 8**. It was limited in its ability to fully characterize direct and indirect costs based on publicly available market information and feedback from stakeholder consultation. Data gaps are present for several of the alternatives and in some cases, such as production volumes to understand whether the alternative is being produced sufficient to meet demand, the information was determined to be "confidential". This is a common barrier when an

alternatives assessment is being conducted by government parties rather than business entities that have more complete knowledge of costs and market information.

TABLE 8: ECHA study – Economic feasibility assessment results (as described in product specifications and through stakeholder consultation)

	Angus Fire Respondol ATF 3-6%	**Solberg** Re-Healing Foam RF3x6 ATC	**Solberg** Re-Healing RF1 1%	**Dr. Sthamer** Mousool FF 3x6 F-15	**Dr. Sthamer** FOAMOUSSE 3% F-15	**BIOex SAS** Ecopol Premium	**Orchidex** BlueFoam 3x3
Unit price in comparison to PFAS	No data	Ranges from similar to 20% more expensive that PFAS products	30% more expensive than PFAS products	~50% less but requires double the volume than PFAS products	Lower	Similar to PFAS products	No data
Use volume needed in comparison to PFAS products	No data	No difference	No difference	100% more	No data	30-50% more	~5-10% of the extinguishing time for PFAS; depends on fuels
Produced in sufficient quantity to meet demand?	No data	Produced in Norway and Spain: No data on production capacity/ production volume in the EU	No data	Produced in Germany; production capacity/ production volume stated as confidential	Produced in Germany; production capacity/ production volume stated as confidential	700,000 l/yr in EU; 500,000 l/yr sale in the EU	Stakeholder estimated volume sold in the EU ~800 t/yr
Storage/shelf life	Minimum of 10 years storage, but unclear what the storage life is for PFAS	20 years	20 years	>10 years; -5˚C – 50˚C (without quality loss after thawing) more storage capacity is needed	>10 years	No data on shelf life, but 10-year warranty	No data

Although only a limited number of cost elements were included in the assessment, the information collected provided insights as to the main question of the cost assessment – *is the cost of alternatives competitive compared to the incumbent that they are trying to replace*? The ECHA study also demonstrated the challenges of government agencies/consultants need to collect cost information from product manufacturers, who may or may not voluntarily comply. All of the cost metrics included a built-in comparison to PFAS (i.e., cost higher or lower than AFFF or volume needed in comparison to AFFF). The exception was the metric of storage/shelf life in which the comparison is not clear although implied: those alternatives with a shorter storage life will require more frequent replacement and disposal, which may drive up the costs. Further analysis of use of such foams would be required to assess the degree to which shelf-life impacts life cycle costs.

As with the technical feasibility section of the ECHA report, two case studies were also used to explore costs associated with the alternatives, which was a useful way to further exemplify specific merits and challenges with the alternatives. For example, at Copenhagen airport, costs of using Solberg Re-healing foam RF3x ATC included additional volume/year that decreased over time based on experience with adjustments to equipment and training. The introduction of the new foam also coincided with the need to purchase new trucks so there was not a significant equipment cost increase associated with the change. In the case of the offshore oil facility in Norway, total costs associated with the replacement were enumerated and indirect cost benefits were qualitatively described such as reduced environmental impact associated with foam discharges to the sea, decreased disposal costs, strengthening of market position as substitution leaders among others.

5. Other Life Cycle Considerations

The NRC and IC2 Approach

Both the NRC and the IC2 frameworks encourage alternatives assessments to include considerations of broader life cycle impacts and trade-offs in the evaluation. The selection of a given alternative can have trade-offs beyond toxicity, performance, and cost, including climate impact, material use, and resource implications. The NRC and IC2 frameworks both include two approaches for addressing life cycle impacts in an alternatives assessment: life cycle thinking and partial or full life cycle assessment. The application of life cycle thinking is recommended as the first approach to use in an alternatives assessment to help qualitatively consider impacts at different points in the chemical/product life cycle, to avoid selecting alternatives that shift impacts from one stage of a product life cycle to another. If qualitative life cycle thinking is insufficient to identify, target and evaluate specific life cycle stages, then more quantitative life cycle assessment approaches using well-defined quantitative methodology, such as ISO 14040, can be pursued. In the context of AFFF for military uses, specifically, the DOD also has developed relevant lifecycle assessment guidance, specifically for lifecycle costing assessments (US DoD 2020).

Neither framework identifies specific life cycle and/or broader sustainability criteria to consider. Inclusion of broader sustainability criteria in alternatives assessment is a current area of evolution in the field though there are concerns that lifecycle assessment approaches may not adequately address toxicity trade-offs.

Strengths and Limitations of the ECHA Alternatives Assessment

The ECHA study did not explicitly address life cycle impacts/trade-offs in the assessment of alternatives. This component of an assessment is not standard when the European Commission considers alternatives in the development of restriction proposals. This is more likely to become commonplace with the European Green Deal's increased focus on climate and circularity impacts of materials. The ECHA study is not unusual in its lack of attention to lifecycle considerations. However, this is a growing area of interest in the field of alternatives assessment with greater attention to meeting the UN Sustainable Development Goals.

6. Decision Making

The NRC and IC2 Approach

The main goal of an alternatives assessment is to inform the selection of a safer, feasible alternative. The selection decision is part of the alternatives assessment approach but is both complicated and challenging especially considering the evaluation of dozens of attributes and often incomplete or missing data and uncertainties. Decision making is inherently subjective, especially when tradeoffs are involved. However, no matter how much objective data were used, subjective decisions in the form of expert judgements are used throughout the assessment including selecting relevant assessment criteria/endpoints in the scoping phase and identifying potential alternatives, assessing health and environmental impacts, and comparing performance and cost characteristics.

The NRC framework does not include a specific section on decision making, but reviews approaches to consider when integrating hazard and exposure data, specifically to help navigate data gaps, uncertainties and tradeoffs across the range of endpoints being considered. Approaches include "eliminate high ratings" such as alternatives that show high concern for hazard endpoints such as reproductive toxicity, "weighted scoring of endpoints," or more elaborate decision approaches, such as use of multi-criteria decision analysis. There is no recommended approach, except for engaging stakeholders on specific decision rules to be used in the assessment and to be transparent about decisions made.

The IC2 framework encourages assessors to identify and describe the decision approach used in an alternatives assessment – the general approach or structure of the decision making. Three decision approaches are outlined in the framework including:

- Sequential: This approach makes decisions along the way in the analysis, screening-out less favorable alternatives as a way of conserving resources and simplifying the number of alternatives considered in the next assessment component.
- Simultaneous: This decision approach considers all or a set of assessment criteria at the same time or together.
- Mixed/Hybrid: This approach is a mixture both sequential and simultaneous approaches. For example, if technical feasibility and economic impact are of particular importance to the decision maker, they may screen out certain alternatives on that basis using a sequential approach and subsequently apply a simultaneous framework for the remaining alternatives.

Strengths and Limitations of the ECHA Alternatives Assessment

The ECHA study did not decide on a specific alternative as the objective of the study was to, "collect information to support the assessment of potential regulatory management options." The study did however identify a short-list of alternatives that warrant additional consideration based on available data. Based on the IC2 framework, a hybrid decision approach appears to have been used. Decisions were made early in the assessment to screen out numerous alternatives. Subsequent decisions considering available data on the alternatives further screened out additional alternatives leaving those on the short-list, excluding some alternatives based on the chemistry used (e.g., siloxanes) or lack of data. The short-listed alternatives seemed to have been selected in large measure given evidence of current use in specific applications of interest (e.g., aviation, petroleum/oil sector etc.) but warranting further examination of performance and cost, as well as top performing alternatives regarding hazard.

SUGGESTED PATHS FORWARD FOR ALTERNATIVES ASSESSMENTS ON AFFF AND F3 OPTIONS

The ECHA study is the only current example identified of a comprehensive alternatives assessment conducted for AFFF. It was conducted to inform potential future regulation and thus was limited by information that 3rd party researchers were able to collect. Despite these challenges, there are several ways that future alternatives assessments of AFFF can learn from and improve upon the ECHA study.

1. **Consider incorporating case studies into alternatives assessment practice.** One of the contributions of the ECHA study to the field of alternatives assessment was the use of case studies to exemplify attributes of the technical and economic feasibility assessments. The case studies added greater understanding of specific assessment criteria beyond just the inclusion in a summary table or comparative matrix. Alternatives assessment practitioners should consider incorporating the use of case studies where appropriate. Such case studies can also help to understand potential concerns and trade-offs (health and safety, performance/feasibility, and cost) during the implementation phase, an important component of an alternatives assessment included in the NRC framework. The fact that an alternative is available or performs well in a laboratory setting, does not mean that it will effectively work in large scale applications without significant process modifications or equipment changes, which may result in exposures that were not originally considered. Thus, use of case studies documenting actual real-world experience is useful, where available and applicable.
2. **Consider broadening the assessment scope (during the problem formulation step) and not limit the functional use for AFFF alternatives to just film forming foams.** Only film forming foams were considered in the ECHA study. This may preclude different alternative processes or technologies that have the capacity to extinguish fires in a number of different scenarios but do so by mechanisms other than the use of chemical surfactants/wetting agents to smother the flames.

3. **Examine a broader set of hazard endpoints using measured and modeled data sources rather than depending solely on SDSs.** Using reviews of primary research studies will go further in terms of building an understanding of specific hazard traits beyond those noted on an SDS. Using stakeholders to identify the list of hazard endpoints to assess will also ensure the hazards of priority concern are considered in these reviews. Modeled data and other *in silico* approaches provide an important supplement to traditional toxicological data that should be considered given gaps in data. In addition, the GreenScreen® certification process for firefighting foams reveals the importance of conducting additional aquatic toxicity testing at the product level rather than investigating only the hazards of individual ingredients in the formulation.
4. **Consider reasonable and foreseeable exposure scenarios and relevant physicochemical properties that would inform the exposure potential of alternatives.** This is especially important if alternatives have different forms, use patterns or physicochemical properties than the AFFF. Although fire personnel will be using personal protective equipment, there are other scenarios by which human and ecosystem receptors may be exposed across the lifecycle of production, use and disposal. These exposure considerations can inform a better understanding of whether specific traits that emerge as problematic in the hazard assessment are expected to pose concerns and an understanding of potential mitigation strategies.
5. **Support deeper engagement by stakeholders to address issues including use parameters, the inclusion of additional hazard traits of primary concern, and whether and which specific life cycle considerations should be addressed in assessments.** Given the global implications of a transition to AFFF alternatives and widespread use of these products, stakes are high to ensure alternatives do not result in regrettable substitutes. Broad engagement of stakeholders can clarify parameters and evaluation criteria for what is considered "regrettable". Stakeholders may recommend the need for additional hazard traits to be considered. They can also help clarify the type of scenarios that mandate an alternative – perhaps an alternative simply not needed in all scenarios that AFFF is currently being used. Lastly, it is important to reveal a full understanding of tradeoffs across the product life cycle.
6. **Augment the alternatives assessment in the near future and on an ongoing basis as needed to stay current with: (a) the emergence of newer alternatives, (b) toxicological research on AFFF alternative formulations, (c) conformance with evolving performance standards for F3 alternatives or performance criteria that are appropriate for broader definitions of functional use/performance for AFFF, and (d) cost information as market adoption begins to change supply volumes and cost.** The global search for non-PFAS alternatives to AFFF that is being driven by legal mandates – the NDAA of 2020 requiring DoD to phase out the military's use of AFFF and all firefighting foam containing PFAS, state laws in the US banning AFFF in specific applications as well as expected restrictions on AFFF in the EU and elsewhere – is creating a very dynamic landscape for alternatives assessments. These policy drivers have opened the door to an abundance of alternatives, including dozens that are still in the R&D stages as supported by DoD programs such as its Environmental Security Technology Certification Program (ESTCP). The ECHA study is already considered outdated by some given this quickly evolving innovation landscape. Additional alternatives assessment that are more comprehensive in nature and that consider the emergence of newer alternatives that are commercially available in the US will be needed the near future. Future alternatives assessments can leverage current and emerging assessments on hazard, performance, and cost. These include for example, hazard assessments conducted under the auspices of the GreenScreen Certified™ Standard for Fire Fighting Foam, performance testing conducted by various research groups supported through DoD's ESTCP, as well as life cycle costing evaluations that are currently ongoing by researchers at Noblis.

This analysis demonstrates that there is only one alternatives assessment for F3 products that meets is a complete alternatives assessment according to the NRC and IC2 frameworks. Even so, the ECHA study lacks information on hazards and physicochemical properties. In addition, it is questionable whether the ECHA study sufficiently addresses alternatives available in the US market and the most relevant performance standards and specifications to US-based users. Although there are several assessments of single elements of an alternatives assessment (e.g., performance or hazard) for specific F3 products, these are hard to compare given limited information on the tradenames of alternatives evaluated or

confidentiality of ingredients. With better access to these data, a more comprehensive alternatives assessment for an informative array of commercially available F3 products is feasible.

REFERENCES

ATSDR [Agency for Toxic Substances and Disease Registry]. 2021. *Toxicological Profile for Perfluoroalkyls*. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

ASTSWMO [Association of State and Territorial Solid Waste Management Officials]. 2015. *Perfluorinated Chemicals (PFCs): Perfluorooctanoic Acid (PFOA) & Perfluorooctane Sulfonate (PFOS): Information Paper*. Accessed April 23, 2021: clu-in.org/download/contaminantfocus/pops/POPs-ASTSWMO-PFCs-2015.pdf

Back J. 2020. *Capabilities Assessment of Commercially Available Fluorine-Free* Agent [poster presentation]. US DoD Strategic Environmental Research and Development Program and Environmental Security Technology Certification Program Symposium 2020.

Back J and Farley J. 2020. *Evaluation of the Fire Protection Effectiveness of Fluorine Free Firefighting Foams*. Fire Protection Research Foundation. January. Accessed April 23, 2021: https://www.nfpa.org/News-and-Research/Data-research-and-tools/Suppression/Evaluation-of-the-fire-protection-effectiveness-of-fluorine-free-firefighting-foams

Clean Production Action. *GreenScreen Certified™ Standard for Firefighting Foam (v.2). Certified Products*. Accessed April 23, 2021: https://www.greenscreenchemicals.org/certified/products

Danish EPA [Danish Environmental Protection Agency]. 2015. *Short-Chain Polyfluoroalkyl Substances (PFAS). A Literature Review of Information on Human Health Effects and Environmental Fate and Effect Aspects of Short-Chain PFAS*. Environmental Project No. 1707.

Farley J. 2020. ESTCP WP20-5373 *Fluorine-Free Military Specification Development*.

US DoD Strategic Environmental Research and Development Program and Environmental Security Technology Certification Program Symposium 2020. [poster presentation].

Frisbee SJ, Shankar A, Knox SS, et al. Perfluorooctanoic acid, perfluorooctanesulfonate, and serum lipids in children and adolescents: results from the C8 Health Project. *Arch Pediatr Adolesc Med*. 2010;164(9):860–869. doi:10.1001/archpediatrics.2010.163

Grandjean P. Delayed discovery, dissemination, and decisions on intervention in environmental health: a case study on immunotoxicity of perfluorinated alkylate substances. *Environ Health*. 2018 Jul 31;17(1):62. doi: 10.1186/s12940-018-0405-y.

Grandjean P, Clapp R. Perfluorinated Alkyl Substances: Emerging Insights into Health Risks. *New Solut*. 2015 Aug;25(2):147-63. doi: 10.1177/1048291115590506.

Hutchings C. Personal Communication. March 10, 2021.

Hu XC, Andrews DQ, Lindstrom AB, Bruton TA, Schaider LA, Grandjean P, Lohmann R, Carignan CC, Blum A, Balan SA, Higgins CP, Sunderland EM. Detection of Poly- and Perfluoroalkyl Substances (PFASs) in U.S. Drinking Water Linked to Industrial Sites, Military Fire Training Areas, and Wastewater Treatment Plants. *Environ Sci Technol Lett*. 2016 Oct 11;3(10):344-350. doi: 10.1021/acs.estlett.6b00260.

IC2 [Interstate Chemicals Clearinghouse] 2017. Alternatives Assessment Guide Version 1.1. January. Accessed April 23, 2021 at: http://theic2.org/article/downloadpdf/file_name/IC2_AA_Guide_Version_1.1.pdf

IPEN. 2018. Fluorine-Free Fire Fighting Foams (3F) – Viable Alternatives to Fluorinated Aqueous Film-Forming Foams (AFFF). POPRC-14. September 2018. Accessed April 23, 2021 at: https://ipen.org/sites/default/files/documents/IPEN_F3_Position_Paper_POPRC-14_12September2018d.pdf

Jacobs MM, Malloy TF, Tickner JA, Edwards S. Alternatives assessment frameworks: Research needs for the informed substitution of hazardous chemicals. *Environ Health Perspect*. 2016;124(3):265–280. doi:10.1289/ehp.1409581.

Lindstrom AB, Strynar MJ, Libelo EL. Polyfluorinated compounds: past, present, and future. *Environ Sci Technol.* 2011 Oct 1;45(19):7954-61. doi: 10.1021/es2011622.

Lopez-Espinosa MJ, Mondal D, Armstrong B, Bloom MS, Fletcher T. Thyroid function and perfluoroalkyl acids in children living near a chemical plant. *Environ Health Perspect*. 2012;120(7):1036–1041. doi:10.1289/ehp.1104370.

NDAA [National Defense Authorization Act]. 2019. National Defense Authorization Act for Fiscal Year 2020. S. 1790 – 11^{6th} Congress (2019-2020). December 20. Accessed May 20, 2021 at: https://www.govinfo.gov/content/pkg/PLAW-116publ92/html/PLAW-116publ92.htm

NDAA [National Defense Authorization Act]. 2021. National Defense Authorization Act for Fiscal Year 2021. H.R. 6395 – 116th Congress (2019-2020). Jan 1. December 20. Accessed May 20, 2021 at: https://www.congress.gov/bill/116th-congress/house-bill/6395

Peshoria S, Nandini D, Tanwar RK, Narang R. 2020. Short-chain and long-chain fluorosurfactants in firefighting foam: a review. *Environ Chem Let*. 18(4):1277. doi:10.1007/s10311-020-01015-8.

Rice PA, Aungst J, Cooper J, Bandele O, Kabadi SV. Comparative analysis of the toxicological databases for 6:2 fluorotelomer alcohol (6:2 FTOH) and perfluorohexanoic acid (PFHxA). *Food Chem Tox*. 138; 111210. doi.org/10.1016/j.fct.2020.111210.

Stein CR, Savitz DA, Dougan M. Serum levels of perfluorooctanoic acid and perfluorooctane sulfonate and pregnancy outcome. *Am J Epidemiol*. 2009;170(7):837–846. doi:10.1093/aje/kwp212.

Tickner J, Jacobs MM, Bakarian Mack N. Alternatives assessment and informed substitution: A global landscape assessment of drivers, methods, policies and needs. *Sus Chem and Pharm*. 2019a; 13: 100161. doi.org/10.1016/j.scp.2019.100161.

Tickner J, Jacobs M, Malloy T, et al. Advancing alternatives assessment for safer chemical substitution: A research and practice agenda. *Integr Environ Assess Manag*. 2019b;15(6):855–866. doi:10.1002/ieam.4094

Tickner JA, Simon RV, Jacobs M, Pollard LD, van Bergen SK. 2021. The nexus between alternatives assessment and green chemistry: supporting the development and adoption of safer chemicals, *Green Chem Let Rev*. 14:1, 23-44, doi: 10.1080/17518253.2020.1856427/

US DoD [United States Department of Defense], Office of the Under Secretary of Defense for Acquisition and Sustainment, Chemical & Material Risk Management Directorate. Chemical & Material Emerging Risk Alert: Aqueous Film Forming Foam (AFFF). Risk Alert #03-11. Accessed April 23, 2021 at: https://static.ewg.org/reports/2019/pfas-dod-timeline/2011_AFFF-Risk-Alert.pdf

US DoD [United States Department of Defense], Under Secretary of Defense for Acquisition and Sustainment. *Alternatives to Aqueous Film Forming Foam – Report to Congress*. June 2018.

US DoD [United States Department of Defense]. 2020. Department of Defense Guidance Sustainability Analysis Guidance: Integrating Sustainability into Acquisition Using Life Cycle Assessment. Version 7.0. June 24. Accessed May 1, 2021 at: https://denix.osd.mil/esohacq/home/dod-guidance/dod-sustainability-analysis-guidance/

US EPA [United States Environmental Protection Agency]. 1996. Office of Pollution Prevention and Toxics. Cleaner Technologies Substitutes Assessment: A Methodology and Resource Guide. EPA-744-R-95-002. December.

US EPA [United States Environmental Protection Agency]. 2017. Technical Fact Sheet – Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoic Acid (PFOA). November. Accessed April 23, 2021 at: https://www.epa.gov/sites/production/files/2017-12/documents/ffrrofactsheet_contaminants_pfos_pfoa_11-20-17_508_0.pdf

US NRC [United States National Research Council]. 2014. A framework to guide selection of chemical alternatives. Washington (DC): National Academies Press. Accessed April 23, 2021 at: https://www.nap.edu/catalog/18872/a-framework-to-guide-selection-of-chemical-alternatives

Vieira VM, Hoffman K, Shin HM, Weinberg JM, Webster TF, Fletcher T. Perfluorooctanoic acid exposure and cancer outcomes in a contaminated community: a geographic analysis. *Environ Health Perspect*. 2013;121(3):318–323. doi:10.1289/ehp.1205829.

Wood, Ramboll and Cowi. June 2018. *The Use of PFAS and Fluorine-Free Alternatives in Fire-Fighting Foams*. Report for European Commission and the European Chemicals Agency.

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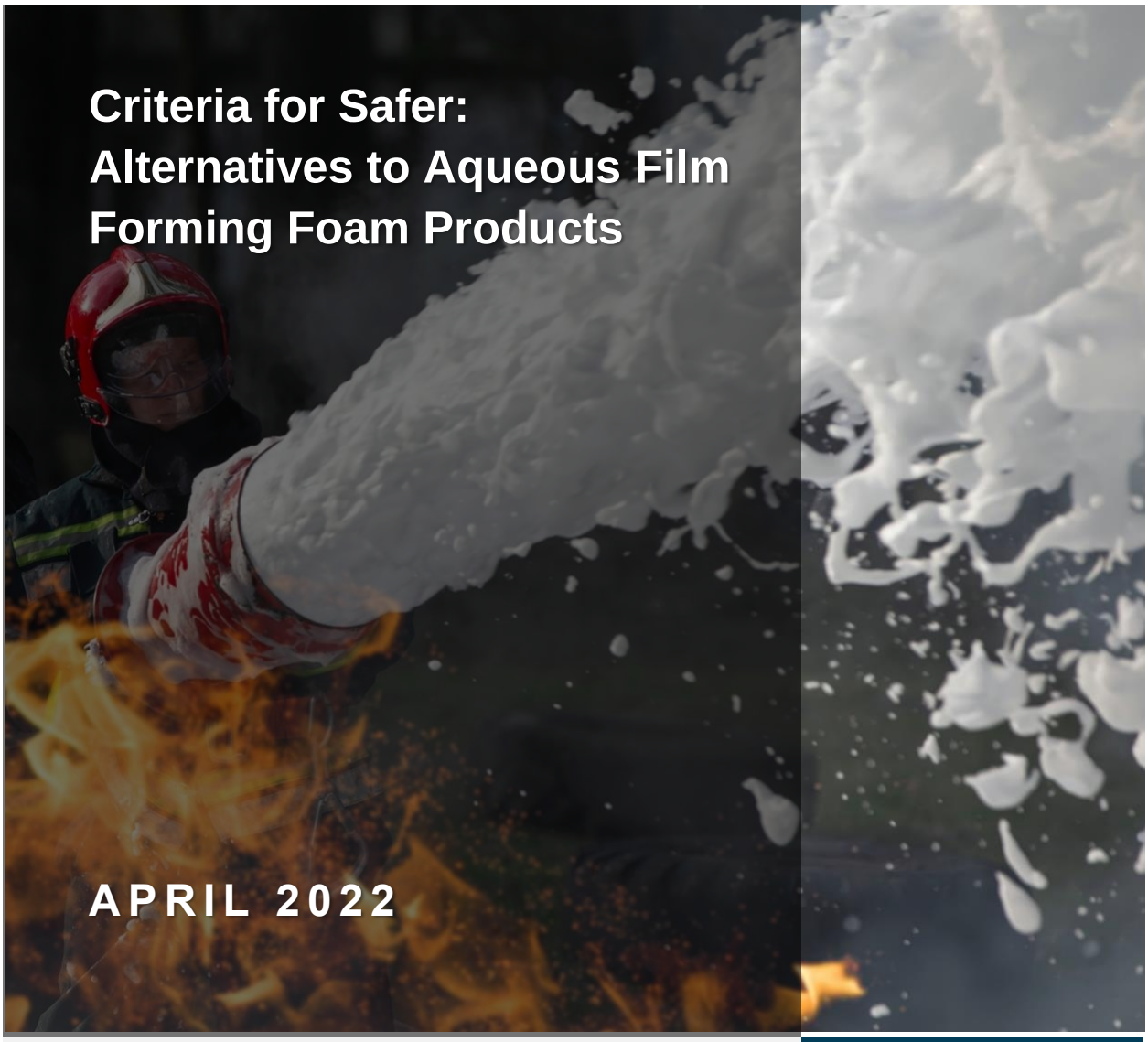
Annex C. Report – *Criteria for Safer: Alternatives to Aqueous Film Forming Foam Products*

University of Massachusetts Lowell

Criteria for Safer: Alternatives to Aqueous Film Forming Foam Products



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ABOUT

The Sustainable Chemistry Catalyst is an independent research and strategy initiative, based at the Lowell Center for Sustainable Production (University of Massachusetts Lowell), that is focused on accelerating the transition to safer, more sustainable chemistry through research and analysis, and stakeholder engagement with scientists, policymakers, and commercial actors.

The Catalyst works to understand barriers and opportunities to commercialization of safe and sustainable chemistry, identifies model solutions and strategies, develops methods to evaluate safer alternatives, and builds a community of expertise to support the transition to safer, more sustainable chemistries and technologies.

Sustainable Chemistry Catalyst

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ACRONYMS USED

AFFF	Aqueous Film Forming Foam
CAS	Chemical Abstract Service
CIC	Combustion Ion Chromatography
D4	Octamethylcyclotetrasiloxane
D5	Decamethylcyclopentasiloxane
D6	Dodecamethylcyclohexasiloxane
DfE	Design for the Environment
ECHA	European Chemicals Agency
EU	European Union
GHS	Globally Harmonized System for the Classification and Labelling of Chemicals
K_{ow}	Octanol-Water partition coefficient
MILSPEC	Military Performance Specification MIL-PRF-24385F(SH)
NAMs	New Approach Methodologies
NDA	Non-Disclosure Agreement
NDAA	National Defense Authorization Act
NGO	Non-governmental organization
NP	Nonylphenol
NPE	Nonylphenol Ethoxylates
OECD	Organization for Economic Cooperation and Development
REACH	Registration, Evaluation and Authorization of Chemicals
PBT	Persistent, Bioaccumulative, and Toxic
PFAS	Per- and polyfluorinated alkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
ppm	Parts per million
SVHC	Substances of Very High Concern
TOF	Total Organic Fluorine
US	United States
US DoD	United States Department of Defense
US EPA	United States Environmental Protection Agency
vPvB	Very Persistent and Very Bioaccumulative

SUMMARY

Policies in the United States (US) and beyond are driving efforts to phase out the use of Aqueous Film Forming Foam (AFFF) products used to extinguish flammable liquid fires at airports, military complexes, oil and gas operations, industrial facilities, and municipal firefighting operations. AFFF contains per- and polyfluorinated alkyl substances (PFAS), which are highly persistent, bioaccumulative and toxic (PBT) substances. This guidance outlines specific criteria to evaluate and determine whether alternatives are safer as compared to current PFAS-containing AFFF products. The criteria should be considered the *minimum requirements* for a safer AFFF alternative determination. Criteria are drawn from existing approaches, in particular the Organization for Economic Cooperation and Development's (OECD) "Guidance on Key Considerations for the Identification and Selection of Safer Alternatives" and supplemented by others such as the Green Screen Certified™ for Fire Fighting Foam and the US Environmental Protection Agency's (US EPA) Safer Choice criteria. This guidance is not a detailed protocol for conducting a hazard assessment; it assumes that users have the necessary toxicological expertise and practicing knowledge for conducting such assessments. Users should recognize that some state, local, or tribal governments in the United States may have additional requirements that should be considered when choosing safer firefighting foams.

The minimum requirements for a safer AFFF alternative determination include Part A and Part B as displayed below in **Table 1**. Conformance with Part A ensures that problematic groups of substances are not used as ingredients (intentionally added or impurities/residuals) in an alternative formulation for such formulation to be considered "safer". Conformance with Part B includes hazard endpoints and/or associated hazard classifications that cannot be of "high" concern for an alternative AFFF formulation to be considered safer.

TABLE 1: Minimum Requirements for a Safer AFFF Alternative

Part A	**Part B**
A **safer** AFFF alternative cannot include the following classes of substances and/or substances: 1. Fluorinated substances (no PFAS) 2. Alkylphenols and alkylphenol ethoxylates unless test data for endpoints in Part B demonstrate safety 3. Cyclic volatile methyl siloxanes: – octamethylcyclotetrasiloxane (D4) – decamethylcyclopentasiloxane (D5) – dodecamethylcyclohexasiloxane (D6)	A **safer** AFFF alternative cannot contain any chemical ingredient* classified as "high" concern associated with the following hazard endpoints: 1. Carcinogenicity* 2. Germ cell mutagenicity* 3. Reproductive/developmental toxicity* 4. Acute mammalian toxicity 5. Systemic toxicity, repeated dose 6. Endocrine disruption 7. Chronic aquatic toxicity Or either of the following classifications: 8. Persistent, Bioaccumulative, and Toxic (PBT)* 9. very Persistent, very Bioaccumulative (vPvB)* A **safer** AFFF alternative tested at the product-level cannot be classified as "high" concern associated with the following hazard endpoint: • Acute aquatic toxicity

**Release, degradation or breakdown products of the formulated product ingredients cannot be of "high" concern either.*

This guidance details methods and criteria for evaluating the minimum requirements above, including use of authoritative lists for an initial rapid screen of problematic ingredients, applying criteria/thresholds using the Globally Harmonized System (GHS) of Classification and Labelling of Chemicals, and using GreenScreen® criteria for persistence and bioaccumulation to support a PBT or very persistent very bioaccumulative (vPvB) classification based on US EPA criteria and/or the Registration, Evaluation and Authorization of Chemicals (REACH) regulation in the EU. The guidance recognizes that GHS criteria for endocrine disruption are currently unavailable. Although such criteria development are anticipated in the coming years, assessors can defer to authoritative lists to ensure problematic endocrine disrupting substances are avoided. The guidance also outlines specific physicochemical properties for evaluating the exposure potential of formulation ingredients, which is especially important for understanding the need for exposure mitigation strategies if ingredients are deemed of "moderate" concern for specific hazard endpoints of interest. Going beyond the minimum is recommended *wherever and whenever possible* to further reduce the likelihood that an alternative to AFFF will result in unintended consequences to the environment, workers, and the public. As such, the guidance outlines additional hazard endpoints to consider beyond the minimum requirements. Of particular importance is the inclusion and evaluation of skin or respiratory sensitization, mobility, the additional data sources for a more comprehensive evaluation of endocrine disruption and adoption of more stringent assessment criteria for aquatic toxicity and environmental fate.

INTRODUCTION / CONTEXT

Background on Aqueous Film Foaming Foams

Introduced in the 1960s, aqueous film forming foam (AFFF) is a type of class B firefighting foam that is formulated using fluorosurfactants to extinguish flammable liquid fires. It is used for firefighting operations at airports, throughout military complexes, by oil and gas operations, at industrial facilities, and at municipal firefighting operations. Up until the early 2000s, AFFF was manufactured with long-chain per- and polyfluorinated alkyl substances (PFAS), such as perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) (ASTSWMO 2015). Because of concerns regarding health and environmental impacts and the extremely persistent, bioaccumulative, and mobile properties of these synthetic chemicals, manufacturers in the United States (US) agreed to a complete phase out of these substances by 2015 under the US Environmental Protection Agency's (US EPA) PFOA Stewardship Program. AFFF was subsequently reformulated with shorter-chain PFAS derivatives (US DoD 2018; ASTSWMO 2015; Peshoria et al. 2020).

A growing body of scientific evidence documents that exposure to PFOA, PFOS, and additional PFAS are associated with a range of health impacts, including changes in liver enzymes, decreased birth weight, increased cholesterol levels, decreased vaccine response in children, and increased risk of kidney and testicular cancer, among other health impacts (ATSDR 2021; Fenton et al. 2021). These health impacts and mounting evidence indicating the likelihood of human and ecosystem exposure from contamination of groundwater and surface waters resulting from the use of AFFF during emergency response or training operations have prompted a number of policy efforts to restrict the use of AFFF. Beginning with Washington state in 2018, approximately 14 states have issued regulations prohibiting the sale and/or use of PFAS for firefighting training purposes (Safer States 2021). In addition, the National Defense Authorization Act (NDAA) of 2020 requires the US Department of Defense (US DoD) to revise its military performance specification (MIL-SPEC; MIL-PRF-24385F(SH)) for AFFF to include PFAS-free foams for shore-based applications by 2023 and to phase out the military's use of AFFF by 2024.

PFAS-free alternatives to AFFF have been in use for nearly a decade at airports in Australia and several European countries (Ross 2019). Municipal fire departments in the US are also switching to PFAS-free alternatives (Dykes 2021). The US DoD has significantly invested in the research, development and testing of PFAS-free alternatives given the need for the military to adopt such products by 2024. This research is being supported by requirements in the FY 2021 for DoD to prioritize research on AFFF alternatives that utilize "green and sustainable chemicals that do not pose a threat to public health or the environment" (NDAA 2021). There is a dual focus in these research programs to ensure the effective performance of the PFAS-free alternatives as well as to ensure that alternatives are not regrettable from an environmental health and safety standpoint.

The existing US DoD performance MIL-SPEC specification for AFFF, includes a minimum set of environmental performance measures to avoid detrimental impacts. These include measuring aquatic toxicity on killifish (*Fundulus herteroclitus*), chemical oxygen demand, and biodegradability. However, these environmental endpoints are insufficient considering standards of practice that have emerged over the last decade to support informed substitution, sustainable product design, and environmentally preferable procurement.

Existing Best Practices for Determining a Safer Alternative

Decisions about whether a chemical is considered sufficiently safe for a particular use are often made through quantitative risk assessments, which can be resource intensive and require a significant amount of exposure data. These assessments generally answer the question of whether an exposure level is sufficiently safe or acceptable and may be conducted in response to policy or market demands.

Over the last three decades, a number of hazard assessment methods, approaches, and tools have emerged to support the use of alternatives assessments in informed substitution and safer product design processes. In an alternatives assessment process as compared to risk assessment, the focus is on comparing the hazards, performance, and cost of alternatives in order to identify options that are safer (i.e., less hazardous) and more feasible (i.e., comparable performance and cost-effective) than the incumbent, with the overall goal of facilitating the informed transition to safer alternatives and minimizing the potential for regrettable substitutes. Many of the more recent hazard assessment methods have evolved from the work of the US EPA's Design for Environment (DfE) program. In 2011, US EPA's DfE Program developed its *Alternatives Assessment Criteria for Hazard Evaluation* as a transparent tool to support a comparative evaluation of chemicals based on their human health and environmental hazards (US EPA 2011). Although several hazard assessment and associated classification schemes are available, those that have been used in the context of evaluating alternatives to chemicals of concern are based on a systematic evaluation of specific environmental and human health criteria (US NRC 2014). The United Nation's Globally Harmonized System (GHS) for the Classification and Labelling of Chemicals provides the underlying methodology to support comparisons across alternatives based on specific hazard levels associated with different environmental and human health criteria.

Alternatives assessment methods most often stop short of dictating specific decision-making criteria about whether an alternative is safer than the incumbent chemical or product to be replaced. Traditionally, decisions are left to those seeking to find substitutes or design new products. However, in 2021, the Organization for Economic Cooperation and Development (OECD) issued guidance that aimed to "advance broader agreement on a general approach and criteria for the selection of safer alternatives, with a focus on chemical substitution" (OECD 2021). The guidance was requested by governments and other stakeholders as a process to more consistently define safer chemicals across jurisdictions. The guidance recognizes that the term "safer" rarely implies "safe". A robust inventory of safe and sustainable chemistries and technologies that are benign to human health is currently unavailable for the vast majority of functions

Box A: Examples of Authoritative Definitions of a "Safer" Alternative

US National Research Council – *A safer alternative represents an option that is less hazardous to humans and the environment than the existing chemical or chemical process* (NRC 2014b).

US Occupational Safety and Health Administration – *A safer alternative is an option that is less hazardous for workers than the existing means of meeting that need* (OSHA 2013).

California Safer Consumer Products regulation (California Code of Regulations 2013, p. 13) – *"Safer alternative" means an alternative that, in comparison with another product or product manufacturing process, has reduced potential adverse impacts and/or potential exposures associated with one or more Candidate Chemicals, Chemicals of Concern, and/or replacement chemicals, whichever is/are applicable* (CCR 2013).

Washington State's Pollution Prevention for Healthy People and Puget Sound Act (aka Safer Products for Washington Act) – *A "safer alternative" means an alternative that is less hazardous to humans or the environment than the existing chemical or chemical process* (WA RCW 2020).

and applications currently being served by substances of concern. As such, the best course of action is to use *less hazardous* or *safer* substances while efforts to speed-up the pace of development and application of safer and sustainable chemistry innovations proceed. The OECD guidance helps provide a structure for evaluating safer (some definitions in Box A, previous page) in support of a number of market and regulatory policies.

The OECD (2021) guidance outlines minimum criteria and recommended assessment practices to support a determination of a safer alternative. The guidance emphasizes that minimum requirements need to be seen as the *baseline* in a broader hierarchy of criteria and assessment practices that may ultimately be needed to provide stakeholders with the confidence that a specific alternative is, indeed, safer. Minimum requirements were determined based on regulatory priorities and hazard criteria where data are generally more available than not. To support more comprehensive approaches, the OECD guidance also outlines criteria and recommended practices for going beyond the minimum where possible (**Figure 1**).

FIGURE 1. Organization for Economic Cooperation and Development's (2021) Spectrum of Safer Criteria for the Selection of Alternatives to Priority Substances

The use of minimum requirements for evaluating and making a determination about safer alternatives has also been adopted by government agencies and NGOs for use in regulatory programs and purchasing, including:

- Phase 3 Working Draft Criteria for Safer outlined by the Safer Products for Washington Program – a regulatory program charged with implementation of the Pollution Prevention for Healthy People and Puget Sound Act (Safer Products for Washington Act) (Safer Products for Washington 2021).
- US EPA's Safer Choice Program – used to certify products that carry the EPA's Safer Choice label (US EPA 2012).
- Green Screen Certified™ for Fire Fighting Foam – Clean Production Action's approach used to certify safer firefighting foam products (CPA 2021).
- Registration, Evaluation, and Authorization of Chemicals (REACH) legislation criteria for defining a Substance of Very High Concern (SVHC) (ECHA 2021).

PURPOSE

This guidance outlines specific criteria to evaluate and determine whether alternatives are safer as compared to current PFAS-containing AFFF products. The criteria should be considered the *minimum requirements* for a safer AFFF alternative determination. Criteria are drawn from existing approaches as reviewed above, in particular the OECD guidance (2021), supplemented

by others such as US EPA Safer Choice (2012) and Green Screen Certified™ for Fire Fighting Foam (CPA 2021) to support a more specific assessment of AFFF alternatives given its use context. Given that data gaps and uncertainty are a perennial barrier when examining an array of human health and ecological endpoints, recommendations for addressing uncertain or absent data in the decision-making process are also outlined, including consideration of evidence associated with New Approach Methodologies (NAMs).

This guidance focuses exclusively on a minimum set of toxicological hazard criteria for making a determination of a safer alternative, based on the use context of current AFFF products. As with AFFF, PFAS-free alternative products will result in exposure to humans (especially fire-fighting/emergency response personal) despite industrial hygiene control measures, and to aquatic and terrestrial species given the direct application in outdoor environments. As such, a few endpoints beyond those considered the minimum requirements in the OECD guidance are included. Physicochemical properties should be evaluated to determine if alternatives result in different exposure pathways or if increased exposure may occur, for example when ingredients that have high vapor pressure could increase concern for inhalation exposure. In addition, different substitutes other than the current array of quasi-drop-in PFAS-free alternatives may confer differences in exposure potential and should be evaluated.

The guidance is not a detailed protocol for conducting a hazard assessment. It assumes that users have a practicing knowledge for conducting hazard assessments and have related toxicological expertise. It outlines a minimum set of hazard and related decision criteria to support a safer determination for an AFFF alternative. For methods to support comprehensive hazard assessments, readers are encouraged to review US EPA's Safer Choice Criteria, Version 2.1 (2012) and the GreenScreen® for Safer Chemicals Hazard Assessment Methods (CPA 2018), both of which utilize GHS standardized hazard classifications and testing methodologies (UNECE 2021). Users should recognize that some state, local, or tribal governments in the US may have additional requirements that should be considered when choosing safer firefighting foams.

MINIMUM REQUIREMENTS–CRITERIA FOR A SAFER DETERMINATION

Table 1 outlines the minimum requirements for a safer AFFF alternative determination. There are two parts to these requirements: Part A focuses on ensuring that potentially problematic classes of substances are not ingredients (intentionally added or impurities/residuals) in a safer alternative formulation. Part B focuses on specific hazard endpoints. Part A is consistent with standards being developed by the US DoD to ensure that alternatives to AFFF are fluorine-free and seeks to avoid additional problematic substances and/or substance classes as supported in the Green Screen Certified™ for Fire Fighting Foam methodology (CPA 2021). Part B is consistent with the OECD guidance minimum criteria for *safer*; data must be available for all listed chemicals and their endpoints as *an absence of data is not demonstration of an absence of* hazard.

Assessing alternative AFFF formulations against the minimum requirements for a *safer* determination will require knowledge of the full list of chemical ingredients, including intentionally added substances and impurities/residuals. Without such knowledge, it is difficult to determine if an alternative is indeed safer. Evaluations will therefore require collaborations with product manufacturers and 3rd-party assessors using non-disclosure agreements (NDAs) or

other mechanisms to protect confidential/proprietary ingredients in the product formulation. Known breakdown products should also be considered for each ingredient. Chemical ingredients that release, degrade to, or form breakdown products that are classified as high concern for carcinogenicity, mutagenicity, reproductive/developmental toxicity, or are persistent, bioaccumulative and toxic (PBT) should not be considered safer. Given that the OECD guidance does not specify *de minimis* concentrations requiring assessment, this guidance adopts criteria used by US EPA's Safer Choice program and requires the assessment of all intentionally added ingredients and impurities/residuals present at 100 ppm.

TABLE 1. Minimum Requirements for a Safer AFFF Alternative

Part A	**Part B**
A *safer* AFFF alternative cannot include the following classes of substances and/or substances: 1. Fluorinated substances (No PFAS) 2. Alkylphenols and alkylphenol ethoxylates unless test data for endpoints in Part B demonstrate safety 3. Cyclic volatile methyl siloxanes: – octamethylcyclotetrasiloxane (D4) – decamethylcyclopentasiloxane (D5) – dodecamethylcyclohexasiloxane (D6)	A *safer* AFFF alternative cannot contain any chemical ingredient* classified as "high" concern associated with the following hazard endpoints: 1. Carcinogenicity* 2. Germ cell mutagenicity* 3. Reproductive/developmental toxicity* 4. Acute mammalian toxicity 5. Systemic toxicity, repeated dose 6. Endocrine disruption 7. Acute aquatic toxicity 8. Chronic aquatic toxicity Or either of the following classifications: 9. Persistent, Bioaccumulative and Toxic (PBT)* 10. very Persistent, very Bioaccumulative (vPvB)* A **safer** AFFF alternative tested at the product-level cannot be classified as "high" concern associated with the following hazard endpoint: • Acute aquatic toxicity

**Release, degradation or breakdown products of the formulated product ingredients cannot be of "high" concern as well.*

Assessment Criteria and Related Methods, Part A

To minimize regrettable substitutions, there is a growing commitment to avoid chemistries where multiple substances within the class have been shown to be hazardous, particularly if sufficient comprehensive hazard information demonstrating safety for human and the environment is not available. Exclusion criteria for three specific substances and/or classes of substances are outlined in Part A of the minimum requirements, including: ensuring that (a) the alternative AFFF product does not include fluorinated substances (i.e., no PFAS); (b) that it does not include the cyclic volatile methyl siloxanes, including octamethylcyclotetrasiloxane (D4), decamethylcyclopentasiloxane (D5) and dodecamethylcyclohexasiloxane (D6); and (c) that it does not include alkylphenols and alkylphenol ethoxylates (considered hazardous by some authorities). These specific substances and chemical classes were selected because they could be used as replacements for the PFAS surfactant function in AFFF.

A. Avoiding Fluorinated Substances

Despite having hazard data for only a few dozen of the 9,000+ PFAS, there is a commitment by the US DoD to avoid all PFAS in future firefighting foams because substitutions to date within the class have proven to be problematic.

This guidance was developed prior to the release of the revised Milspec for PFAS-free products, which is expected to also dictate testing methodologies to qualify products as PFAS-free. Until such testing standards and specifications are released, total organic fluorine (TOF) testing methodology using combustion ion chromatography (CIC) to ensure a threshold of 0.0001% fluorine by mass can be used as per the GreenScreen Certified™ Standard for Fire Fighting Foam (CPA 2021). TOF/CIC provides for a quantitative assessment of PFAS compounds that are currently detected by liquid chromatography coupled with tandem mass spectrometry methods. TOF/CIC also detects other fluoroorganic compounds that are not readily determined by tandem mass spectrometry methods and is currently the preferred methodology for determining that a product is "PFAS-free" (Bureau Veritas North America, 2021). However, caution is warranted as its unclear whether these testing technologies can achieve the extremely low level of detection (1ppb) for PFAS which will be required in the updated MILSPEC.

B. Avoiding Alkylphenols and Alkylphenol Ethoxylates

The use, discharge, and biodegradation of alkylphenols and alkylphenol ethoxylates represents an ecological hazard. Nonylphenol, an alkylphenol, is used to manufacture nonylphenol ethoxylates (NPEs) and can also become a degradation product of NPEs. NPEs are used as nonionic surfactants and part of the broader category of surfactants known an alkyphenol ethoxylates. Additional NPs and NPEs include octylphenol and octylphenol ethoxylates, respectively. NPs and NPEs are considered environmentally persistent, can range from toxic to extremely toxic to aquatic organisms, and can exert endocrine disruption effects as they mimic estrogen (Soares et al. 2012; US EPA 2009). They also degrade to more toxic and environmentally persistent compounds (Soares et al. 2012). NPEs often partition to sediment and can accumulate (US EPA 2009).

Agencies, including the European Chemicals Agency, have issued restrictions on the use of these NP/NPE compounds. The GreenScreen Certified™ methodology includes alkylphenols and alkylphenol ethoxylates as a class of chemistries that must not be present in order to meet its product certification requirements (CPA 2021). Additional compounds in this chemical class should be considered hazardous unless test data on the range of hazard endpoints in part B demonstrate otherwise. While the extent to which these compounds are being used in PFAS-free foams is unclear, there is a possibility of their use.

C. Avoiding Cyclic Volatile Methyl Siloxanes D4, D5 and D6

In 2018, an alternatives assessment for AFFF was conducted for the European Chemicals Agency (ECHA) to inform risk management options. Siloxane-based alternatives were excluded from the alternatives that were short-listed for further consideration based on stakeholder concerns regarding the toxicity of these substances (Wood, Ramboll and Cowi, 2018). Siloxanes are of interest in PFAS-free formulations because of the surfactant function they provide. However, there is growing understanding that cyclic volatile methyl siloxanes are hazardous. In 2018, the

EU added three cyclic siloxanes, octamethylcyclotetrasiloxane (D4), decamethylcyclopentasiloxane (D5), and dodecamethylcyclohexasiloxane (D6), to the Candidate List of Substances of Very High Concern (SVHC) for Authorization under REACH based on evidence of PBT and very persistent, very bioaccumulative (vPvB) properties (ECHA 2019). As outlined in **Table 1**, PFAS-free alternatives cannot be considered safer if ingredients in the product formulation have such hazard characteristics. Chemicals on the EU SVHC Candidate List for Authorization do not meet the minimum criteria for defining a safer alternative and should be screened-out. Although it is beyond the purpose of this document to review the science associated with these cyclic siloxanes, we refer readers to the review as outlined in the EU restriction proposals (ECHA, 2019). The GreenScreen Certified™ methodology also includes cyclic volatile methyl siloxanes as a class of chemistries that must not be present to meet product certification requirements (CPA 2021). Additional compounds in this chemical class should be considered hazardous unless test data on the range of hazard endpoints in Part B demonstrates otherwise.

Assessment Criteria and Related Methods, Part B

Ensuring that AFFF alternatives meet minimum criteria for a safer determination associated with priority human and environmental health hazard endpoints requires: (a) the use of authoritative lists for an initial rapid screening of problematic ingredients; (b) applying criteria/thresholds using GHS criteria; and (c) using criteria developed by US EPA Safer Choice Program and GreenScreen® for aquatic toxicity, persistence, and bioaccumulation.

A. Using Authoritative Lists

Authoritative lists are developed by government agencies or authoritative scientific organizations and used in hazard assessment to screen out unacceptable substances based on demonstrated scientific concern for human health and the environment. These lists are developed based on extensive expert review of the scientific evidence. Use of authoritative lists is an established approach in alternatives assessment to support efficient screening out of alternatives that are deemed "chemicals of concern" and may be a current or future focus of regulatory or market-based actions that restrict use (NRC 2014; OECD 2021). Assessors should cross-reference AFFF ingredients using both chemical names and chemical abstract service (CAS) numbers against a given authoritative list. If a chemical ingredient is on the given authoritative list, the alternative formulation would *not* be considered safer.

A set of 13 authoritative lists are outlined in this document as part of the minimum requirements in support of a safer AFFF alternative determination. These lists are outlined in association with the ten required hazard endpoints noted in **Table 1** and outlined in **Tables 2-11** below. Additional authoritative lists that do not easily fit within an individual hazard endpoint evaluation, but which should be reviewed when considering a safer AFFF alternative, are outlined in **Table 12**. This minimum set of authoritative lists include those created by US, Canadian, and European government authorities and those used in international treaties. All are included in the OECD guidance's minimum criteria (2021) and additional lists have been added given the need to also prioritize aquatic toxicity and acute mammalian toxicity. One additional list is also included to support the assessment of carcinogenicity – the National Institute for Occupational Safety and Health's Occupational Carcinogen List (NIOSH 2021). Numerous services are available to

support quick queries of authoritative lists in hazard assessments. Pharos Project (www.pharosproject.net) is one such service and includes all authoritative lists outlined in the minimum requirements in this document as well as dozens of others. US EPA's Center for Computational Toxicology will soon be releasing its Hazard Comparison Dashboard, which also includes a number of authoritative lists outlined in this guidance.

It is important to note that the primary criteria for endocrine disruption in the assessment of the minimum requirements for a safer alternative determination is based on review of authoritative lists. As of this writing, there are no standardized GHS criteria for the evaluation of endocrine disruption. As such, assessors should use authoritative lists. The main authoritative list that addresses endocrine disrupting chemicals is the EU Candidate List of Substances of Very High Concern (SVHC) for Authorization.

B. Apply Globally Harmonized System (GHS) of Classification and Labelling of Chemicals

Ensuring that an alternative AFFF formulation is safer requires going beyond the use of authoritative lists, as only a small subset of substances have been assessed and reviewed by government authorities for their addition to such lists. GHS provides internationally harmonized and standardized criteria for classifying substances and mixtures according to their human health, physical, and environmental hazards (UNECE 2019). Applying GHS criteria for a specific hazard endpoint allows assessors to review the current scientific evidence and categorize an alternative as Low, Moderate, or High concern for a given hazard. Those considered of "High" concern associated with specific hazard criteria among the minimum requirements should be *removed* from further consideration as a safer alternative.

It is important to note that although safety data sheets including GHS hazard statements, these sources should not be used as the primary means to evaluate the hazard profile of alternatives. SDSs are often incomplete and may not represent an updated understanding of toxicity information for the array of hazard endpoints. In addition, not all ingredients are required to be disclosed in an SDS making understanding of hazards more complicated. Lastly, in the US not all GHS recommended fields are required to be outlined in an SDS – neither ecological information nor disposal information sections are required by the US Occupational Safety and Health Administration.

As stated above, assessing the hazard of alternative AFFF formulations against GHS criteria requires knowledge of the full list of chemical ingredients, including intentionally added substances (present at any % in the concentration) and impurities/residuals (present at more than 100 ppm). Chemical ingredients are assessed against the minimum requirements for each hazard endpoint, with the exception of acute aquatic toxicity where the assessment supports the use of test data at the product level. This guidance adopts GreenScreen Certified™ provision for product-level testing for acute aquatic toxicity given challenges with evaluating surfactants – the vast majority of surfactants demonstrate inherent acute aquatic toxicity at the ingredient level. Using the product-level evaluation allows for considerations such as conditions of use, but should be revisited over time as new methodologies are developed for the evaluation of surfactants

As mentioned above, data must be available and reviewed for the minimum set of hazard endpoints in **Table 1**; *an absence of data is not demonstration of an absence of hazard.* Minimizing

regrettable substitutes requires avoiding the transition towards an alternative for which the hazards are not adequately understood. Sources for hazard data may include the scientific literature, peer reviewed industry data, and government reports and databases. Data may include:

- Measured data on the chemical ingredient following a test guideline
- Measured data on a suitable analog for the chemical ingredient following a test guideline
- Estimated data on the chemical ingredient or suitable analog chemical
- Additional new Approach Methodologies (NAMs), including *in vitro* or *in silico* data to support addressing data gaps and uncertainties

Nearly every assessment examining the hazard profile of chemical ingredients in a product formulation will encounter data uncertainties. Assessors should use their expert judgement to reconcile conflicting studies using a strength of the evidence approach to assign a GHS classification. As stated earlier in this guidance, only those assessors with a practicing knowledge for conducting hazard assessments and related toxicological expertise should undertake such state-of-evidence reviews. Significant investment in the development of NAMs to assess the human and ecological toxicity of chemicals has resulted in validated assays and data repositories to help predict potential hazards, which can be a useful resource to reconcile data uncertainties and data gaps. Appendix A outlines a range of methodologies and data tools for the hazard endpoints/classification that need to be assessed to meet minimum requirements for a safer alternative determination**.** *If any of the key hazard endpoints/classifications cannot be addressed due to significant data gaps or uncertainties, then the product should not be considered a safer alternative.*

GHS does not include criteria for persistence or bioaccumulation. These are crucial given concerns with AFFF. As such, this guidance adopts the standard used by GreenScreen® and includes additional assays beyond the aquatic environment, including soil/sediment and air impacts (CPA 2018). Evaluation of persistence and bioaccumulation should be used for establishing a PBT or vPvB classification per the minimum requirements. See Appendix B for classification criteria based on criteria established by the US EPA and under the REACH regulations in Europe.

Tables 2-11 below outline the authoritative lists, GHS and GreenScreen® criteria, and the associated classifications and/or thresholds for a determination of "high concern" related to the 10 hazard endpoints required for a determination of a *safer* alternative. **Table 12** outlines additional authoritative lists that should be reviewed.

TABLE 2. Authoritative Lists and GHS Criteria to Assess a High Concern for Carcinogenicity

These criteria assess whether a compound is known, presumed, or suspected to increase the incidence of cancer.	
	Exclusion Criteria If a substance in an AFFF alternative formulation is included on the following authoritative lists or carries the following GHS classifications, the AFFF alternative cannot be considered safer.
High Concern for Carcinogenicity	***Authoritative Lists*** US National Toxicology Program • Known to be a Human Carcinogen • Reasonably Anticipated to be a Human Carcinogen International Agency for Research on Cancer • Group 1 – Carcinogenic to humans • Group 2A – Probably carcinogenic to humans • Group 2B – Possibly carcinogenic to humans NIOSH Occupational Carcinogen List California Proposition 65 List of Chemicals Known to Cause Cancer EU Substances of Very High Concern (SVHC) Candidate List for Authorization EU Substances of Very High Concern (SVHC) Authorization List Harmonized GHS Classifications -- Annex VI of the EU Classification, Labeling and Packaging (CLP) Regulation • Category 1A: Substances known to have carcinogenic potential for humans • Category 1B: Substances presumed to have carcinogenic potential for humans • Category 2: Suspected human carcinogen
	GHS Criteria^* • Category 1A • Category 1B
^Use test methods as outlined in UNECE, GHS, Revision 9, 2021 * Although GHS Category 1A/1B is consistent with a classification of high concern for carcinogenicity across the methodologies used in this report, chemicals classified as GHS Category 2 carcinogens should be used with caution as data from available animal or mechanistic studies support concern for carcinogenicity, but sufficient data from epidemiological studies to verify effects in humans are lacking.	

TABLE 3. Authoritative lists and GHS Criteria to Assess a High Concern for Mutagenicity

These criteria are designed to assess whether a compound is known, presumed, or suspected to cause heritable mutations in the germ cells of humans.	
	Exclusion Criteria If a substance in an AFFF alternative formulation is included on the following authoritative lists or carries the following GHS classifications, the AFFF alternative **cannot** be considered safer.
High Concern for Mutagenicity	***Authoritative Lists*** EU Substances of Very High Concern (SVHC) Authorization List EU Substances of Very High Concern (SVHC) Candidate List for Authorization Harmonized GHS Classifications -- Annex VI of the EU Classification, Labeling and Packaging (CLP) Regulation • Category 1A: Substances known to induce heritable mutations in the germ cells of humans • Category 1B: Substances to be regarded as if they induce heritable mutations in the germ cells of humans
	GHS Criteria^ • GHS Category 1A • GHS Category 1B
^Use test methods as outlined in UNECE, GHS, Revision 9, 2021	

TABLE 4. Authoritative Lists and GHS Criteria to Assess a High Concern for Reproductive and/ or Developmental Toxicity

These criteria are designed to assess whether a compound is known, presumed, or reproductive and/or developmental toxicant. Reproductive toxicity may include alterations to the female or male reproductive organs, the related endocrine system, or pregnancy outcomes. The manifestation of such toxicity may include, but not be limited to, adverse effects on onset of puberty, gamete production and transport, reproductive cycle normality, sexual behavior, fertility, gestation, parturition, lactation, developmental toxicity, premature reproductive senescence, or modifications in other functions that are dependent on the integrity of the reproductive systems. Developmental toxicity includes adverse effects in the developing organism that may result from exposure prior to conception (either parent), during prenatal development, or postnatally to the time of sexual maturation. Adverse developmental effects may be detected at any point in the lifespan of the organism including: (1) death (2) structural abnormality, (3) altered growth, and (4) functional deficiency.	
High Concern for Reproductive and/or Developmental Toxicity	**Exclusion Criteria** If a substance in an AFFF alternative formulation is included on the following authoritative lists or carries the following GHS classifications, the AFFF alternative **cannot** be considered safer. ***Authoritative Lists*** California Proposition 65 List of Chemicals Known to Cause Cancer or Reproductive Harm EU Substances of Very High Concern (SVHC) Candidate List for Authorization Harmonized GHS Classifications -- Annex VI of the EU Classification, Labeling and Packaging (CLP) Regulation • Category 1A/B: Known to have produced an adverse effect on reproductive ability or capacity or on development in humans; presumed to produce an adverse effect on reproductive ability or capacity or on development in humans. US NIH – Reproductive & Developmental Monographs • Clear evidence of adverse effects – Reproductive ***GHS Criteria^*** • Category 1A/B
^Use test methods as outlined in UNECE, GHS, Revision 9, 2021	

TABLE 5. Authoritative Lists to Assess a High Concern for Endocrine Disruption

Given that no GHS criteria are available to assess endocrine disruption at this time, assessors should use authoritative lists.	
High Concern for Endocrine Disruption	**Exclusion Criteria** If a substance in an AFFF alternative formulation is included on the following authoritative lists or carries the following GHS classifications, the AFFF alternative **cannot** be considered safer. ***Authoritative Lists*** • EU Substances of Very High Concern (SVHC) Candidate List for Authorization • EU Substances of Very High Concern (SVHC) Authorization List

TABLE 6. Authoritative Lists and GHS Criteria to Assess a High Concern for Acute Mammalian Toxicity

These criteria evaluate the acute mammalian toxicity occurring following oral or dermal administration of a single dose of a substance, or multiple doses given within 24 hours, or an inhalation exposure of 4 hours. Animal LD_{50} (oral, dermal) or LC_{50} (inhalation) are used.	
High Concern for Acute Mammalian Toxicity	**Exclusion Criteria** If a substance in an AFFF alternative formulation carries the following GHS classifications, in conjunction with a high classification for persistence (Table 10) or a high classification for bioaccumulation (Table 11),the AFFF alternative **cannot** be considered safer. GHS Criteria^ for any route of exposure (oral, dermal, inhalation (vapor/gas), inhalation (dust/mist/fume), LD/LC_{50}: • Category 1/2 oral, dermal and inhalation. Fatal if swallowed; fatal in contact with skin; fatal if inhaled. • Category 3 dermal and inhalation. Toxic if swallowed; toxic in contact with skin; toxic if inhaled.
^Use test methods as outlined in UNECE, GHS, Revision 9, 2021	

TABLE 7. GHS Criteria to Assess a High Concern for Systemic Organ Toxicity (Repeated Dose)

These criteria evaluate mammalian toxicity using repeated doses and different routes of exposure. Such studies yield information regarding toxicity to specific target organs as well as understanding additional features of toxicity, such as delayed responses, cumulative effects and information on the reversibility/irreversibility of the effect among others.	
	Exclusion Criteria If a substance in an AFFF alternative formulation carries the following GHS classifications in conjunction with a high classification for persistence (Table 10) or a high classification for bioaccumulation (Table 11), the AFFF alternative cannot be considered safer.
High Concern for Systemic Organ Toxicity	GHS Criteria^ for any route of exposure (oral, dermal, inhalation (vapor/gas), inhalation (dust/mist/fume). Toxicity thresholds based on 90 day studies (tripled if 28-day studies conducted). • Category 1 oral, dermal and inhalation. Causes damage to organs through prolonged or repeated exposure • Category 2 oral, dermal and inhalation. May cause damage to organs through prolonged or repeated exposure
^Use test methods as outlined in UNECE, GHS, Revision 9, 2021	

TABLE 8. Authoritative Lists and GHS Criteria to Assess a High Concern for Acute Aquatic Toxicity

Acute aquatic toxicity refers to the intrinsic ability of a substance to invoke injury to an organism based on short-term aquatic exposures. Tests should be conducted at the product level.	
	Exclusion Criteria If a substance in an AFFF alternative formulation is included on the following authoritative lists or carries the following GHS classifications, the AFFF alternative cannot be considered safer.
High Concern for Acute Aquatic Toxicity	*Authoritative Lists* Harmonized GHS Classifications -- Annex VI of the EU Classification, Labeling and Packaging (CLP) Regulation • Category 1 [Hazard Statement]: Very toxic to aquatic life • Category 2 [Hazard Statement]: Toxic to aquatic life
	*GHS Criteria^* • Category 1 • Category 2
^Use test methods as outlined in UNECE, GHS, Revision 9, 2021	

TABLE 9. Authoritative Lists and GHS Criteria to Assess a High Concern for Chronic Aquatic Toxicity

Chronic aquatic toxicity refers to the intrinsic property of a substance to cause adverse effects to aquatic organisms during aquatic exposures which are determined in relation to the life cycle of the organism. Measures of degradability of the substance and bioaccumulation factors are also considered.	
	Exclusion Criteria If a substance in an AFFF alternative formulation is included on the following authoritative lists or carries the following GHS classifications, the AFFF alternative cannot be considered safer.
High Concern for Chronic Aquatic Toxicity	*Authoritative Lists* Harmonized GHS Classifications -- Annex VI of the EU Classification, Labeling and Packaging (CLP) Regulation • Category 1 [Hazard Statement]: Very toxic to aquatic life with long lasting effects • Category 2 [Hazard Statement]: Toxic to aquatic life with long lasting effects
	*GHS Criteria^* • Category 1 • Category 2
^Use test methods as outlined in UNECE, GHS, Revision 9, 2021	

TABLE 10. Authoritative Lists and GHS Criteria to Assess a High Concern for Persistence for consideration in a PBT or vPvB classification (See Appendix B)

Persistence criteria are based the length of time the chemical can exist in the environment before being degraded or destroyed (i.e., transformed) by natural processes. Degradation as the result of microbial action, hydrolysis, photolysis, and other relevant mechanisms should be considered.	
	Exclusion Criteria If a substance in an AFFF alternative formulation demonstrates the following, the AFFF alternative **cannot** be considered safer in connection with a PBT or vPvB classification.
High Concern for Persistence	*Authoritative Lists* Canadian Environmental Protection Act's Toxic Substances List EU Substances of Very High Concern (SVHC) Authorization List EU Substances of Very High Concern (SVHC) Candidate List for Authorization Stockholm Convention: List of Persistent Organic Pollutants
	*GreenScreen Criteria^* • Soil/sediment: ½ life > 60 days • Water: ½ life > 40 days • Air: ½ life > 2 days
^GreenScreen for Safer Chemicals Hazard Assessment Guidance: Standard for Persistence	

TABLE 11. Authoritative Lists and GHS Criteria to Assess a High Concern for Bioaccumulation for consideration in a PBT or vPvB classification (See Appendix B)

Bioacummulation criteria reflect the capacity for a compound to bioaccumulate as measured by the bioconcentration factor (BCF) and the bioaccumulation factor (BAF).	
	Exclusion Criteria If a substance in an AFFF alternative formulation is included on the following authoritative lists or carries the following GHS classifications, the AFFF alternative **cannot** be considered safer in connection with a PBT or vPvB classification.
High Concern for Bioaccumulation	*Authoritative Lists* Canadian Environmental Protection Act's Toxic Substances List EU Substances of Very High Concern (SVHC) Authorization List EU Substances of Very High Concern (SVHC) Candidate List for Authorization US EPA Persistent Bioaccumulative Toxic (PBT) Chemicals Covered by the TRI Program
	*GreenScreen Criteria^* • Bioaccumulation Factor (BAF): > 1,000 • Bioconcentration Factor (BCF): >1,000 • Log Octanol-Water Coefficient (K_{ow}): >4.5 • Monitoring Evidence: Evidence of the presence in humans or wildlife
^GreenScreen for Safer Chemicals Hazard Assessment Guidance: Standard for Bioaccumulation	

TABLE 12. Additional Authoritative Lists Required to Review (not incorporated into Tables 2-11, but in the OECD Guidance)

Exclusion Criteria If a substance in an AFFF alternative formulation is included on the following authoritative lists, the AFFF alternative **cannot** be considered safer
Montreal Protocol: List of Controlled Ozone-depleting Substances
Canadian Environmental Protection Act's Virtual Elimination List

COMPARATIVE EXPOSURE CONSIDERATIONS

The OECD guidance (2021) includes a section on the conduct of a comparative exposure assessment in conjunction with a hazard assessment to support identifying and selecting a safer alternative. Such an assessment focuses primarily on characterizing "reasonable and foreseeable exposure scenarios" and using physicochemical properties to understand the intrinsic exposure potential of specific substances in the product formulation. The assessment aims to address the question: Is the alternative preferable, equivalent to, or potentially worse than the priority chemical given the potential for exposure? The OECD guidance (2021) states that conducting such an assessment may not be necessary, "if the alternatives have similar forms, use patterns, and physical-chemical properties". In such circumstances, the potential for exposure is expected to be similar to the chemical of concern/product being replaced.

This guidance assumes that the routes of exposure for AFFF alternatives and the intrinsic physicochemical properties of alternatives will be similar to AFFF given similar use conditions and the need for a foam agent/mechanism of action being sought. However, current knowledge of existing PFAS-free alternatives suggests that more product will be needed to fulfill extinguishment requirements in comparison to AFFF. If there is a "high" concern for any of the hazard endpoints/classifications in **Table 1**, Part B, the alternative to AFFF cannot be considered safer, irrespective of exposure potential. If more product is used, the result of the hazard assessment still drives considerations for determinations of being safer.

However, if alternative mechanisms and product types are being pursued to replace the function of AFFF, it will be important to assess whether intrinsic physicochemical properties of the alternatives will change the potential for exposure. For example, if an alternative to AFFF has a significantly lower octanol-water coefficient (log K_{ow}) or higher water solubility compared to the priority chemical, differences in bioavailability should be expected, including increased exposure potential to ecological receptors. This is especially important if for example hazard endpoints in **Table 1** are ranked as "moderate" concern as opposed to of "high" concern. With a "moderate" classification of concern, the alternative is considered "safer", but additional controls to mitigate exposure should be pursued. Understanding the potential for exposure and associated routes of exposure will support such mitigation measures. Additionally, if alternative mechanisms and product types are being pursued resulting in changes in application technologies, potential changes in use and exposure potential should be examined.

Critical physicochemical properties used to estimate and compare the exposure potential for both human and ecological receptors are reviewed by Greggs et al. (2019) and the US National Research Council (2014). **Table 13** (next page) describes these properties with an explanation regarding exposure potential as outlined by the Interstate Chemicals Clearinghouse (2017) and informed by the US National Research Council's (2014) report. Some of these physicochcemical characteristics may be more useful than others in helping to consider the intrinsic exposure potential of alternative AFFF products.

TABLE 13. Physicochemical Properties that Inform Exposure Potential (IC2 2017)

Property	Reason	Guidelines
Volatility/vapor pressure	Volatility/vapor pressure influences how likely the chemical is to be found in the air or how likely it is to enter the body	<10-8 mmHg is considered likely to found in the air; <10-4 mmHg is considered to be more likely to enter the body
Molecular weight	Generally, as molecular weight and size increase, bioavailability decreases (leading to a lower toxicity potential)	>1,000 amu is less likely to be bioavailable
Solubility in water	Generally, a chemical that is highly soluble in water will be more bioavailable, and potentially toxic	
Log Kow	The log of the octanol-water coefficient is an indicator of potential for bioaccumulation, as well as bioavailability	>5 for mammals >4 for aquatic species
Boiling point	The boiling point helps to determine if the chemical will be a liquid or gas at a certain temperature	<25 C will be a gas at room temperature
Melting point	The melting point will determine if the chemical will be a solid or liquid at a certain temperature	<25 C will be a liquid at room temperature
Density/specific gravity	Has implications for where the chemical might partition when with other liquids or gases	
pH	A measure of free hydrogen. Has implications for water solubility and potential damage to cells	For certain products, a pH of >2 and <11.5 is safest for eyes and skin
Corrosivity	Associated with the ability to gradually destroy materials by chemical reaction	GHS criteria used to determine level of concern. Typically, the more extreme the pH (either high or low), the more corrosive the substance will be to the eye, skin, respiratory system, etc.
Environmental partitioning	A measure of how easily molecules or salts will break apart under certain conditions (primarily in solution)	The higher the constant (K_d), the more likely the molecules or salts will break apart
Use characteristics (binding properties) or synergistic effects	Other properties that can help determine the state of the chemical in the environment and biological compartments or interactions with other chemicals found in the environment	The acid dissociation constant (pKa) is used to help identify availability of chemicals to bind to one another. pKas of concern typically range between <3 (acids) and >11 (bases). Synergistic effects identify how other chemicals may impact availability of the chemical of concern. For example, dimethyl sulfoxide (DMSO) easily enters skin. Chemicals dissolved in DMSO can be more biologically available than chemicals dissolved in other solvents

GOING BEYOND MINIMUM REQUIREMENTS

As stated earlier, criteria in this guidance are considered *the minimum requirements for making a safer alternative determination.* Going beyond the minimum is recommended *wherever and whenever possible* to reduce the likelihood that an alternative to AFFF will result in unintended consequences to the environment, workers, and the public more broadly. Where data are available for a broader range of hazard criteria, they should be evaluated and considered. Depending on the context, stakeholders and decision makers may also seek to make additional hazard criteria part of the minimum requirements.

Table 14 outlines hazard criteria that assessors could evaluate to go "beyond the minimum" to support a more comprehensive understanding of hazards associated with an alternative to AFFF. Although a finding of "high concern" related to any one of the hazard endpoints may warrant a decision to still use the alternative, such a finding is important to enhance understanding of risk mitigation measures that need to be implemented while products that are more benign are developed. Going "beyond the minimum" includes a more comprehensive assessment of sustainability metrics as well, such as upstream or downstream chemical or product impacts, resource depletion, circularity, energy use, climate change potential, environmental justice considerations, and worker and community health. Hazard endpoints outlined in **Table 14** are derived from OECD's 2021 guidance. The OECD guidance (2021) also includes a section on broader sustainability metrics that should be considered and added to over time.

TABLE 14. Beyond the Minimum: Additional Hazard Criteria to Consider in Comprehensive Hazard Assessments

Human Health Hazards	Environmental Hazards	Physical Hazards
• Aspiration hazard • Endocrine Disruption • Neurotoxicity • Respiratory and skin sensitization • Serious eye damage/eye irritation • Skin corrosion/irritation	• Mobility • Wildlife toxicity • Eutrophication • Greenhouse gas emissions, ozone depletion, waste generation, and other sustainability endpoints	• Corrosivity • Explosivity • Oxidizing properties • Pyrophoric properties • Self-reactivity • Other physical hazards: aerosols, gases under pressure, organic peroxides, ergonomics, vibration, noise, etc.
OECD 2021: Guidance on Key Considerations for the Identification and Selection of Safer Chemical Alternatives		

Beyond the Minimum for AFFF Substitutes

Priority considerations for an evaluation of AFFF substitutes that go beyond an assessment of minimum requirements for a safer alternative determination, includes consideration of skin or respiratory sensitization, mobility, the additional data sources for a more comprehensive evaluation of endocrine disruption and adoption of more stringent assessment criteria for aquatic toxicity and environmental fate.

Skin and Respiratory Sensitization

Skin and respiratory sensitization are two critical hazard endpoints to consider for AFFF alternatives, especially given a likelihood of both inhalation and dermal exposure to fire and rescue personnel using the product. Once sensitized, very low levels of exposure can induce an

allergic response and some workers will require complete removal from the work setting to control exacerbations of contact dermatitis or asthma – manifestations of allergic sensitization. Data gaps are often prominent for respiratory sensitization, however, as data supporting GHS classifications are limited to direct evidence in humans rather than data derived from animal models.

Mobility

Current efforts are underway to establish criteria for "mobile" substances, particularly those that are considered, "very persistent and very mobile" or "persistent, mobile, and toxic" (Arp et al. 2017; Reemstma et al. 2016). "Mobility" as a hazard criterion reflects intrinsic physicochemical properties that enable substances to easily transport through aquatic systems, including rivers and groundwater and potentially impact drinking water sources. Drinking water treatment processes may not be able to control such substances, which may survive treatment technologies including ozonation and chlorination (Arp et al. 2017). If the same substances have toxic properties, this could lead to serious health consequences. As of this writing, there is a lack of authoritative criteria for "mobility" as connected with persistence as well as with toxic classifications. However, this is a fast-moving topic, and governments, such as those in Europe, are likely to establish such criteria in the near future (Arp et al. 2019). Given that PFAS in AFFF are considered highly mobile substances, this criterion will be important to consider when evaluating substitutes.

Additional Endocrine Disruption Data

Despite being of concern for human health and the environment, the OECD guidance (2021) did not include endocrine disruption as part of the minimum requirements for a safer alternative determination because of the lack of comprehensive testing and data availability on this endpoint and a lack of GHS criteria for standardized assessment purposes. In this guidance, endocrine disruption is considered only in the review of authoritative lists because of the absence of GHS criteria at the time of this writing. However, evaluation of available data on endocrine activity for AFFF alternatives should be pursued wherever possible given increasing scientific and regulatory concern and the fact that the use context will result in an exposure to aquatic ecosystems, including possibly drinking water systems.

Consideration of More Stringent Aquatic Toxicity and Environmental Fate Criteria

AFFF products and their alternatives are applied directly in the environment. As such, they bypass sewage treatment systems which enhance chemical degradation prior to release to sensitive aquatic environments. To go beyond the minimum requirements for aquatic toxicity and environmental fate criteria (bioaccumulation and persistence), assessors should consider using US EPA's Safer Choice criteria for direct release products (US EPA 2021). The Safer Choice Program has tightened its standard beyond those outlined by GHS for acute and chronic aquatic toxicity for direct release products. This standard has also been adopted by GreenScreen Certified™ Standard for Firefighting Foam (CPA 2021) for its gold and platinum-level certifications, given that AFFF products are used in the ambient environment near streams, rivers and oceans.

Consideration of Additional Sustainability Criteria

The minimum requirements do not include additional sustainability criteria that are ultimately critical for that trade-offs associated with a chemical choice are considered in the context of a product's lifecycle. The US DoD Sustainability Analysis Guidance contains sustainability endpoints that are important to consider, including climate change, ecosystem quality, and resource availability (US DoD 2020).

CONCLUSION

Transitioning away from the use of AFFF requires ensuring that alternatives are indeed, safer. Use of the minimum criteria for making a safer alternative determination as outlined in this guidance will support consistency across decision makers with regards to what safer means in practice. As data availability and standards for "safer" evolve, so must the minimum requirements. As such, this guidance should be revisited and enhanced over time to support the use and adoption of inherently safer and more sustainable alternatives to AFFF. The approach used in this guidance, adapting the OECD guidance for the specific case of AFFF, can help support consistent review of alternatives for other chemicals and applications of concern, while supporting the transition to safer alternatives.

REFERENCES

Arp HPH, Brown TN, Berger U, Hale SE. 2017. Ranking REACH registered neutral, ionizable and ionic organic chemicals based on their aquatic persistency and mobility. Environ Sci Process Impacts. 19(7):939-955. doi: 10.1039/c7em00158d.

Arp HPH and Hale SE. 2019. REACH: Improvement of guidance methods for the identification and assessment of PMT/vPvM substances. On behalf of the German Environment Agency. June 28. Accessed September 15, 2021

ATSDR [Agency for Toxic Substances and Disease Registry]. 2021. Toxicological profile for Perfluoroalkyls. Atlanta, GA: US Department of Health and Human Services, Public Health Service. Accessed September 14, 2021.

ASTSWMO [Association of State and Territorial Solid Waste Management Officials]. 2015. Perfluorinated Chemicals (PFCs): Perfluorooctanoic Acid (PFOA) & Perfluorooctane Sulfonate (PFOS): Information Paper. Accessed April 23, 2021.

Bureau Veritas North America. 2021. PFAS Analysis Toolkit: LC/MS/MS, Total Oxidizable Precursors (TOPS) and Total Organic Fluorine (TOF). February. Accessed July 30, 2021.

CCR [California Code of Regulations]. 2013. Title 22, Division 4.5, § 69501.1. Definitions. Accessed July 30, 2021.

CPA [Clean Production Action]. 2018. GreenScreen for Safer Chemicals Hazard Assessment Guidance V 1.4. January. Accessed July 30, 2021.

CPA [Clean Production Action]. 2021. GreenScreen Certified™ Standard for Fire Fighting Foam V 2.1. Accessed July 30, 2021.

Dykes K. 2021. Memo: Order Pursuant to General Statutes § 22a-6: Identification of an alternative fluorine-free firefighting foam. June 30. Accessed September 14, 2021.

ECHA [European Chemicals Agency]. Substances of Very High Concern Identified. Accessed July 30, 2021 *[Note this definition is outlined in Article 57 of the REACH regulation - (EC) No 1907/2006]*

ECHA [European Chemicals Agency]. 2019. Annex XV Restriction Report Proposal for a Restriction: Substance Name(s): Octamethylcyclotetrasiloxane (D4), Decamethylcyclopentasiloxane (D5), Dodecamethylcyclohexasiloxane (D6). January 11. Accessed July 30, 2021.

Greggs W, Burns T, Egeghy P, Embry MR, Fantke P, Gaborek B, Heine L, Jolliet O, Lee C, Muir D, Plotzke K, Rinkevich J, Sunger N, Tanir JY, Whittaker M. 2019. Qualitative approach to comparative exposure in alternatives assessment. Integr Environ Assess Manag. Nov;15(6):880-894. doi: 10.1002/ieam.4070.

Houge, C. 2021. Tight EU regulation of three siloxanes recommended. D4, D5, and D6 are persistent, bioaccumulative, and toxic, European Chemicals Agency says. Chemical and Engineering News. April 15. Accessed July 30, 2021.

Fenton SE, Ducatman A, Boobis A, DeWitt JC, et al. 2021. Per- and Polyfluoroalkyl Substance Toxicity and Human Health Review: Current State of Knowledge and Strategies for Informing Future Research. Environ Toxicol Chem. Mar;40(3):606-630. doi: 10.1002/etc.4890.

IC2 [Interstate Chemicals Clearinghouse] 2017. Alternatives Assessment Guide Version 1.1. Accessed September 15, 2021.

NDAA [National Defense Authorization Act]. 2019. National Defense Authorization Act for Fiscal Year 2020. S. 1790 – 11^{6th} Congress (2019-2020). December 20. Accessed May 20, 2021 at:

NDAA [National Defense Authorization Act]. 2021. National Defense Authorization Act for Fiscal Year 2021. H.R. 6395 – 116th Congress (2019-2020). Jan 1. December 20. Accessed May 20, 2021 at:

National Institute for Occupational Safety and Health. 2021. Occupational Carcinogen List. Accessed July 30, 2021.

OECD [Organization for Economic Cooperation and Development]. 2021. Guidance on Key Considerations for the Identification and Selection of Safer Chemical Alternatives. Series on Risk Management No. 60. Accessed September 14, 2021.

Peshoria S, Nandini D, Tanwar RK, Narang R. 2020. Short-chain and long-chain fluorosurfactants in firefighting foam: a review. *Environ Chem Let.* 18(4):1277. doi:10.1007/s10311-020-01015-8.
RCW [Revised Code of Washington]. 2020. Washington Pollution Prevention for Healthy People and Puget Sound Act. RCW 70A.350.010 [Definitions]. Accessed July 30, 2021.

Reemtsma T, Berger U, Arp HP, Gallard H, Knepper TP, Neumann M, Quintana JB, Voogt P. 2016. Mind the Gap: Persistent and Mobile Organic Compounds-Water Contaminants That Slip Through. Environ Sci Technol. Oct 4;50(19):10308-10315. doi: 10.1021/acs.est.6b03338.

Ross I. 2019. Is the burst of the AFFF bubble a precursor to long term environmental liabilities? International Airport Review. July 29. Accessed September 14, 2021.

Safer Products for Washington. 2021. Safer Products for Washington | Phase 3 Working Draft Criteria for Safer. Washington Department of Ecology. Accessed April 26, 2022.

Safer States. Bill Tracker. Accessed September 14, 2021.

State of Washington, Department of Ecology. Safer Products for Washington | Phase 3 Working Draft Criteria for Safer. Accessed July 30, 2021.

Soares A, Guieysse B, Jefferson B, et al. Nonylphenol in the environment: a critical review on occurrence, fate, toxicity and treatment in wastewaters. 2008. Environ Int. Oct;34(7):1033-49. doi: 10.1016/j.envint.2008.01.004.

UNECE [United Nations Economic Commission for Europe]. 2021. GHS (Rev.9) (2021). Accessed April 26, 2022.

US DoD [United States Department of Defense], Under Secretary of Defense for Acquisition and Sustainment. 2018. Alternatives to Aqueous Film Forming Foam – Report to Congress. Accessed September 14, 2021.

US DoD [United States Department of Defense]. 2020. Sustainability Analysis Guidance: Integrating Sustainability into Acquisition Using Life Cycle Assessment. Version 7.0. Accessed April 26, 2022.

US EPA [United States Environmental Protection Agency]. 2005. Aquatic Life Ambient Water Quality Criteria - Nonylphenol. Final. EPA-822-R-05-005. Office of Water, Washington, DC. Accessed September 15, 2021.

US EPA [United States Environmental Protection Agency]. 2009. DfE Alternatives Assessment for Nonphenol Ethyoxlates. May. Accessed September 15, 2021.

US EPA [United States Environmental Protection Agency]. 2011. Design for the Environment Program Alternatives Assessment Criteria for Hazard Evaluation Version 2.0. August. Accessed July 30, 2021.

US EPA [United States Environmental Protection Agency]. 2012. EPA's Safer Choice Program Master Criteria for Safer Ingredients. Office of Pollution Prevention & Toxics. Accessed July 30, 2021.

US EPA United States Environmental Protection Agency]. 2021. Criteria for environmental toxicity and fate for chemicals in direct release products. Accessed July 30, 2021.

US NRC [United States National Research Council]. 2014. A framework to guide selection of chemical alternatives. Washington (DC): National Academies Press. Accessed April 23, 2021.

US NRC [United States National Research Council]. 2014b. A framework to guide selection of chemical alternatives. Washington (DC): National Academies Press. P.13. Accessed April 23, 2021.

US OSHA [United States Occupational Safety and Health Administration]. Transitioning to Safer Chemicals: A Tookit for Employers. Basics of Informed Substitution and Alternatives Assessment. Accessed July 30, 2021.

Wood, Ramboll and Cowi. 2018. The Use of PFAS and Fluorine-Free Alternatives in Fire-Fighting Foams. Report for European Commission and the European Chemicals Agency. June. Accessed July 30, 2021.

APPENDIX A: NAMS FOR EVALUATING HAZARD ENDPOINTS

Carcinogenicity

- QSAR methods such as the US EPA's OncoLogic™ tool to estimate the carcinogenicity potential of a chemical
- The *in vitro* Ames test uses *Salmonella typhimurium* bacteria to identify potential chemical carcinogens, using mutagenicity as an endpoint

Mutagenicity

- OECD TG No. 471: Bacterial Reverse Mutation Test Evaluates to evaluate mutagenicity in bacterial cells
- OECD TG No. 473: *In Vitro* Mammalian Chromosome Aberration Test to evaluate chromosomal effects in either human or rodent cells
- OECD TG No. 476: *In Vitro* Mammalian Cell Gene Mutation Tests using the Hprt and xprt genes to evaluate gene mutations in either human or rodent cells
- OECD TG No. 487: *In Vitro* Mammalian Cell Micronucleus Test to evaluate chromosomal effects in either human or rodent cells
- OECD TG No. 490: *In Vitro* Mammalian Cell Gene Mutation Tests Using the Thymidine Kinase Gene to evaluate gene mutations in either human or rodent cells

Reproductive toxicity

- QSAR methods as described in Basant et al., 2016, *Toxicology Research* (doi: 10.1039/c6tx00083e)

Developmental toxicity

- QSAR methods as described in Marzo et al., 2016, Methods in Molecular Biology (doi: 10.1007/978-1-4939-3609-0_8)

Persistence

- QSAR methods such as the EPI Suite™ KOWWIN™ program to estimate the log octanol-water partition coefficient (log KOW)

Bioaccumulation

- QSAR methods such as the EPI Suite™ BCFBAF™ program to estimate fish bioconcentration factor

Chronic aquatic toxicity

- QSAR methods such as the EPI Suite™ ECOSAR™ program to estimate long-term or delayed aquatic toxicity in fish aquatic invertebrates, and green algae
- US EPA Whole Effluent Toxicity (WET) Method 1000.0: Fathead Minnow, Pimephales promelas, Larval Survival and Growth; Chronic Toxicity Test
- US EPA Whole Effluent Toxicity (WET) Method 1001.0: Fathead Minnow, Pimephales promelas, Larval Survival and Teratogenicity; Chronic Toxicity
- US EPA Whole Effluent Toxicity (WET) Method 1002.0: Daphnid, Ceriodaphnia dubia, Survival and Reproduction Test; Chronic Toxicity
- US EPA Whole Effluent Toxicity (WET) Method 1003.0: Green Alga, Selenastrum capricornutum, Growth Test; Chronic Toxicity

Acute aquatic toxicity

- QSAR methods such as the EPI Suite™ ECOSAR™ program to estimate short-term aquatic toxicity in fish aquatic invertebrates, and green algae
- OECD TG No. 201: Freshwater Alga and Cyanobacteria, Growth Inhibition Test to evaluate toxicity to algae

- OECD TG No. 202: *Daphnia sp.* Acute Immobilization test to evaluate toxicity to freshwater invertebrates
- OECD TG No. 211: *Daphnia magna* Reproduction Test to evaluate reproductive effects in freshwater invertebrates
- OECD TG No. 212: Fish, Short-term Toxicity Test on Embryo and Sac-Fry Stages to evaluate toxicity to fish development.
- OECD TG No. 218: Sediment-Water Chironomid Toxicity Using Spiked Sediment to evaluate toxicity to sediment-dwelling invertebrates
- OECD TG No. 219: Sediment-Water Chironomid Toxicity Using Spiked Water to evaluate toxicity to sediment-dwelling invertebrates
- OECD TG No. 221: *Lemna sp.* Growth Inhibition Test to evaluate toxicity to freshwater aquatic plants of the genus *Lemna* (duckweed)
- OECD TG No. 222: Earthworm Reproduction Toxicity Test (*Eisenia fetida/Eisenia andrei*) to evaluate reproductive effects in soil invertebrates
- OECD TG No. 225: Sediment-Water Lumbriculus Toxicity Test Using Spiked Sediment to evaluate toxicity of sediment-associated chemicals endobenthic living organisms
- OECD TG No. 233: Sediment-Water Chironomid Life-Cycle Toxicity Test Using Spiked Water or Spiked Sediment to evaluate chronic toxicity to the life-cycle of sediment-dwelling freshwater dipteran Chironomus species
- OECD TG No. 235: Chironomus sp., Acute Immobilisation test to evaluate acute toxicity (immobilisation) to chironomids
- OECD TG No. 236: Fish Embryo Acute Toxicity (FET) to evaluate toxicity to fish using zebrafish embryos
- OECD TG No. 238: Sediment-Free *Myriophyllum spicatum* Toxicity Test to evaluate toxicity to a submerged, rooted macrophyte species (water milfoil)
- OECD TG No. 239: Water-Sediment *Myriophyllum spicatum* Toxicity Test to evaluate toxicity to a submerged, rooted macrophyte species (water milfoil)
- OECD TG No. 242: *Potamopyrgus antipodarum* Reproduction Test to evaluate reproductive toxicity to the mudsnail
- OECD TG No. 243: *Lymnaea stagnalis* Reproduction Test to evaluate reproductive toxicity to a freshwater snail
- OECD TG No. 319A2: Determination of In Vitro Intrinsic Clearance Using Cryopreserved Rainbow Trout Hepatocytes (RT-HEP) to evaluate the capacity for fish (rainbow trout) to metabolically clear chemical via the liver. This in vitro clearance measurement can be applied to models to predict chemical bioconcentration in fish (BCF). The application is described in the guidance document (see OECD Guidance Document [GD] No. 280 under "Other Useful Information" in Appendix B
- OECD TG No. 319B2: Determination of In Vitro Intrinsic Clearance Using Rainbow Trout Liver S9 Sub-Cellular Fraction (RT-S9) to evaluate the capacity for fish (rainbow trout) to metabolically clear chemical via the liver. This in vitro clearance measurement can be applied to models to predict chemical bioconcentration in fish (BCF). The application is described in the guidance document (see OECD Guidance Document [GD] No. 280 under "Other Useful Information" in Appendix B

APPENDIX B: CRITERIA FOR THE IDENTIFICATION OF PERISTENCE, BIOACCUMULATIVE AND TOXIC SUBSTANCES AND VERY PERSISTENT AND VERY BIOACCUMULATIVE SUBSTANCES

PBT criteria as defined by US EPA (as described in US EPA's PBT Profiler documentation)

Persistence

a) Half-life in water, soil, and sediment >60 days; or
b) Half-life in air > 2 days

Bioaccumulation

a) BCF ≥ 1,000

Toxic

a) High concern: Fish chronic value ChV <0.1mg/L. *Note: when EPA reviews when EPA reviews a chemical for its PBT characteristics, they also consider potential human health effects due to environmental exposure in addition to aquatic toxicity.*

PBT criteria as defined under EU's Registration, Evaluation and Authorization of Chemicals (REACH). Annex XIII

Persistence:

A substance fulfills the persistence criterion (P) in any of the following situations:

a) The degradation half-life in marine water is higher than 60 days
b) The degradation half-life in fresh or estuarine water is higher than 40 days
c) The degradation half-life in marine sediment is higher than 180 days
d) The degradation half-life in fresh or estuarine water sediment is higher than 120 days
e) The degradation half-life in soils higher than 120 days

Bioaccumulation:

A substance fulfills the bioaccumulation (B) when the bioconcentration factor (BCF) in aquatic species is higher than 2,000.

Toxic:

A substance fulfils the toxicity criterion (T) in any of the following situations:

a) The long-term no-observed effect concentration (NOEC) or EC10 for marine or freshwater organisms is less than 0.01 mg/l
b) The substance meets the criteria for a GHS classification as carcinogenic (category 1A or 1B), germ cell mutagenic (category 1A or 1B), or toxic for reproduction (category 1A)
c) There is other evidence of chronic toxicity, as identified by the substance meeting the criteria for classification: specific target organ toxicity after repeated exposure (category 1 or 2)

vPvB criteria as defined under EU's Registration, Evaluation and Authorization of Chemicals (REACH).

Persistence:

A substance fulfils the 'very persistent' criterion (vP) in any of the following situations:

(a) the degradation half-life in marine, fresh or estuarine water is higher than 60 days
(b) the degradation half-life marine, fresh or estuarine water sediment is higher than 180 days
(c) the degradation half-life n soil is higher than 180 days

Bioaccumulation:

A substance fulfills the bioaccumulation (B) when the bioconcentration factor (BCF) n aquatic species is higher than 5,000.

Sustainable Chemistry Catalyst

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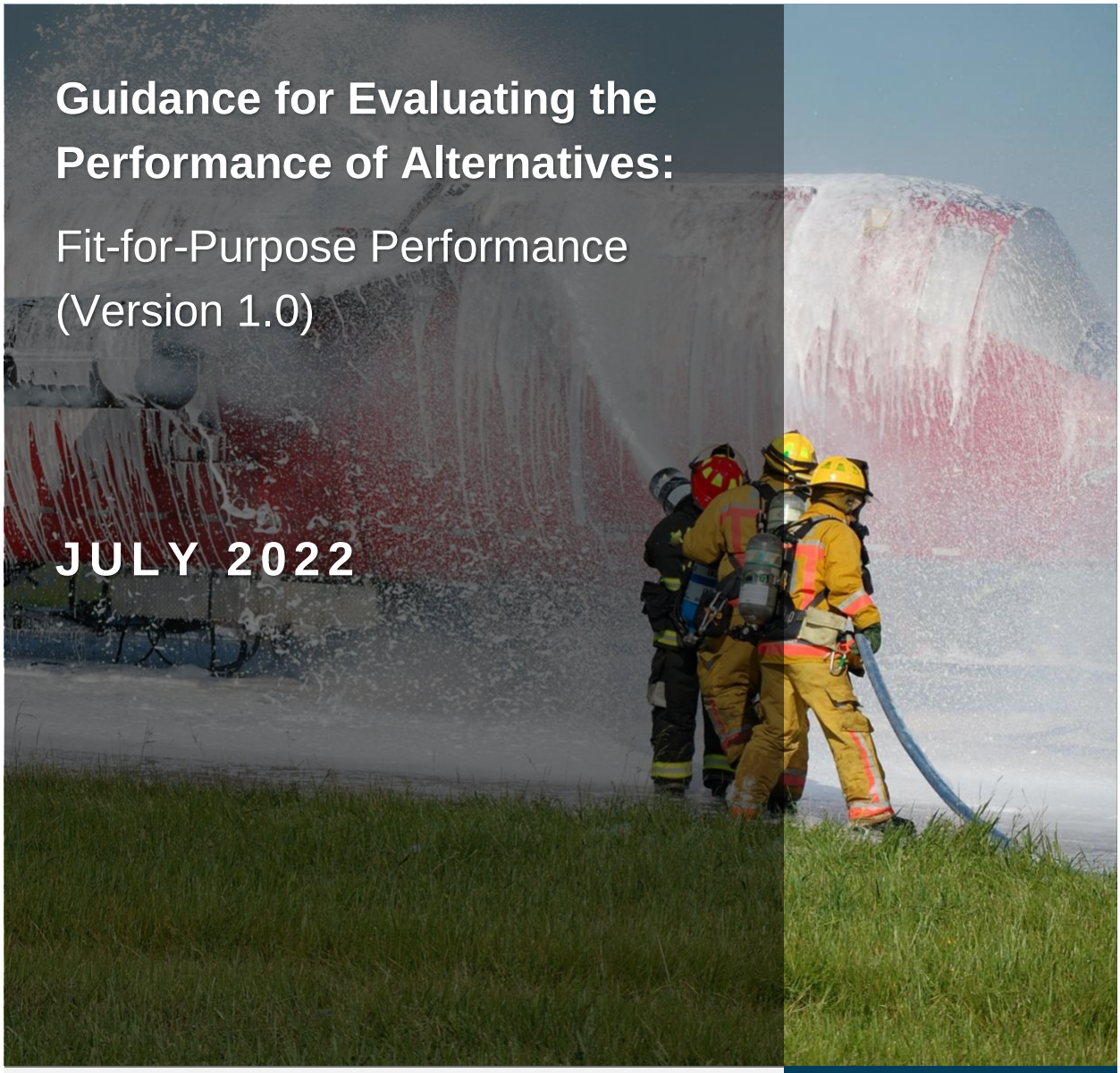
Annex D: Report – *Guidance for Evaluating the Performance of Alternatives: Fit-for-Purpose Performance (Version 1.0)*

University of Massachusetts Lowell

Guidance for Evaluating the Performance of Alternatives:

Fit-for-Purpose Performance (Version 1.0)



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Sustainable Chemistry Catalyst

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The Lowell Center for Sustainable Production at UMass Lowell is a leading academic center for action-oriented research, policy development, and collaborative initiatives focused on eliminating hazards in products, workplaces, and communities by promoting the development, evaluation and adoption of safer and sustainable chemistries, materials, and products.

For more information, visit www.uml.edu/research/lowell-center.

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Established by the Massachusetts Toxics Use Reduction Act (TURA) of 1989, TURI at UMass Lowell collaborates with businesses, community organizations and government agencies to reduce the use of toxic chemicals, protect public health and the environment and promote the competitiveness of Massachusetts businesses.

For more information, visit www.turi.org.

ABOUT

The Sustainable Chemistry Catalyst is an independent research and strategy initiative, based at the Lowell Center for Sustainable Production at UMass Lowell, that is focused on accelerating the transition to safer, more sustainable chemistry through research and analysis, and stakeholder engagement with scientists, policymakers, and commercial actors.

The Catalyst works to understand barriers and opportunities to commercialization of safe and sustainable chemistry, identifies model solutions and strategies, develops methods to evaluate safer alternatives, and builds a community of expertise to support the transition to safer, more sustainable chemistries and technologies.

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LIST OF ABBREVIATIONS

AFFF	Aqueous Film Forming Foam
IC2	Interstate Chemicals Clearinghouse (Alternatives Assessment Guide)
MILSPEC	Military Performance Specification MIL-PRF-24385F(SH)
NRC	National Research Council (Framework on the Selection of Chemical Alternatives)
PFAS	Per- and polyfluoroalkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
QPL	Qualified Product List
US DoD	United States Department of Defense

EXECUTIVE SUMMARY

This guidance is intended to support decision-making by governments, businesses, and others associated with the evaluation of performance in the conduct of an alternatives assessment. It emphasizes a focus on *fit-for-purpose* performance, a strategy for assessing performance based on application-specific contexts. This guidance builds on and broadens the thinking around performance when evaluating and choosing safer alternatives and draws primarily from two well-established alternatives assessment frameworks: The Interstate Chemicals Clearinghouse (IC2) Alternatives Assessment Guide and the National Research Council (NRC) Framework on the Selection of Chemical Alternatives.

Regrettable substitutions can occur if specific performance metrics cannot be achieved under real-world conditions. However, performance can also be a barrier to the adoption of safer and available alternatives if evaluations are based around a single "best in class" performance metric, require performance through specific mechanisms, or require consideration of adoption feasibility as part of the performance evaluation. This guidance was developed to help minimize extended debates over whether alternatives perform equally to the incumbent chemistry. A fit-for-purpose performance approach underscores the importance of evaluating whether the function of the chemical, material, product, or process of concern achieves sufficient performance, recommends using a range of acceptable thresholds, and acknowledges important considerations around tradeoffs with environmental health and safety performance.

Six guiding considerations shape this performance evaluation process. Depending on the context, some considerations may be revisited more than once, as the evaluation is an iterative process. The amount of information and testing required to address each consideration is likely case specific. These guiding considerations balance the need for detailed key performance criteria but include flexibility for a broad range of alternatives that achieve sufficient performance for the intended application. They include:

1. **Determine the *function* of the chemical/material/product/process of concern for the specific application and understand this function within the production chain.**
    - *What is the function of the chemical, and is it necessary?*
    - *If upstream processes are changed, is the function of the chemical/material/product/process of concern needed?*
    - *If the function is still needed, is it changed in any way?*
2. **Define the *application*-specific scenario(s) in which the substance of concern is used and identify alternatives that are suitable for that particular purpose.**
    - *For what application(s) is the chemical/material/product/process of concern being used?*
    - *Do alternatives under consideration meet the functional performance need for the application(s) (even if they are used in different ways for other applications), perhaps with minor adjustments?*
3. **Establish and/or use performance standards that have been developed *independent* of the existing chemicals/materials/products/processes of concern (as much as possible) and adjust them based on available alternatives or alternatives on the horizon.**
    - *What are the technical/standard performance requirements that the potential alternatives need to meet? Are there regulatory, industrial sector, customer, and/or other specification requirements?*

- *Were performance standards built around specific existing technologies or mechanisms of action? If so, can new iterations of the standard be adopted that are more function-oriented?*

4. **Develop and use a *range* of performance standard benchmarks, from "inadequate" to "sufficient" to "best in class" to evaluate the alternative for the specific application(s).**
    - *Have potential alternatives already been eliminated based on binary performance criteria (meets or does not meet a gold standard) that should be reconsidered?*
    - Define a range of fit-for-purpose performance criteria that encompass "inadequate", "sufficient", and "best in class" benchmarks for the application. *How do different alternatives compare within this range?*
5. **Consider technical performance *separately* from technical feasibility (feasibility of adoption) of potential alternatives.**
    - *When only performance is considered (and not the feasibility of their adoption), what are the alternative solutions that can be assessed and compared?*
    - *What additional process/product modifications may be needed to increase the feasibility of adoption?*
6. **Consult *stakeholders* to determine acceptable tradeoffs between performance results and other elements such as environmental health and safety.**
    - Hold discussions with an appropriately diverse group of stakeholders on the tradeoffs that would occur for each alternative under consideration. *Which tradeoffs are acceptable under various application-specific scenarios and chemical exposure scenarios?*
    - *What alternatives under consideration best minimize potential trade-offs between performance and environmental and health and safety concerns?*

These considerations are elaborated in the guidance itself, and a version that differentiates the considerations established by the IC2 and NRC frameworks from the considerations proposed here can be found in the appendix. Throughout this guidance, a case example on aqueous film-forming foam (AFFF) in military land-based firefighting applications is used to illuminate different aspects of performance. The case study is built from interviews conducted with firefighting experts as part of a Department of Defense (DoD) sponsored project to improve the use of alternatives assessment in evaluating alternatives to AFFF. Ultimately, the performance evaluation will form part of a broader alternatives assessment process that considers hazard, comparative exposure, economic feasibility, and other factors to compare alternative solutions to replace the chemical, material, product, or process of concern.

INTRODUCTION AND CONTEXT

The performance of a product or process is a priority for manufacturers and consumers. When a chemical, material, product, or process is identified as problematic for environmental or human health, manufacturers must evaluate replacement options with regards to their ability to meet specific performance requirements and expectations (in addition to other requirements). Alternatives assessment is a critical tool to support the transition to safer and effective alternatives, minimizing the potential for regrettable substitutions. The approach has been used by governments, businesses, and other organizations to evaluate potential chemical and process/product redesign options to arrive at a safer solution. Alternatives assessments include evaluation of performance, economic feasibility, hazard, and exposure, but may also include components on social impact and life cycle considerations.

This guidance focuses on the performance component of an alternatives assessment, the traditional approaches to which have often constrained a wide range of options as they were not conceived in the context of supporting the transition to safer alternatives. These limits include tying performance of potential alternatives to specific performance metrics (which may be rigid and unnecessary for many applications), comparing performance of potential alternatives to the incumbent chemical/material/ product/process of concern, or including feasibility of adoption as integral to the assessment of performance. As a result, lower or different performance is often used as an argument against transitioning to safer alternatives. For example, the European Chemicals Agency (ECHA) authorized the continued use of lead chromate – derived from lead, a neurotoxin, and hexavalent chromium, a carcinogen – in pigments used in road markings for years as it was argued by product manufacturers that no other replacement could provide the bright color needed on road surfaces to prevent vehicle accidents, though it had already been phased out in other places. This may be due to a limited view of what constitutes an "alternative" or how performance is defined. Often, specific performance criteria and acceptable types of options are dictated by standards. Other times, policies may note the need for equal performance; and still other times, there may be a resistance to performance changes that necessitate changes in process, customer education, or worker retraining.

This guidance outlines critical questions that can be used to reshape the evaluation of performance in the alternatives assessment process. In the guidance, a "fit-for-purpose" focus is emphasized, defined as *an alternative solution that achieves sufficient performance for a specific context or application, even though it may perform differently in other applications*.

The first step for evaluating the performance of potential alternatives is to determine the *function* of the existing chemical/material/product/process of concern in the application. This function can range from simple to complex, with the chemical/material/ product/process of concern involved in several different functions required to achieve the desired product or process level outcome. Determining these details will help an assessor appropriately determine whether a safer alternative can provide "sufficient" performance for the intended application, a concept discussed in more detail below. If no alternative can provide sufficient performance, then new options may need to be developed.

For chemicals/materials/products/processes of concern that have been in use over decades, there is often an assumption that the key performance criteria are immutable. However, as technologies and understanding advance over time, these criteria should be reexamined and reset as appropriate, opening more opportunities to evolve expectations about functional needs. This process requires first *letting go of the expectation that an alternative should demonstrate equivalent performance compared to the chemical of concern it is intending to replace*. One of the most important – and most difficult – responsibilities of an alternatives assessment practitioner is to challenge manufacturers and specifiers to reevaluate performance expectations and key performance indicator setpoints. The goal is to look

at the process with a willingness to innovate and identify performance criteria that fit the purpose of the application.

This guidance builds on existing government and industry approaches for evaluating performance for assessing alternative options as well as the Interstate Chemicals Clearinghouse (IC2) (Interstate Chemicals Clearinghouse 2017) and National Research Council (NRC) (National Research Council, 2014) performance evaluation frameworks. Throughout this guidance, aqueous film-forming foam (AFFF), a widely used fire extinguishment agent and product of concern, is used as a case example to demonstrate the guiding considerations presented. The case study includes the perspectives of several experts and users of AFFF or their alternatives in a series of interviews conducted in the summer of 2021 as part of a Department of Defense (DoD) project to improve the use of alternatives assessments in evaluating alternatives to AFFF.

What is AFFF and the MIL-PRF-24385F?

AFFF is a fire suppressant applied with mechanical foam-generating equipment that forms a film over the ignited fuel to suppress and extinguish the fire. AFFF contains per- and poly-fluoroalkyl substances (PFAS). After AFFF application, PFAS can enter adjacent water bodies and bypass conventional water treatment systems to enter drinking water and human bodies. Scientific research has presented concerning data connecting PFAS exposure to human health effects (Pelch et al. 2019), spurring several initiatives to develop PFAS-free alternatives to AFFF (Dubocq et al. 2020; Hinnant et al. 2020). The U.S. Department of Defense (DoD) has stated that its goal is to "validate more environmentally sustainable PFAS-free fire suppression alternatives against the current performance requirements outlined in MIL-PRF-24385F" (Department of Defense 2021).

DoD performance specifications for AFFF are designated by MIL-PRF-24385F. This performance specification requires extinguishing a 28 ft^2 fire in 30 seconds, with a minimum burnback time of 360 seconds. The MIL-PRF-24385F also outlines other performance-related characteristics such as spreading coefficient, foamability and film formation and sealability, as well as physicochemical properties such as viscosity, pH, and corrosion rate. The MIL-PRF-24385F designates the maximum amount of two PFAS chemicals, perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), allowed in AFFF and includes an aquatic toxicity threshold that must not be exceeded. Importantly, AFFF must meet these and all other specifications on the MIL-PRF-24385F to be listed on the Qualified Product List (QPL) for procurement purposes.

CONCERNS WITH EXISTING APPROACHES FOR EVALUATING PERFORMANCE

Many challenges exist with performance evaluation frameworks used today, including that they may be limited to evaluating a single performance metric, require performance through a specific mechanism, or include feasibility of adoption as a component of a performance evaluation. For instance, overly rigid performance requirements can lead to the conclusion that no feasible alternatives exist or that only potentially regrettable substitutes (i.e., alternatives that are structurally similar to the incumbent and may therefore exhibit similar toxicity) can meet a specific function. This type of framing locks in one type of technology or chemical mode of action and can hinder innovation, limits investment into innovation of alternative technologies, and limits the range of potential alternatives that could achieve the necessary function.

The development of the MIL-PRF-24385F and fire extinguishment times

PFAS-based fire suppressants were developed in the 1960s first as "protein foam" and then as "light water", which included foam that formed a more suppressant-efficient film. AFFF was then developed and the MIL-PRF-24385F standard was written around its performance. Over time, the MIL-PRF-24385F standard evolved as AFFF and deployment technology evolved. For instance, initial versions of the standard designated that fires be extinguished in 180 seconds, while the current version's requirement is 30 seconds, presumably based solely on the fire extinguishing efficiency of available AFFF products. A critical question is whether these replacement products need to meet the very specific and technical performance specifications outlined in the MIL-PRF-24385F. For instance, it may not be necessary for a fire suppressant to extinguish a fire at an airport. If the aircraft is not salvageable, the goal may be to suppress the fire long enough to save lives.

Any MIL-PRF should achieve the required results with criteria for verifying compliance, but without stating the methods for achieving the required results. A performance specification defines the functional requirements for the item, the environment in which it must operate, and the interface and interchangeability characteristics. Ideally, the MIL-PRF-24385F would allow for functional flexibility to meet a desired result, with the recognition that an overly specific standard may constrain performance. However, the overly prescriptive approach for AFFF may be counter to the intent of the use of a MIL-PRF. For instance, it may be unnecessary for a fire suppressant to form a film if it achieves sufficient performance through another mechanism. Once these contexts and goals for the fire suppression are established, then the functional aspects of alternatives can be analyzed as to whether they – or any modification or reformulation of the product – sufficiently meet the performance needs for the specific context.

More emphasis could be placed on understanding the function of the chemical/material/product/process of concern, especially for the context in which it is used. Too often, failure to comprehensively understand the functional requirements for performance can result in:

- Overlooking potential alternatives that could meet the functional needs of the application but were eliminated because the criteria were not well-defined or were overprescribed to achieve a specific goal (i.e., assuming performance is achieved by a certain mechanism, chemical ingredient, or that the function is required to achieve an end goal),
- Failure of an alternative to perform as needed under specific circumstances, and/or
- The inability to differentiate performance levels among the alternatives, especially if only binary performance requirements are provided.

Challenges in developing alternatives that match the fire suppression performance of AFFF

AFFF is a one-solution-fits-all product that can be used for any fuel fire extinguishment scenario. Many PFAS-free products, including non-film-forming products, achieve the MIL-PRF-24385F performance requirements for many aviation-based fire and rescue events, but may fail in other contexts. Although the details of a fire event may be unclear at the onset, having multiple products available specific to certain scenarios, or having an alternative that can achieve sufficient performance for most scenarios, may be the most effective way to transition to safer products. Deployment gear such as hoses, nozzles, and applicators are important aspects of firefighting performance. An alternative could pass technical specifications but might not work depending on the deployment device and application scenario. For instance, adjusting or changing the proportioning system, adding an aspirating system, or enhancing firefighter training may be important for thinking about performance.

In many cases, products must comply with government, industry, or sector-specific standards or certifications that outline specific performance specifications. These certifications may have been developed decades ago, when the context of performance and hence performance needs were very different or were developed by the "owners" of a specific technology, locking in its use. Some of these certifications may be relevant during the beginning stages of product development such as for material purchasing, some may be relevant during product development such as design specifications, and some may be relevant once the product is completed, such as specifications built into procurement programs. For instance, procurement standards that detail conditions that must be met for a product to be

considered for purchasing may move the focus from functionality and may limit alternative solutions. Institutional procurement groups are key stakeholders to engage in conversations around appropriate performance indicators (**see guiding consideration #6**), though the result of these conversations should not restrict the development of potential alternative solutions.

AFFF and Related Certifications

The MIL-PRF-24385F is the DoD specification that specifies characteristics of AFFF and its fire suppressant performance, but there are many other standards within the MIL-PRF-24385F, for instance that test the storage containers for AFFF, the deployment equipment for AFFF, and environmental toxicity, among others. For example, the National Fire Protection Association NFPA 412 is the standard for evaluating aircraft rescue and firefighting (ARFF) equipment that deploy foam and is referenced by the MIL-PRF-24385F. All of these individual component standards within the MIL-PRF-24385F need to be satisfied by testing before a product can be listed for procurement and sold.

Outside of the United States, the United Kingdom's Civil Aviation Authority (CAA) uses the International Civil Aviation Organization (ICAO) standards for onshore civilian airports which specify three levels of performance certification for heptane-based fires; the tests for these levels range from extinguishment of a 2.8 m^2 fire at an application rate of 4.1 L/min/m^2 for Level A to extinguishment of a 7.32 m^2 fire at an application rate of 1.75 L/min/m^2 for Level C performance. In non-aircraft situations, other standards related to AFFF use might be important, such as NFPA 11, which is the standard for low-, medium-, and high-expansion foam and covers the design, installation, operations, testing, and maintenance fixed, semi-fixed, and portable systems for interior and exterior hazards. It is important to be aware of all the related standards that may be important for applications where AFFF or a potential alternative may be used.

The term "feasibility" can be used in several ways in an alternatives assessment (e.g., technical feasibility, economic feasibility, etc.). In this evaluation guidance, feasibility is considered with regards *to the technical performance* of the chemical/material/product/process of concern and the associated alternative solutions. For the purposes of this guidance, *technical feasibility* is considered separately from performance, focusing on the feasibility of adoption using existing technologies or whether there are transition barriers or challenges that may make adoption more difficult (e.g., cleaning application equipment). Considering these two concepts at the same time may hinder the landscape of potential options if some options require further research and development, process modification, or training to becoming a more viable and potentially advantageous solution. *Ideally, the feasibility of adoption related to cost, training needs, and other factors should be discussed after performance-specific testing has been completed* (**see guiding consideration #5**).

Testing and training challenges for AFFF and alternatives

Performance tests have been scaled down over the years and today firefighters rarely train via full scenario simulated fires, which can limit firefighters' experience and ability to respond effectively. The MIL-PRF-24385F designates a smaller-than-realistic fire area to be extinguished within a certain time frame. This standardized test is used when screening potential AFFF alternatives and is a tool to distinguish products that perform well from those that do not. While a potential alternative may pass this test, its performance is not necessarily representative of how it would perform during an actual fire event. As one firefighting professional noted, "if we were able to train on full-scale scenarios with a PFAS-free alternative without worrying that it would negatively affect the environment, we would be much better prepared, which can translate into saving lives."

"BEST PRACTICE" PERFORMANCE EVALUATION CONSIDERATIONS

The performance evaluation component of an alternatives assessment generally occurs after both a hazard evaluation and a comparative exposures evaluation have been completed, potentially resulting in some alternatives being eliminated from the assessment due to health and environmental concerns. However, performance is also considered at the scoping phase of an alternatives assessment. At this stage, it is important to articulate general parameters for solutions and any new approaches or designs

that could be considered during the alternatives assessment, to expand the range of options to be considered for further evaluation. Scoping can also be used narrow the range of options to be considered, for example, if a substitution is required over a limited timeframe, which may limit the assessment to only readily available or ready to scale options.

The function of the chemical/material/product/process should be clearly defined when conducting a performance evaluation. In addition, assessors must be open to considering chemical and non-chemical (process or product design change) solutions that might fully or partially fulfill the function as defined. Chemical alternatives under consideration may not work as well as or may work differently from the incumbent. Process changes are typically even more complex, potentially impacting numerous other components of the assessment (for example hazard and life cycle attributes). In these cases, it is important to not eliminate such options right away, but rather, to investigate to see if these alternatives can fulfill the functional and/or performance requirements if amended in some way. Assessors can use the alternatives scoping process, as described in the NRC alternatives assessment guidance, to document this process, including consideration of innovations to meet functional and/or performance requirements. The scoping process is where the decision-rules, performance needs, timelines for substitution, and stakeholder engagement aspects of an alternatives assessment are outlined.

With the appropriate framing of function and performance requirements, stakeholder engagement, and a willingness to innovate, more optimal outcomes can be achieved that:

- Lead to the conclusion that the chemical of concern can be eliminated without affecting product performance
- Lead to the conclusion that existing alternatives or alternatives on the horizon can replace the chemical of concern to meet the functional requirements and performance specifications, and/or
- Lead to collaborations with other organizations that result in the development of a range of options to meet the performance needs in safer ways for specific applications.

Guiding Considerations for a Performance Evaluation

This guidance creates a comprehensive, yet flexible approach to support the identification and evaluation of safer alternatives. The amount of information and testing required to implement the guidance will depend on the specific context of its use. For example, in some contexts, such as for policy decisions, the availability of an alternative that meets the specific functional need may be sufficient to support a substitution decision. However, in other contexts, such as for a procurement decision, more detailed performance discussions and testing will be required.

The guidance is underscored by the concept of "functional substitution" or the use of functional information to identify fit-for-purpose options for the identified application. These options will undergo a performance evaluation to determine their sufficiency (do they adequately meet performance needs), which should involve consultation with stakeholders such as process and product engineers, vendors, manufacturing line supervisors and/or operators, quality control managers, and other key stakeholders. This guidance is based on six guiding considerations that suggest to:

1. **Determine the *function* of the chemical/material/product/process of concern for the specific application and understand this function within the production chain.**
    - Key questions to consider:

- *What is the function of the chemical, and is it necessary?*
- *If upstream processes are changed, is the function of the chemical/material/product/process of concern needed?*
- *If the function is still needed, is it changed in any way?*

- Starting a substitution process by identifying the function of the chemical/material/product/process of concern provides a solutions-oriented approach to reducing risk (Tickner et al. 2015). Understanding the production chain and how upstream process changes can influence functional requirements may lead to making changes that remove or reduce the need for the chemical/material/product/process of concern (Tickner et al. 2019). This may require access to current or historical production line data from in-house experts.
- Another initial question that should be considered is whether the function of the chemical/material/product/process of concern is in fact necessary. This question of "essentiality" is being debated in Europe in the context of the Chemicals Strategy for Sustainability and elsewhere (Cousins, et al., 2019). In some cases where a particular chemical use is deemed not essential – for example decorative uses – a detailed performance assessment is likely not needed. In others, considering function and performance requirements may help determine whether a chemical application is essential. For now, simply asking whether a function is necessary based on the intended use of the resulting product or process should be part of any performance evaluation. Maintaining some independence of thought in considering this question can be challenging. This is an opportunity to solicit external stakeholder perspectives.

2. Define the *application*-specific scenario(s) in which the substance of concern is used and identify alternatives that are suitable for that particular purpose.

- Key questions to consider:
  - *For what application(s) is the chemical/material/product/process of concern being used?*
  - *Do alternatives under consideration meet the functional performance need for the application(s) (even if they are used in different ways for other applications), perhaps with minor adjustments?*

- The application context of the chemical/material/product/process of concern needs to be well-defined to establish "sufficient" performance criteria appropriately (**see guiding consideration #4**). If there are various functional use scenarios satisfied by the incumbent (or the incumbent chemistry works effectively in multiple applications), it is important to be open to finding alternatives that act as solutions for some, but not all, scenarios. In this case, finding more than one alternative that provides sufficient performance for the full suite of functional use scenarios is the goal.
- Assessors must look for industry/technology-related scientific journal articles, conferences, or other business or technical organizations that can provide insight into the opportunities around functional substitution. This should include considering alternatives that provide sufficient performance for different but compatible uses. For example, a safer surfactant used in a cleaning formulation could provide necessary functionality for use in a textile dyeing application.

3. **Establish and/or use performance standards that have been developed *independent* of the existing chemicals/materials/products/processes of concern (as much as possible) and adjust them based on available alternatives or alternatives on the horizon.**

   - Key questions to consider:

     - *What are the technical/standard performance requirements that the potential alternatives need to meet? Are there regulatory, industrial sector, customer and/or other specification requirements?*

     - *Were performance standards built around specific existing technologies or mechanisms of action? If so, can new iterations of the standard be adopted that are more function-oriented?*

   - Assessors should identify relevant performance specifications established by customers, regulators, or other entities. It is best practice to look for the historical evolution of those performance standards. Performance standards that developed in parallel with the development of a related chemical/material/product/process may have evolved over time to become overly specific, narrow, or rigid, making it difficult for other options to be considered, thus impeding innovation. In some cases, it may be optimal to rewrite a performance standard altogether rather than to work with an incumbent standard. Performance standards that focus on functional needs (performance-based design), and that are determined as independently as possible from existing products can allow for more product innovation development to meet those standards. An important consideration is how the performance goal is defined.

   - In cases where the performance standards were built around specific existing technologies, the assessor should determine if the standard can be modified to accommodate a more function- and performance-oriented approach. When standards are internal to a company, this is a relatively straightforward thing to do. When standards have been developed by external stakeholders like customers, specification bodies, or regulators, the assessor should engage in dialog to evaluate the possibility of collaborating to modify those standards. This is a far less straightforward process, regardless of where the assessor sits (e.g., as a user, a customer, or a regulator). As fields develop and technology advances, it may be necessary for the specification and certification bodies to revisit specifications and update them accordingly, in a way that allows for innovation and that focuses on fit-for-purpose performance.

4. **Develop and use a *range* of performance standard benchmarks, from "inadequate" to "sufficient" to "best in class" to evaluate the alternative for the specific application(s).**

   - Key questions to consider:

     - *Have potential alternatives been eliminated based on binary performance criteria (meets or does not meet a gold standard) that should be reconsidered?*

     - Define a range of fit-for-purpose performance criteria that encompass "inadequate", "sufficient", and "best in class" benchmarks for the application. *How do different alternatives compare within this range?*

   - "Sufficient" performance should be established by those most familiar with the chemical/material/product/process of concern and the application-specific context, for instance manufacturing and customer stakeholders. Likewise, a range of relevant performance criteria around "sufficient" should be established by these experts so that when several alternatives are assessed, it is clear how each one ranks against the others (as is the case of the ICAO standard which includes three levels of performance for firefighting foams). This requires

thoughtful discussions from experts across the supply chain as well as end-users to determine a range of quantifiable performance metrics for the defined application.

- Absolute minimum criteria should be used to determine the lower bound of the performance range. This may be a controversial process, requiring debate about the goal of the chemical/material/product/process and what is acceptable with various stakeholders. For example, in some contexts, the fact that an alternative is available for a specific application may be adequate to determine sufficient performance but not "best in class", an upper tier of alternatives or incumbents that exceeds the defined criteria for "sufficient" performance. The expectation is that alternatives should achieve "sufficient" performance for the application, but over time can strive to perform at the "best in class" level for a specific or multiple applications.
- It is important that performance evaluation metrics be consistent and robust. It is equally important that the process be adaptable for different contexts (Jacobs et al. 2016). Establishing minimum standards to achieve sufficient performance as well as ideal/optimal setpoints of performance criteria creates benchmarks that can be used when assessing alternatives, allowing for new alternatives to be developed over time. Testing against these benchmarks will help identify which alternatives are inadequate, sufficient, or best in class for a range of applications. These benchmark criteria can be set by an expert committee and can also evolve over time as new alternatives emerge, are tested, and are evolved. They also help set goals for innovation in new alternatives.

5. Consider technical performance *separately* from technical feasibility (feasibility of adoption) of potential alternatives.

- Key questions to consider:
    - *When only performance is considered (and not the feasibility of their adoption), what are the alternative solutions that can be assessed and compared?*
    - *What additional process/product modifications may be needed to increase the feasibility of adoption?*
- Technical performance relates to whether the alternative adequately achieves the desired function in a chemical/material/product/process for a specific application, whereas technical feasibility relates to issues of availability and adoptability (i.e., barriers and challenges to making the transition to an alternative – including supply, reformulation, retraining, etc.). Consideration of technical performance and technical feasibility are often intertwined in the alternatives assessment process. This can initially inhibit consideration of certain alternatives (for instance alternatives that may reduce operating costs over time but require initial retooling investments) and should be considered secondarily. For example, a potential alternative may be high-performing but may require significant equipment changes and further research to be technically feasible – this alternative should be kept on the table for later discussions on the tradeoffs of adoption for the potential alternatives (**see guiding consideration #6**).
- Determining the feasibility of an option requires considerations of limitations associated with very specific use scenarios, such as are seen in individual manufacturing facilities. The assessor needs to gather information from a wider range of stakeholders within facilities to determine feasibility. An equally important role for the assessor at this point is to question information presented that would indicate the infeasibility of an alternative (e.g., initial capital costs exceeding available cash) and to develop additional strategic actions to improve

an alternative's feasibility. This may include additional research and development, work to provide utilities necessary for manufacturing, etc.

6. **Consult *stakeholders* to determine acceptable tradeoffs between performance results and other elements such as environmental health and safety.**

   - Key question to consider:
     - Hold discussions with an appropriately diverse group of stakeholders on the tradeoffs that would occur for each alternative under consideration. *Which tradeoffs are acceptable under various application-specific scenarios?*
     - *What alternatives under consideration best minimize potential trade-offs between performance and environmental and health and safety concerns?*
   - Stakeholders such as companies (including workers), consumers, environmental groups, and the public are important throughout the performance assessment process. Assessors need to first determine the range of stakeholder perspectives needed, including from those involved in the production of chemistries and equipment, sourcing and use of products, and potentially impacted communities and ecosystems. Obtaining and synthesizing such input into choices of chemistries can be challenging given the potentially wide-ranging perspectives presented. A narrower net is more manageable but can limit access to creative ideas that could yield more long-term sustainable and competitive solutions.
   - Once other elements of the process have been completed, stakeholders can help the assessor determine acceptable tradeoffs between performance, feasibility of adoption, and other environmental and human health considerations (within the context of specific applications and chemical exposure circumstances). Ideally, these scenarios would be described in a matrix that lays out the cost of the options along with other performance and environmental characteristics. There will almost always be tradeoffs associated with adopting alternatives, so it is best to have all information available for decision-makers to view.
   - Gathering the perspectives of diverse stakeholders is important for vetting the acceptability of potential alternative solutions, including discussing challenges that alternatives would need to overcome, such as industry standards, procurement considerations, and acceptability. Stakeholder discussions can be particularly important to help avoid regrettable substitutions and assure that human and environmental health are adequately considered regarding viable options. Engagement of stakeholders helps ensure that environmental performance is considered on par with technical performance (Tickner et al. 2017).

Despite rethinking performance requirements, there may be no option that meets technical performance, technical feasibility, and environmental health expectations. In these cases, investment in the development of alternatives will be required. However, applying the questions in this guidance will likely open-up a broader range of potential options to explore, including options on the horizon.

Sweden and Denmark's approach to transitioning to a PFAS-free alternative

As more became known about the hazards associated with AFFF, both Sweden and Denmark switched to using PFAS-free foams in 2012. For both countries, the change was able to be made rapidly by prioritizing the switch to the alternative first and then later adjusting to other factors such as the number of vehicles and people needed to fight the fire. The transition was relatively easy because the alternative could be used in the existing AFFF deployment system. The alternative performed similarly to AFFF following minor adjustments to account for viscosity differences, however, Denmark and Sweden are in the process of re-examining performance requirements such as the "time to control" and "time to extinguishment" specifications for alternatives in specific fire event scenarios.

Performance Evaluation Guidance Using AFFF as an Example

In this section, AFFF is used as a case example to demonstrate how this performance assessment guidance outlined above would work for a specific application. This case example is not an in-depth assessment of all the potential PFAS-free alternatives, nor does it provide detailed answers to the guiding considerations. Rather, it presents a high-level context, walks through the general thinking that might take place in of each of the six considerations, and in some cases offers follow-up questions to explore. This case example was developed before MIL-PRF-24385F was re-written for PFAS-free alternatives.

1. **Determine the *function* of the chemical/material/product/process of concern for the specific application and understand this function within the production chain.**
    - *What is the function of the chemical, and is it necessary?*
        - PFAS were traditionally important surfactants used in foams. The surfactants reduce surface tension, helping the foam spread quickly as a film over a burning fuel to suppress it. AFFF formulations are proprietary, so it is difficult to determine individual constituent performance, but PFAS-free surfactants used in AFFF have been shown to provide the film-forming function necessary for the extinguishment of fuel fires indicating that PFAS are not exclusively necessary. Industry and most standards rely on the film-forming aspect provided by the PFAS surfactants, so it is reasonable to say that the function at this point is necessary, though limiting since options using other mechanisms to extinguish fires do exist.
    - *If upstream processes are changed, is the function of the chemical/material/product/process of concern needed?*
        - Potential non-foam alternatives may not require the function of surfactants at all. From a broader and more long-term perspective, transitioning aircraft away from highly flammable fuels could reduce the overall fire hazard and fire suppression need.
    - *If the function is still needed, is it changed in any way?*
        - For some foam-based alternatives, modifications to the proportioning system and in some cases the addition of an aspirating system allow the alternative to perform as well as traditional AFFF. However, the function in this case remains the same or similar.
2. **Define the *application*-specific scenario(s)in which the substance of concern is used and identify alternatives that are fit for that particular purpose.**
    - *For what application is the chemical/material/product/process of concern being used?*
        - Examples of different scenarios for the application of AFFF include aircraft fires, hangar fires, and shipboard fires, among others. The MIL-PRF-24385F dictates performance as the total extinguishment of a 28 ft^2 fire within 30 seconds under testing scenarios. However, the performance needs under real fire event conditions should be defined. For example, is it important to continue using AFFF to suppress a fire if there are no lives at stake and property damage is minimal? Another question to consider is what is "safe enough to get people out of fire situation," minimizing risks to life and health.
    - *Do alternatives under consideration meet the functional performance need for the application(s) (even if they are used in different ways for other applications), perhaps with minor adjustments?*

- AFFF is being used for aircraft fire and rescue scenarios. Currently, several PFAS-free foams work with existing deployment equipment and meet most of the performance requirements of the MIL-PRF-24385F, but as described above, some of these alternatives require minor adjustments to the deployment equipment to function well. These alternatives may not meet performance needs in other contexts where AFFF would be used, or they might require different kinds of adjustments compared to the adjustments made for an aircraft fire and rescue scenario.

3. **Establish and/or use performance standards that have been developed *independent* of the existing chemicals/materials/products/processes (as much as possible) and adjust them based on available alternatives or alternatives on the horizon.**

- *What are the technical/standard performance requirements that the potential alternatives need to meet? Are there regulatory, industry sector, customer, and/or other specification requirements?*
  - The MIL-PRF-24385F designates an extinguishment requirement as described above, with a minimum burn back time of 360 seconds. This standard is also a procurement specification, where all aspects of fire performance, foam characteristics, and toxicity testing need to be met before the product can be certified for purchase.
- *Were performance standards built around specific existing technologies or mechanisms of action? If so, can new iterations of the standard be adopted that are more function-oriented?*
  - The MIL-PRF-24385F is a stringent standard designed around AFFF with few opportunities to deviate, and currently, PFAS-free foam alternatives are held to the same fire extinguishment standards as traditional AFFF. Perhaps in future iterations of the MIL-PRF-24385F, other performance aspects such as foam characteristics and toxicity from environmental and human health exposure pathways could be adopted as separate but required components when considering alternatives.

4. **Develop and use a *range* of performance standard benchmarks, from "inadequate" to "sufficient" to "best in class" to evaluate the alternative for the specific application(s).**

- *Have potential alternatives already been eliminated based on binary performance criteria (meets or does not meet a gold standard) that should be reconsidered?*
  - Currently, alternatives either "pass" or "fail" the MIL-PRF-24385F. Under the current performance specification paradigm, there is no option for considering the use of alternatives that failed.
- Define a range of fit-for-purpose performance criteria that encompass "inadequate", "sufficient", and "best in class" benchmarks for the application. *How do different alternatives compare within this range?*
  - A binary system rather than criteria ranges are used in the MIL-PRF-24385F. However, future specification revisions that establish ranges of performance criteria would support use of products that show performance that is within the range of sufficiency to be used for certain firefighting scenarios.

5. **Consider technical performance *separately* from technical feasibility (feasibility of adoption) of potential alternatives.**

- *When only performance is considered (and not the feasibility of their adoption), what are the alternative solutions that can be assessed and compared?*

- For alternatives that currently exist, they could be tested against the current MIL-PRF-24385F specifications, with current deployment equipment for foam-based technologies. The use of current deployment equipment has been a limiting factor for consideration of alternatives, except in cases where equipment is near retirement age. Or, as described in guiding consideration #4, ranges of performance criteria could be developed, which may be more appropriate for non-foam-based alternatives.

- *What additional process/product modifications may be needed to increase the feasibility of adoption?*
    - Several foam-based PFAS-free alternatives exist already, have been tested for sufficient performance, and are in use. Several others are in development but may not have been tested yet for technical performance or adopted for other feasibility considerations (for example the need for new deployment equipment or retraining). Other ideas for alternative solutions, including application equipment changes or modifications, may still be in the conceptual phase and require further development. All these potential options should remain at this point for consideration.

6. **Consult *stakeholders* to determine acceptable tradeoffs between performance results and other elements such as environmental health and safety.**

- Hold discussions with an appropriately diverse group of stakeholders on the tradeoffs that would occur for each alternative under consideration. *Which tradeoffs are acceptable under various application-specific scenarios and chemical exposure scenarios?*
    - A first step is to consider is who are the people, organizations, and other entities that can contribute thoughtful and productive insights towards understanding and weighing of the trade-offs between the range of performance criteria required for each of the alternatives and the potential environmental and health impacts for each. This group of stakeholders may look different in areas with different PFAS issues, communities, histories, etc. The stakeholder group for the specific place will help determine what the tradeoffs considerations are and how they are weighted.

- *What alternatives under consideration best minimize potential trade-offs between performance and environmental and health and safety concerns?*
    - AFFF alternatives may perform well in different ways. Or, they may perform similarly in different scenarios, but stakeholders for each of these scenarios may perceive the tradeoffs differently, depending on the factors that are important for each group (e.g., persistence, impacts on a wildlife population, association with a disease risk, etc.). Only upon consultation with the stakeholder group can it be useful to understand these factors and especially in the context of choosing an appropriate alternative.

The future of PFAS-free foams and avoiding regrettable substitutions

Globally, the firefighting industry is moving to PFAS-free fire suppressants, and there are many examples of governments and companies that have already made the transition to safer alternatives. One major question raised by firefighting professionals is “What are we transitioning to?” When AFFF was first developed, it was considered a product that performed extremely well with minimal risk to human health or the environment. Likewise, an alternative could be adopted that is supposed to be better, but the data about long-term impact might not become clear until years or decades later. More firefighting and health experts are now calling for multiple health and environmental endpoints to be considered when evaluating potential alternatives, with a focus on ensuring that replacements are not persistent. One positive aspect of this transition is that fluorosurfactants are expensive to both produce and clean up. By removing them from the supply chain, financial resources may become available for the research, development, and testing of PFAS-free alternatives.

CONCLUSIONS

This guidance is intended to serve as a "best practice" performance evaluation guide for decision-making on potentially safer alternatives, emphasizing a focus on *fit-for-purpose* performance, a strategy for assessing performance based on application-specific contexts. This approach highlights the importance of evaluating the function of the chemical, material, product, or process of concern, expands the thinking around performance as a range, and acknowledges important considerations around tradeoffs with environmental health and safety performance. The challenges that exist with current performance evaluation frameworks are outlined, such as their focus on a single performance metric, requiring performance through a specific mechanism, or including feasibility of adoption as a necessary component during performance evaluations. These factors can hinder the transition to safer and effective options.

Building on the IC2 and NRC frameworks, the guidance provides an iterative set of six primary considerations and leading questions to evaluate the performance of alternatives in a broad range of contexts, starting with functional needs. A high-level overview of how AFFF could be assessed using these guiding considerations is presented. The guidance considerations encourage users to be flexible over time as new alternatives emerge, are tested and adopted, and as more performance and environmental health data are collected. Performance assessment is context-specific and hence there is no one approach to evaluating performance. Different companies, sectors, and technical applications may have specific performance requirements. Decisions made at the government policy level versus at the product design or procurement level require differing levels of granularity in understanding performance. Many perspectives (e.g., toxicologists, engineers, consumers, etc.,) are required to both contribute to and interpret a performance evaluation for the most robust outcomes, and many other stakeholders may be required when debating the tradeoffs inherent in evaluating and adopting potential alternatives.

Overall, performance evaluations that focus on scoping the function of the chemical, material, product, or process of concern and on critically assessing the specific performance requirements of the product or application provide a strong foundation for a broader range of fit-for-purpose, safer solutions. The ultimate goal of this guidance is to facilitate the transition to safer and effective options to meet identified functional needs, while avoiding "paralysis by analysis" or the frequent "there is no alternative that meets the same performance" rationale to avoid substitution. Ultimately, potential tradeoffs between these need to be transparently discussed during decision-making. Where options do not currently exist that can meet environmental, technical, and economic performance requirements, investments in R&D in new options will be required.

Additional case examples using the guidance are needed, to refine and add more specific detail to the performance assessment process – including minimum information requirements and information sources. As a result, the guidance is expected to evolve based on these examples and other insights from experts conducting alternatives assessments in the future.

REFERENCES

Cousins, I.T., Goldenman, G., Herzke, D., Lohmann, R., Miller, M., Ng, C.A., Patton, S., Scheringer, M., Trier, X., Vierke, L., Wang, Z. and DeWitt, J.C. 2019. The concept of essential use for determining when uses of PFASs can be phased out. Environ Sci Process Impacts 21, 1803-1815.

Department of Defense. 2021. FY 2022 Broad agency announcement: Topic B6. Demonstration and validation of PFAS-free fire suppression alternatives. In: E.S.T.C.P. (ESTCP) (Ed), Department of Defense (DoD), Alexandria, VA.

Dubocq, F., Wang, T., Yeung, L.W.Y., Sjöberg, V. and Kärrman, A. 2020. Characterization of the Chemical Contents of Fluorinated and Fluorine-Free Firefighting Foams Using a Novel Workflow Combining Nontarget Screening and Total Fluorine Analysis. Environ Sci Technol 54, 245-254.

Gil, S. 2011. Planning for substitution: Analysis of alternatives and the Substitution plan. European Commission - DG Environment, Helsinki.

Hinnant, K.M., Giles, S.L., Smith, E.P., Snow, A.W. and Ananth, R. 2020. Characterizing the Role of Fluorocarbon and Hydrocarbon Surfactants in Firefighting-Foam Formulations for Fire-Suppression. Fire Technology 56, 1413-1441.

Interstate Chemicals Clearinghouse. 2017. Alternatives Assessment Guide. p. 183.

Jacobs, M.M., Malloy, T.F., Tickner, J.A. and Edwards, S. 2016. Alternatives Assessment Frameworks: Research Needs for the Informed Substitution of Hazardous Chemicals. Environ Health Perspect 124, 265-280.

National Research Council. A Framework to Guide Selection of Chemical Alternatives. The National Academies Press, Washington, DC.

National Research Council. 2014. A Framework to Guide Selection of Chemical Alternatives. The National Academies Press, Washington, DC.

Pelch, K.E., Reade, A., Wolffe, T.A.M. and Kwiatkowski, C.F. 2019. PFAS health effects database: Protocol for a systematic evidence map. Environ Int 130, 104851.

Tickner, J., Jacobs, M. and Mack, N. 2019. Alternatives assessment and informed substitution: A global landscape assessment of drivers, methods, policies and needs. Sustainable Chemistry and Pharmacy 13, 100161.

Tickner, J., Weis, C.P. and Jacobs, M. 2017. Alternatives assessment: new ideas, frameworks and policies. J Epidemiol Community Health, England, pp. 655-656.

Tickner, J.A., Schifano, J.N., Blake, A., Rudisill, C. and Mulvihill, M.J. 2015. Advancing safer alternatives through functional substitution. Environ Sci Technol 49, 742-749.

APPENDIX A: Definitions

"Fit-for-purpose" performance refers to an alternative solution that achieves sufficient performance for a specific context or application, even though it may perform differently in for other applications.

Functional substitution refers to identifying the function of the chemical of concern as a starting point for exploring potential alternatives beyond drop-in chemical substitutions. This approach requires thinking more broadly of how system modifications, product use modifications, or other non-chemical solutions could be employed to achieve an acceptable outcome (Tickner et al. 2015).

Essentiality refers to whether the use of a chemical/material/product/process is needed for the health, wellbeing, or functioning of society, whereby determining essentiality can help with substitution decision-making (Cousins et al. 2019). Essentiality is not a particular focus of this guidance.

MIL-PRF is a performance specification that states the compliance requirements for a product but without stating the methods for achieving the required results. A performance specification defines the functional requirements for the item, the environment in which it must operate, and the interface and interchangeability characteristics.

Technical performance refers to how well the alternative performs against the appropriate performance criteria when tested. Data collected from these assessments can be used to determine technical feasibility (Interstate Chemicals Clearinghouse 2017).

Technical feasibility or feasibility of adoption refers to the ability of an alternative chemical/material/product/process in question to be adopted in practice for the specific application. Considerations include the possibility of process adaptations, product design changes, capital investments or training that may need to be put in place in order for the alternative to adequately perform the desired function (Gil 2011).

Technical standards industry, government, or customer standards or specifications that may be required for a particular application (Interstate Chemicals Clearinghouse 2017).

Economic feasibility refers to whether it is financially reasonable to implement the proposed alternative. Considerations include the potential change in costs and revenues from implementing the alternative, including the pass-through of costs to customers (Gil 2011).

APPENDIX B: Summary of the Interstate Chemicals Clearinghouse (IC2) & National Research Council (NRC) Performance Evaluation Frameworks

Two alternatives assessment frameworks were specifically reviewed in the development of this guidance. The first is the Alternatives Assessment Guide, originally published in 2013 and updated in 2017 by the Interstate Chemicals Clearinghouse (IC2), an association of state, local and tribal governments and supporting members from industry and the environmental community. The second is the National Research Council (NRC) document "A Framework to Guide Selection of Chemical Alternatives" published in 2014. The performance evaluation aspects of these frameworks are summarized below as a jumping off point for the objective of this guidance – to further the thinking of performance evaluations beyond what has been outlined in existing guidance documents.

Interstate Chemicals Clearinghouse (IC2) Alternatives Assessment Guide

The IC2 Guide was developed to assist companies (particularly smaller companies not well versed in assessing alternatives thoroughly) in identifying viable alternatives to their use of chemicals of concern. It includes a Performance Evaluation module as a critical component of an alternatives assessment framework, and it ensures that the chemical alternatives under consideration meet the performance requirements for the desired application. The module identifies three levels of evaluation: Basic, Extended, and Detailed Performance Evaluations. The Basic Performance Evaluation uses qualitative information of alternatives readily available from manufacturers and other sources, the Extended Performance Evaluation additionally uses quantitative data of alternatives reviewed by technical experts, and the Detailed Performance Evaluation additionally uses data from specified tests that were reviewed and validated by technical experts.

The Performance Evaluation module is designed to be used by a wide range of assessors to determine performance characteristics. For a Basic Performance Evaluation, the main questions assessors may ask to determine whether alternatives under consideration meet performance standards are:

1. What are the performance needs for the application, process, or product that contain the chemical of concern? Why is the chemical being used? Is the chemical a byproduct, an impurity of another chemical, or a historical artifact (a chemical intentionally added in original formulations but which might not enhance the product)?
2. Can the chemical be eliminated without affecting performance? If so, perhaps an alternatives assessment can be avoided.
3. Is the addition of the chemical required by legislation or some type of technical specification? Is the use of an alternative chemical specifically prohibited? If so, an alternatives assessment may not be able to be conducted.
4. Has a favorable alternative already been identified that does not result in the byproduct or impurity? Is it already being used by others for the same or similar application? If the alternative only reduces the hazard, by how much and are there other opportunities for reduction?
5. Has an authoritative body demonstrated and documented adequate performance of identified alternatives? Have identified alternatives been deemed as *not* favorable based on performance?

For an Extended Performance Evaluation, additional questions assessors may ask technical experts in determining whether alternatives under consideration meet performance standards are:

- Are specific tests available that would indicate the likelihood of the alternative satisfying the performance criteria for this application? Have the tests been conducted and are the associated data readily available? If not, can technical feasibility (technical performance) be determined by other means?
- Would the use of an alternative have an adverse impact on the reliability of the process or product, the quality and useful life of the final product, acceptance of the product by consumers, the efficiency or throughput of the associated production process, or the maintenance requirements of the associated manufacturing process? If so, are there known modifications that could mitigate these impacts?

For a Detailed Performance Evaluation, additional questions assessors may ask technical experts in determining whether alternatives under consideration meet performance standards are:

- Has the alternative passed the thresholds according to the appropriate test protocols? If no, can the product or process be modified to accommodate the alternative?
- Do the test results support the assessment of the technical experts and indicate the product meets performance criteria? If no, is the discrepancy sufficient to disqualify the alternative?

National Research Council (NRC) Framework to Guide Selection of Chemical Alternatives

The NRC alternatives assessment framework is a summary review of many existing frameworks, including the IC2 Guide. Many of these frameworks include a performance evaluation component, ranging as an optional to a required component, and from simple to comprehensive evaluations. The performance evaluation component for the NRC framework is optional on the basis that that assessor may not have the ability to test and thoroughly evaluate alternatives. However, while the NRC framework acknowledges that the characterization of function and performance requirements is often an undervalued part of alternative assessment frameworks, it emphasizes that it is essential for the effective prioritization and adoption of alternatives.

In particular, the NRC framework emphasizes understanding the particular *function* or service the chemical of concern provides in the product or process. This approach enables assessors to determine how and why a chemical is used to broaden the scope of potential solutions beyond drop-in replacement chemicals. This scoping approach helps appropriately determine specific performance criteria within the context of safer options and may lead to innovative ways to meet the performance requirements. The framework highly encourages conducting this scoping process in the initial problem-formulation stages so that the information can be used later during the performance testing stage of potential alternatives.

This NRC framework specifically suggests to:

- Define the specific function of the chemical of concern within the product, process, or application. This process may open the possibility of having non-chemical options achieve the desired performance, such as through material substitutions or design changes.
- Define acceptable criteria for alternatives at the chemical, material, product, or process level. These might include ranges of specific properties such as boiling points, vapor pressure, or water solubility that are determined based on process or use conditions.

- Determine the appropriate methods for testing alternatives, and if standard methods are not available, qualitative or specialized test methods might need to be developed.
- Identify regulatory, customer, specification, and/or any certification requirements that the alternative would be required to meet. Stakeholders can provide insights on performance requirements that might lead to favoring one alternative over another.
- Identify process or use conditions or constraints? which might include a specific temperature range, pH, purity, or drying time, among other factors, which might be useful in identifying potential exposure pathways.

Conducting this evaluation produces both an understanding of and documentation of the chemical function and performance requirements needed for the alternative, as well as a plan for the testing of the chemical or non-chemical alternative. It is important that when alternatives are first considered overly conservative predictions of their performance do not lead to the elimination of potentially viable alternatives that could be further developed to meet the performance requirements.

APPENDIX C: Schematic Exhibiting the Thinking of the IC2/NRC Guidance and the Additions of this Guidance

For the six guiding considerations presented in this guidance, baseline thinking outlined in the IC2 and NRC frameworks related to these considerations is shown in black, and the evolved thinking presented in this guidance is shown in red.

1. **Determine the *function* of the chemical/material/product/process of concern for the specific application and understand this function within the production chain.**
    - Why is the chemical being used? What is the function of the chemical, and is it necessary?
    - Is the function of the chemical overprescribed?
    - If upstream processes are changed, is the function of the chemical/material/product/process of concern necessary?
    - If the function is still needed, is it changed in any way?
2. **Define the *application*-specific scenario(s) in which the substance of concern is used and identify alternatives that are suitable for that particular purpose.**
    - What are the performance needs for the chemical/material/product/process?
    - For what application is the chemical/material/product/process of concern being used?
    - Do alternatives under consideration meet the functional need for this application (even if they are used in different ways for other applications), perhaps with minor adjustments?
3. **Establish and/or use performance standards that have been developed *independent* of the existing chemicals/materials/products/processes of concern (as much as possible) and adjust them based on available alternatives or alternatives on the horizon.**
    - What are the technical/standard performance requirements that the potential alternatives need to meet? Are there regulatory, customer and/or other specification requirements?
    - Were performance standards built around specific existing technologies? If so, can new iterations of the standard be adopted that are more function-oriented?
4. **Develop and use a *range* of performance standard benchmarks, from "inadequate" to "sufficient" to "best in class" to evaluate the alternative for the specific application(s).**
    - Define the acceptable performance criteria for alternatives at the chemical/material/product/process level. Have potential alternatives been eliminated based on performance?
    - Have potential alternatives already been eliminated based on binary performance criteria that should be reconsidered?

- Define a range of fit-for-purpose performance criteria that encompass “inadequate”, “sufficient”, and “best in class” benchmarks for the application. How do different alternatives compare within this range?

5. **Consider technical performance *separately* from technical feasibility (feasibility of adoption) of potential alternatives.**
    - Can performance be determined through available and established tests?
    - When only performance is considered (and not the feasibility of their adoption), what are the alternative solutions that can be assessed and compared?
    - Then, what additional modifications may be needed to increase the feasibility of adoption?
6. **Consult *stakeholders* to determine acceptable tradeoffs between performance results and other elements such as environmental health and safety.**
    - Gather stakeholders that might provide insights on performance requirements that might lead to favoring one alternative over another.
    - Hold discussions with an appropriately diverse group of stakeholders on the tradeoffs that would occur for each alternative under consideration. Which tradeoffs are acceptable and what alternatives under consideration meet these conditions?

Sustainable Chemistry Catalyst

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Annex E: Report – *Scaling Adoption of Alternatives to Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous Film-Forming Foams (AFFF): Lessons Learned on Needs and Opportunities*

University of Massachusetts Lowell

Scaling Adoption of Alternatives to Per- and Polyfluoroalkyl Substances in Aqueous Film-Forming Foams: Lessons Learned on Needs and Opportunities

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SERDP Project WP19-1424

Sustainable Chemistry Catalyst

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The Lowell Center for Sustainable Production at the University of Massachusetts Lowell is a leading academic center for action-oriented research, policy development, and collaborative initiatives focused on eliminating hazards in products, workplaces, and communities by promoting the development, evaluation and adoption of safer and sustainable chemistries, materials and products. For more information, visit www.uml.edu/research/lowell-center.

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NEWMOA is a non-profit, non-partisan, interstate association whose membership is composed of the state environment agency programs that address pollution prevention, toxics use reduction, sustainability, materials management, hazardous waste, solid waste, emergency response, waste site cleanup, underground storage tanks, and related environmental challenges in Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont. For more information, visit www.newmoa.org.

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Established by the Massachusetts Toxics Use Reduction Act (TURA) of 1989, TURI at UMass Lowell collaborates with businesses, community organizations and government agencies to reduce the use of toxic chemicals, protect public health and the environment and promote the competitiveness of Massachusetts businesses. For more information, visit www.turi.org.

ABOUT

The Sustainable Chemistry Catalyst is an independent research and strategy initiative, based at the Lowell Center for Sustainable Production at UMass Lowell, that is focused on accelerating the transition to safer, more sustainable chemistry through research and analysis, and stakeholder engagement with scientists, policymakers, and commercial actors.

The Catalyst works to understand barriers and opportunities to commercialization of safe and sustainable chemistry, identifies model solutions and strategies, develops methods to evaluate safer alternatives, and builds a community of expertise to support the transition to safer, more sustainable chemistries and technologies.

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ACRONYMS USED

6:2 FTS	6:2 Fluorotelomer Sulfonate
AFFF	Aqueous Film Forming Form
ARFF	Aircraft Rescue and Firefighting
C6	Carbon chain length of six
CBI	Confidential Business Information
EN	European Standard, from the German name Europäische Norm ("European Norm")
FAA	Federal Aviation Administration
IC2	Interstate Chemicals Clearinghouse
ICAO	International Civil Aviation Organization
MilSpec	Military Specification MIL-PRF-2435F(SH)
NDAA	National Defense Authorization Act
NGO	Non-governmental organizations
PFHxA	Perfluorohexanesulfonate
PFHxS	Perfluorohexanoic Acid
PFAS	Per and polyfluoroalkyl Substances
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulfonate
R&D	Research and Development
SERDP/ESTCP	Strategic Environmental Research and Development Program/Environmental Security Technology Certification Program
UL	Underwriters Laboratories
US	United States
US DoD	US Department of Defense
US EPA	US Environmental Protection Agency

SUMMARY

The objective of this project was to explore lessons learned from existing efforts to accelerate the adoption of substitutes for firefighting foams containing per- and poly fluorinated alkyl substances (PFAS). Key objectives included: (1) understanding critical technology, market or policy factors (actual and perceived) that are inhibiting the implementation of alternatives to Aqueous Film Forming Foam (AFFF) and other PFAS containing firefighting products; (2) understanding critical technology, market or policy factors that are enabling and scaling a transition to safer and feasible alternatives to AFFF and other PFAS based firefighting products; and (3) understanding lessons learned from the US Department of Defense's (US DoD) current efforts to accelerate the adoption of safer and effective PFAS-free alternatives that can improve efficacy in firefighting scenarios. Key informant interviews were conducted to explore barriers and enablers in transitioning from AFFF to alternatives. Reviews of the literature, including peer-reviewed publications and reports in the gray literature, were used to delve deeper into topics and themes that emerged in the interviews.

Five primary factors were repeatedly identified as barriers to an effective transition to safer and feasible AFFF alternatives including:

1. **Transition costs:** Although the purchase price of PFAS-free alternatives to AFFF is cost competitive, replacement costs related to equipment/components, decontamination and disposal costs of contaminated components and legacy fluorinated foams may be significant.

2. **Lack of knowledge of performance for specific real-world scenarios:** Proof of concept or demonstration-level performance tests of the PFAS-free alternatives are simply not enough to give assurances to some users that alternatives will work as needed for their firefighting circumstances.

3. **Substitution regret:** Some users are unwilling or unable to transition to PFAS-free alternatives to AFFF because of the lack of certifications/approvals needed in some sectors. There are also lingering questions about the health and safety of alternatives for both workers and the environment given the limited test data on formulations, that need to be addressed.

4. **Standards:** Performance standards/specifications, especially the US DoD performance specification (MIL-PRF-2435F(SH)) (MilSpec) in the US, are hindering adoption of alternatives. In addition, there are an array of standards related to the use of firefighting foams, which has created confusion related to procurement among some entities and has limited continued innovation in fire extinguishment technologies for Class B fires due to costs involved in achieving certifications.

5. **Lack of a coherent national transition strategy:** The lack of a clearly communicated strategy to support the transition to PFAS-free alternatives has left users, especially in the US with more questions than answers about addressing needs related to financial support, technical assistance and training related to both the use of PFAS-free alternatives to AFFF and decontamination and disposal challenges associated with the legacy fluorinated foams and related equipment.

Four primary enabling factors that are working to accelerate a transition to PFAS-free alternatives were also identified, including:

1. **"Just do it" – using direct experience and mock exercises to understand performance of alternatives and adoption needs:** The counterpoint to only having proof of concept/demonstration performance testing is the utility of users participating in large-scale tests. Collaborative testing programs have proven to be effective in demonstrating the capacities of PFAS-free alternatives as well as equipment needs and firefighting tactics to tune performance.

2. **Financial liabilities with continued use of AFFF:** Insurance liabilities and the potential for future litigation and financial responsibilities associated with the continued use and contamination from PFAS containing firefighting products is a significant substitution driver.

3. **Fit-for-purpose performance standards:** Standards designed to reveal varying performance levels that are suitable for a range of firefighting uses have been able to support a quicker transition to PFAS-free alternatives than those designed only for the worst-case/maximum credible event firefighting scenario.

4. **Policy mandates:** Policy requirements to stop using AFFF have been instrumental in the transition to PFAS-free alternatives.

Going forward, priority needs to accelerate an effective and broad-based transition to safer PFAS-free alternatives include:

- **Issuing a comprehensive and collaborative implementation strategy.** Such a strategy should be a multi-agency/institutional effort given the expertise and engagement needed to address the array of substitution challenges including ensuring a sufficiency of market supply of the alternatives, addressing firefighting performance/technical feasibility needs, providing firefighting education and training, addressing occupational health and safety concerns and ensuring environmental compliance and public health protections related to AFFF decontamination and disposal.

- **Enhancing education and training.** Continued education and training activities need to address "resistance to change" that is still being experienced among some facets of fire and rescue personnel, including a lack of understanding of the problem and a lack of confidence about the solution. Training programs will need to be co-developed along with the PFAS-free alternatives to AFFF as changes in firefighting techniques are expected. Programs should also use PFAS-free products that will be deployed in real incidents using the same fuels which will be encountered will increase confidence in the foams ability to extinguish fires.

- **Establishing collaborative performance testing/demonstration sites.** Enhanced collaborative large-scale performance tests are needed where the burden of costs is shared among interested parties/organizational partners who also contribute to designing parameters of the testing protocol. Results of such tests need to be broadly disseminated. Collaboration is also needed to fill gaps in testing to obtain accreditation for specific uses of PFAS-free products (such as in sprinkler systems) where insurers are still not willing to underwrite risk for facilities using these AFFF alternatives.

- **Establishing systems for ongoing monitoring.** Monitoring and evaluation are essential for the early identification of potential unintended consequences of the adoption process. Systems need to include, but are not limited to, environmental surveillance programs to monitor for impacts on a broader array of ecological endpoints, testing to ensure adequate decontamination of PFAS in reused equipment, agree-upon validation testing to ensure that new foams are indeed PFAS-free, industrial hygiene evaluations and discussions with firefighting personnel about the impacts of the transition and to adjust training, equipment and standards of practice as needed. Many of these issues need to be inserted into an AFFF substitution implementation strategy outlined above.

Although substitution efforts for AFFF are ongoing and not every substitution challenge is the same, there are a series of lessons learned that can be generalized from this experience to inform the adoption of safer and feasible substitutes for future chemical-product challenges going forward. Lessons learned include:

- **Policy mandates are a critical enabler for substitution**. Investment in the development of alternatives and broad implementation of substitutes will often be held back unless there are policy (government or private sector) mandates that motivate and accelerate the pace of change.

- **Expand the use of collaborative performance testing programs.** Collaborative and comparative performance testing programs are helpful when there is an array of users that have lingering questions about the performance of alternatives in specific scenarios. Filling gaps in the understanding of performance for specific use scenarios through the expansion of collaborative performance testing programs where costs are shared and distributed among interested stakeholders, who also are involved in designing the test parameters, will support broader trust and understanding of the performance capabilities of alternatives under conditions of use that specifically align with users' needs. Additionally, communities of stakeholders working collaboratively to drive innovation and adoption of safer, and feasible options (a collaborative innovation community) as the US Department of Defense's Strategic Environmental Research and Development Program and its Environmental Security Technology Certification Program (SERDP/ESTCP) has done for AFFF can accelerate the innovation and adoption process, allowing researchers, those conducting performance evaluations, scientists, innovators, and established companies to share and receive knowledge that support solutions.

- **Changes in processes and equipment need to be anticipated when adopting safer alternatives**. This is particularly likely when the safer alternatives are not simply modifications of the same fluorinated chemistry. Implementation of substitutes needs to anticipate: (a) changes to the product or process; (b) changes in work practices; and (c) the need for continuous improvement.

- **Share information about alternatives.** Lack of communication about the viability of alternatives often hampers their adoption. Lack of transparency of ingredient information about formulations hinders research and understanding about hazards. Government agencies, NGOs and trade organizations all play role in sharing and disseminating information about safer and feasible alternatives using forums that best reach user audiences.

- **Anticipate the need for and the promise of continued innovation.** It is important for users to monitor progress in innovations that have the possibility of continued reductions in

hazard with better performance for the application of interest. Performance standards and specifications need to also support innovation and avoid criteria around only one product type or option.

There is global interest in replacing AFFF and related firefighting foams with PFAS-free alternatives. Efforts to date demonstrate that substitution is possible. With continued focus on correcting those factors that are inhibiting the implementation of alternatives to AFFF and replicating/scaling those factors that are enabling substitution, we can collectively accelerate substitution of PFAS containing firefighting foams and towards safer, feasible alternatives.

I. Background and Context

Aqueous film forming foam (AFFF) is a highly efficient fire suppressant agent used for Class B fires – flammable and combustible liquids and gases; petroleum greases, tars, oils and gasoline; and solvents and alcohols. Developed in the 1960s, AFFF is widely used at airports for emergency incidents, fire training exercises, and in sprinkler-based fire-suppressant systems in aircraft hangers. It is also used in the petrochemical sector to extinguish tank fires or fires associated with fuel storage or fuel handling systems. The introduction of AFFF was particularly desirable to the US military complex because it offered rapid extinguishment time, which was considered critical for military crew safety, especially when considering the additional hazards posed by the presence of munitions and related equipment as well as fuel spills at a given fire scene (NAVSEA 2019).

AFFF is formulated with fluorosurfactants, which are part of a class of chemicals known as per-and polyfluoroalkyl substances (PFAS). Additional types of firefighting foams, including film forming fluoroprotein foams (FFFP) and fluoroprotein foams (FP), also contain fluorosurfactants (IRTC 2021).

Up until the early 2000s, the 3M Light Water AFFF product containing perfluorooctane sulfonate (PFOS) was sold and used widely (ITRC 2021). Other forms of AFFF were also used which contained polyfluorinated precursors that could degrade to PFOA (ITRC 2021). As a result of the US Environmental Protection Agency's (US EPA) PFOA stewardship program, between 2010 and 2018 some AFFF was reformulated to diminish levels of PFOS and PFOA content (otherwise known as C8 compounds) and increase the concentration of C6 using perfluorohexanoic acid (PFHxA) precursors such as 6:2 fluorotelomer sulfonate (6:2 FTS) derivatives (ITRC 2021; US DoD 2018; ASTSWMO 2015; Peshoria et al. 2020).

These compounds, while considered key to the "film forming" capability of AFFF, are hazardous to human health and the environment. A growing body of scientific evidence documents that exposure to PFOA, PFOS and additional PFAS are associated with a range of health impacts, including changes in liver enzymes, decreased birth weight, increased cholesterol levels, decreased vaccine response in children, and increased risk of kidney and testicular cancer among other health impacts (ATSDR 2021; Fenton et al. 2021). In addition, PFOS and PFOA are extremely persistent, mobile and bioaccumulative (ATSDR 2021; Lindstrom et al 2011). Analysis of shorter chain AFFF products in 2004 revealed that 20% of the PFAS present were PFOA precursors that had the potential to form PFOA in the environment (Ross and Storch 2020). Although a full understanding of the toxicity of shorter-chain PFAS is still emerging, there are concerns especially regarding breakdown/transformation products of 6:2 FTS under certain environmental conditions, such as the formation of PFHxA which is extremely persistent and mobile in the environment (Rice et al. 2020; Danish EPA 2015; Ross and Storch 2020; ATSDR 2021).

AFFF is a known source of drinking water contamination throughout the US and globally. As of 2017, the US Department of Defense (US DoD) tested 2,445 off-base public and private drinking water systems (US DoD 2019). Nearly 25% of which had PFAS levels that far exceed regulatory drinking water standards now in place in several states (US DoD 2019). Analyses by non-governmental organizations in the US suggest that drinking water sources for over 110 million people in the US may be contaminated by PFAS (EWG 2019). Areas included among the priority sources of contamination are US DoD facilities, municipal and airport firefighting training facilities, and legacy sites where AFFF was used to extinguish residential and industrial fires (EWG 2019).

Industries representing a broad range of firefighting scenarios have transitioned to PFAS-free alternatives, including emergency response and fire and rescue operations in the chemical industry, airports, bulk fuel storage, ports, oil and gas platforms, refineries and some military operations (IPEN 2018). Firefighting foams and their delivery systems have evolved to be far more effective, without a need for PFAS in most circumstances. The first PFAS-free foams were successfully tested at large scale in 2002, with evolving improvements in performance (Ross 2019). Substitution efforts to date have mostly occurred outside of the US, mainly in Europe and in Australia. In the US, restrictive policies are supporting initiatives to identify, evaluate, and adopt PFAS-free alternatives, although substitution efforts are on a slower pace. The National Defense Authorization Act (NDAA) of 2020 requires the US DoD to revise its military performance specification (MIL-PRF-2435F(SH)) (MilSpec) for AFFF to include PFAS-free foams for shore-based applications by 2023 and to phase out the military's use of AFFF by 2024 NDAA 2020). In addition, a number of municipalities and states have issued regulations prohibiting the sale and/or use of PFAS for firefighting training purposes – currently 14 states and growing (Safer States 2021).

Lessons learned from efforts to substitute chemicals of concern to date reveal that even if alternatives are available, implementation of the alternatives can be challenging, and a broad transition may be limited. As outlined by the European Chemicals Agency (2011), implementing alternatives often requires:

- Assurances that alternatives can be produced in sufficient quantities.
- Investments that take resources (time and money) to plan necessary changes such as purchasing and installing needed equipment to train personnel.
- New regulatory approvals or demonstration of meeting specific institutional standards or specifications.
- Customer approvals to ensure that alternatives perform as needed for specific use scenarios.

The US National Academies (2014) expanded on these elements and included additional challenges such as:

- Additional process design or formulation chemistry changes to achieve the necessary functionality that may not have been considered or identified during research and development stages.
- Changes in environmental safety and health management practices to ensure that residual risks associated with the alternatives are sufficiently controlled across the life cycle, including controls for workers, the public and the environment during manufacturing, point of use, and disposal.

Further the incumbency or "lock-in" of existing chemistries, built on existing, capitalized infrastructure and highly integrated into production systems may inhibit innovation and adoption of alternatives (Fennelly, 2015).

II. Objective and Methods

To support an effective transition to safer and feasible PFAS-free alternatives to AFFF in military applications and beyond, this project sought to explore lessons learned from existing efforts to accelerate the adoption of substitutes for AFFF. Key objectives included:

- An understanding of critical technology, market or policy factors (actual and perceived) that are inhibiting the implementation of alternatives to AFFF.
- An understanding of critical technology, market or policy factors that are enabling and scaling a transition to safer and feasible alternatives to AFFF.
- An understanding of lessons learned from DoD's current efforts to accelerate the adoption of safer and effective AFFF alternatives that can improve efforts to address future material challenges.

Key informant interviews were conducted to explore barriers and enablers in transitioning from AFFF to alternatives. Seventeen interviews were conducted with a range of stakeholders both domestically and internationally to explore challenges and successes in the deployment and adoption of PFAS-free firefighting products. Interviews were conducted with US fire suppression experts, DoD procurement officials, European defense agency environmental safety and health officials, alternative AFFF product developers including those at the R&D and commercialization stages, US fire marshals, emergency management agencies, state environmental departments, and airport firefighting personnel in the US, Europe and Australia. Reviews of the literature, including peer-reviewed publications and reports in the gray literature, were used to delve deeper into topics and themes that emerged in the interviews. Interviews were supplemented by conversations held as part of meetings convened by the US Department of Defense's Strategic Environmental Research and Development Program and its Environmental Security Technology Certification Program (SERDP/ESTCP) program team. Factors that were explored included:

- Difficulties for new alternatives to compete with the incumbent product given issues such as existing infrastructure, established global supply chains, costs, and entrenched supplier-customer relationships.
- Confusion such as potentially conflicting information from studies and research, policy uncertainties, etc.
- Concerns about regrettable substitutions from an environmental health and safety perspective.
- Increased cost.
- Performance, including incompatibility concerns.
- Transition challenges including training, decontamination, and waste.

Perspectives of interviewees are considered confidential and are described in the report in the aggregate. Non-attributed quotes are used in the report to help illuminate notable themes on the primary inhibitory and enabling factors identified.

III. Primary Inhibitory Factors: Transitioning to AFFF Alternatives

Across interviewees and the literature, five primary factors were repeatedly identified that are inhibiting an effective transition to safer and feasible AFFF alternatives. These include: (A) transition costs; (B) lack of knowledge of performance for specific real-world scenarios; (C) substitution regret; (D) constraining standards; and (E) lack of a coherent national transition strategy. Each are reviewed below.

A. Transition Costs

Transition costs that are inhibiting an effective transition to AFFF alternatives are multi-faceted. Based on the experience of early PFAS-free adopters in Europe and Australia, the purchase cost of PFAS-free products is competitive with AFFF products (Wood, Ramboll and Cowi, 2018). However,

additional costs were highlighted as significant barriers associated with the adoption of PFAS-free alternatives, including equipment changes, decontamination challenges, and disposal.

Equipment Changes

If current users of AFFF decide on their own, or due to future regional, state or national regulations or programs, to switch out their current AFFF-contaminated fire suppression equipment, interviewees estimated the total quantity of equipment and components that would need replacement to be in the range of 7,500 to 9,000 parts. These include, for example, foam delivery components, such as proportioner pumps, jets and nozzles for discharge (Wood, Ramboll and Cowi, 2018). Replacement costs for specific components are not prohibitive, ranging from ~$6 - ~$200 (converted from Euros) or ~$3,100 for mobile foam units (Wood, Ramboll and Cowi, 2018). However, a recent 2020 progress report from DoD's Per and Polyfluoroalkyl Substances Task Force estimated retrofit costs at nearly $200,000 per vehicle and anticipated that that Aircraft Rescue and Firefighting (ARFF) vehicles may need to be replaced in total, exacerbating cost concerns. Replacement of the US DoD's ~3,000 ARFF vehicles would cost from $4 to $6 billion and may take over 18 years given current commercial production capacity (US DoD, 2020). However, commercial airports in the US employ nearly twice the size of the DoD ARFF fleet (US DoD, 2020). Such costs spiral upwards and will impact the availability and vehicle replacement timelines. Costs associated with equipment replacement for municipal fire vehicles are not currently available nor are the costs for those who use AFFF in industrial sprinkler systems.

Replacing this volume of equipment and components with a transition away from AFFF to PFAS-free alternatives will be a major undertaking due to both the barriers of cost as well as supply. If fire authorities choose to use existing equipment and components, there are concerns about residual PFAS contamination and costs associated with decontamination.

One solution to this barrier noted by interviewees is to replace fire equipment and vehicles alongside a transition to PFAS-free alternatives. The Swedish Air Force is planning to address the issue of transition costs as well as concerns about PFAS contamination of their ARFF vehicles after adoption of AFFF alternatives by coordinating their need to replace 22 vehicles in their fleet with timelines for AFFF substitution. Schiphol Airport in Amsterdam also adopted this strategy and successfully adopted a substitute foam alongside the procurement of its new ARFF trucks (Bruinstroop 2021). Others have noted that based on recent experience within the UK fire services, no new equipment was needed in the transition to PFAS-free foams. Direct experience will help to illuminate whether the concerns regarding transition costs have been over estimated.

Decontamination Challenges

PFAS decontamination of existing firefighting trucks and equipment was noted during interviews as a significant substitution barrier. Future entities transitioning to PFAS-free products will need to address the issue of PFAS contamination of their existing equipment, whether with a decontamination process, through purchasing new equipment, or planning to replace equipment at the end of its intended lifespan, as in the case of the Swedish Air Force. Without employing decontamination processes, use of PFAS-free products can create future liabilities related to environmental impacts at application areas. In one case study, samples of fire suppression systems that substituted with a PFAS-free products 20 months earlier demonstrated PFAS concentration in the foam as high as 1.6 g/L after employing a double water rinse clean out method (Ross and Storch 2020). It is believed that PFAS from the former AFFF products are bound to the surface of the fire suppression equipment and can self-assemble into multiple layers of a waterproof coating that continue to dissolve into the substitute

foam with use (Ross 2021a; Ross and Storch 2020). Such circumstances can reduce the benefit of switching to PFAS-free foams without an equipment change or proper decontamination.

Interviewees cited a very broad range for decontamination costs: $3,000 to $50,000 per fire truck. However, recent experience suggests that onsite assessments can help to determine whether equipment components need to be "removed and replaced" or "cleaned and retained" resulting in significant cost savings and risk reduction (Horst et al. 2021; Ross and Storch 2020). For example, components that are single use or never contained nor in contact with AFFF do not need cleaning nor replacement. Components such as the interior workings of firefighting equipment that are inaccessible are best cleaned as replacement would require significant costs and prolonged maintenance time that would impact the availability of the fire suppression unit. Newer cleaning agents are coming online that demonstrate efficacies and are orders of magnitude more effective than employing a double water rinse or using hot water (Ross 2021a). For the interior surface of fire suppression systems that were in direct contact with AFFF, it is often more cost efficient to replace certain parts rather than cleaning (Horst et al. 2021).

Interviewees in the US looking to transition from AFFF to PFAS-free products stated uncertainty in what will be required for decontamination of their existing trucks and equipment that have housed AFFF. They voiced a lack of communication and direction from any governing body regarding requirements for decontamination and the lack of currently available financial resources to cover the transition, including disposal costs. Having a well-developed, site-specific strategy in a foam transition could best be accomplished by utilizing a qualified team of fire engineers, environmental engineers/scientists, technology providers, equipment specialists, and operations contractors. Incorporating a cost-benefit analysis regarding whether the situation calls for a "remove and replace" or a "clean and retain" could assist with cost savings and optimizing risk reductions (Horst et al. 2021).

Disposal

PFAS waste disposal can be complicated and quite expensive. US fire marshals interviewed for this project do not currently have any guidance on proper disposal of their legacy AFFF product, their contaminated equipment, nor their contaminated rinse waters. They await guidance on future disposal options, including who will pay for the disposal, whether their state, DoD or some other entity. With an estimated cost of $50 per gallon to dispose of AFFF product, disposing of the legacy foam will be very expensive, especially for large cities, with an estimated 11,000 gallons of AFFF to dispose of, equaling with a potential disposal cost for just the foam of $550,000.

"That disposal piece is a big unknown right now for a lot of people; a lot of (US) states."

Disposal of PFAS products also can impart indirect costs, including continued releases of PFAS into the environment from disposal techniques. Use of incineration is under scrutiny due to evidence of incomplete destruction of PFAS and increasing levels of contamination, including PFAS being identified in residences surrounding incineration facilities (Ross and Storch 2020; Lerner 2020). Alternative destruction technologies is currently an area of active research by the US EPA and other government agencies and research institutes (US EPA 2020). As mandated in the 2022 NDAA, a moratorium on the incineration of AFFF went into effect in April 2022.

B. Lack of Knowledge of Performance in Specific Real-World Scenarios

Standard setting organizations use small scale fire testing to support alternative foam performance certifications. Yet some interviewees questioned an over-reliance on these small-scale fires as proof that products will work as needed under the harsh and demanding conditions of a major fire incident. Some users express concern about how the performance of the new PFAS-free products differ from their experience with AFFF. With AFFF, there is long-standing experience and associated trust such that "proof of concept" testing is simply insufficient to overcome the perceived risk involved when adopting alternative firefighting products. The majority of PFAS-free alternatives developed to date lack the film forming capacity of AFFF. Although this may not be an issue for a small-scale pan fire, some of the interviewees questioned such implications for real world fires and assume that tactical changes in how fires are fought will be needed. They also question if more ARFF vehicles and additional fire personnel would also be needed. The direct experience of peer firefighting authorities is also not sufficient to answer these questions. Users see their own needs and use scenarios as being unique compared to scenarios where evidence is currently available, for example in fires where explosive material or munitions may be present.

> *"The lack of real-scale tests is holding people back."*
>
> *"The standards show proof of concept, but I'm not convinced about their applicability to the military context."*

Heathrow Airport in London is now using PFAS-free alternatives. In a recent article, Heathrow's Fire Service Compliance Manager noted that the PFAS-free product they are using has, "no operational problems and performs perfectly in an ARFF setting. Since purchasing our fluorine free foam, we have used it on two separate aircraft fires, and it worked perfectly." Project interviewees in the US airports have also tested PFAS-free products using existing equipment without any problems. The Danish Air Force indicated they have used PFAS-free products in real world scenarios with good results. LASTFIRE tests have been performed in 2021 proving multiple PFAS-free foams can successfully extinguish very large-scale fires (some 50m in length) in a variety of tests using application rates outlined by the National Fire Protection Agency. However, this evidence is not enough for some users who need additional assurances to better understand the capacities of various PFAS-free products specifically in *their* firefighting scenario or setting.

C. Substitution Regret

Interviewees expressed concern about being an early adopter of PFAS-free firefighting foam products because of the potential for substitution regret if the product they transitioned to is determined not to be what will be required or approved for use in the future. Some US airports have switched to PFAS-free products for the structural environment (buildings, etc.), but are awaiting the Federal Aviation Administration (FAA) to authorize their use for aircraft rescue and firefighting. Although such decisions were anticipated in October 2021 per the FAA Reauthorization Act of 2018, which directed the FAA to cease requiring the use of fluorinated chemicals to meet its fire extinguishment performance standards within three years, no PFAS-free alternative has been approved for use. In its statement issued on October 4, 2021, the FAA stated, that "while fluorinated

> *"PFAS-free manufacturers need to pitch to users about the lack of persistence, biodegradability and mobility attributes given these hazards in AFFF. But for many, the hazard information still isn't available, especially based on testing at the product-level."*

foams are no longer required, the existing performance standard for firefighting foam remains unchanged" (FAA 2021). This situation has created a barrier for US airports that want to transition to PFAS-free products for their structural environment, but still need to have available AFFF onsite as required by the FAA for aircraft rescue operations.

Interviewees also expressed concerns about the potential for regrettable substitutes from an environmental health and safety perspective. Given the health and safety rationale for substituting AFFF alternatives, there remain lingering questions about the safety of PFAS-free products. Data provided on a safety datasheet are insufficient for revealing the health and environmental hazards to new users (NRC 2014). Although the general approach to understanding the hazard of alternative products is focused on the ingredient level, that information may not be available. Further, interviewees expressed the need to test the full product for key endpoints, especially knowing that it will be released to the environment. Some PFAS-free alternatives to AFFF lack data regarding persistence and bioaccumulation, two key hazard traits of PFAS that alternatives need to avoid (Wood, Ramboll and Cowi, 2018). Some alternatives show hazards related to aquatic toxicity – also a concern knowing that releases to the environment will be commonplace (Wood, Ramboll and Cowi, 2018; Hoverman 2021). Enhancing understanding of the hazards of PFAS-free alternatives to AFFF will provide more confidence to new customers and clarify what additional risk mitigation measures will be needed to ensure that emergency personnel, the public and the environment are protected. The US DoD's SERDP program is sponsoring research to test the ecotoxicity of a number of commercially available PFAS-free AFFF substitutes at the product-level (US DoD 2022). This research is being supported in part by requirements in the FY 2021 NDAA for DoD to prioritize research on AFFF alternatives that utilize "green and sustainable chemicals that do not pose a threat to public health or the environment" (NDAA 2021). Programs such as the GreenScreen Certified™ standard for PFAS-free firefighting foams may also ease some concerns.

D. Standards

Regulations and performance standards can both hinder and support a transition away from AFFF use. Standards can run the risk of over prescribing performance needs, inhibiting innovation in safer products/technologies given testing costs and, depending on how they are written, can lock in only one type of technology to achieve the performance function needed. The MilSpec provides important lessons regarding the danger of developing overly prescriptive standards that lock-in the use of only one type of technology to achieve the function of fire extinguishment/ suppression and that are designed for a "worst-case" scenario. Although the Danish military and dozens of airports in Europe and Australia are now using PFAS-free alternatives, adoption of such AFFF substitutes by US airports and its military is in a holding pattern – still hampered by existing standards. Unlike standards for firefighting foams used in Europe such as International Civil Aviation Organization (ICAO) or the European Standard, EN 1568, that have guided the adoption of PFAS-free

"I don't believe we will be able to make this transition in the US unless the FAA and DoD give up on the standard of 'equal replacement'….I believe that whatever we find as a suitable replacement will not be equivalent. I just need the men and women to be able to put out that fire."

"We don't need an equal substitute for the MilSpec…maybe on a ship but not in other applications."

"Is the point to put the fire out or to provide a rescue path …such as to get off the plane? If it's that significant of a fire, the plane is likely lost anyway (without having AFFF to put it out quicker than water only…)"

alternatives in numerous European countries, both US airports and the US military are limited by provisions in the MilSpec, which mandates the use of fluorinated surfactants in firefighting foams and dictates specific mechanisms and equipment compatibility requirements that only fluorinated products can achieve. ICAO and EN 1568 standards were not written around the capacities of AFFF and thus never precluded non fluorinated products from achieving the specified fire extinguishing performance criteria.

Legislative mandates within the FAA Reauthorization Act of 2018 and the US NDAA of 2020 have paved the way for both airports and the military to phase out their use of AFFF – a significant enabling factor to the transition to PFAS-free alternatives. Yet progress is on a much slower time scale than elsewhere. A revision to the MilSpec is in process, in line with the National Defense Authorization Act of 2020, which mandates the US military to phase out fluorine-based firefighting foams by 2024. As outlined in the FAA Reauthorization Act of 2018, the FAA no longer sets forth requirements for US airports to use fluorinated foams. However, airports remain in a predicament as AFFF remains the only product approved for use by the FAA for aircraft rescue and firefighting operations. The FAA has not met the October 4, 2021, deadline outlined in the FAA Reauthorization Act of 2018 to phase out use of AFFF. In its October 4, 2021, memo the reasons for not moving forward were the inability to identify alternatives that had equivalent performance to AFFF and that existing alternatives could not act as a drop-in replacement (FAA 2021).

> *"If my peers around the world do it [i.e., use PFAS-free products] so can we."*

There is an array of standards related to the use of firefighting foams. This has created confusion related to procurement among some entities. According to interviewees, firefighting foam customers have outlined requirements in their procurement specifications for certifications related to multiple standards that have competing attributes. For example, one standard may favor a foam that spreads quickly over a fuel, while another may favor a foam that penetrates deeper and sticks to substrates to resist burn-back.

Today's firefighting solution may be different than tomorrow's solution. Interviewees expressed the barrier of standards in limiting continued innovation in fire extinguishment technologies for Class B fires due to costs involved in achieving certifications. For example, interviewees noted a $150,000 cost per fire performance test to receive an Underwriters Laboratories (UL) listing. Smaller manufacturers often don't have the budget to undergo certification tests for multiple formulations. One PFAS-free product manufacturer interviewed noted that these cost barriers inhibit manufacturers to innovate further given the dynamics of internal incumbency once specific performance standards/certifications have been achieved. Depending on the amount of tests/listings needed, the cost can run into the millions of dollars for multi-component or multiple formulations of products. However, interviewees also noted that companies do innovate to a standard. In the case of the MilSpec, the revised version will likely require the use of Newtonian (e.g., low viscosity) products whereas most products available currently are non-Newtonian (high viscosity) products. Learning of this provision, several manufacturers have recently launched Newtonian products, showcasing that standards can also drive innovation in specific directions as well.

E. Lack of a Coherent National Transition Strategy

Many end users in both the US and abroad have stated the need for guidance and support as they substitute fluorinated firefighting foams with PFAS-free alternatives. In the US, many states are using AFFF only in emergency measures, but have not received any further guidance from government agencies about next steps such as decontamination needs or new PFAS-free options that are both safer and feasible. Without a national transition strategy in the US, end users such as fire departments and airport fire and rescue/facility personnel are particularly struggling with more questions than answers, such as:

> *"There should be an entity in D.C. that would hold the three areas of health, safety, and environmental performance standards accountable…maybe in the FAA or the DoD."*

- Will the substitution requirements be voluntary or regulatory?
- Will the guidance be issued from the states or from the federal government?
- Who will define criteria for an alternative?
- Who will develop a standard of what is considered "clean" when decontaminating equipment?
- Who will coordinate and implement the decontamination process?
- Where should contaminated components/equipment be sent for disposal and who bears the cost?
- Will there be technical support offered to help change and/or tune equipment and firefighting techniques to maximize the performance of alternatives?
- Who will issue new training guidance?
- What residual human and environmental risks need to be mitigated with regard to the PFAS-free alternatives and what are the strategies for doing so?
- Who will coordinate the collection and final disposal of the legacy fluorinated foam products?

Some interviewees suggested that a potential solution could be the establishment of regional/centralized "cleaning" centers for the decontamination needs. No strategy is available that addresses these needs, and no national agency or interagency task force has taken responsibility for issuing such a strategy.

IV. Primary Enabling Factors: Transitioning to AFFF Alternatives

Several factors were identified among interviewees as critical to accelerating a transition to AFFF alternatives. Several of these are counterpoints to the barriers noted above. Primary enabling factors included: (A) "just do it" – using mock exercises to understand performance of alternatives and adoption needs; (B) financial liabilities with continued use of AFFF; (C) fit-for-purpose performance standards; and (D) policy mandates.

A. "Just do it": Use of Direct Experience and Mock Exercises to Understand Performance of Alternatives and Adoption Needs

Some entities have already made the transition to PFAS-free firefighting foam products with their existing technology (nozzles, aspirators, etc.). In the early 2010's, based on a parliamentary mandate, the Danish Royal Air Force directed its airports to stop using AFFF products within a two-day period,

requiring them to send the legacy product to a central collection site. This was feasible due to their small size and the military governance structure. They received a PFAS-free product to use, and after a couple weeks of adjustment with their equipment to get the correct product viscosity and percentage, they made the transition. It should be noted that they were not required to decontaminate trucks nor equipment.

> *"(The Danish Royal Air Force) delivered the new (FFF) product just in time…the day after we got rid of the old one, we got the new one so that it was quick and easy for us to adapt to the new foam because it worked almost exactly as good as the old one."*

LastFire's large-scale "real life" testing program for tank fires is another example of what is needed for end users in other firefighting scenarios to further understand the capacities of PFAS-free products and what is needed to maximize performance (LastFire undated). This collaborative testing program included the participation of six PFAS-free product suppliers who helped to contribute to the effort by providing funding for fuel costs as well as supplying products for the test (LastFire undated). The US DoD has recently also conducted a large-scale test of 5 commercially available PFAS-free alternatives at its China Lake Facility to support further understanding of product capabilities (Back 2021). Test results suggest that the capabilities of the alternatives mirror the pilot-scale test results in terms of extinguishment times (Back 2021). One interviewee suggested a facilitated convening between those who remain unsure/unclear about the effectiveness of PFAS-free products and those that have converted. Such a meeting would show video recordings of large-scale tests and subsequent discussion could address residual questions, including: (a) effectiveness; (b) anticipated changes to equipment and (c) anticipated changes to firefighting tactics.

B. Financial Liabilities with Continued Use of AFFF

Realization of financial liabilities has provided significant motivation for numerous early adopters to substitute their fluorinated firefighting foams. While some end users who adopted PFAS-free alternatives early raised concerns about financial losses if these are not eventually approved others described a growing trend especially among industrial facility insurers to limit insurance coverage or simply not pay for any type of potential liability associated with PFAS discharges or contamination as part of a fire suppression scenario. Additional liabilities also include potential litigation associated with the past use of PFAS-containing foams that may result in local/regional contamination issues. This is a significant factor motivating users to transition to PFAS-free alternatives.

> *"The main point for facilitating change is with the end-user, once they realize that they carry all the liability (not the manufacturer, not the supplier, not the incident controller) they are the polluter, they are responsible and that the Polluter Pays."*
>
> *"The costs of transition including equipment changes can be significant or not depending on the circumstances, however, the costs are far outweighed by the risks and liabilities to the end-user, other industry and the community of harm caused by PFAS releases on a very broad range of community and environmental values."*

C. *Fit for Purpose Performance Standards*

Based on existing performance testing of PFAS-free alternatives against the current MilSpec, no PFAS-free product can extinguish a 28 ft^2 pan fire within the 30 second requirement of the specification, but several can do so within 45 seconds (Back 2021). Interviewees noted the importance of considering comparable performance versus equivalent performance when it comes to identifying feasible substitutes for fluorinated firefighting foams. Rather than performance standards that are written for the worst-case scenario – as the MilSpec is perceived – interviewees encouraged standards that fit the purpose of a given firefighting scenario. Such standards would help to certify that a product meets a required level of fire extinguishment performance for the most likely event while also recognizing the range of firefighting scenarios that exist. ICAO was mentioned as an example, such that it certifies products based on three levels of performance (levels A-C) leaving it to users to decide which level of performance is necessary for their fire incident needs. To address the issue of different scenarios, use of multiple standards that reflect such scenarios, rather than a one size fits all approach, was also encouraged.

> *"Matching performance and capabilities with various scenarios will be key going forward."*
>
> *"The terminology used to describe the performance difference between a flurosurfactants based foam and a fluorine free (foam) in Europe has been 'comparable' performance…and that some fluorine free foams are better than some C6 AFFF's in putting out fires and some AFFF's are better than some fluorine free foams…they are exhibiting comparable performance."*

D. *Policy Mandates*

Policy mandates are clearly an enabling factor supporting a transition in the use of PFAS-free firefighting alternatives. As is the case with most chemical substitution efforts, policy is a key driver (Tickner et al. 2019). These mandates have come in various forms, including: (a) changes in policy handed-down from institutional leadership as is the case with dozens of airports and decisions by military officials in Scandinavia, (b) government mandates, such as national policies issued by the Queensland Government of Australia, New Zealand and through programmatic reauthorization legislation issued by the US Congress and (c) state-level government policies in the US, among others.

> *"The Queensland (Australia) foam policy was seen as setting a new best-practice standard with industries operating across Australia, so the support extended to other State regulators, large industry operators and fire brigades using the Queensland Policy as a performance benchmark"*
>
> *"Once the mandate [US National Defense Authorization Act of FY 2020] came online you see all these industries coming up with new products and experiencing progress very quickly."*

The anticipatory effect of potential changes in regulation and policy is also a powerful force for change. The PFAS-free transition at Schiphol Airport in Amsterdam was stimulated in part because their supplier was no longer going to produce/distribute C6 foams due to the increased regulatory focus on PFAS-containing firefighting foams (Bruinstoop 2021). To signal intentions to users and allow for the necessary transition time, funding and training, draft policies, such as those from the Queensland Government, have been an effective tool for industry and other end users. Such policies give end users time to consider all the options as well as time to address decontamination needs of existing equipment (Queensland Department of Environment and Science 2016). The Queensland Government worked

with the firefighting community for six years throughout their policy discussions, an inclusive process that enabled impacted entities to address needs along the way.

In the US, the Federal Aviation Authorization Act FY 2020 (FAA Authorization Act 2019) and the NDAA of FY 2020 (NDAA 2019) included provisions that recognized the main factor limiting adoption of PFAS-free alternatives – the MilSpec. Although the US is a "late-comer" to the transition because of modifications needed to this standard, without the two Authorization Acts, a broad transition in the US would be nearly impossible as the MilSpec dictates use of AFFF in aviation and military firefighting. The National Defense Authorization Act also made possible targeted research support on PFAS-free alternatives. These efforts sponsored through US DoD's SERDP/ESTCP activities have helped to address systematic uncertainties in existing knowledge, including equipment capability concerns with the PFAS-free alternatives as well and concerns regarding health and safety, such as aquatic and terrestrial toxicity, that will benefit both PFAS-free developers and end users alike. This research is being supported by requirements in the FY 2021 NDAA for DoD to prioritize research on AFFF alternatives that utilize "green and sustainable chemicals that do not pose a threat to public health or the environment" (NDAA 2021). Interviewees noted that the pace of innovation in and enhanced understanding of the hazards and performance of available alternatives would not have been possible without policy driver and research support made possible through the mandates.

V. Lessons Learned: Core Recommendations for an Efficient and Effective Transition to AFFF Alternatives and Future Substitution Challenges

Review of Core Findings

This project identified five primary inhibitory factors that are acting as barriers to an effective transition to safer and feasible AFFF alternatives and four enabling factors as outlined in **Table 1**.

TABLE 1: Primary Inhibitory and Enabling Factors Impacting a Transition to Safer and Feasible AFFF Alternatives

Primary Inhibitory Factors	Primary Enabling Factors
Transition costs	"Just do it" – using mock exercises to understand performance of alternatives and adoption needs
Lack of knowledge of performance for specific real-world scenarios	Financial liabilities with continued use of AFFF
Substitution regret	Fit-for-purpose performance standards
Standards that limit innovation	Policy mandates
Lack of a coherent national transition strategy	

A dominant theme across the inhibitory and enabling factors is the issue of performance, including questions about the utility of existing standards, testing programs, compatibility of the PFAS-free alternatives with existing firefighting equipment/components and who decides that a given performance level is sufficient for a given use. There are clear differences of opinion regarding compromising on performance capabilities. As noted earlier, some users feel that we need to move away from seeking replacements for AFFF that are of equivalent performance given that many believe that an alternative's lesser performance is still sufficient in many firefighting scenarios. Others are

simply unwilling to take the chance when seconds matter in the ability for fire and rescue personnel to save lives. Policy mandates however are forcing decisions because the clear risks to human health and the environment outweigh the benefits of continued use of AFFF and other PFAS-containing firefighting foams in many current settings.

Recommendations to Accelerate the Adoption of Safer and Effective AFFF Alternatives

There is growing acceptance that alternatives to AFFF are available. Yet implementation is often the most challenging part of the substitution process and requires planning and ongoing monitoring to identify and minimize potential impacts. The following recommendations to help accelerate successful adoption of safer and effective AFFF alternatives were derived from lessons learned revealed in this project.

A comprehensive and collaborative implementation strategy. There is a clear need for a comprehensive implementation strategy to support the transition to PFAS-free alternatives. The strategy needs to support the various fire and rescue user segments that are currently dependent on AFFF. The strategy needs to recognize the varying policies, standards and procurement specifications that impact the use of firefighting foam products. Such a strategy should be a multi-agency/institution effort given the expertise and engagement needed to address the array of substitution challenges including ensuring a sufficiency of market supply of the alternatives, addressing firefighting performance/technical feasibility needs, addressing decontamination, providing firefighting education and training, addressing occupational health and safety concerns, and ensuring environmental compliance and public health protections related to AFFF decontamination and disposal. Such a national strategy should be incorporated into current White House Council on Environmental Quality's effort to coordinate PFAS-response activities across governmental agencies (White House 2021).

The Fire Protection Research Foundation, a research affiliate of the National Fire Protection Association has launched an effort to establish a Firefighting Foam: Fire Service Road Map, whose stated goal is "to develop a strategy roadmap for the fire service while transitioning from fluorinated foam usage to fluorine free foam technology (Back et al. 2022). This Roadmap is an example of the type of guidance needed. Moving forward, it should be expanded upon in collaboration with other authoritative bodies that have a role to play in supporting fire service personal in the transition to PFAS-free alternatives.

Education and training. Important to any implementation strategy are provisions related to education and training as noted above. Education and training activities need to address the current "resistance to change" that is still being experienced among some facets of the fire and rescue communities. This resistance is experienced in two ways: (a) a lack of understanding of the problem; (b) a lack of confidence about the solutions. Personnel need to be educated regarding PFAS contamination occurring globally and the contribution of AFFF to the problem. They need to understand the risks that PFAS poses to their own health, the health of their colleagues, the public and the environment. As described earlier, some fire personnel have such trust in the performance and comfort associated with working with AFFF that they don't want to change to something different. Overcoming this resistance requires education about the PFAS-free alternatives in order to alleviate concerns about changes in performance as well as fears that their firefighting tactics will have to change dramatically; these fears are not borne out based on current experience. Changes in firefighting tactics need to be anticipated and thus training programs for AFFF substitutes need to be co-developed alongside results from real-world performance tests (Back, 2021).

In addition, education and training programs need to address topics related to the correct use of PFAS-free alternatives, associated equipment needs and changes, as well as specialized topics such as decontamination and treatment of legacy AFFF foams. Changes to routine training programs will need to be co-developed along with the PFAS-free alternatives as changes in firefighting techniques are expected. However, interviewees suggested that fire fighters are eager to be trained on the PFAS-free alternatives and are used to regular training and changes in technique. Virtual reality training programs could be explored (Engelbrecht et al. 2021). Programs should also train with PFAS-free products that will deployed in real incidents that use the same fuels which will be encountered in order to increase confidence in the products' ability to extinguish fires.

Collaborative performance testing/demonstration sites. Real-scale performance tests related to a range of firefighting scenarios is needed to enhance users' understanding of the capabilities of the various PFAS-free products and what is needed to maximize performance. Yet such large-scale comparative tests can be prohibitively expensive. Enhanced collaborative performance tests are needed where the burden of costs is shared among interested parties/organizational partners who also contribute to designing parameters of the testing protocol. Results of such tests need to be broadly disseminated, targeting trade journals/magazines and other media and conference outlets that reach firefighting and facility management professionals.

As mentioned earlier, LastFire and the US DoD's SERDP/ESTCP program provide examples of support for real-scale collaborative performance testing program. In these comparative performance tests, multiple commercially available PFAS-free alternatives were subjected to performance questions relevant to specific fire scenarios, e.g., tank fires, fuel spills, and debris fires (Pepper 2021; Back 2021). Although the testing parameters may not address all residual questions about the performance capabilities in additional firefighting scenarios, these types provide models for future collaborative test programs.

The Massachusetts Toxics Use Reduction Institute has engaged in multiple collaborative performance testing programs over the last two decades. Based on this experience, they outlined 10 criteria to ensure success of such program, which align with the current context of the need for large scale performance testing of PFAS-free substitutes for AFFF (Morose, 2013):

1. Use of a toxic chemical(s) of concern is pervasive in an industry sector
2. The toxic chemical is not used for competitive advantage
3. There are strong market and/or regulatory drivers to reduce the use of the toxic chemical
4. Significant research is required to switch to the use of safer alternatives
5. It is both time and cost intensive for companies to individually conduct research
6. An independent third party is available to manage and coordinate the effort
7. Voluntary participation by government, academic, and industry collaborators is possible
8. Participants provide either in-kind contributions (production equipment, technical expertise, materials, supplies, testing, etc.) or direct funding
9. The intent of participants is to adopt the safer alternative solutions identified
10. All results are made public so that other companies can adopt solutions identified

In addition, the SERDP/ESTCP funding program for AFFF has shown the importance of creating a "collaborative innovation community" of stakeholders working together to accelerate innovation and adoption of safer, and feasible options. Interviewees noted the value of the diverse community created through the SERDP/ESTCP funding for AFFF alternatives, which has allowed researchers, those

conducting performance evaluations, military experts, innovators, and established companies to share and jointly develop knowledge that support solutions. Importantly, one small company creating innovative PFAS-free alternatives noted that without this program they would have never had the resources to develop an alternative that may be available in the future. Given the resources and time horizons needed for commercialization and scale of innovative safer alternatives, and the fact that only currently on market options have sufficient scale for military applications, programs such as this can reduce time to market for new entrants that may be improvements over existing available options. This approach should be repeated for additional chemical challenges faced by DoD.

Systems for ongoing monitoring. Regular monitoring and evaluation are essential to the early identification of potential unintended consequences from the adoption process. Although performance and environmental/human health impact criteria that are deemed critical to making decisions about a safer and feasible alternative should be well understood at the time of adoption, knowledge gaps will remain. Moreover, controlled testing environments cannot address all factors that may impact the feasibility or hazards/exposures of the alternatives under real world conditions. It is therefore imperative to set up systems for ongoing monitoring and evaluation. Systems need to include but are not limited to environmental surveillance programs to monitor for impacts on a broader array of ecological endpoints, testing to ensure adequate capture of PFAS in reused equipment, use of approved validation testing to ensure that new foams are indeed fluorine-free (the appropriate testing method is under discussion at the time of this writing), industrial hygiene evaluations and discussions with firefighting personnel about the impacts of the transition and to adjust training, equipment and standards of practice as needed.

Substitution is a continuous improvement process and decisions should be regularly revisited and updated. Given that innovation in the PFAS-free market is ongoing, there may be safer, better performing, less costly innovations coming on the market in the future. Adoption decisions are based on the best available information at a given point of time. But new information is to be anticipated, especially for newer chemistries, materials and technologies.

Lessons Learned from AFFF to Inform Other Substitution Initiatives

Although substitution efforts for AFFF remain ongoing and not every substitution challenge is the same, there are a series of lessons learned that can be generalized from this experience to inform the adoption of safer and feasible substitutes for future chemical-product challenges going forward. Lessons learned include:

Policy mandates are a critical enabler for substitution. Research and development in alternatives as well as broad implementation of substitutes will always be held back unless there are clear policy mandates that motivate both innovation and adoption. Policy mandates are often the main enabling factor that can overcome the dominant power that incumbent products (such as AFFF) have in the market, enabling a transition to safer and feasible alternatives.

Expand the use of collaborative performance testing and demonstration programs. Users will debate whether existing performance tests are relevant to their needs/use scenarios. Yet performance testing can be prohibitively expensive. Filling gaps in the understanding of performance for specific use scenarios can advance through the expansion of collaborative performance testing programs where costs are shared and distributed among interested user stakeholders, who also are involved in designing the test parameters will support broader trust and understanding of the performance capabilities of alternatives under conditions of use that better align with user's needs. Such collaborative performance testing programs should be combined with demonstration and

knowledge sharing programs where entities that have transitioned can demonstrate their experience and stakeholders can discuss challenges and how these have been addressed. Collaboration is also needed to fill gaps in testing to obtain accreditation for specific uses of PFAS-free products (such as in sprinkler systems) where insurers are still not willing to underwrite risk for facilities using these alternatives.

Changes in processes and equipment need to be anticipated when adopting safer alternatives. Past experiences to date suggest that drop-in replacements are mostly viable when substitutes utilize the same class of chemistry, which may provide little to no advantage in terms of improving health and safety. Examples of this abound and include moving from C8 to C6 alternatives in the case of AFFF (Fenton et al. 2020); moving from bisphenol-A to bisphenol-S in resin can linings (Rochester and Bolden 2015) or substituting methylene chloride with 1-bromopropane in paint stripping applications or for the solvent carrier function used in adhesives (Ichihara 2012). Implementation of alternatives needs to anticipate:

- *Changes to product or process.* Identified acceptable alternatives will likely require process or equipment modifications to achieve the desired performance. Such changes will impart costs associated with the substitution process. Often these costs are considered cost-effective given the overall return-on-investment given decreased regulatory, insurance, and liability costs associated with continued use of the incumbent. In addition, costs can be absorbed if substitutes are implemented at the same time equipment needs to be routinely replaced or upgraded.

- *Changes in work practices.* Implementing alternatives will typically require changes in work practice changes. It is always critical to ensure that changes do not affect worker exposure pathways, increase potential hazards, and affect productivity if they do not work as well as the incumbent product. Training will often be needed to address changes in performance or delivery of alternatives.

- *Continuous improvement needs.* Continued monitoring is needed to reveal new information about potential impacts of alternatives across its lifecycle of production, use and disposal and to adjust standards of practice in the use of the alternative to maximize performance and productivity.

Share information about alternatives. Lack of communication about the viability of alternatives often hampers their adoption. Lack of transparency of ingredient information in formulations hinders research and understanding about hazards. Government agencies, NGOs and trade organizations all play role in sharing and disseminating information about safer and feasible alternatives using forums that best reach user audiences.

Anticipate the need for and the promise of continued innovation. Innovative solutions for a given application can often take 10+ years to commercialize at scale. As such, available substitute for a specific application at a given point and time will evolve. It is important for users to monitor progress in innovations that have the possibility of continued reductions in hazard with equal or better performance for their application of interest. It is also important for government agencies to continue supporting the commercialization and growth of innovative new options. Performance standards and specifications need to also support innovation and avoid criteria around only one product type or option.

VI. Conclusion

There is global interest to replace PFAS containing firefighting foam with safer and effective alternatives. Efforts to date demonstrate that substitution is possible. With continued focus on correcting those factors that are inhibiting the implementation of alternatives to AFFF and replicating/scaling those factors that are enabling substitution, we can collectively accelerate efforts to effectively move beyond the use PFAS containing firefighting foams and towards safer, feasible alternatives.

REFERENCES

ATSDR [Agency for Toxic Substances and Disease Registry]. 2021. Toxicological profile for Perfluoroalkyls. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

ASTSWMO [Association of State and Territorial Solid Waste Management Officials]. 2015. Perfluorinated Chemicals (PFCs): Perfluorooctanoic Acid (PFOA) & Perfluorooctane Sulfonate (PFOS): Information Paper.

Back G. 2020. Capabilities Assessment of Commercially Available Fluorine-Free Agents. WP19-5324. US Department of Defense 2020 SERDP/ESTCP Symposium.

Back G. 2021. What are the actual firefighting capabilities of the best commercially available PFAS-free foams in DoD applications. US Department of Defense 2021 SERDP/ESTCP Symposium.

Back GE, Lieb NJ, Hawthorne E, Grant C. National Fire Protection Agency. 2022. Firefighting Foams: Fire Service Road Map. NFPA Research Foundation. May.

Bruinstoop A. 2021. Experience of Schiphol Airport Amsterdam with FFF. Fire Protection Research Foundation's Firefighting Foams: Fire Service Roadmap Virtual Workshop. October 12-14.

Danish EPA [Danish Environmental Protection Agency]. 2015. Short-chain Polyfluoroalkyl Substances (PFAS) A literature review of information on human health effects and environmental fate and effect aspects of short-chain PFAS Environmental project No. 1707.

Engelbrecht H, Lindeman RW, Hoermann S. 2019. A SWOT Analysis of the Field of Virtual Reality for Firefighter Training. Frontiers in Robotics and AI. 6. https://www.frontiersin.org/article/10.3389/frobt.2019.00101

ECHA [European Chemicals Agency]. 2011. Guidance on the Preparation of an Application for Authorization. European Chemical Agency, Helsinki, Finland. January. Accessed September 15, 2021.

EWG [Environmental Working Group]. 2018. Report: Up to 110 Million Americans Could Have PFAS-Contaminated Drinking Water. May 22. *Note this analysis was updated in 2020, but it did not update the 110 million figure.*

FAA [Federal Aviation Administration] Reauthorization Act of 2018. 2018. H.R. 302 (P.L. 115-254). https://www.congress.gov/115/plaws/publ254/PLAW-115publ254.pdf

FAA [Federal Aviation Administration]. 2021. National Part 139 Cert Alert. No.21-05. October 4.

Fennelly, T. 2015 Advancing green chemistry: Barriers to adoption & ways to accelerate green chemistry in supply chains. Green Chemistry & Commerce Council (GC3).

Fenton SE, Ducatman A, Boobis A, DeWitt JC, et al. Per- and Polyfluoroalkyl Substance Toxicity and Human Health Review: Current State of Knowledge and Strategies for Informing Future Research. Environ Toxicol Chem. 2021 Mar;40(3):606-630. doi: 10.1002/etc.4890.

Hoverman J. 2021. Aquatic systems as a tool for evaluating the toxicity of PFAS-free AFFF. 2021 SERDP/ESTCP Symposium.

Ichihara G, Kitoh, J, Li W, Ding X, Ichihara S, Takeuchi Y. 2012. Neurotoxicity of 1-bromopropane: evidence from animal experiments and human studies. J. Adv. Res.3, 91–98. https://doi.org/10.1016/j.jare.2011.04.005.I

IPEN [International Pollutant Elimination Network]. 2018. Fluorine-Free Firefighting Foams (3F): Viable Alternatives to Fluorinated Aqueous Film-Forming Foams (AFFF). Independent Expert Panel Convened by IPEN. September.

IRTC [Interstate Technology Regulatory Council. 2021. PFAS – Per- and Polyfluoroalkyl Substances. 3. Firefighting foams.

Lerner S. 2020. Toxic PFAS Fallout Found Near Incinerator in Upstate New York. The Intercept. April 28.

LastFire. Undated. Large Scale Test Programme for Storge Tank Fires. Press Release.

Lindstrom AB, Strynar MJ, Libelo EL. Polyfluorinated compounds: past, present, and future. Environ Sci Technol. 2011 Oct 1;45(19):7954-61. doi: 10.1021/es2011622.

NAVSEA. 2019. MIL-PRF-24385. Aqueous Film Forming Foam (AFFF). AFFF Alternatives: Art of the Possible. Nov 19.

Morose, G. 2013. Successful industry collaborations for evaluating the performance of safer chemical alternatives. Green Chemistry & Commerce Council (GC3) Webinar Series. September 11.

NDAA [National Defense Authorization Act]. 2019. National Defense Authorization Act for Fiscal Year 2020. S. 1790 – 11^{6th} Congress (2019-2020). December 20. Accessed May 20, 2021 at: https://www.govinfo.gov/content/pkg/PLAW-116publ92/html/PLAW-116publ92.htm

NDAA [National Defense Authorization Act]. 2021. National Defense Authorization Act for Fiscal Year 2021. H.R. 6395 – 116th Congress (2019-2020). Jan 1. December 20. Accessed May 20, 2021 at: https://www.congress.gov/bill/116th-congress/house-bill/6395

Pepper SR. 2021. Has SFFF Come of Age? Industrial Fire World. July 14.

Peshoria S, Nandini D, Tanwar RK, Narang R. 2020. Short-chain and long-chain fluorosurfactants in firefighting foam: a review. *Environ Chem Let.* 18(4):1277. doi:10.1007/s10311-020-01015-8.

Queensland Department of Environment and Science. 2016. Operational Policy Environmental Management of Firefighting Foam.

Rice PA, Aungst J, Cooper J, et al. Comparative analysis of the toxicological databases for 6:2 fluorotelomer alcohol (6:2 FTOH) and perfluorohexanoic acid (PFHxA). Food Chem Toxicol. 2020 Apr;138:111210. doi: 10.1016/j.fct.2020.111210.

Rochester JR, Bolden AL, 2015. Bisphenol S and F: a systematic review and comparison of the hormonal activity of Bisphenol A substitutes. Environ. Health Perspect.123 (7), 643–650. http://doi.org/10.1289/ehp.1408989.

Ross, I. 2019. Is the burst of the AFFF bubble a precursor to long term environmental liabilities?. International Airport Review. July 29.

Ross I and P Storch. 2020. Foam transition: Is it as simple as "foam out/foam in"? The Catalyst. Q2 Supplement.

Ross I. 2021a Now AFFF is defunct, what's the way forward? International Fire Fighter. June 5.

Ross I. 2021b Decontamination of PFAS from fire suppression systems The JOIFF Catalyst Q4 2021

Safer States. Bill Tracker. Accessed September 14, 2021.

Tickner J, Jacobs M, Bekarian-Mack N. 2019. Alternatives assessment and informed substitution: A global landscape assessment of drivers, methods, policies and needs. Sus Chem Pharm. 13:100161. https://doi.org/10.1016/j.scp.2019.100161

US DoD [United States Department of Defense]. 2018. Alternatives to Aqueous Film Forming Foam – Report to Congress. Under Secretary of Defense for Acquisition and Sustainment. June.

US DoD [United States Department of Defense]. 2020. Per- and Polyfluoroalkyl Substances (PFAS) Task Force. Progress Report. March.

US DoD [US Department of Defense]. 2019. Drinking Water Contamination Report to Congress. Under Secretary of Defense for Acquisition and Sustainment. July.

US DoD [US Department of Defense]. 2022. News and Events – Ecotoxicity of Novel PFAS-free Firefighting Formulations.

US EPA [US Environmental Protection Agency]. 2020. Technical Brief: Per- and Polyfluoroalkyl Substances (PFAS): Incineration to Manage PFAS Waste Streams. February.

US NRC [United States National Research Council]. 2014. A framework to guide selection of chemical alternatives. Washington (DC): National Academies Press.

White House. 2021. Fact Sheet: Biden-Harris Administration Launches Plan to Combat PFAS Pollution. October 18.

Wood, Ramboll and Cowi. 2018. The Use of PFAS and Fluorine-Free Alternatives in Fire-Fighting Foams. Report for European Commission and the European Chemicals Agency. June.

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