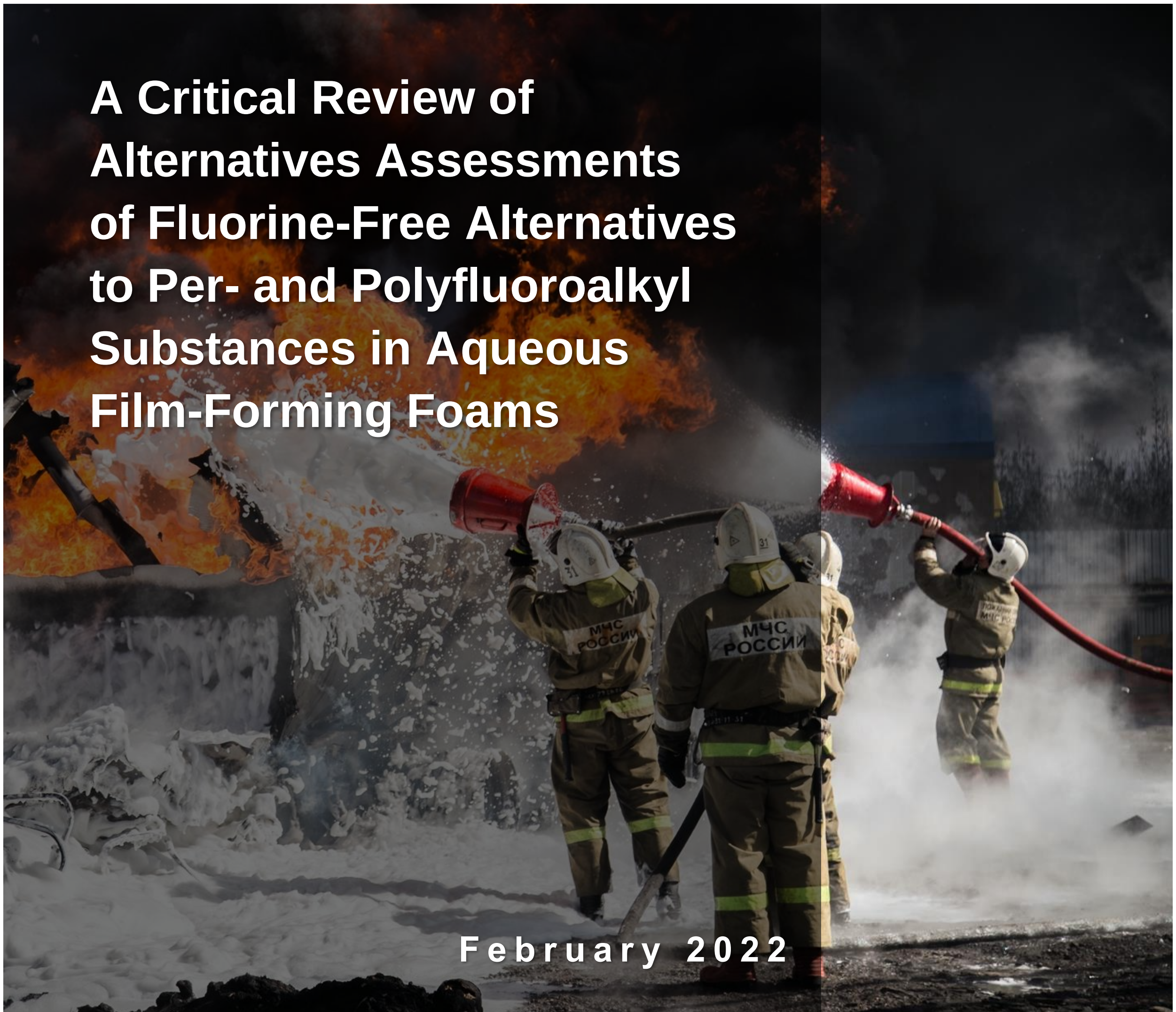
UMASS University of Massachusetts Lowell

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



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Sustainable Chemistry Catalyst

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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 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]* | Understand performance efficacy to fight various types of fires, including liquid fuel fires (Class B) – compliance with specific international performance standards. |
| | | Conduct performance tests based on specific standards to indicate likelihood of satisfying the performance criteria within accepted tolerances. *[more comprehensive assessment]* | |
| | 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)<br><br>No "real world" use identified | Class B hydrocarbon fuels at 3% and polar solvent fuels at 6%/ Class A fuels<br><br>Used for airport fire service, rescue, and training<br><br>Copenhagen Airport; Melbourne Metropolitan Fire Brigade | Class B hydrocarbon fuels (see limitations below) Class A fuels<br><br>Used at offshore facilities in Norway | Polar and non-polar hydrocarbons and their mixtures (Class A and B)<br><br>Used at Swedish airports, UK Heathrow airport, and Norwegian offshore oil sector | Non-polar hydrocarbon fires<br><br>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<br><br>Actual use experience unclear, but product specification states use in oil, chemical, pharmaceutical, aviation, marine and fire/rescue industries | Aviation, petrochemical sector<br><br>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.

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